

**UNITED STATES DEPARTMENT OF COMMERCE**

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**Photon Cross Sections, Attenuation Coefficients,  
and Energy Absorption Coefficients  
From 10 keV to 100 GeV**

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## Foreword

The National Standard Reference Data System is a Government-wide effort to provide for the technical community of the United States effective access to the quantitative data of physical science, *critically evaluated and compiled for convenience, and readily accessible through a variety of distribution channels.* The System was established in 1963 by action of the President's Office of Science and Technology and the Federal Council for Science and Technology.

The responsibility to administer the System was assigned to the National Bureau of Standards and an Office of Standard Reference Data was set up at the Bureau for this purpose. Since 1963, this Office has developed systematic plans for meeting high-priority needs for reliable reference data. It has undertaken to coordinate and integrate existing data evaluation and compilation activities (primarily those under sponsorship of Federal agencies) into a comprehensive program, supplementing and expanding technical coverage when necessary, establishing and maintaining standards for the output of the participating groups, and providing mechanisms for the dissemination of the output as required.

The System now comprises a complex of data centers and other activities, carried on in Government agencies, academic institutions, and nongovernmental laboratories. The independent operational status of existing critical data projects is maintained and encouraged. Data centers that are components of the NSRDS produce compilations of critically evaluated data, critical reviews of the state of quantitative knowledge in specialized areas, and computations of useful functions derived from standard reference data. In addition, the centers and projects establish criteria for evaluation and compilation of data and make recommendations on needed modifications or extensions of experimental techniques.

Data publications of the NSRDS take a variety of physical forms, including books, pamphlets, loose-leaf sheets and computer tapes. While most of the compilations have been issued by the Government Printing Office, several have appeared in scientific journals. Under some circumstances, private publishing houses are regarded as appropriate primary dissemination mechanisms.

The technical scope of the NSRDS is indicated by the principal categories of data compilation projects now active or being planned: nuclear properties, atomic and molecular properties, solid state properties, thermodynamic and transport properties, chemical kinetics, colloid and surface properties, and mechanical properties.

An important aspect of the NSRDS is the advice and planning assistance which the National Research Council of the National Academy of Sciences-National Academy of Engineering provides. These services are organized under an overall Review Committee which considers the program as a whole and makes recommendations on policy, long-term planning, and international collaboration. Advisory Panels, each concerned with a single technical area, meet regularly to examine major portions of the program, assign relative priorities, and identify specific key problems in need of further attention. For selected specific topics, the Advisory Panels sponsor subpanels which make detailed studies of users' needs, the present state of knowledge, and existing data resources as a basis for recommending one or more data compilation activities. This assembly of advisory services contributes greatly to the guidance of NSRDS activities.

The NSRDS—NBS series of publications is intended primarily to include evaluated reference data and critical reviews of long-term interest to the scientific and technical community.

A. V. ASTIN, *Director.*

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# Photon Cross Sections, Attenuation Coefficients, and Energy Absorption Coefficients From 10 keV to 100 GeV\*

J. H. Hubbell

This report updates and extends previous NBS tabulations. Section 1 contains the information of most immediate practical use: (a) a tabulation of the attenuation coefficient for 23 elements ( ${}_{1}H$  to  ${}_{92}U$ ) between 10 keV and 100 GeV and (b) a tabulation of the energy absorption coefficient for air, water, and 18 elements between 10 keV and 10 MeV, and for air, water, and 7 elements up to 100 MeV. Section 2 contains detailed information on the predominant processes (photoelectric absorption, Compton scattering and pair production) and a brief discussion of other processes which combine to give the attenuation coefficient. Theoretical and experimental data are reviewed, and auxiliary tables and approximation formulas are given. Section 3 contains tabulations of cross sections for the predominant processes between 10 keV and 100 GeV for 23 elements and for 13 compounds and mixtures.

Key words: Attenuation coefficient; Compton scattering; cross section; energy absorption coefficient; gamma rays; pair production; photoelectric absorption; photons; x-rays.

## 1. Attenuation and Energy Absorption Coefficients

### 1.1. Introduction

The first modern systematic compilation of photon<sup>1</sup> interaction cross sections and attenuation coefficients, covering the energy range 10 keV to 100 MeV, was done by White<sup>2</sup> [1952] and appeared in NBS Report 1003 (unpublished).<sup>3</sup> Her tables were subsequently published in the Handbook of Radiology [1955] and in the 1955 edition of Beta and Gamma-Ray Spectroscopy [1955]. Storm, Gilbert, and Israel [1958] further extended these tables by interpolation to include all elements from  $Z=1$  to 100.

With some revisions the tables from NBS Report 1003 were published in NBS Circular 583 [1957], and were revised in the 10–100 keV region by McGinnies [1959] in NBS Circular 583 (Supplement). Davisson [1965] further updated these tables using more recent theoretical estimates of atomic photoeffect and electron-field pair production.<sup>4</sup>

The present compilation, an earlier version of which has been presented elsewhere (Hubbell and

Berger [1968]), is based on a new analysis of all available information. We were of course guided strongly by methods and results contained in previous compilations, particularly those of White [1952], but have also gone back to the original experimental and theoretical literature.

We retain the format of White for the main tables (sec. 3) but we have extended the energy range up to 100 GeV and have taken into account new data including the following:

- (a) Photoeffect calculations by Hultberg et al. [1968], Rakavy and Ron [1965–7] and Pratt and Schmickley [1967].
- (b) Calculations of double Compton scattering and radiative corrections to Compton scattering by Mork [1968].
- (c) Nuclear-field pair-production radiative corrections calculated by Mork and Olson [1965] and screening effects evaluated by Sörensen [1965–6].
- (d) Electron-field pair-production calculations by Mork [1967] which combine Votruba's [1948] theory with that of Borsellino [1947] and Ghizetti [1947], and include the radiative correction.
- (e) Calculations of coherent and incoherent scattering by Storm and Israel [1967].
- (f) Additional experimental data including, among others, the total cross section measurements by Barkan [1956], Wiedenbeck [1962], Barlett and Donahue [1963, 1965], Heinrich [1966], Hughes and Woodhouse [1966], Carter et al. [1967], McCrary, Plassman et al. [1967], Perkin and Douglas [1967], and Knerr and Vonach [1967].

\*Supported primarily by the NBS Office of Standard Reference Data. Support was also received from the Defense Atomic Support Agency.

<sup>1</sup>The terms "x-ray," "gamma-ray," and "photon" are used interchangeably throughout this work.

<sup>2</sup>Referred to in her later work [1957], as White-Grodstein.

<sup>3</sup>Earlier compilations which are partly theoretical, and which cover less extensive or lower energy ranges, include those of Jönsson [1927–8], Victoreen [1943–9], Woo and Sun [1947], Davisson and Evans [1952], and G. Allen [1950–1967]. The well-known data of S. J. M. Allen [1930–1967] appearing in the Handbook of Chemistry and Physics are experimental and have not been revised since 1933.

<sup>4</sup>Davisson's [1965] tables are accompanied by an extensive review article. Other reviews include those by Latyshev [1947], Bethe and Ashkin [1953], Fano [1953], Evans [1955, 1963], Hayward [1958], Fano, Spencer, and Berger [1959], Fano, Zerby, and Berger [1962], and Koch, MacGillavry, and Milledge [1962]. For further references to original data and to other compilations there are available extensive bibliographies by Glocker [1950] and Stainer [1963] in the low energy region and by Toms [1965] in the high energy region.

In addition, we tabulate various related coefficients that can be used to compute the transfer of energy to the medium, namely: (a) the mass energy-absorption coefficient, (b) the mass energy-transfer coefficient, and (c) the mass absorption coefficient.<sup>5</sup> These coefficients were obtained by updating and extending the work of R. Berger [1961] and Allison [1961].

In the present work we have taken 10 keV as a lower limit on the energy range considered. Tabulations which extend to lower energies include those by Brown [1966] ( $Z=1$  to 100; 1 keV–10 MeV), McMaster et al. [1967] (87 elements  $Z=1$  to 94; 1 keV–1 MeV), and by Storm and Israel [1967] ( $Z=1$  to 100; 1 keV–100 MeV). For light elements at lower energies, Henke et al. [1967] have used their own experimental data and those of others to provide a compilation of attenuation coefficients versus energy for the 17 elements He through Ar over the energy range 0.030 to 6.0 keV. Additional low-energy attenuation coefficient tabulations for use by electron microprobe analysts (the coefficients are given at characteristic x-ray emission wavelengths) include, among others, those by Birks [1963], Heinrich [1966], Frazer [1967], and Theisen and Vollath [1967].

## 1.2. Physical Constants; Units; Notation

### 1.2.1. Physical Constants and Conversion Factors<sup>6</sup>

|        |   |
|--------|---|
| $Z$    | atomic number,  |
| $M$    | atomic weight in g/g-atom,  |
| $m$    | electron rest-mass = $9.1091 \cdot 10^{-28}$ g,                   |
| $mc^2$ | electron rest-mass energy = $5.11006 \cdot 10^5$ eV,              |
| $c$    | velocity of light = $2.997925 \cdot 10^{10}$ cm s <sup>-1</sup> , |

<sup>5</sup> For definitions of these coefficients see Secs. 1.2. and 1.5. A great variety of names and symbols have been used for these coefficients, and readers interested in the nomenclature used by various authors should consult R. Berger [1961].

<sup>6</sup> Note: Numerical values given here are those recommended in 1964 by the Committee on Fundamental Constants of the National Academy of Sciences—National Research Council [1964]. They are based on the atomic weight scale in which  $M=12.0000$  for C<sup>12</sup>.

|                       |   |
|-----------------------|---|
| $e$                   | elementary charge = $1.60210 \cdot 10^{-19}$ Coulomb<br>= $4.80298 \cdot 10^{-10}$ cm <sup>3/2</sup> g <sup>1/2</sup> s <sup>-1</sup> (e.s.u.), |
| $r_e$                 | classical electron radius<br>= $e^2/(mc^2) = 2.81777 \cdot 10^{-13}$ cm,  |
| $r_e^2$               | = $7.9398 \cdot 10^{-26}$ cm <sup>2</sup> ,   |
| $\sigma_T$            | cross section for classical Thomson scattering from an electron = $8\pi r_e^2/3 = 6.6516 \cdot 10^{-25}$ cm <sup>2</sup> ,                      |
| $N_A$                 | Avogadro constant = $6.02252 \cdot 10^{23}$ = atoms/mole,   |
| $\alpha$              | fine structure constant<br>= $7.29720 \cdot 10^{-3} = 1/137.0388 \approx 1/137$ ,   |
| $E$                   | photon energy in eV units (e.g.: keV, MeV or GeV),  |
| $k$                   | photon energy in units of the electron rest-mass energy (i.e., $mc^2$ units) = $E[\text{MeV}]/0.511006$ ,                                       |
| $q$                   | momentum transfer to an atom or electron in units of $mc$ ,   |
| $\lambda$             | photon wavelength in Compton units<br>= $1/k = 0.511006/E[\text{MeV}]$ ,  |
| $\lambda(\text{\AA})$ | photon wavelength in angstroms<br>(1 angstrom = $10^{-8}$ cm) = $1.23981 \cdot 10^{-2}/E[\text{MeV}]$ <sup>7</sup>                              |
| $b$                   | barn = $10^{-24}$ cm <sup>2</sup> .   |

<sup>7</sup> In addition to the angstrom, which is based on the centimeter, two photon wavelength units,  $\text{\AA}^*$  and  $xu$ , are in use which are based on characteristic x-ray emission wavelengths. The recently-introduced  $\text{\AA}^*$ -unit (Bearden [1967]) is presently identical with the angstrom within an uncertainty of 5 ppm. i.e.:

$$1\text{\AA}^* = 1\text{\AA} \pm 5 \text{ ppm.}$$

The tungsten  $K\alpha_1$  emission line has been recommended by Bearden as the x-ray wavelength primary standard with the value

$$\lambda(WK\alpha_1) \equiv 0.2090100 \text{\AA}^*$$

and hence

$$\lambda(WK\alpha_1) = 0.2090100 \text{\AA} \pm 5 \text{ ppm.}$$

The  $xu$ -unit, used in much of the older literature and occasionally in the present literature, was intended to be  $10^{-3}\text{\AA}$  but has taken on a variety of values because of errors and inconsistencies in the various wavelength standards used. If the molybdenum  $K\alpha_1$  emission line is taken as a reference with the value (Bearden [1967]):

$$\lambda(\text{Mo } K\alpha_1) \equiv 707.831 xu$$

then

$$1 xu = 1.002056 \cdot 10^{-3} \text{\AA}^*$$

and

$$\lambda(xu) = 12.37/E(\text{MeV}).$$

### 1.2.2. Notation and Units

| Symbol                  | Name or definition  | Units                             | Where used   |
|-------------------------|---|-----------------------------------|--|
| $\mu$                   | “narrow beam” linear attenuation coefficient  | $\text{cm}^{-1}$                  | Table 1.-5;<br>Eqs (1.-1) to (-4)                        |
| $\rho$                  | absorber density  | $\text{g cm}^{-3}$                | Tables 1.-, 2  |
| $\mu/\rho$              | mass attenuation coefficient<br>= $\sigma_{\text{tot}} [\text{b/atom}] \cdot (N_A/M) \cdot 10^{-24}$<br>[ $(\text{cm}^2\text{g}^{-1})/(\text{b/atom})$ ]  | $\text{cm}^2 \text{g}^{-1}$       | Tables 1.-4; 3.-1 to 36;<br>Eqs (1.-5) to (-7)           |
| mfp                     | mean free path = $1/\mu$ ,<br>= $1/(\mu/\rho)$  | $\text{cm}$<br>$\text{g cm}^{-2}$ | Eq (1.-4a)<br>Fig 1.-2                                   |
| $t_{1/2}$               | Half-value layer = $0.69315/\mu$ ,<br>= $0.69315/(\mu/\rho)$  | $\text{cm}$<br>$\text{g cm}^{-2}$ | Eq (1.-4b)<br>Fig 1.-2                                   |
| $t_{1/10}$              | 1/10-value layer = $2.3026/\mu$ ,<br>= $2.3026/(\mu/\rho)$  | $\text{cm}$<br>$\text{g cm}^{-2}$ | Eq (1.-4c)<br>Fig 1.-2                                   |
| $\Delta V$              | “volume of interest” in a medium,<br>for photon energy transfer estimates   | $\text{cm}^3$                     | Eq (1.-9)  |
| $\mu_{\text{en}}/\rho$  | mass energy-absorption coefficient, allowing for escape from the volume of interest of all secondary photons, including bremsstrahlung, as given in definition (17) in NBS Handbook 85 (ICRU Rep. 10b) [1964]   | $\text{cm}^2 \text{g}^{-1}$       | Fig 1.-3; Tables 1.-7, 8, 9;<br>Eq (1.-10)               |
| $\mu_{\text{K}}/\rho$   | mass energy-transfer coefficient allowing only for the escape of Compton-scattered, fluorescence and annihilation photons, as given in definition (16) in NBS Handbook 85 (ICRU Rep. 10b) [1964]  | $\text{cm}^2 \text{g}^{-1}$       | Tables 1.-7, 8   |
| $\mu_{\text{a}}/\rho$   | mass absorption coefficient allowing for escape of Compton scattered photons only, as defined in eq (8f-48) of Evans [1963]   | $\text{cm}^2 \text{g}^{-1}$       | Tables 1.-7, 8, 9  |
| $f_z$                   | average fraction of photon energy transferred to the medium as a result of photoelectric absorption   | dimensionless                     | Eq (1.-10)   |
| $f_c$                   | average fraction of photon energy transferred to the medium as a result of a Compton collision  | dimensionless                     | Eqs (1.-10), (2.-13)<br>Table 2.-8                       |
| $f_k$                   | average fraction of photon energy transferred to the medium as a result of a pair production event  | dimensionless                     | Eq (1.-10)   |
| $R_e$                   | electron range (here used in the “continuous-slowing-down-approximation”)   | $\text{g cm}^{-2}$                | Table 1.-6   |
| $\sigma_{\text{tot}}$   | total photon interaction cross section per atom (defined in this paper to include only photoelectric absorption, Compton collision, and pair production)  | $\text{b/atom}$                   | Eqs (1.-5), (2.-24);<br>Fig 2.-1                         |
| $\tau_{pe}$             | total photoelectric absorption cross section per atom = $\tau_K + \tau_L + \dots$   | $\text{b/atom}$                   | Sec. 2.3.; Tables 2.-4, 5,<br>3.-1 to 3.-23;<br>Fig 2.-1 |
| $\mu_{pe}/\rho$         | $\tau_{pe} [\text{b/atom}] \cdot (N_A/M) \cdot 10^{-24}$ [ $(\text{cm}^2\text{g}^{-1})/(\text{b/atom})$ ]   | $\text{cm}^2 \text{g}^{-1}$       | Eq (1.-10)   |
| $\tau_K, \tau_L, \dots$ | photoelectric absorption cross section per atom for $K$ -shell electrons, $L$ -shell electrons, etc.  | $\text{b/atom}$                   | Table 2.-6;<br>Eq (2.-1)                                 |
| $\tau_{pe}/\tau_K$      | ratio of total photoelectric to $K$ -shell photoelectric cross section (above the $K$ -edge)<br>= $\frac{\tau_K + \tau_L + \tau_M + \dots}{\tau_K} = \frac{\delta}{\delta - 1}$ ,<br>where $\delta$ is the $K$ -edge “jump ratio”<br>$\frac{\tau_K + \tau_L + \tau_M + \dots}{\tau_L + \tau_M + \dots}$ as defined by Kirchner [1930] | dimensionless                     | Table 2.-6<br>Eq (2.-2)                                  |

### 1.2.2. Notation and Units—Continued

| Symbol                                    | Name or definition   | Units                           | Where used   |
|---|--|---------------------------------|--|
| $\sigma_C$                                | Compton (“incoherent”) collision cross section   | b/electron or b/atom            | Sec. 2.4.; Table 2.-8; Eq (1.-8); Fig. 2.-1                      |
| $\mu_C/\rho$                              | $\sigma_C[\text{b/atom}] \cdot (N_A/M) \cdot 10^{-24}$<br>[(cm <sup>2</sup> g <sup>-1</sup> )/(b/atom)]      | cm <sup>2</sup> g <sup>-1</sup> | Eq (1.-10)   |
| $\sigma_C^{KN}$                           | $\sigma_C$ as given by the Klein-Nishina formula   | b/electron                      | Table 2.-8; Eqs (2.-8), (-9), (-11)                              |
| $\sigma_C^H$                              | $\sigma_C$ as given by Hasting’s empirical fit to $\sigma_C^{KN}$  | b/electron                      | Eq (2.-12)   |
| $\sigma_C^{BD}$                           | $\sigma_C$ for bound electrons   | b/electron or b/atom            | Sec. 2.4.2; Eq (2.-18); Fig. 2.-3                                |
| $\sigma_C^K$                              | $\sigma_C$ for a K-shell electron  | b/electron                      | Fig 2.-2   |
| $S(q, Z)$                                 | incoherent scattering function   | dimensionless                   | Eq (2.-18)   |
| $\sigma_R$                                | Rayleigh (“coherent”) scattering cross section per atom  | b/atom                          | Sec. 2.4.2; eq (2.-22); Fig. 2.-4                                |
| $F(q, Z)$                                 | atomic form factor   | dimensionless                   | Eq (2.-22)   |
| $\theta_c$                                | criterion angle for assessing importance of Rayleigh scattering  | degrees or radians              | Eq (2.-23); Fig. 2.-4  |
| $\sigma$ (“scattering, with coherent”)    | total bound-electron scattering cross section = $\sigma_C^{BD} + \sigma_R$                                   | b/atom                          | Sec. 2.4.2; Tables 2.-9, 3.-1 to -23                             |
| $\Delta\sigma_C^M$                        | Mork correction to $\sigma_C = \sigma$ (double Compton) + $\sigma$ (radiative correction)                    | b/electron                      | Tables 2.-8; Eq (2.-25)  |
| $\sigma$ (“scattering, without coherent”) | free-electron scattering cross section, including radiative corrections = $\sigma_C^{KN} + \Delta\sigma_C^M$ | b/electron or b/atom            | Tables 2.-8, 3.-1 to -23   |
| $\kappa$                                  | total pair production cross section = $\kappa_n + \kappa_e$  | b/atom                          | Sec. 2.5; Eq (2.-42)   |
| $\mu_\kappa/\rho$                         | $\kappa[\text{b/atom}] \cdot (N_A/M) \cdot 10^{-24}$ [(cm <sup>2</sup> g <sup>-1</sup> )/(b/atom)]           | cm <sup>2</sup> g <sup>-1</sup> | Eq (1.-10)   |
| $\kappa_n$                                | cross section for pair production in the field of an atomic nucleus  | b/atom                          | Sec. 2.5.2; Tables 2.-10, 3.-1 to -23; Eqs (2.-26), (-30), (-31) |
| $\kappa_e$                                | cross section for pair production in the field of the atomic electrons (“triplet” production)                | b/atom                          | Sec. 2.5.3; Tables 2.-15, 3.-1 to -23; Eqs (2.-27), (-38), (-39) |
| $\eta$                                    | $Z \cdot (\kappa_e/\kappa_n)$  | dimensionless                   | Secs. 2.5.1, 2.5.3; Table 2.-15; Eqs (2.-41) to (-43)            |
| $\kappa_n^{BH}(\text{Born})$              | $\kappa_n$ as formulated by Bethe and Heitler in the Born approximation                                      | b/atom                          | Table 2.-11; Eqs (2.-30), (-31), (-33), (-34), (-36)             |
| $-\Delta\kappa_n^{DBM}$                   | Davies-Bethe-Maximon Coulomb correction to $\kappa_n^{BH}(\text{Born})$                                      | b/atom                          | Table 2.-12; Eqs (2.-28), (-30), (-31)                           |
| $s^{HFS}$                                 | Hartree-Fock-Slater screening corrections to $\kappa_n$  | b/atom                          | Table 2.-13; Eq (2.-31)  |
| $\sigma_{ph. n.}$                         | total photonuclear cross section = $\sigma(\gamma, n) + \sigma(\gamma, p) + \dots$                           | b/atom or mb/atom               | Sec. 2.-6; Eq (2.-44)  |
| $E_0$                                     | energy at which the maximum, $\sigma_0$ , of the $\sigma_{ph. n.}$ resonance peak occurs                     | MeV                             | Table 2.-16; Eq (2.-44)  |
| $\Gamma$                                  | width at half-max. of the $\sigma_{ph. n.}$ peak   | MeV                             | Table 2.-16; Eq (2.-44)  |



### 1.3. Definition and Significance of Narrow-Beam Attenuation Coefficient

The most important quantity characterizing the penetration and diffusion of gamma radiation in extended media is the attenuation coefficient,  $\mu$ . This quantity depends on the photon energy  $E$  and on the atomic number  $Z$  of the medium, and may be defined as the probability per unit pathlength that a photon will interact with the medium.

Consider, as a typical situation, a slab of material of thickness  $t$  located between a narrowly collimated source of monoenergetic gamma ray photons and a narrowly collimated detector, as indicated in figure 1.-1. In a layer  $dx$  within the slab there will occur a reduction of the intensity,  $I$ , of the gamma ray beam, due to:

- (1) outright absorption, or
- (2) scattering out of the beam.

The resulting fractional reduction of the beam intensity,  $-dI/I$ , is proportional to the "narrow beam" attenuation coefficient,  $\mu$ , and to the layer thickness,  $dx$ , i.e.,

$$-dI/I = \mu dx. \quad (1.-1)$$

Integrating this equation and assuming that the beam intensity incident on the slab has the value  $I_0$ , one obtains for the intensity transmitted through the slab the value

$$I(t) = I_0 \exp \left\{ - \int_0^t \mu(x) dx \right\}. \quad (1.-2)$$

For a homogeneous medium this reduces to

$$I(t) = I_0 e^{-\mu t}. \quad (1.-3)$$

For situations more complicated than the narrow-beam experiment, the attenuation is still basically exponential but is modified by two additional factors. The first of these, sometimes called a "geometry factor," depends essentially on the source geometry and involves, for example, the insertion of the inverse square law in eq (1.-3) for a point isotropic source. The other factor, often called the "buildup factor," takes into account secondary photons produced in the absorber (mainly as the result of one or more Compton scatters) which reach the detector. The determination of such

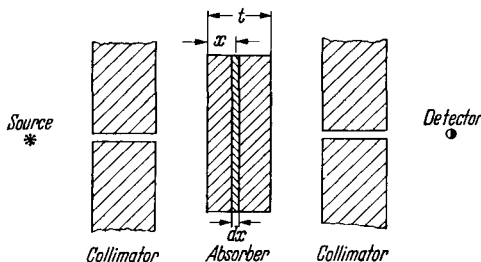


FIGURE 1.-1. Arrangement for experimental determination of narrow-beam attenuation coefficients.

buildup factors constitutes a large part of gamma ray transport theory.

In the narrow-beam equation (1.-3), the absorber thickness  $t$  in which the beam intensity is reduced by a factor  $e$  (i.e.,  $I/I_0 = 1/e = 0.36788$ ), is called the mean-free-path. One mean-free-path (mfp) also represents the average distance traveled by a photon between successive interactions. Analogous quantities are the half-value layer and one-tenth-value layer,  $t_{1/2}$  and  $t_{1/10}$ , in which the intensity is reduced by  $\frac{1}{2}$  and  $\frac{1}{10}$ , respectively.<sup>7a</sup> These quantities can be evaluated graphically from an experimental narrow beam attenuation curve, as indicated in figure 1.-2 for  $^{137}\text{Cs}$  ( $E = 0.662$  MeV) gamma rays in concrete and lead. They are related to the attenuation coefficient according to

$$1 \text{ mfp} = 1/\mu, \quad (1.-4a)$$

$$t_{1/2} = (-\ln \frac{1}{2})/\mu = 0.69315/\mu, \quad (1.-4b)$$

and

$$t_{1/10} = (-\ln \frac{1}{10})/\mu = 2.3026/\mu. \quad (1.-4c)$$

From the above discussion it is apparent that the attenuation coefficient  $\mu$  has dimensions of an inverse length. Hence, if  $t$  is in cm, in, ft, etc., the corresponding values of  $\mu$  must be in units of  $\text{cm}^{-1}$ ,  $\text{in}^{-1}$ ,  $\text{ft}^{-1}$ , etc., and as such are called "linear attenuation coefficients". However, although linear attenuation coefficients are convenient for engineering application, they are proportional to the absorber density,  $\rho$ , which usually does not have a unique value but depends to some extent on the physical state of the material. Therefore, it is common practice, for purposes of tabulation, to remove this density dependence and to use the "mass attenuation coefficient"  $\mu/\rho$  which, if  $\mu$  is in  $\text{cm}^{-1}$  and  $\rho$  is in  $\text{g}/\text{cm}^3$ , will be in the customary units of  $\text{cm}^{-2}/\text{g}$ .

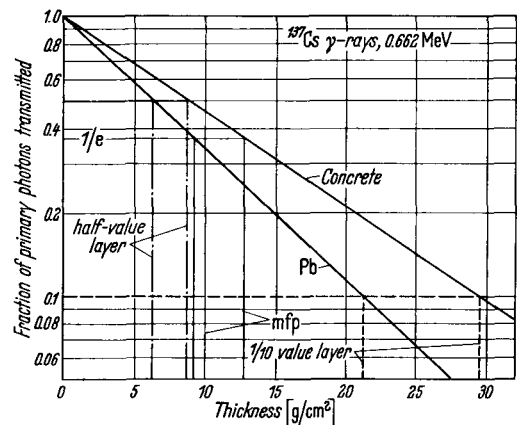


FIGURE 1.-2. Semilog plot of narrow-beam attenuation of  $^{137}\text{Cs}$  (0.662 MeV) gamma rays in lead and concrete.

Graphical determinations of the mean-free-path and of the 1/2- and 1/10-value layers are indicated.

<sup>7a</sup> It should be noted that the ICRU (see, for example, NBS Handbook 85 [1964]) defines a half-value layer (HVL) in terms of exposure rate (intensity weighted by the ability of the radiation to produce ion pairs in air) rather than intensity. The difference between these definitions can lead to different half-value layer thicknesses if the source is not monoenergetic.

The mass attenuation coefficient  $\mu/\rho$  is proportional to the total photon interaction cross section per atom,  $\sigma_{\text{tot}}$ , i.e., to the sum of the cross sections for all the elementary scattering and absorption process. This relation is

$$\frac{\mu}{\rho} \left[ \frac{\text{cm}^2}{\text{g}} \right] = \sigma_{\text{tot}} \left[ \frac{\text{cm}^2}{\text{atom}} \right] \cdot \frac{N_A \left[ \frac{\text{atoms}}{\text{g-atom}} \right]}{M \frac{\text{g}}{\text{g-atom}}},$$

$$= \sigma_{\text{tot}} \left[ \frac{\text{b}}{\text{atom}} \right] \cdot N_A/M \cdot 10^{-24}, \quad (1.-5)$$

where  $N_A$  is Avogadro's number ( $6.02252 \cdot 10^{23}$  atoms/g-atom) and  $M$  is the atomic weight of the absorber material. Table 1.-1 lists values of  $(N_A/M) \cdot 10^{-24}$  for a number of elements, in addition to typical values for  $\rho$ , and similar information is given in table 1.-2 for some mixtures. The cross section per atom,  $\sigma_{\text{tot}}$ , should be used in preference to  $\mu/\rho$  as a basis for interpolation vs.  $Z$  because of the dependence of  $\mu/\rho$  on the atomic weight,  $M$ . Not only does  $M$  vary irregularly from element to element, but values of  $M$  can differ from those given in table 1.-1 depending on the isotopic composition of a given sample. The effects of isotopic variation on  $\sigma_{\text{tot}}$  (excluding photo-nuclear interactions) are negligible in comparison with effects on  $\mu/\rho$ .

TABLE 1.-1. Values of the atomic weight  $M$ , the factor  $(N_A/M) \times 10^{-24}$  for converting attenuation data from  $b/\text{atom}$  to  $\text{cm}^2\text{g}^{-1}$ , and typical densities  $\rho$  for converting from  $\text{cm}^2\text{g}^{-1}$  to  $\text{cm}^{-1}$ .

| Element |             | $M,^*$<br>atomic wt. | $\frac{N_A}{M} \times 10^{-24} **$                            | $\rho^{***}$                    |
|---------|-------------|----------------------|---|---------------------------------|
| $Z$     | Sym-<br>bol | $\text{g/g-atom}$    | $\frac{\text{cm}^2}{\text{g}} / \frac{\text{b}}{\text{atom}}$ | $\text{g/cm}^3$                 |
| 1       | H           | 1.00797              | 0.5975  | 0.00008988 g, (H <sub>2</sub> ) |
| 2       | He          | 4.0026               | .1505   | .0001785 g                      |
| 3       | Li          | 6.939                | .08679  | .534                            |
| 4       | Be          | 9.0122               | .06683  | 1.85                            |
| 5       | B           | 10.811               | .05571  | 2.535                           |
| 6       | C           | 12.01115             | .05014  | 2.25 (graphite)****             |
| 7       | N           | 14.0067              | .04300  | .001250 g, (N <sub>2</sub> )    |
| 8       | O           | 15.9994              | .03764  | .001429 g, (O <sub>2</sub> )    |
| 9       | F           | 18.9984              | .03170  | .001696 g, (F <sub>2</sub> )    |
| 10      | Ne          | 20.183               | .02984  | .0008999 g                      |
| 11      | Na          | 22.9898              | .02620  | .971                            |
| 12      | Mg          | 24.312               | .02477  | 1.74                            |
| 13      | Al          | 26.9815              | .02232  | 2.70                            |
| 14      | Si          | 28.086               | .02144  | 2.42                            |
| 15      | P           | 30.9738              | .01944  | 1.8-2.7                         |
| 16      | S           | 32.064               | .01878  | 1.96-2.07                       |
| 17      | Cl          | 35.453               | .01699  | .003214 g, (Cl <sub>2</sub> )   |
| 18      | Ar          | 39.948               | .01508  | .001784 g                       |
| 19      | K           | 39.102               | .01540  | .87                             |
| 20      | Ca          | 40.08                | .01503  | 1.55                            |

TABLE 1.-1. Values of the atomic weight  $M$ , the factor  $(N_A/M) \times 10^{-24}$  for converting attenuation data from  $b/\text{atom}$  to  $\text{cm}^2\text{g}^{-1}$ , and typical densities  $\rho$  for converting from  $\text{cm}^2\text{g}^{-1}$  to  $\text{cm}^{-1}$ .—Continued

| Element |             | $M,^*$<br>atomic wt. | $\frac{N_A}{M} \times 10^{-24} **$                            | $\rho^{***}$    |
|---------|-------------|----------------------|---|-----------------|
| $Z$     | Sym-<br>bol | $\text{g/g-atom}$    | $\frac{\text{cm}^2}{\text{g}} / \frac{\text{b}}{\text{atom}}$ | $\text{g/cm}^3$ |
| 21      | Sc          | 44.956               | .01340  | 3.02            |
| 22      | Ti          | 47.90                | .01257  | 4.5             |
| 23      | V           | 50.942               | .01182  | 5.87            |
| 24      | Cr          | 51.996               | .01158  | 7.14            |
| 25      | Mn          | 54.9380              | .01096  | 7.3             |
| 26      | Fe          | 55.847               | .01078  | 7.86            |
| 27      | Co          | 58.9332              | .01022  | 8.71            |
| 28      | Ni          | 58.71                | .01026  | 8.8             |
| 29      | Cu          | 63.54                | .009478   | 8.93            |
| 30      | Zn          | 65.37                | .009213   | 6.92            |
| 31      | Ga          | 69.72                | .008638   | 5.93            |
| 32      | Ge          | 72.59                | .008297   | 5.46            |
| 33      | As          | 74.9216              | .008038   | 5.73            |
| 34      | Se          | 78.96                | .007627   | 4.82            |
| 35      | Br          | 79.909               | .007537   | 3.12 1          |
| 36      | Kr          | 83.80                | .007187   | .003743 g       |
| 37      | Rb          | 85.47                | .007046   | 1.53            |
| 38      | Sr          | 87.62                | .006873   | 2.6             |
| 39      | Y           | 88.905               | .006774   | 3.8             |
| 40      | Zr          | 91.22                | .006602   | 6.44            |
| 41      | Nb          | 92.906               | .006482   | 8.4             |
| 42      | Mo          | 95.94                | .006277   | 9.01            |
| 43      | Tc          | (99)                 | (.006083)   | [11.50]         |
| 44      | Ru          | 101.07               | .005959   | 12.1            |
| 45      | Rh          | 102.905              | .005853   | 12.44           |
| 46      | Pd          | 106.4                | .005660   | 12.25           |
| 47      | Ag          | 107.870              | .005583   | 10.49           |
| 48      | Cd          | 112.40               | .005358   | 8.65            |
| 49      | In          | 114.82               | .005245   | 7.43            |
| 50      | Sn          | 118.69               | .005074   | 5.75-7.29       |
| 51      | Sb          | 121.75               | .004947   | 6.62            |
| 52      | Te          | 127.60               | .004720   | 6.25            |
| 53      | I           | 126.9044             | .004746   | 4.94            |
| 54      | Xe          | 131.30               | .004587   | .005896 g       |
| 55      | Cs          | 132.905              | .004531   | 1.873           |
| 56      | Ba          | 137.34               | .004385   | 3.5             |
| 57      | La          | 138.91               | .004336   | 6.15            |
| 58      | Ce          | 140.12               | .004298   | 6.90            |
| 59      | Pr          | 140.907              | .004274   | 6.48            |
| 60      | Nd          | 144.24               | .004175   | 7.00            |
| 61      | Pm          | (145)                | (.004153)   | [7.22]*****     |
| 62      | Sm          | 150.35               | .004006   | 7.7-7.8         |
| 63      | Eu          | 151.96               | .003963   | [5.259]         |
| 64      | Gd          | 157.25               | .003830   | [7.948]         |
| 65      | Tb          | 158.924              | .003790   | [8.272]         |
| 66      | Dy          | 162.50               | 0.003706  | [8.536]         |
| 67      | Ho          | 164.930              | .003652   | [8.803]         |
| 68      | Er          | 167.26               | .003601   | [9.051]*****    |
| 69      | Tm          | 168.934              | .003565   | [9.332]         |
| 70      | Yb          | 173.04               | .003480   | [6.977]         |
| 71      | Lu          | 174.97               | .003442   | [9.872]         |
| 72      | Hf          | 178.49               | .003374   | 13.3            |
| 73      | Ta          | 180.948              | .003328   | 17.1            |
| 74      | W           | 183.85               | .003276   | 19.3            |
| 75      | Re          | 186.2                | .003234   | 20.53           |

TABLE 1.-1. Values of the atomic weight  $M$ , the factor  $(N_A/M) \times 10^{-24}$  for converting attenuation data from  $b$  (atom to  $\text{cm}^2\text{g}^{-1}$ ), and typical densities  $\rho$  for converting from  $\text{cm}^2\text{g}^{-1}$  to  $\text{cm}^{-1}$ .—Continued

| Element |             | $M$ ,*<br>atomic wt. | $\frac{N_A}{M} \times 10^{-24}$ **                     | $\rho$ ***        |
|---------|-------------|----------------------|--|-------------------|
| Z       | Sym-<br>bol | g/g—atom             | $\frac{\text{cm}^2}{\text{g}} / \frac{b}{\text{atom}}$ | g/cm <sup>3</sup> |
| 76      | Os          | 190.2                | .003166  | 22.8              |
| 77      | Ir          | 192.2                | .003133  | 22.42—22.8        |
| 78      | Pt          | 195.09               | .003087  | 21.4              |
| 79      | Au          | 196.967              | .003058  | 19.3              |
| 80      | Hg          | 200.59               | .003002  | 13.55 1           |
| 81      | Tl          | 204.37               | .002947  | 11.86             |
| 82      | Pb          | 207.19               | .002907  | 11.34             |
| 83      | Bi          | 208.980              | .002882  | 9.78              |
| 84      | Po          | (210)                | (.002868)  | [9.32]            |
| 85      | At          | (210)                | (.002868)  | .....             |
| 86      | Rn          | (222)                | (.002713)  | .00996 g          |
| 87      | Fr          | (223)                | (.002701)  | .....             |
| 88      | Ra          | (226)                | (.002665)  | 5(?)              |
| 89      | Ac          | (227)                | (.002653)  | [10.07]           |
| 90      | Th          | 232.038              | .002595  | 11.00             |
| 91      | Pa          | (231)                | (.002607)  | [15.37]           |
| 92      | U           | 238.03               | .002530  | 18.7              |
| 93      | Np          | (237)                | (.002541)  | [19.36]           |
| 94      | Pu          | (242)                | (.002489)  | [19.84]           |
| 95      | Am          | (243)                | (.002478)  | [11.7]            |
| 96      | Cm          | (247)                | (.002438)  | [~ 7]             |
| 97      | Bk          | (249)                | (.002419)  | .....             |
| 98      | Cf          | (251)                | (.002399)  | .....             |
| 99      | Es          | (254)                | (.002371)  | .....             |
| 100     | Fm          | (253)                | (.002380)  | .....             |

\*Atomic weights are those recommended in 1961 by the International Union of Pure and Applied Chemistry, based on  $M=12.0000$  for  $\text{C}^{12}$  (Weast and Selby [1966-1967]). These values are based on average isotopic abundances and ignore natural and artificial variations. In practice, for example,  $M$  can vary from 6.01513 for pure  $^6\text{Li}$  to 7.01601 for pure  $^7\text{Li}$ , with a corresponding variation in the conversion factor from 0.1001 to 0.08584.

\*\* $N_A$  = Avogadro's number =  $6.02252 \times 10^{23}$  atoms/g-atom,  $\text{C}^{12}$  scale (National Academy of Sciences—National Research Council Committee on Fundamental Constants [1964]).

\*\*\*Densities are for common solids, except as denoted liquid (l) or gas (g), at 20°C, from the compilation by Trent, Stone, and Lindsay [1963] and in square brackets [ ] from the Handbook of Chemistry and Physics (Hammond [1966-1967]). Gas densities are at S.T.P.: 0°C, 76 cm Hg.

\*\*\*\*Graphite theoretical density, based on x-ray diffraction data. Commercial-grade pile graphite, according to Loch [1960], has a density range of 1.5–1.9 g/cm<sup>3</sup>.

\*\*\*\*\*Density values for erbium vary in the literature from 4.77 as listed by Trent, Stone, and Lindsay [1963] to the values 9.05 and 9.16 given in the Handbook of Chemistry and Physics (Hammond [1966-1967]).

\*\*\*\*\*The density of  $\text{Pm}^{147}$  as measured by Wheelwright [1969] is 7.22 g/cm<sup>-3</sup>.

Rau and Fano [1968] have examined the possible effect of irregularities in atomic shell structure on interpolation of atomic cross sections with respect to  $Z$ . Their results suggest that irregularities in the cross sections are most likely at the noble gases: He, Ne, Ar, Kr, Xe, and Rn, and at the noble metals (filling of the  $d$ -subshells): Cu, Pd and Au. At low energies ( $E \leq 10$  keV) where the outer atomic electrons can play a significant role Manson and Cooper [1968] predict such irregularities in the photoeffect (see sec. 2.3) and Storm and Israel [1967] predict similar effects for Compton scattering (see fig. 2.-3, sec. 2.4.2.). Also Sörensen [1965, 1966] predicts irregularities in the nuclear-fission pair production cross section (see sec. 2.5.2)

TABLE 1.-2. Conversion factors and densities, similar to those in table 1.-1, for a few compounds and mixtures.

| Substance  | Conversion factor  | $\rho$              |
|--|--|---------------------|
|  | $\frac{\text{cm}^2}{\text{g}} / \frac{b}{\text{molecule}}$ | g/cm <sup>3</sup>   |
| H <sub>2</sub> O   | 0.03344  | 1.00 1, 0.917 (ice) |
| SiO <sub>2</sub>   | .01002   | 2.32                |
| NaI  | .004019  | 3.667               |
| Air (20 °C, 76 cm Hg)  | .....  | 0.001205 g          |
| Concrete   | .....  | 2.2–2.4             |
| 0.8 N H <sub>2</sub> SO <sub>4</sub> soln  | .....  | 1.049 1             |
| Bone   | .....  | 1.7–2.0             |
| Muscle   | .....  | ~1                  |
| Polystyrene, (C <sub>8</sub> H <sub>8</sub> ) <sub>n</sub>                                     | .....  | 1.05–1.07           |
| Polyethylene, (CH <sub>2</sub> ) <sub>n</sub>  | .....  | 0.92                |
| Polymethyl methacrylate (Lucite), (C <sub>5</sub> H <sub>8</sub> O <sub>2</sub> ) <sub>n</sub> | .....  | 1.19                |
| Bakelite (typical), C <sub>43</sub> H <sub>38</sub> O <sub>7</sub>                             | .....  | 1.20–1.70           |
| Pyrex glass (Corning No. 7740)   | .....  | 2.23                |

for energies above 100 MeV where screening of the nuclear charge by the atomic electrons becomes important. Experimental evidence for such irregularities is still inconclusive for photon energies between 10 keV and 100 MeV.

If the absorber is a chemical compound or a mixture, its mass attenuation coefficient  $\mu/\rho$  can be approximately evaluated from the coefficients  $\mu_i/\rho_i$  for the constituent elements according to the weighted average

$$\mu/\rho = \sum_i w_i \mu_i/\rho_i, \quad (1.-6)$$

where  $w_i$  is the proportion by weight of the  $i$ th constituent. For example, for water (H<sub>2</sub>O:  $M_H = 1.00797$ ;  $M_O = 15.9994$ ),

$$\begin{aligned} \frac{\mu}{\rho} (\text{H}_2\text{O}) &= \frac{2 \cdot 1.00797}{18.0153} \frac{\mu}{\rho} (\text{H}) + \frac{15.9994}{18.0153} \frac{\mu}{\rho} (\text{O}), \\ &= 0.1119 \frac{\mu}{\rho} (\text{H}) + 0.8881 \frac{\mu}{\rho} (\text{O}). \end{aligned} \quad (1.-7)$$

Values of  $w_i$  for some additional compounds and mixtures are given in table 1.-3.

The limitations of the "mixture rule" in eq (1.-6) are that it ignores changes in the atomic wave-function resulting from changes in the molecular, chemical or crystalline environment of an atom. Above 10 keV errors from this approximation are expected to be less than a few percent (except in the fine-structure regions just above absorption edges which are most sensitive to such changes), but at very low energies (10–100 eV) errors of as much as a factor of two can occur. A survey of present knowledge of limitations of the mixture rule is given by Deslattes [1969].

TABLE 1.-3. Fractions-by-weight,  $w_i$ , of elements in some mixtures and compounds. These values were used for deriving tables 3.-24 to 3.-36 from tables 3.-1 to 3.-23 according to eq (1.-6).

| Element |         | H <sub>2</sub> O | SiO <sub>2</sub> | NaI    | Air <sup>a</sup> | Concrete <sup>b</sup> | 0.8 N H <sub>2</sub> SO <sub>4</sub> soln. <sup>c</sup> | Bone, compact <sup>a</sup> | Muscle, striated <sup>a</sup> | Poly-styrene, (C <sub>8</sub> H <sub>8</sub> ) <sub>n</sub> | Lucite, (C <sub>5</sub> H <sub>8</sub> O <sub>2</sub> ) <sub>n</sub> | Poly-ethylene, (CH <sub>2</sub> ) <sub>n</sub> | Bakelite, <sup>a</sup> C <sub>45</sub> H <sub>38</sub> O <sub>7</sub> | Pyrex glass <sup>d</sup> |
|---------|---------|------------------|------------------|--------|------------------|-----------------------|---|----------------------------|-------------------------------|---|--|--|---|--------------------------|
| Z       | Sym-bol |                  |                  |        |                  |                       |   |                            |                               |   |  |  |   |                          |
| 1       | H       | 0.1119           |                  |        |                  | 0.0056                | 0.1084  | 0.064                      | 0.102                         | 0.0774  | 0.0805   | 0.1437   | 0.0574  | 0.0401                   |
| 5       | B       |                  |                  |        |                  |                       |   | .278                       | .123                          | .9226   | .5999  | .8563  | .7746   |                          |
| 6       | C       |                  |                  |        | 0.755            |                       |   | .027                       | .035                          |   |  |  |   |                          |
| 7       | N       |                  |                  |        | .232             |                       | .8791   | .410                       | .72893                        |   | .3196  |  | .1680   | .5396                    |
| 8       | O       | .8881            | 0.5326           |        |                  | .4983                 |   |                            | .0008                         |   |  |  |   | .0282                    |
| 11      | Na      |                  |                  | 0.1534 |                  | .0171                 |   | .002                       | .0002                         |   |  |  |   |                          |
| 12      | Mg      |                  |                  |        |                  | .0024                 |   |                            |                               |   |  |  |   |                          |
| 13      | Al      |                  |                  |        |                  | .0456                 |   |                            |                               |   |  |  |   |                          |
| 14      | Si      |                  | .4674            |        |                  | .3158                 |   |                            |                               |   |  |  |   |                          |
| 15      | P       |                  |                  |        |                  |                       |   | .070                       | .002                          |   |  |  |   | .0116                    |
| 16      | S       |                  |                  |        |                  | .0012                 | .0125   | .002                       | .005                          |   |  |  |   | .3772                    |
| 18      | Ar      |                  |                  |        | .013             |                       |   |                            |                               |   |  |  |   |                          |
| 19      | K       |                  |                  |        |                  |                       |   |                            |                               |   |  |  |   |                          |
| 20      | Ca      |                  |                  |        |                  | .0192                 |   |                            | .003                          |   |  |  |   | .0083                    |
| 26      | Fe      |                  |                  |        |                  | .0826                 |   | .147                       | .00007                        |   |  |  |   |                          |
| 53      | I       |                  |                  | .8466  |                  | .0122                 |   |                            |                               |   |  |  |   |                          |

<sup>a</sup> Composition taken from National Bureau of Standards Handbook 85 [1964].

<sup>b</sup> Composition assumed by White-Grodstein [1957], adjusted by McGinnies [1959] to make total = 100 percent.

<sup>c</sup> 3.832 percent H<sub>2</sub>SO<sub>4</sub>, 96.168 percent H<sub>2</sub>O by weight, based on values in the 30th edition, p. 1635 in the Handbook of Chemistry and Physics (Hodgman [1948]). Same values, rounded off, given in the 47th edition, p. D-176 (Wolf and

Brown [1966-1967]) for this range of concentration.

<sup>d</sup> SiO<sub>2</sub>, 80.7 percent; B<sub>2</sub>O<sub>3</sub>, 2.9 percent; Na<sub>2</sub>O, 3.8 percent; Al<sub>2</sub>O<sub>3</sub>, 2.2 percent; K<sub>2</sub>O, 0.4 percent by weight, 0.2 percent has been added to SiO<sub>2</sub> to make total = 100 percent. Otherwise these percentages, with 80.5 percent SiO<sub>2</sub>, are those given for Pyrex glass (Corning 7740) by Morey [1954] and also by Shand [1955].

## 1.4. Tabulation of Attenuation Coefficients

Table 1.-4 contains mass attenuation coefficients,  $\mu/\rho$  [ $\text{cm}^2/\text{g}$ ], obtained by inserting in eq (1.-5) values of  $N_A/M \cdot 10^{-24}$  [ $(\text{cm}^2\text{g}^{-1})/(\text{b}/\text{atom})$ ] from table 1.-1 and values of  $\sigma_{\text{tot}}$  combined from individual cross sections quantitatively discussed in section 2. Specifically, we have used for  $\sigma_{\text{tot}}$  the sum

$$\sigma_{\text{tot}} \approx \tau_{pe} + \sigma_C + \kappa \quad (1.-8)$$

of the photoelectric absorption ( $\tau_{pe}$ ), Compton collision ( $\sigma_C$ ) and pair production ( $\kappa$ ) cross sections per atom. For reasons discussed in section 2.4.2. the Rayleigh scattering cross section,  $\sigma_R$ , is omitted from the sum in eq (1.-8) in table 1.-4. Hence, our resulting values of  $\mu/\rho$  correspond to the columns "total, without coherent (scattering)" of White-Grodstein [1957] and Davisson [1965].

Values of the attenuation coefficient including coherent scattering and the effect of electron binding on incoherent scattering are given in the tables in section 3. The relative importance of these effects is indicated in table 2.-15. The photonuclear effect has been omitted from the tables in section 3 but could be included using information in section 2.6. Values of  $\mu/\rho$  extrapolated to the absorption edges can be found in the tables in section 3.

For convenience, we have reproduced in table 1.-5 the Hungerford [1960] compilation of linear attenuation coefficients,  $\mu$  [ $\text{cm}^{-1}$ ], at 1, 3, and 6 MeV for a number of common materials associated with shielding. With the exception of air, these values have not been revised, but agreement with table 1.-4 is within 1 to 2 percent.

### *Estimated uncertainties:*

Due to gaps in available experimental data, and the various approximations and ranges of applicability of different theories, the accuracy of the  $\mu/\rho$  entries in table 1.-4 is not the same for all values of  $E$  and  $Z$ . In the region dominated by the Compton effect, we estimate the uncertainty to be about 1 percent. Estimates of uncertainties for low-, medium- and high- $Z$  materials are as follows:

#### (1) Low- $Z$ materials:

For elements hydrogen through oxygen this 1 percent uncertainty estimate extends from 100 MeV down to about 30 keV. Below 30 keV uncertainties of as much as 5 to 10 percent may be present because of (a) poor knowledge of the photoeffect for low  $Z$ 's, (b) corrections to experiments for high- $Z$  impurities and (c) departures of the Compton cross section from Klein-Nishina theory. Above 100 MeV the contribution of the triplet cross section (see sec. 2.5.3) is increasingly important and strongly affected by screening. The theory of the triplet cross section has, except for hydrogen (Wheeler and Lamb [1939]) and for results for He by Knasel [1968], so far only been worked out with the Thomas-Fermi model of the atom. Uncertainties in  $\mu/\rho$  from this source may be 5-10 percent.

#### (2) Medium- $Z$ materials:

For elements sodium through copper uncertainties of 1 to 2 percent are present at low energies (10 keV to 1 MeV) because of uncertain partitioning of experimental totals into photoeffect and scattering totals. At medium energies (1 to 100 MeV) uncertainties of 2 to 3 percent are present because of uncertainties in the pair production cross section, particularly in the 10 to 30 MeV photonuclear giant resonance region. Above 100 MeV the pair production in the field of both nucleus and electrons is better-known theoretically than at lower  $Z$ . Uncertainties in  $\mu/\rho$  in this region are estimated to be 1 to 2 percent.

#### (3) High- $Z$ materials:

For elements molybdenum through uranium the uncertainties at low energies (10 keV to 1 MeV) range from 1 to 2 percent far from an absorption edge to 5 to 10 percent in the vicinity of an edge. In the range 1 to 100 MeV uncertainties from pair production estimates are 2 to 3 percent and above 100 MeV 1 to 2 percent.

The high-energy data from 100 MeV to 100 GeV in this report are based completely on theory. As shown in figure 1.-3, they are in general agreement with available experimental data up to 13.5 GeV.

## 1.5. Definition and Significance of Energy-Absorption Coefficients and Related Quantities

### 1.5.1. Modes of Energy Transfer

The effects of gamma rays on irradiated media are largely indirect, i.e., they occur via electrons (or positrons) which are set in motion as a result of gamma ray interactions with matter, and then dissipate their energy as they are brought to rest. The relation between electron (or positron) energy deposition in a medium and the various physical, chemical, and biological effects is complicated and, in most cases, not well understood. However, it is commonly assumed that the amount of energy absorbed per unit mass of the medium (absorbed dose) is a significant parameter which provides a basis for discussing radiation effects.

The transfer of energy from photons to electrons, and vice versa, takes place in a complex chain of events with feedbacks as indicated in the flow diagram in figure 1.-4.<sup>8</sup> Following this flow diagram, a complete treatment of an energy deposition problem should take into account all indicated energy transfer routes leading to electron collision losses and associated typical effects such as are listed in the bottom triangle.<sup>9</sup>

<sup>8</sup> Although the diagram in fig. 1.-4 treats electrons and positrons alike, there are actually small differences in the rates by which they lose energy (see Nelms [1956, 1958] and Berger and Seltzer [1964]).

<sup>9</sup> Additional energy transfer routes, not shown in fig. 1.-4, occur in the case of nuclear absorption. The neutrons, charged particles and gamma rays resulting from such an event will, in turn, either directly or indirectly transfer additional kinetic energy to electrons. These additional routes were disregarded by R. Berger [1961], Allison [1961] and in the present work.

TABLE 1.-4. Values of the mass attenuation coefficient  $\mu/\rho$  [cm<sup>2</sup>/g], excluding Rayleigh (coherent) scattering, the effect of binding on Compton scattering, and the photonuclear effect, for a number of elements.

That is, values here are  $(\tau_{pe} + \sigma_c + \kappa_n + \kappa_e)$  b/atom  $\cdot (N_A/M) \cdot 10^{-24}$  [(cm<sup>2</sup>g<sup>-1</sup>)/(b/atom)] using values of  $\tau_{pe}$ ,  $\sigma_c$ ,  $\kappa_n$  and  $\kappa_e$  discussed in section 2 and tabulated in section 3. For coefficients extrapolated to absorption-edges, see sec. 3 tables.

| PHOTON ENERGY | HYDROGEN<br>Z=1 | BERYLLIUM<br>Z=4 | BORON<br>Z=5 | CARBON<br>Z=6           | NITROGEN<br>Z=7 | OXYGEN<br>Z=8 | SODIUM<br>Z=11 | MAGNESIUM<br>Z=12 |
|---------------|-----------------|------------------|--------------|-------------------------|-----------------|---------------|----------------|-------------------|
| <i>Mev</i>    |                 |                  |              | <i>cm<sup>2</sup>/g</i> |                 |               |                |                   |
| 1.00-02       | 3.85-01         | 5.36-01          | 1.09+00      | 2.17+00                 | 3.57+00         | 5.58+00       | 1.51+01        | 2.03+01           |
| 1.50-02       | 3.76-01         | 2.68-01          | 4.18-01      | 7.22-01                 | 1.09+00         | 1.62+00       | 4.37+00        | 5.98+00           |
| 2.00-02       | 3.69-01         | 2.06-01          | 2.66-01      | 3.88-01                 | 5.41-01         | 7.54-01       | 1.88+00        | 2.56+00           |
| 3.00-02       | 3.57-01         | 1.71-01          | 1.92-01      | 2.30-01                 | 2.76-01         | 3.35-01       | 6.39-01        | 8.39-01           |
| 4.00-02       | 3.46-01         | 1.59-01          | 1.71-01      | 1.93-01                 | 2.12-01         | 2.36-01       | 3.55-01        | 4.37-01           |
| 5.00-02       | 3.35-01         | 1.52-01          | 1.61-01      | 1.79-01                 | 1.87-01         | 1.99-01       | 2.54-01        | 2.98-01           |
| 6.00-02       | 3.26-01         | 1.47-01          | 1.55-01      | 1.70-01                 | 1.74-01         | 1.81-01       | 2.09-01        | 2.36-01           |
| 8.00-02       | 3.09-01         | 1.39-01          | 1.45-01      | 1.58-01                 | 1.60-01         | 1.62-01       | 1.70-01        | 1.83-01           |
| 1.00-01       | 2.94-01         | 1.32-01          | 1.38-01      | 1.50-01                 | 1.50-01         | 1.52-01       | 1.52-01        | 1.61-01           |
| 1.50-01       | 2.65-01         | 1.19-01          | 1.24-01      | 1.34-01                 | 1.34-01         | 1.34-01       | 1.31-01        | 1.36-01           |
| 2.00-01       | 2.43-01         | 1.09-01          | 1.13-01      | 1.23-01                 | 1.23-01         | 1.23-01       | 1.18-01        | 1.22-01           |
| 3.00-01       | 2.11-01         | 9.45-02          | 9.85-02      | 1.07-01                 | 1.06-01         | 1.07-01       | 1.02-01        | 1.06-01           |
| 4.00-01       | 1.89-01         | 8.47-02          | 8.83-02      | 9.55-02                 | 9.54-02         | 9.54-02       | 9.14-02        | 9.44-02           |
| 5.00-01       | 1.73-01         | 7.73-02          | 8.06-02      | 8.72-02                 | 8.71-02         | 8.71-02       | 8.34-02        | 8.61-02           |
| 6.00-01       | 1.60-01         | 7.15-02          | 7.45-02      | 8.07-02                 | 8.05-02         | 8.06-02       | 7.72-02        | 7.96-02           |
| 8.00-01       | 1.40-01         | 6.29-02          | 6.55-02      | 7.09-02                 | 7.08-02         | 7.08-02       | 6.78-02        | 6.99-02           |
| 1.00+00       | 1.26-01         | 5.65-02          | 5.89-02      | 6.37-02                 | 6.36-02         | 6.37-02       | 6.09-02        | 6.29-02           |
| 1.50+00       | 1.03-01         | 4.60-02          | 4.79-02      | 5.19-02                 | 5.18-02         | 5.18-02       | 4.97-02        | 5.12-02           |
| 2.00+00       | 8.75-02         | 3.94-02          | 4.11-02      | 4.45-02                 | 4.45-02         | 4.46-02       | 4.28-02        | 4.42-02           |
| 3.00+00       | 6.91-02         | 3.14-02          | 3.28-02      | 3.57-02                 | 3.58-02         | 3.60-02       | 3.49-02        | 3.61-02           |
| 4.00+00       | 5.81-02         | 2.66-02          | 2.80-02      | 3.05-02                 | 3.07-02         | 3.10-02       | 3.04-02        | 3.16-02           |
| 5.00+00       | 5.05-02         | 2.35-02          | 2.48-02      | 2.71-02                 | 2.74-02         | 2.78-02       | 2.76-02        | 2.87-02           |
| 6.00+00       | 4.50-02         | 2.12-02          | 2.25-02      | 2.47-02                 | 2.51-02         | 2.55-02       | 2.56-02        | 2.68-02           |
| 8.00+00       | 3.75-02         | 1.82-02          | 1.95-02      | 2.16-02                 | 2.21-02         | 2.26-02       | 2.32-02        | 2.44-02           |
| 1.00+01       | 3.25-02         | 1.63-02          | 1.75-02      | 1.96-02                 | 2.02-02         | 2.09-02       | 2.18-02        | 2.31-02           |
| 1.50+01       | 2.54-02         | 1.36-02          | 1.49-02      | 1.70-02                 | 1.78-02         | 1.86-02       | 2.02-02        | 2.16-02           |
| 2.00+01       | 2.15-02         | 1.22-02          | 1.37-02      | 1.58-02                 | 1.67-02         | 1.77-02       | 1.96-02        | 2.12-02           |
| 3.00+01       | 1.74-02         | 1.10-02          | 1.25-02      | 1.47-02                 | 1.58-02         | 1.70-02       | 1.96-02        | 2.13-02           |
| 4.00+01       | 1.54-02         | 1.04-02          | 1.21-02      | 1.44-02                 | 1.56-02         | 1.69-02       | 1.99-02        | 2.17-02           |
| 5.00+01       | 1.41-02         | 1.02-02          | 1.19-02      | 1.42-02                 | 1.56-02         | 1.70-02       | 2.02-02        | 2.22-02           |
| 6.00+01       | 1.33-02         | 1.00-02          | 1.18-02      | 1.43-02                 | 1.57-02         | 1.72-02       | 2.06-02        | 2.27-02           |
| 8.00+01       | 1.24-02         | 9.91-03          | 1.18-02      | 1.44-02                 | 1.60-02         | 1.75-02       | 2.13-02        | 2.35-02           |
| 1.00+02       | 1.19-02         | 9.92-03          | 1.19-02      | 1.46-02                 | 1.63-02         | 1.79-02       | 2.18-02        | 2.41-02           |
| 1.50+02       | 1.13-02         | 1.00-02          | 1.22-02      | 1.50-02                 | 1.68-02         | 1.86-02       | 2.28-02        | 2.53-02           |
| 2.00+02       | 1.12-02         | 1.02-02          | 1.24-02      | 1.53-02                 | 1.72-02         | 1.91-02       | 2.35-02        | 2.60-02           |
| 3.00+02       | 1.11-02         | 1.04-02          | 1.28-02      | 1.59-02                 | 1.78-02         | 1.98-02       | 2.44-02        | 2.70-02           |
| 4.00+02       | 1.12-02         | 1.06-02          | 1.30-02      | 1.62-02                 | 1.82-02         | 2.02-02       | 2.49-02        | 2.76-02           |
| 5.00+02       | 1.13-02         | 1.08-02          | 1.32-02      | 1.64-02                 | 1.85-02         | 2.05-02       | 2.52-02        | 2.80-02           |
| 6.00+02       | 1.13-02         | 1.09-02          | 1.34-02      | 1.66-02                 | 1.87-02         | 2.07-02       | 2.55-02        | 2.83-02           |
| 8.00+02       | 1.15-02         | 1.11-02          | 1.36-02      | 1.69-02                 | 1.90-02         | 2.10-02       | 2.59-02        | 2.87-02           |
| 1.00+03       | 1.16-02         | 1.12-02          | 1.37-02      | 1.71-02                 | 1.92-02         | 2.12-02       | 2.61-02        | 2.90-02           |
| 1.50+03       | 1.17-02         | 1.14-02          | 1.40-02      | 1.73-02                 | 1.95-02         | 2.16-02       | 2.65-02        | 2.93-02           |
| 2.00+03       | 1.18-02         | 1.15-02          | 1.41-02      | 1.75-02                 | 1.96-02         | 2.18-02       | 2.67-02        | 2.96-02           |
| 3.00+03       | 1.20-02         | 1.16-02          | 1.43-02      | 1.77-02                 | 1.99-02         | 2.20-02       | 2.69-02        | 2.98-02           |
| 4.00+03       | 1.20-02         | 1.17-02          | 1.44-02      | 1.78-02                 | 2.00-02         | 2.21-02       | 2.70-02        | 3.00-02           |
| 5.00+03       | 1.21-02         | 1.18-02          | 1.44-02      | 1.79-02                 | 2.00-02         | 2.22-02       | 2.71-02        | 3.01-02           |
| 6.00-03       | 1.21-02         | 1.18-02          | 1.45-02      | 1.79-02                 | 2.01-02         | 2.22-02       | 2.72-02        | 3.02-02           |
| 8.00+03       | 1.22-02         | 1.19-02          | 1.45-02      | 1.80-02                 | 2.02-02         | 2.23-02       | 2.72-02        | 3.02-02           |
| 1.00+04       | 1.22-02         | 1.19-02          | 1.46-02      | 1.80-02                 | 2.02-02         | 2.23-02       | 2.73-02        | 3.03-02           |
| 1.50+04       | 1.22-02         | 1.19-02          | 1.46-02      | 1.81-02                 | 2.03-02         | 2.24-02       | 2.74-02        | 3.03-02           |
| 2.00+04       | 1.23-02         | 1.20-02          | 1.47-02      | 1.81-02                 | 2.03-02         | 2.24-02       | 2.74-02        | 3.04-02           |
| 3.00+04       | 1.23-02         | 1.20-02          | 1.47-02      | 1.82-02                 | 2.03-02         | 2.25-02       | 2.74-02        | 3.04-02           |
| 4.00+04       | 1.23-02         | 1.20-02          | 1.47-02      | 1.82-02                 | 2.03-02         | 2.25-02       | 2.75-02        | 3.05-02           |
| 5.00+04       | 1.23-02         | 1.20-02          | 1.47-02      | 1.82-02                 | 2.04-02         | 2.25-02       | 2.75-02        | 3.05-02           |
| 6.00+04       | 1.23-02         | 1.20-02          | 1.47-02      | 1.82-02                 | 2.04-02         | 2.25-02       | 2.75-02        | 3.05-02           |
| 8.00+04       | 1.23-02         | 1.20-02          | 1.47-02      | 1.82-02                 | 2.04-02         | 2.25-02       | 2.75-02        | 3.05-02           |
| 1.00+05       | 1.23-02         | 1.20-02          | 1.47-02      | 1.82-02                 | 2.04-02         | 2.25-02       | 2.75-02        | 3.05-02           |

TABLE 1-4. (Continued)

| PHOTON ENERGY | ALUMINUM<br>Z = 13 | SILICON<br>Z = 14 | PHOS-<br>PHORUS<br>Z = 15 | SULFUR<br>Z = 16        | ARGON<br>Z = 18 | POTASSIUM<br>Z = 19 | CALCIUM<br>Z = 20 | IRON<br>Z = 26 |
|---------------|--------------------|-------------------|---------------------------|-------------------------|-----------------|---------------------|-------------------|----------------|
| <i>Mev</i>    |                    |                   |                           | <i>cm<sup>2</sup>/g</i> |                 |                     |                   |                |
| 1.00-02       | 2.58+01            | 3.36+01           | 4.02+01                   | 5.03+01                 | 6.38+01         | 8.01+01             | 9.56+01           | 1.72+02        |
| 1.50-02       | 7.66+00            | 9.97+00           | 1.20+01                   | 1.52+01                 | 1.95+01         | 2.46+01             | 2.96+01           | 5.57+01        |
| 2.00-02       | 3.24+00            | 4.19+00           | 5.10+00                   | 6.42+00                 | 8.27+00         | 1.05+01             | 1.26+01           | 2.51+01        |
| 3.00-02       | 1.03+00            | 1.31+00           | 1.55+00                   | 1.94+00                 | 2.48+00         | 3.14+00             | 3.82+00           | 7.88+00        |
| 4.00-02       | 5.14-01            | 6.35-01           | 7.31-01                   | 8.91-01                 | 1.11+00         | 1.39+00             | 1.67+00           | 3.46+00        |
| 5.00-02       | 3.34-01            | 3.96-01           | 4.44-01                   | 5.27-01                 | 6.30-01         | 7.77-01             | 9.25-01           | 1.84+00        |
| 6.00-02       | 2.55-01            | 2.92-01           | 3.18-01                   | 3.67-01                 | 4.20-01         | 5.12-01             | 5.95-01           | 1.13+00        |
| 8.00-02       | 1.89-01            | 2.07-01           | 2.15-01                   | 2.38-01                 | 2.52-01         | 2.96-01             | 3.34-01           | 5.50-01        |
| 1.00-01       | 1.62-01            | 1.73-01           | 1.75-01                   | 1.89-01                 | 1.89-01         | 2.16-01             | 2.37-01           | 3.42-01        |
| 1.50-01       | 1.34-01            | 1.40-01           | 1.38-01                   | 1.45-01                 | 1.36-01         | 1.50-01             | 1.59-01           | 1.84-01        |
| 2.00-01       | 1.20-01            | 1.25-01           | 1.22-01                   | 1.27-01                 | 1.17-01         | 1.28-01             | 1.33-01           | 1.39-01        |
| 3.00-01       | 1.03-01            | 1.07-01           | 1.04-01                   | 1.08-01                 | 9.79-02         | 1.06-01             | 1.09-01           | 1.07-01        |
| 4.00-01       | 9.22-02            | 9.54-02           | 9.28-02                   | 9.58-02                 | 8.68-02         | 9.38-02             | 9.66-02           | 9.21-02        |
| 5.00-01       | 8.41-02            | 8.70-02           | 8.46-02                   | 8.72-02                 | 7.90-02         | 8.52-02             | 8.78-02           | 8.29-02        |
| 6.00-01       | 7.77-02            | 8.05-02           | 7.82-02                   | 8.06-02                 | 7.29-02         | 7.87-02             | 8.09-02           | 7.62-02        |
| 8.00-01       | 6.83-02            | 7.06-02           | 6.86-02                   | 7.08-02                 | 6.40-02         | 6.90-02             | 7.09-02           | 6.65-02        |
| 1.00+00       | 6.14-02            | 6.35-02           | 6.17-02                   | 6.36-02                 | 5.75-02         | 6.20-02             | 6.37-02           | 5.96-02        |
| 1.50+00       | 5.00-02            | 5.18-02           | 5.03-02                   | 5.19-02                 | 4.69-02         | 5.06-02             | 5.20-02           | 4.87-02        |
| 2.00+00       | 4.32-02            | 4.48-02           | 4.36-02                   | 4.49-02                 | 4.07-02         | 4.39-02             | 4.52-02           | 4.25-02        |
| 3.00+00       | 3.54-02            | 3.68-02           | 3.59-02                   | 3.71-02                 | 3.38-02         | 3.66-02             | 3.78-02           | 3.62-02        |
| 4.00+00       | 3.11-02            | 3.24-02           | 3.17-02                   | 3.29-02                 | 3.02-02         | 3.28-02             | 3.40-02           | 3.31-02        |
| 5.00+00       | 2.84-02            | 2.97-02           | 2.92-02                   | 3.04-02                 | 2.80-02         | 3.06-02             | 3.17-02           | 3.14-02        |
| 6.00+00       | 2.66-02            | 2.79-02           | 2.75-02                   | 2.87-02                 | 2.67-02         | 2.91-02             | 3.03-02           | 3.05-02        |
| 8.00+00       | 2.44-02            | 2.57-02           | 2.55-02                   | 2.68-02                 | 2.51-02         | 2.76-02             | 2.89-02           | 2.98-02        |
| 1.00+01       | 2.31-02            | 2.46-02           | 2.45-02                   | 2.58-02                 | 2.44-02         | 2.70-02             | 2.83-02           | 2.98-02        |
| 1.50+01       | 2.19-02            | 2.34-02           | 2.36-02                   | 2.51-02                 | 2.41-02         | 2.68-02             | 2.83-02           | 3.07-02        |
| 2.00+01       | 2.16-02            | 2.33-02           | 2.35-02                   | 2.52-02                 | 2.44-02         | 2.73-02             | 2.89-02           | 3.21-02        |
| 3.00+01       | 2.19-02            | 2.38-02           | 2.42-02                   | 2.61-02                 | 2.55-02         | 2.86-02             | 3.05-02           | 3.45-02        |
| 4.00+01       | 2.24-02            | 2.45-02           | 2.50-02                   | 2.70-02                 | 2.66-02         | 2.99-02             | 3.19-02           | 3.65-02        |
| 5.00+01       | 2.30-02            | 2.52-02           | 2.57-02                   | 2.78-02                 | 2.75-02         | 3.10-02             | 3.31-02           | 3.82-02        |
| 6.00+01       | 2.35-02            | 2.57-02           | 2.64-02                   | 2.86-02                 | 2.84-02         | 3.19-02             | 3.42-02           | 3.95-02        |
| 8.00+01       | 2.44-02            | 2.67-02           | 2.74-02                   | 2.98-02                 | 2.96-02         | 3.34-02             | 3.58-02           | 4.16-02        |
| 1.00+02       | 2.51-02            | 2.75-02           | 2.83-02                   | 3.07-02                 | 3.06-02         | 3.45-02             | 3.70-02           | 4.32-02        |
| 1.50+02       | 2.63-02            | 2.89-02           | 2.98-02                   | 3.24-02                 | 3.25-02         | 3.68-02             | 3.94-02           | 4.58-02        |
| 2.00+02       | 2.71-02            | 2.99-02           | 3.07-02                   | 3.34-02                 | 3.34-02         | 3.77-02             | 4.05-02           | 4.75-02        |
| 3.00+02       | 2.82-02            | 3.10-02           | 3.19-02                   | 3.48-02                 | 3.48-02         | 3.93-02             | 4.22-02           | 4.94-02        |
| 4.00+02       | 2.88-02            | 3.17-02           | 3.27-02                   | 3.56-02                 | 3.56-02         | 4.02-02             | 4.32-02           | 5.06-02        |
| 5.00+02       | 2.92-02            | 3.22-02           | 3.32-02                   | 3.61-02                 | 3.61-02         | 4.08-02             | 4.38-02           | 5.14-02        |
| 6.00+02       | 2.95-02            | 3.25-02           | 3.35-02                   | 3.65-02                 | 3.65-02         | 4.12-02             | 4.43-02           | 5.19-02        |
| 8.00+02       | 3.00-02            | 3.30-02           | 3.40-02                   | 3.70-02                 | 3.71-02         | 4.19-02             | 4.50-02           | 5.27-02        |
| 1.00+03       | 3.02-02            | 3.33-02           | 3.44-02                   | 3.74-02                 | 3.75-02         | 4.23-02             | 4.55-02           | 5.32-02        |
| 1.50+03       | 3.07-02            | 3.38-02           | 3.48-02                   | 3.80-02                 | 3.80-02         | 4.29-02             | 4.61-02           | 5.39-02        |
| 2.00+03       | 3.09-02            | 3.41-02           | 3.51-02                   | 3.83-02                 | 3.82-02         | 4.32-02             | 4.64-02           | 5.43-02        |
| 3.00+03       | 3.12-02            | 3.44-02           | 3.54-02                   | 3.86-02                 | 3.86-02         | 4.36-02             | 4.68-02           | 5.48-02        |
| 4.00+03       | 3.13-02            | 3.45-02           | 3.56-02                   | 3.88-02                 | 3.87-02         | 4.38-02             | 4.70-02           | 5.50-02        |
| 5.00+03       | 3.14-02            | 3.46-02           | 3.57-02                   | 3.89-02                 | 3.89-02         | 4.39-02             | 4.72-02           | 5.51-02        |
| 6.00+03       | 3.15-02            | 3.47-02           | 3.58-02                   | 3.90-02                 | 3.89-02         | 4.40-02             | 4.73-02           | 5.52-02        |
| 8.00+03       | 3.16-02            | 3.48-02           | 3.59-02                   | 3.91-02                 | 3.91-02         | 4.41-02             | 4.74-02           | 5.54-02        |
| 1.00+04       | 3.16-02            | 3.48-02           | 3.59-02                   | 3.91-02                 | 3.91-02         | 4.42-02             | 4.75-02           | 5.55-02        |
| 1.50+04       | 3.17-02            | 3.49-02           | 3.60-02                   | 3.92-02                 | 3.92-02         | 4.43-02             | 4.76-02           | 5.56-02        |
| 2.00+04       | 3.17-02            | 3.50-02           | 3.61-02                   | 3.93-02                 | 3.93-02         | 4.43-02             | 4.77-02           | 5.56-02        |
| 3.00+04       | 3.18-02            | 3.50-02           | 3.61-02                   | 3.93-02                 | 3.93-02         | 4.44-02             | 4.77-02           | 5.57-02        |
| 4.00+04       | 3.18-02            | 3.51-02           | 3.61-02                   | 3.94-02                 | 3.93-02         | 4.45-02             | 4.77-02           | 5.57-02        |
| 5.00+04       | 3.18-02            | 3.51-02           | 3.62-02                   | 3.94-02                 | 3.93-02         | 4.45-02             | 4.78-02           | 5.58-02        |
| 6.00+04       | 3.18-02            | 3.51-02           | 3.62-02                   | 3.94-02                 | 3.94-02         | 4.45-02             | 4.78-02           | 5.58-02        |
| 8.00+04       | 3.18-02            | 3.51-02           | 3.62-02                   | 3.94-02                 | 3.94-02         | 4.45-02             | 4.78-02           | 5.58-02        |
| 1.00+05       | 3.19-02            | 3.51-02           | 3.62-02                   | 3.94-02                 | 3.94-02         | 4.45-02             | 4.78-02           | 5.58-02        |

TABLE 1.-4. (Continued)

| PHOTON ENERGY | COPPER<br>Z=29 | MOLYB-<br>DENUM<br>Z=42 | TIN<br>Z=50 | IODINE<br>Z=53          | TUNGSTEN<br>Z=74 | LEAD<br>Z=82 | URANIUM<br>Z=92 | ABSORPTION<br>EDGES                     |
|---------------|----------------|-------------------------|-------------|-------------------------|------------------|--------------|-----------------|---|
| <i>Mev</i>    |                |                         |             | <i>cm<sup>2</sup>/g</i> |                  |              |                 |   |
| 1.00-02       | 2.23+02        | 8.40+01                 | 1.39+02     | 1.58+02                 | 9.12+01          | 1.28+02      | 1.73+02         |   |
| 1.50-02       | 7.33+01        | 2.68+01                 | 4.53+01     | 5.34+01                 | 1.39+02          | 1.12+02      | 6.03+01         | L <sub>III</sub> EDGE                   |
| 2.00-02       | 3.30+01        | 1.17+01                 | 2.02+01     | 2.47+01                 | 6.51+01          | 8.34+01      | 6.85+01         | L <sub>III</sub> , L <sub>I</sub> EDGES |
| 3.00-02       | 1.06+01        | 2.83+01                 | 4.07+01     | 7.98+00                 | 2.18+01          | 2.84+01      | 3.96+01         |   |
| 4.00-02       | 4.71+00        | 1.30+01                 | 1.89+01     | 2.23+01                 | 9.97+00          | 1.31+01      | 1.87+01         |   |
| 5.00-02       | 2.50+00        | 6.97+00                 | 1.04+01     | 1.23+01                 | 5.40+00          | 7.22+00      | 1.04+01         |   |
| 6.00-02       | 1.52+00        | 4.25+00                 | 6.32+00     | 7.55+00                 | 3.28+00          | 4.43+00      | 6.45+00         |   |
| 8.00-02       | 7.18-01        | 11.92+00                | 2.90+00     | 3.52+00                 | 7.66+00          | 2.07+00      | 3.04+00         |   |
| 1.00-01       | 4.27-01        | 1.05+00                 | 1.60+00     | 1.91+00                 | 4.29+00          | 5.23+00      | 1.71+00         | K EDGE                                  |
| 1.50-01       | 2.08-01        | 3.99-01                 | 5.77-01     | 6.74-01                 | 1.50+00          | 1.89+00      | 2.47+00         |   |
| 2.00-01       | 1.48-01        | 2.28-01                 | 3.07-01     | 3.49-01                 | 7.38-01          | 9.45-01      | 1.23+00         |   |
| 3.00-01       | 1.08-01        | 1.31-01                 | 1.55-01     | 1.68-01                 | 3.02-01          | 3.83-01      | 4.85-01         |   |
| 4.00-01       | 9.19-02        | 1.01-01                 | 1.10-01     | 1.16-01                 | 1.80-01          | 2.20-01      | 2.73-01         |   |
| 5.00-01       | 8.22-02        | 8.59-02                 | 9.11-02     | 9.36-02                 | 1.29-01          | 1.54-01      | 1.85-01         |   |
| 6.00-01       | 7.52-02        | 7.67-02                 | 7.91-02     | 8.07-02                 | 1.03-01          | 1.20-01      | 1.40-01         |   |
| 8.00-01       | 6.55-02        | 6.52-02                 | 6.55-02     | 6.61-02                 | 7.73-02          | 8.56-02      | 9.64-02         |   |
| 1.00+00       | 5.86-02        | 5.77-02                 | 5.71-02     | 5.75-02                 | 6.39-02          | 6.90-02      | 7.54-02         |   |
| 1.50+00       | 4.79-02        | 4.68-02                 | 4.59-02     | 4.60-02                 | 4.88-02          | 5.10-02      | 5.39-02         |   |
| 2.00+00       | 4.19-02        | 4.14-02                 | 4.08-02     | 4.09-02                 | 4.34-02          | 4.50-02      | 4.70-02         |   |
| 3.00+00       | 3.59-02        | 3.66-02                 | 3.67-02     | 3.69-02                 | 4.01-02          | 4.16-02      | 4.35-02         |   |
| 4.00+00       | 3.32-02        | 3.48-02                 | 3.54-02     | 3.59-02                 | 3.98-02          | 4.14-02      | 4.34-02         |   |
| 5.00+00       | 3.18-02        | 3.43-02                 | 3.53-02     | 3.59-02                 | 4.06-02          | 4.24-02      | 4.44-02         |   |
| 6.00+00       | 3.10-02        | 3.43-02                 | 3.57-02     | 3.63-02                 | 4.16-02          | 4.34-02      | 4.54-02         |   |
| 8.00+00       | 3.06-02        | 3.50-02                 | 3.69-02     | 3.78-02                 | 4.39-02          | 4.59-02      | 4.79-02         |   |
| 1.00+01       | 3.08-02        | 3.62-02                 | 3.85-02     | 3.95-02                 | 4.63-02          | 4.84-02      | 5.06-02         |   |
| 1.50+01       | 3.23-02        | 3.93-02                 | 4.25-02     | 4.38-02                 | 5.24-02          | 5.48-02      | 5.73-02         |   |
| 2.00+01       | 3.39-02        | 4.23-02                 | 4.61-02     | 4.76-02                 | 5.77-02          | 6.06-02      | 6.36-02         |   |
| 3.00+01       | 3.68-02        | 4.70-02                 | 5.17-02     | 5.36-02                 | 6.59-02          | 6.96-02      | 7.33-02         |   |
| 4.00+01       | 3.91-02        | 5.05-02                 | 5.57-02     | 5.78-02                 | 7.16-02          | 7.57-02      | 7.99-02         |   |
| 5.00+01       | 4.10-02        | 5.32-02                 | 5.88-02     | 6.11-02                 | 7.60-02          | 8.04-02      | 8.50-02         |   |
| 6.00+01       | 4.25-02        | 5.53-02                 | 6.13-02     | 6.37-02                 | 7.94-02          | 8.41-02      | 8.89-02         |   |
| 8.00+01       | 4.48-02        | 5.86-02                 | 6.51-02     | 6.76-02                 | 8.45-02          | 8.96-02      | 9.48-02         |   |
| 1.00+02       | 4.65-02        | 6.09-02                 | 6.77-02     | 7.04-02                 | 8.81-02          | 9.34-02      | 9.84-02         |   |
| 1.50+02       | 4.94-02        | 6.48-02                 | 7.21-02     | 7.50-02                 | 9.39-02          | 9.96-02      | 1.06-01         |   |
| 2.00+02       | 5.11-02        | 6.72-02                 | 7.48-02     | 7.78-02                 | 9.76-02          | 1.03-01      | 1.10-01         |   |
| 3.00+02       | 5.32-02        | 7.00-02                 | 7.80-02     | 8.11-02                 | 1.02-01          | 1.08-01      | 1.15-01         |   |
| 4.00+02       | 5.44-02        | 7.16-02                 | 7.98-02     | 8.30-02                 | 1.04-01          | 1.11-01      | 1.17-01         |   |
| 5.00+02       | 5.52-02        | 7.27-02                 | 8.10-02     | 8.42-02                 | 1.06-01          | 1.12-01      | 1.19-01         |   |
| 6.00+02       | 5.58-02        | 7.35-02                 | 8.19-02     | 8.51-02                 | 1.07-01          | 1.13-01      | 1.21-01         |   |
| 8.00+02       | 5.66-02        | 7.45-02                 | 8.31-02     | 8.64-02                 | 1.08-01          | 1.15-01      | 1.22-01         |   |
| 1.00+03       | 5.72-02        | 7.53-02                 | 8.38-02     | 8.71-02                 | 1.09-01          | 1.16-01      | 1.23-01         |   |
| 1.50+03       | 5.79-02        | 7.62-02                 | 8.49-02     | 8.84-02                 | 1.11-01          | 1.18-01      | 1.25-01         |   |
| 2.00+03       | 5.83-02        | 7.67-02                 | 8.56-02     | 8.90-02                 | 1.11-01          | 1.18-01      | 1.26-01         |   |
| 3.00+03       | 5.88-02        | 7.73-02                 | 8.62-02     | 8.96-02                 | 1.12-01          | 1.19-01      | 1.27-01         |   |
| 4.00+03       | 5.90-02        | 7.77-02                 | 8.65-02     | 9.00-02                 | 1.13-01          | 1.20-01      | 1.27-01         |   |
| 5.00+03       | 5.91-02        | 7.79-02                 | 8.67-02     | 9.02-02                 | 1.13-01          | 1.20-01      | 1.28-01         |   |
| 6.00+03       | 5.93-02        | 7.80-02                 | 8.68-02     | 9.04-02                 | 1.13-01          | 1.20-01      | 1.28-01         |   |
| 8.00+03       | 5.94-02        | 7.81-02                 | 8.70-02     | 9.05-02                 | 1.13-01          | 1.20-01      | 1.28-01         |   |
| 1.00+04       | 5.95-02        | 7.83-02                 | 8.71-02     | 9.06-02                 | 1.14-01          | 1.21-01      | 1.28-01         |   |
| 1.50+04       | 5.96-02        | 7.85-02                 | 8.73-02     | 9.08-02                 | 1.14-01          | 1.21-01      | 1.29-01         |   |
| 2.00+04       | 5.96-02        | 7.85-02                 | 8.74-02     | 9.10-02                 | 1.14-01          | 1.21-01      | 1.29-01         |   |
| 3.00+04       | 5.98-02        | 7.86-02                 | 8.75-02     | 9.11-02                 | 1.14-01          | 1.21-01      | 1.29-01         |   |
| 4.00+04       | 5.98-02        | 7.86-02                 | 8.76-02     | 9.11-02                 | 1.14-01          | 1.21-01      | 1.29-01         |   |
| 5.00+04       | 5.98-02        | 7.86-02                 | 8.77-02     | 9.11-02                 | 1.14-01          | 1.21-01      | 1.29-01         |   |
| 6.00+04       | 5.98-02        | 7.87-02                 | 8.77-02     | 9.12-02                 | 1.14-01          | 1.21-01      | 1.29-01         |   |
| 8.00+04       | 5.98-02        | 7.88-02                 | 8.77-02     | 9.12-02                 | 1.14-01          | 1.21-01      | 1.29-01         |   |
| 1.00+05       | 5.98-02        | 7.88-02                 | 8.77-02     | 9.12-02                 | 1.14-01          | 1.21-01      | 1.29-01         |   |



TABLE 1.-5. *Gamma-ray linear attenuation coefficients*  $\mu$  [ $\text{cm}^{-1}$ ], for various materials of interest in shielding.

Except for slight revisions for air,<sup>a</sup> this is the compilation by Hungerford [1960] from data in the Hogerton-Grass Reactor Handbook [1955].

| Material   | Density $\rho$<br>[ $\text{g}/\text{cm}^3$ ] | Linear attenuation coefficient $\mu$ [ $\text{cm}^{-1}$ ] |           |           |
|--|--|---|-----------|-----------|
|  |  | 1 MeV   | 3 MeV     | 6 MeV     |
| Air <sup>a</sup> (20 °C, 76 cm Hg pressure)                | 0.001205                                     | 0.0000765   | 0.0000431 | 0.0000304 |
| Aluminum   | 2.7  | 0.166   | 0.0953    | 0.0718    |
| Ammonia (liquid)   | 0.771  | 0.0612  | 0.0322    | 0.0221    |
| Beryllium  | 1.85   | 0.104   | 0.0579    | 0.0392    |
| Beryllium carbide  | 1.9  | 0.112   | 0.0627    | 0.0429    |
| Beryllium oxide (hot-pressed blocks)                       | 2.3  | 0.140   | 0.0789    | 0.0552    |
| Bismuth  | 9.80   | 0.700   | 0.409     | 0.440     |
| Boral  | 2.53   | 0.153   | 0.0865    | 0.0678    |
| Boron (amorphous)  | 2.45   | 0.144   | 0.0791    | 0.0679    |
| Boron carbide (hot pressed)                                | 2.5  | 0.150   | 0.0825    | 0.0675    |
| Bricks   |  |   |           |           |
| Fire clay  | 2.05   | 0.129   | 0.0738    | 0.0543    |
| Kaolin   | 2.1  | 0.132   | 0.0750    | 0.0552    |
| Silica   | 1.78   | 0.113   | 0.0646    | 0.0473    |
| Carbon   | 2.25 <sup>b</sup>                            | 0.143   | 0.0801    | 0.0554    |
| Clay   | 2.2  | 0.130   | 0.0801    | 0.0590    |
| Cements  |  |   |           |           |
| Colemanite borated   | 1.95   | 0.128   | 0.0725    | 0.0528    |
| Plain (1 Portland cement: 3 sand mixture)                  | 2.07   | 0.133   | 0.0760    | 0.0559    |
| Concretes  |  |   |           |           |
| Barytes <sup>c</sup>                                       | 3.5  | 0.213   | 0.127     | 0.110     |
| Barytes-boron frits <sup>c</sup>                           | 3.25   | 0.199   | 0.119     | 0.101     |
| Barytes-limonite <sup>c</sup>                              | 3.25   | 0.200   | 0.119     | 0.0991    |
| Barytes-lumnite-colemanite <sup>c</sup>                    | 3.1  | 0.189   | 0.112     | 0.0939    |
| Iron-Portland <sup>c</sup>                                 | 6.0  | 0.364   | 0.215     | 0.181     |
| MO (ORNL mixture)  | 5.8  | 0.374   | 0.222     | 0.184     |
| Portland <sup>d</sup> (1 cement: 2 sand: 4 gravel mixture) | { 2.2  | { 0.141   | { 0.0805  | { 0.0592  |
|  | { 2.4  | { 0.154   | { 0.0878  | { 0.0646  |
| Flesh <sup>e</sup>   | 1.0  | 0.0699  | 0.0393    | 0.0274    |
| Fuel oil (medium weight)                                   | 0.89   | 0.0716  | 0.0350    | 0.0239    |
| Gasoline   | 0.739  | 0.0537  | 0.0299    | 0.0203    |
| Glass  |  |   |           |           |
| Borosilicate   | 2.23   | 0.141   | 0.0805    | 0.0591    |
| Lead (Hi-D)  | 6.4  | 0.439   | 0.257     | 0.257     |
| Plate (avg)  | 2.4  | 0.152   | 0.0862    | 0.0629    |
| Iron   | 7.86   | 0.470   | 0.282     | 0.240     |
| Lead   | 11.34  | 0.797   | 0.468     | 0.505     |
| Lithium hydride (pressed powder)                           | 0.70   | 0.0444  | 0.0239    | 0.0172    |
| Lucite (polymethyl methacrylate)                           | 1.19   | 0.0816  | 0.0457    | 0.0317    |
| Paraffin   | 0.89   | 0.0646  | 0.0360    | 0.0246    |
| Rocks  |  |   |           |           |
| Granite  | 2.45   | 0.155   | 0.0887    | 0.0654    |
| Limestone  | 2.91   | 0.187   | 0.109     | 0.0824    |
| Sandstone  | 2.40   | 0.152   | 0.0871    | 0.0641    |
| Rubber   |  |   |           |           |
| Butadiene copolymer  | 0.915  | 0.0662  | 0.0370    | 0.0254    |
| Natural  | 0.92   | 0.0652  | 0.0364    | 0.0248    |
| Neoprene   | 1.23   | 0.0813  | 0.0462    | 0.0333    |
| Sand   | 2.2  | 0.140   | 0.0825    | 0.0587    |
| Type 347 stainless steel                                   | 7.8  | 0.462   | 0.279     | 0.236     |
| Steel (1% carbon)  | 7.83   | 0.460   | 0.276     | 0.234     |
| Uranium  | 18.7   | 1.46  | 0.813     | 0.881     |
| Uranium hydride  | 11.5   | 0.903   | 0.504     | 0.542     |
| Water  | 1.0  | 0.0706  | 0.0396    | 0.0277    |
| Wood   |  |   |           |           |
| Ash  | 0.51   | 0.0345  | 0.0193    | 0.0134    |
| Oak  | 0.77   | 0.0521  | 0.0293    | 0.0203    |
| White pine   | 0.67   | 0.0452  | 0.0253    | 0.0175    |

<sup>a</sup> From table 3.-27.

<sup>b</sup> Graphite theoretical density. See table 1.-1, footnote \*\*\*\*.

<sup>c</sup> Concrete mixtures for shielding reported by Gallaher and Kitzes [1953].

<sup>d</sup> Elemental composition, wt %: hydrogen, 1.0; oxygen, 52.9; silicon, 33.7; aluminum, 3.4; iron, 1.4; calcium, 4.4; magnesium, 0.2; carbon, 0.1; sodium, 1.6; potassium, 1.3.

<sup>e</sup> Composition, wt %: oxygen, 65.99; carbon, 18.27; hydrogen, 10.15; nitrogen, 3.05; calcium, 1.52; phosphorus, 1.02.

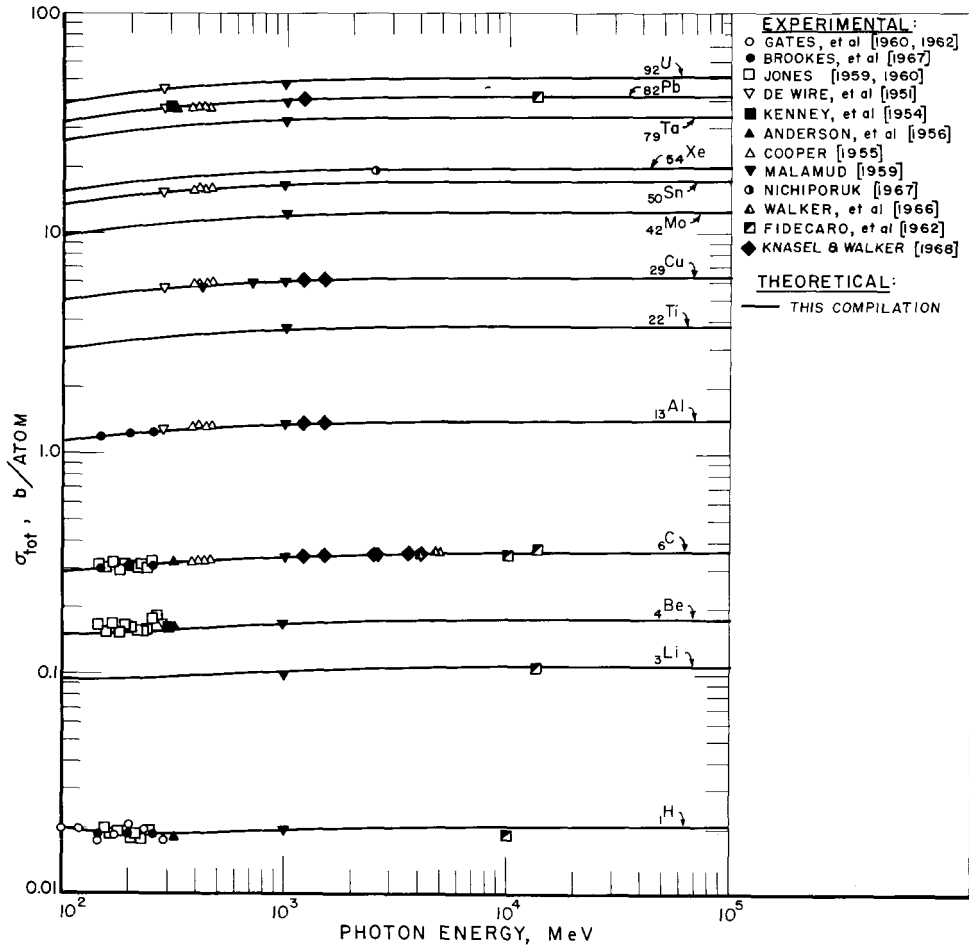


FIGURE 1.-3. Comparison of present total cross sections  $\sigma_{\text{tot}} (= \tau_{\text{pe}} + \sigma_{\text{C}} + \kappa_{\text{n}} + \kappa_{\text{e}})$  (see tables in section 3) above 100 MeV with available experimental data.

### 1.5.2. Conditions Under Which the Coefficients are Useful

At high energies the range of secondary electrons tends to become comparable with the gamma-ray mean free path, as indicated by the ratios in table 1.-6. Under such conditions the computation of gamma-ray energy deposition in a medium requires a cascade calculation involving coupled electron and photon transport equations.<sup>10</sup>

However, at energies below 10 MeV where the travel of electrons is of less significance, it may be sufficient to treat the problem in terms of the gamma-ray flux and either the "mass energy-absorption coefficient" or one of the various approximations such as the "mass energy-transfer coefficient" or "mass absorption coefficient" discussed in the following section 1.5.3.

The amount of energy,  $\epsilon$ , absorbed per unit time in a "volume of interest,"  $\Delta V$ , at a point  $\mathbf{r}$  in the medium, can be expressed as the sum of two terms. The first term describes the conversion of photon energy to electron kinetic energy and involves the mass energy-absorption coefficient. The second term describes the migration of energy into and out of the volume of interest in the form of kinetic energy of electrons. Thus one can set up the energy balance equation:

$$\epsilon = \int_{\Delta V} (dr)^3 \rho(\mathbf{r}) \int_0^{E_{\text{max}}} dE \cdot \phi(E, \mathbf{r}) \cdot E \cdot \frac{\mu_{\text{en}}}{\rho}(E) + [\epsilon_{\text{in}} - \epsilon_{\text{out}}] \quad (1.-9)$$

in which  $\epsilon$ ,  $\epsilon_{\text{in}}$ , and  $\epsilon_{\text{out}}$  are in  $\text{MeV s}^{-1}$ ,  $\rho(\mathbf{r})$  is the density of the medium in  $\text{g cm}^{-3}$  at  $\mathbf{r}$ ,  $E$  is the photon energy in MeV, and  $\mu_{\text{en}}/\rho(E)$  is in  $\text{cm}^2 \text{g}^{-1}$ . The quantity  $\phi(E, \mathbf{r})$ , with dimensions  $\text{MeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$ , represents the flux per unit energy interval (integrated over all directions) of photons, including secondaries, with energies between  $E$  and  $E + dE$ .

<sup>10</sup> For a calculation of this type see, for example, that of Brysk [1954].

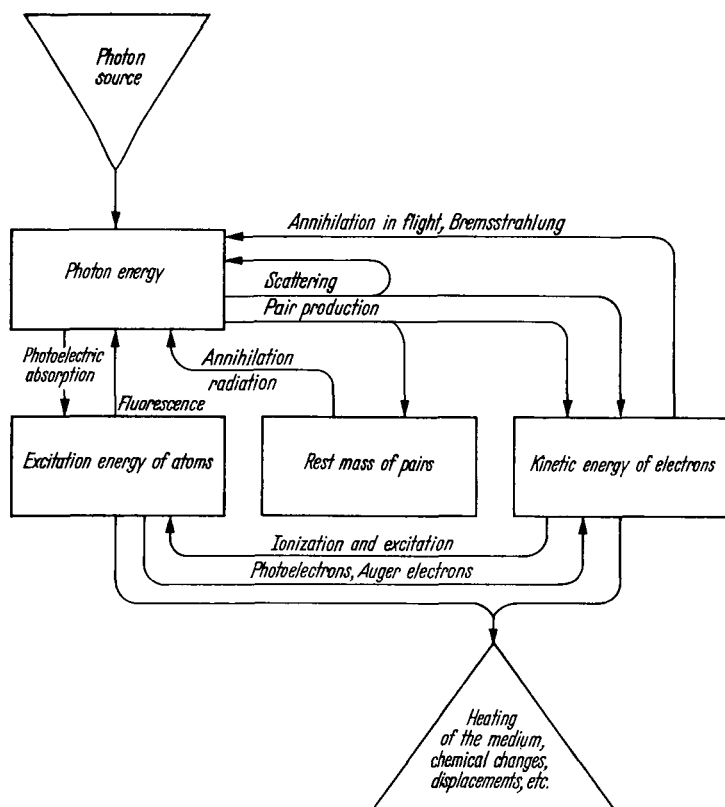


FIGURE 1.-4. Flow diagram of conversion of energy from one form to another in the course of photon energy absorption in a medium.

To be complete, the diagram should also contain a box labelled "excitation energy of nuclei," as well as lines representing the emission of secondary neutrons, charged particles, and gamma rays. This box has been omitted in order to prevent the diagram from becoming unduly complicated, and because the energy absorption coefficients presented here do not take into account photonuclear absorption.

TABLE 1.-6. Ratios of the electron range,<sup>a</sup>  $R_e$ , to the photon mean-free-path,  $(1/\mu)$ , based on electron data of Berger and Seltzer [1964] and photon data from tables 1.-4 and 3.-24, -26, -27, and -28.

| Photon energy [MeV] | $_1\text{H}$ | $_6\text{C}$ | $_{13}\text{Al}$ | $_{26}\text{Fe}$ | $_{50}\text{Sn}$ | $_{82}\text{Pb}$ |                 | Air    | $\text{H}_2\text{O}$ | Concrete | NaI   |               |
|---------------------|--------------|--------------|------------------|------------------|------------------|------------------|-----------------|--------|----------------------|----------|-------|---------------|
|                     |              |              |                  |                  |                  |                  | $R_e \cdot \mu$ |        |                      |          |       |               |
| 0.01                | 0.000041     | 0.00058      | 0.0091           | 0.076            | 0.087            | 0.11             | L-edges         | 0.0014 | 0.0012               | 0.0074   | 0.085 | Iodine K-edge |
| 0.1                 | 0.0020       | 0.0024       | 0.0030           | 0.0073           | 0.043            | 0.17             | K-edge          | 0.0025 | 0.0023               | 0.0029   | 0.041 |               |
| 1.0                 | 0.027        | 0.031        | 0.034            | 0.036            | 0.040            | 0.053            |                 | 0.031  | 0.030                | 0.033    | 0.039 |               |
| 10.0                | 0.077        | 0.11         | 0.13             | 0.18             | 0.23             | 0.29             |                 | 0.11   | 0.11                 | 0.12     | 0.22  |               |
| 100.0               | 0.22         | 0.55         | 0.81             | 1.1              | 1.5              | 1.8              |                 | 0.53   | 0.56                 | 0.69     | 1.4   |               |

<sup>a</sup>) Here we use the mean range as calculated in the continuous-slowning-down approximation.

Under conditions of electronic equilibrium,<sup>11</sup>  $\epsilon_{in} = \epsilon_{out}$ , and the second term vanishes. When the size of the volume of interest,  $\Delta V$ , is large compared with the ranges of the secondary electrons involved, the term  $[\epsilon_{in} - \epsilon_{out}]$  is small compared with the integral term and may be disregarded.

<sup>11</sup> Electronic equilibrium prevails if the gamma-ray flux distribution is effectively constant over a region having dimensions of the order of the range of the secondary electrons. Discussions of this concept and its application are given in NBS Handbook 85 [1964] and in a number of dosimetry texts (see, for example, Whyte [1959] and Johns [1961]).

### 1.5.3. Evaluation of the Coefficients From the Cross Sections

The "mass energy-absorption coefficient,"  $\mu_{en}/\rho$ , as specified in definition (17) in Appendix I of NBS Handbook 85 [1964], takes into account all the modes of energy transfer to electrons shown in figure 1.-4. The other coefficients treated here, namely the "mass energy-transfer coefficient"  $\mu_K/\rho$  as specified in definition (16) in Appendix I of

NBS Handbook 85 [1964], and the "mass absorption coefficient"  $\mu_a/\rho$  (sec. e.g., eq (8f-48) of Evans [1963]), are approximate and neglect some of these modes. The coefficients,  $\mu_{en}/\rho$ ,  $\mu_K/\rho$ , and  $\mu_a/\rho$ , are differently weighted sums of the probabilities per unit pathlength (in g/cm<sup>2</sup>) for photoelectric absorption ( $\mu_T/\rho$ ), Compton collision ( $\mu_C/\rho$ ), and pair production ( $\mu_K/\rho$ ):

$$\left. \begin{array}{l} \mu_{en}/\rho = \\ \mu_K/\rho = \\ \mu_a/\rho = \end{array} \right\} \left( \frac{\mu_T}{\rho} \right) f_T + \left( \frac{\mu_C}{\rho} \right) f_C + \left( \frac{\mu_K}{\rho} \right) f_K. \quad (1.-10)$$

The weights  $f_T$ ,  $f_C$ , and  $f_K$  are conversion factors which indicate, for the respective interactions, the average fraction of the photon energy which is eventually converted into kinetic energy of electrons in the volume of interest. These weights, therefore, must discount the amount of energy that escapes from the volume of interest in the form of secondary photons (which may include scattered photons, annihilation radiation, bremsstrahlung, and fluorescence radiation).

For  $\mu_{en}/\rho$  the weights account for the escape of Compton-scattered, fluorescence, annihilation, and bremsstrahlung photons. For  $\mu_K/\rho$  the weights account for the escape of all of these except bremsstrahlung photons. For  $\mu_a/\rho$  they account for the escape of Compton-scattered photons only.

A certain part of the escaping photon radiation may also interact with the medium in the volume of interest and set electrons into motion there. This possibility is automatically taken into account if one includes in the flux  $\phi(E, \mathbf{r})$  which multiplies the coefficient not only unscattered (primary) photons, but also scattered photons, and all other secondary photons, such as annihilation radiation.<sup>12</sup> On the other hand, the treatment must be consistent. That is, if in eq (1.-9) one uses values of  $\mu_a/\rho$  or  $\mu_K/\rho$ , from which the escape of certain secondary radiations is not discounted, then one should use values of  $\phi(E, \mathbf{r})$  computed without considering the contributions from these radiations.

R. Berger [1961] has evaluated the coefficients  $f_K$ ,  $f_C$ , and  $f_T$ , including all energy transfer routes shown in figure 1.-4, and from them the mass energy-absorption coefficient  $\mu_{en}/\rho$  for air, water, and 15 elements and  $\mu_K/\rho$  for Al, Fe, and Pb over the energy range  $10 \text{ keV} \leq E \leq 10 \text{ MeV}$ . Tabulations of  $\mu_{en}/\rho$  and  $\mu_a/\rho$  have been made by Allison [1961]

for air, water, and seven elements over the range  $10 \text{ keV} \leq E \leq 100 \text{ MeV}$ . His procedures are essentially the same as those of Berger, with the exception that in discounting the escape of annihilation radiation he did not consider the possibility of annihilation of the positron while in flight. Thus, for heavy elements ( $Z \geq 26$ ) the Allison data are slightly different from those of Berger at energies above the pair production threshold, i.e., for  $E > 1.022 \text{ MeV}$ . This effect of annihilation in flight amounts to  $\sim 2$  to 3 percent at 10 MeV, and presumably more in the region  $E > 10 \text{ MeV}$ , which was not included by Berger.

Various other authors have presented values of  $\mu_a/\rho$  which, as has been discussed, discount only the energy-escape by the deflected photon in Compton scattering. Data in this approximation include the tabulations by White [1952] and Storm, Gilbert, and Israel [1958], and the graphical data of Evans [1955, 1963].

## 1.6. Tabulation of Energy Absorption Coefficients

In tables 1.-7 and 1.-8 we present values of  $\mu_{en}/\rho$ ,  $\mu_a/\rho$ , and  $\mu_K/\rho$ , for air, water, and 18 elements over the range  $10 \text{ keV} \leq E \leq 10 \text{ MeV}$ . These data are based on the interaction cross sections in section 2 and hence are consistent with the attenuation coefficients in table 1.-4 and in section 3.

For  $\mu_a/\rho$ , values of Compton scatter losses  $(1-f_C)\mu_C/\rho$  were subtracted from entries in table 1.-4. For  $\mu_K/\rho$ , the compilation of fluorescence yields and average fluorescence photon energies of R. Berger [1961] was used plus values for Sn and U from Wapstra et al. [1959].<sup>13</sup> For  $\mu_{en}/\rho$  the weights  $f_T$ ,  $f_C$ , and  $f_K$  were taken directly or interpolated from Berger [1961], except values of  $f_T$  for Sn and U, for which bremsstrahlung yield data from Berger and Seltzer [1964] were used.

In addition, in table 1.-9, we have excerpted the values of  $\mu_{en}/\rho$  over the range  $10 \text{ MeV} \leq E \leq 100 \text{ MeV}$  from the tabulation by Allison [1961]. We also include, for comparison, values of  $\mu_a/\rho$  computed from present cross sections for the same substances. As discussed in section 1.5.3, the Allison data differ from those of Berger in that positron annihilation in flight was not taken into account. However, at energies above 10 MeV the approximation involved in the use of energy-absorption or related coefficients loses some of its validity because of the comparable distances traveled by electrons and photons (see table 1.-6).

<sup>12</sup> Calculations of  $\phi(E, \mathbf{r})$  often include only Compton scattered photons in the secondary flux (see, for example, Goldstein and Wilkins [1954]). However, for 6- to 10-MeV primary photons in lead, the annihilation photon flux has been theoretically estimated to contribute from 4 to 7 percent to  $\phi(E, \mathbf{r})$  by Goldstein [1954] and by Berger, Hubbell, and Reingold [1959], and contributions of this order of magnitude have been observed experimentally by Hubbell, Hayward, and Titus [1957]. Also, theoretical estimates of the fluorescence radiation component have been made by Goldstein [1954], Veigele and Roper [1966], and Veigele and Balogh [1968].

<sup>13</sup> For a more recent and extensive summary of K-, L-, and M-shell fluorescence yield data, see Fink et al. [1966].

TABLE 1.-7. Values of (a) the mass absorption coefficient  $\mu_a/\rho$ ; (b) the mass energy-transfer coefficient  $\mu_K/\rho$ ; and (c) the mass energy-absorption coefficient  $\mu_{en}/\rho$ .

Units are  $\text{cm}^2/\text{g}$  (see footnote a).

| Photon energy [MeV] | $^1\text{H}$ |              |                 | $^{12}\text{C}$ |              |                 | $^{14}\text{N}$ |              |                 |
|---------------------|--------------|--------------|-----------------|-----------------|--------------|-----------------|-----------------|--------------|-----------------|
|                     | $\mu_a/\rho$ | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$    | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$    | $\mu_K/\rho$ | $\mu_{en}/\rho$ |
| 0.01                | 0.00991      |              |                 | 1.98            |              |                 | 3.38            |              |                 |
| 0.015               | 0.0110       |              |                 | 0.538           |              |                 | 0.908           |              |                 |
| 0.02                | 0.0136       |              |                 | 0.208           |              |                 | 0.362           |              |                 |
| 0.03                | 0.0186       |              |                 | 0.0596          |              |                 | 0.105           |              |                 |
| 0.04                | 0.0231       |              |                 | 0.0307          |              |                 | 0.0494          |              |                 |
| 0.05                | 0.0271       |              |                 | 0.0234          |              |                 | 0.0319          |              |                 |
| 0.06                | 0.0305       |              |                 | 0.0212          |              |                 | 0.0256          |              |                 |
| 0.08                | 0.0362       |              |                 | 0.0205          |              |                 | 0.0223          |              |                 |
| 0.10                | 0.0406       |              |                 | 0.0216          |              |                 | 0.0224          |              |                 |
| 0.15                | 0.0481       |              |                 | 0.0246          |              |                 | 0.0248          |              |                 |
| 0.2                 | 0.0525       |              |                 | 0.0266          |              |                 | 0.0267          |              |                 |
| 0.3                 | 0.0569       |              |                 | 0.0288          |              |                 | 0.0287          |              |                 |
| 0.4                 | 0.0586       |              |                 | 0.0296          |              |                 | 0.0295          |              |                 |
| 0.5                 | 0.0590       |              |                 | 0.0298          |              |                 | 0.0297          |              | 0.0296          |
| 0.6                 | 0.0587       |              |                 | 0.0297          |              | 0.0295          | 0.0296          |              | 0.0295          |
| 0.8                 | 0.0574       |              |                 | 0.0290          |              | 0.0288          | 0.0289          |              | 0.0289          |
| 1.0                 | 0.0555       |              |                 | 0.0280          |              | 0.0279          | 0.0280          |              | 0.0279          |
| 1.5                 | 0.0507       |              |                 | 0.0257          |              | 0.0255          | 0.0257          |              | 0.0255          |
| 2                   | 0.0465       |              | 0.0464          | 0.0238          | 0.0235       | 0.0234          | 0.0238          | 0.0236       | 0.0234          |
| 3                   | 0.0400       | 0.0399       | 0.0398          | 0.0210          | 0.0206       | 0.0204          | 0.0211          | 0.0207       | 0.0205          |
| 4                   | 0.0355       | 0.0353       | 0.0352          | 0.0191          | 0.0187       | 0.0185          | 0.0194          | 0.0189       | 0.0186          |
| 5                   | 0.0320       | 0.0319       | 0.0317          | 0.0178          | 0.0174       | 0.0171          | 0.0181          | 0.0177       | 0.0173          |
| 6                   | 0.0294       | 0.0292       | 0.0290          | 0.0169          | 0.0164       | 0.0161          | 0.0172          | 0.0167       | 0.0163          |
| 8                   | 0.0255       | 0.0253       | 0.0252          | 0.0156          | 0.0151       | 0.0147          | 0.0161          | 0.0156       | 0.0151          |
| 10                  | 0.0229       | 0.0227       | 0.0225          | 0.0147          | 0.0143       | 0.0138          | 0.0154          | 0.0149       | 0.0143          |

a) Values for  $\mu_K/\rho$  and  $\mu_{en}/\rho$  given only if different from  $\mu_a/\rho$ .

| Photon energy [MeV] | $^{16}\text{O}$ |              |                 | $^{23}\text{Na}$ |              |                 | $^{24}\text{Mg}$ |              |                 |
|---------------------|-----------------|--------------|-----------------|------------------|--------------|-----------------|------------------|--------------|-----------------|
|                     | $\mu_a/\rho$    | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ |
| 0.01                | 5.39            |              |                 | 14.9             |              |                 | 20.1             |              |                 |
| 0.015               | 1.44            |              |                 | 4.20             |              |                 | 5.80             |              |                 |
| 0.02                | 0.575           |              |                 | 1.70             |              |                 | 2.38             |              |                 |
| 0.03                | 0.165           |              |                 | 0.475            |              |                 | 0.671            |              |                 |
| 0.04                | 0.0734          |              |                 | 0.199            |              |                 | 0.276            |              |                 |
| 0.05                | 0.0438          |              |                 | 0.106            |              |                 | 0.144            |              |                 |
| 0.06                | 0.0322          |              |                 | 0.0669           |              |                 | 0.0888           |              |                 |
| 0.08                | 0.0249          |              |                 | 0.0382           |              |                 | 0.0475           |              |                 |
| 0.10                | 0.0237          |              |                 | 0.0297           |              |                 | 0.0346           |              |                 |
| 0.15                | 0.0251          |              |                 | 0.0260           |              |                 | 0.0279           |              |                 |
| 0.2                 | 0.0268          |              |                 | 0.0265           |              |                 | 0.0277           |              |                 |
| 0.3                 | 0.0288          |              |                 | 0.0278           |              |                 | 0.0288           |              |                 |
| 0.4                 | 0.0296          |              |                 | 0.0284           |              |                 | 0.0294           |              |                 |
| 0.5                 | 0.0298          |              |                 | 0.0285           |              |                 | 0.0294           |              |                 |
| 0.6                 | 0.0296          |              |                 | 0.0284           |              |                 | 0.0293           |              |                 |
| 0.8                 | 0.0289          |              |                 | 0.0277           |              | 0.0275          | 0.0286           |              | 0.0285          |
| 1.0                 | 0.0280          |              | 0.0278          | 0.0268           |              | 0.0266          | 0.0277           |              | 0.0275          |
| 1.5                 | 0.0257          |              | 0.0254          | 0.0246           | 0.0245       | 0.0243          | 0.0254           | 0.0253       | 0.0251          |
| 2                   | 0.0239          | 0.0236       | 0.0234          | 0.0230           | 0.0227       | 0.0225          | 0.0238           | 0.0234       | 0.0232          |
| 3                   | 0.0213          | 0.0208       | 0.0206          | 0.0208           | 0.0202       | 0.0199          | 0.0216           | 0.0210       | 0.0206          |
| 4                   | 0.0196          | 0.0191       | 0.0188          | 0.0195           | 0.0188       | 0.0184          | 0.0204           | 0.0196       | 0.0191          |
| 5                   | 0.0185          | 0.0179       | 0.0175          | 0.0186           | 0.0179       | 0.0174          | 0.0196           | 0.0187       | 0.0181          |
| 6                   | 0.0177          | 0.0171       | 0.0166          | 0.0181           | 0.0173       | 0.0167          | 0.0190           | 0.0182       | 0.0175          |
| 8                   | 0.0166          | 0.0160       | 0.0155          | 0.0174           | 0.0167       | 0.0159          | 0.0185           | 0.0177       | 0.0168          |
| 10                  | 0.0160          | 0.0154       | 0.0148          | 0.0171           | 0.0164       | 0.0155          | 0.0183           | 0.0176       | 0.0165          |

TABLE 1.-7 (Continued)

| Photon energy [MeV] | <sup>13</sup> Al |              |                 | <sup>14</sup> Si |              |                 | <sup>15</sup> P |              |                 |
|---------------------|------------------|--------------|-----------------|------------------|--------------|-----------------|-----------------|--------------|-----------------|
|                     | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$    | $\mu_K/\rho$ | $\mu_{en}/\rho$ |
| 0.01                | 25.6             | 25.5         | 25.5            | 33.4             | 33.3         | 33.3            | 40.1            | 39.8         | 39.8            |
| 0.015               | 7.48             | 7.47         | 7.47            | 9.78             | 9.75         | 9.75            | 11.9            | 11.8         | 11.8            |
| 0.02                | 3.06             |              |                 | 4.02             | 4.01         | 4.01            | 4.93            | 4.91         | 4.91            |
| 0.03                | 0.868            |              |                 | 1.14             | 1.14         | 1.14            | 1.39            | 1.39         | 1.39            |
| 0.04                | 0.357            |              |                 | 0.473            | 0.472        | 0.472           | 0.573           | 0.572        | 0.572           |
| 0.05                | 0.184            |              |                 | 0.241            |              |                 | 0.293           |              |                 |
| 0.06                | 0.111            |              |                 | 0.144            |              |                 | 0.173           |              |                 |
| 0.08                | 0.0562           |              |                 | 0.0701           |              |                 | 0.0820          |              |                 |
| 0.10                | 0.0386           |              |                 | 0.0459           |              |                 | 0.0511          |              |                 |
| 0.15                | 0.0286           |              |                 | 0.0312           |              |                 | 0.0323          |              |                 |
| 0.2                 | 0.0276           |              |                 | 0.0293           |              |                 | 0.0292          |              |                 |
| 0.3                 | 0.0283           |              |                 | 0.0294           |              |                 | 0.0288          |              |                 |
| 0.4                 | 0.0287           |              |                 | 0.0298           |              |                 | 0.0291          |              |                 |
| 0.5                 | 0.0288           |              | 0.0286          | 0.0298           |              |                 | 0.0290          |              |                 |
| 0.6                 | 0.0286           |              | 0.0286          | 0.0296           |              | 0.0295          | 0.0288          |              |                 |
| 0.8                 | 0.0279           |              | 0.0277          | 0.0289           |              | 0.0288          | 0.0281          |              | 0.0278          |
| 1.0                 | 0.0270           |              | 0.0269          | 0.0279           |              | 0.0277          | 0.0272          |              | 0.0270          |
| 1.5                 | 0.0248           | 0.0247       | 0.0245          | 0.0257           | 0.0255       | 0.0253          | 0.0250          | 0.0248       | 0.0246          |
| 2                   | 0.0233           | 0.0229       | 0.0226          | 0.0241           | 0.0237       | 0.0234          | 0.0235          | 0.0231       | 0.0228          |
| 3                   | 0.0213           | 0.0206       | 0.0202          | 0.0221           | 0.0214       | 0.0210          | 0.0217          | 0.0209       | 0.0204          |
| 4                   | 0.0201           | 0.0193       | 0.0188          | 0.0211           | 0.0202       | 0.0196          | 0.0207          | 0.0198       | 0.0192          |
| 5                   | 0.0194           | 0.0185       | 0.0179          | 0.0204           | 0.0194       | 0.0187          | 0.0201          | 0.0191       | 0.0184          |
| 6                   | 0.0190           | 0.0181       | 0.0172          | 0.0201           | 0.0191       | 0.0182          | 0.0198          | 0.0188       | 0.0179          |
| 8                   | 0.0186           | 0.0177       | 0.0168          | 0.0197           | 0.0187       | 0.0177          | 0.0197          | 0.0187       | 0.0175          |
| 10                  | 0.0185           | 0.0176       | 0.0165          | 0.0197           | 0.0188       | 0.0175          | 0.0197          | 0.0188       | 0.0174          |

| Photon energy [MeV] | <sup>16</sup> S |              |                 | <sup>18</sup> Ar |              |                 | <sup>19</sup> K |              |                 |
|---------------------|-----------------|--------------|-----------------|------------------|--------------|-----------------|-----------------|--------------|-----------------|
|                     | $\mu_a/\rho$    | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$    | $\mu_K/\rho$ | $\mu_{en}/\rho$ |
| 0.01                | 50.1            | 49.7         | 49.7            | 63.6             | 62.3         | 62.3            | 79.9            | 77.6         | 77.6            |
| 0.015               | 15.0            | 14.9         | 14.9            | 19.3             | 19.1         | 19.1            | 24.4            | 23.9         | 23.9            |
| 0.02                | 6.24            | 6.21         | 6.21            | 8.10             | 8.02         | 8.02            | 10.3            | 10.2         | 10.2            |
| 0.03                | 1.77            | 1.77         | 1.77            | 2.33             | 2.31         | 2.31            | 2.97            | 2.94         | 2.94            |
| 0.04                | 0.729           | 0.727        | 0.727           | 0.967            | 0.962        | 0.962           | 1.23            | 1.23         | 1.23            |
| 0.05                | 0.372           |              |                 | 0.490            | 0.488        | 0.488           | 0.626           | 0.623        | 0.623           |
| 0.06                | 0.218           |              |                 | 0.285            | 0.284        | 0.284           | 0.368           | 0.366        | 0.366           |
| 0.08                | 0.101           |              |                 | 0.128            |              |                 | 0.162           | 0.162        | 0.162           |
| 0.10                | 0.0610          |              |                 | 0.0735           |              |                 | 0.0915          | 0.0913       | 0.0913          |
| 0.15                | 0.0357          |              |                 | 0.0377           |              |                 | 0.0442          |              |                 |
| 0.2                 | 0.0311          |              |                 | 0.0304           |              |                 | 0.0343          |              |                 |
| 0.3                 | 0.0300          |              |                 | 0.0278           |              |                 | 0.0304          |              |                 |
| 0.4                 | 0.0301          |              |                 | 0.0275           |              |                 | 0.0298          |              |                 |
| 0.5                 | 0.0300          |              |                 | 0.0273           |              |                 | 0.0295          |              | 0.0293          |
| 0.6                 | 0.0298          |              |                 | 0.0270           |              | 0.0268          | 0.0292          |              | 0.0290          |
| 0.8                 | 0.0290          |              | 0.0288          | 0.0262           |              | 0.0261          | 0.0283          |              | 0.0282          |
| 1.0                 | 0.0280          |              | 0.0278          | 0.0253           |              | 0.0251          | 0.0273          |              | 0.0270          |
| 1.5                 | 0.0258          | 0.0256       | 0.0253          | 0.0233           | 0.0232       | 0.0229          | 0.0252          | 0.0250       | 0.0247          |
| 2                   | 0.0243          | 0.0238       | 0.0235          | 0.0220           | 0.0215       | 0.0212          | 0.0238          | 0.0233       | 0.0229          |
| 3                   | 0.0225          | 0.0216       | 0.0211          | 0.0206           | 0.0198       | 0.0192          | 0.0224          | 0.0214       | 0.0208          |
| 4                   | 0.0216          | 0.0205       | 0.0199          | 0.0199           | 0.0189       | 0.0182          | 0.0218          | 0.0206       | 0.0198          |
| 5                   | 0.0211          | 0.0200       | 0.0192          | 0.0197           | 0.0185       | 0.0177          | 0.0215          | 0.0202       | 0.0193          |
| 6                   | 0.0209          | 0.0197       | 0.0188          | 0.0196           | 0.0184       | 0.0174          | 0.0215          | 0.0202       | 0.0190          |
| 8                   | 0.0208          | 0.0197       | 0.0184          | 0.0197           | 0.0186       | 0.0173          | 0.0218          | 0.0205       | 0.0190          |
| 10                  | 0.0210          | 0.0200       | 0.0184          | 0.0201           | 0.0190       | 0.0174          | 0.0222          | 0.0210       | 0.0191          |

TABLE 1.-7 (Continued)

| Photon energy [MeV] | <sup>20</sup> Ca |              |                 | <sup>26</sup> Fe |              |                 | <sup>29</sup> Cu |              |                 |
|---------------------|------------------|--------------|-----------------|------------------|--------------|-----------------|------------------|--------------|-----------------|
|                     | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ |
| 0.01                | 95.4             | 91.6         | 91.6            | 171.             | 142.         | 142.            | 223.             | 160.         | 160.            |
| 0.015               | 29.4             | 28.6         | 28.6            | 55.5             | 49.3         | 49.3            | 73.2             | 59.4         | 59.4            |
| 0.02                | 12.4             | 12.2         | 12.2            | 24.9             | 22.8         | 22.8            | 32.8             | 28.2         | 28.2            |
| 0.03                | 3.65             | 3.60         | 3.60            | 7.72             | 7.28         | 7.28            | 10.5             | 9.50         | 9.50            |
| 0.04                | 1.51             | 1.50         | 1.50            | 3.31             | 3.17         | 3.17            | 4.56             | 4.24         | 4.24            |
| 0.05                | 0.770            | 0.764        | 0.764           | 1.69             | 1.64         | 1.64            | 2.35             | 2.22         | 2.22            |
| 0.06                | 0.447            | 0.444        | 0.444           | 0.989            | 0.961        | 0.961           | 1.39             | 1.32         | 1.32            |
| 0.08                | 0.197            | 0.196        | 0.196           | 0.422            | 0.414        | 0.414           | 0.593            | 0.573        | 0.573           |
| 0.10                | 0.109            |              |                 | 0.223            | 0.219        | 0.219           | 0.311            | 0.302        | 0.302           |
| 0.15                | 0.0498           |              |                 | 0.0821           | 0.0814       | 0.0814          | 0.108            | 0.106        | 0.106           |
| 0.2                 | 0.0371           |              |                 | 0.0498           | 0.0495       | 0.0495          | 0.0602           | 0.0597       | 0.0597          |
| 0.3                 | 0.0318           |              |                 | 0.0342           | 0.0335       | 0.0335          | 0.0371           | 0.0370       | 0.0370          |
| 0.4                 | 0.0309           |              |                 | 0.0308           |              |                 | 0.0318           |              |                 |
| 0.5                 | 0.0304           |              |                 | 0.0295           |              |                 | 0.0298           |              |                 |
| 0.6                 | 0.0300           |              | 0.0299          | 0.0287           |              | 0.0286          | 0.0287           |              | 0.0286          |
| 0.8                 | 0.0291           |              | 0.0289          | 0.0275           |              | 0.0273          | 0.0273           | 0.0272       | 0.0271          |
| 1.0                 | 0.0281           | 0.0280       | 0.0278          | 0.0264           |              | 0.0262          | 0.0261           | 0.0261       | 0.0258          |
| 1.5                 | 0.0259           | 0.0257       | 0.0254          | 0.0243           | 0.0241       | 0.0237          | 0.0240           | 0.0237       | 0.0233          |
| 2                   | 0.0245           | 0.0240       | 0.0236          | 0.0233           | 0.0225       | 0.0220          | 0.0230           | 0.0222       | 0.0217          |
| 3                   | 0.0231           | 0.0220       | 0.0214          | 0.0225           | 0.0212       | 0.0204          | 0.0225           | 0.0211       | 0.0202          |
| 4                   | 0.0226           | 0.0213       | 0.0205          | 0.0225           | 0.0209       | 0.0199          | 0.0228           | 0.0211       | 0.0200          |
| 5                   | 0.0224           | 0.0211       | 0.0200          | 0.0228           | 0.0211       | 0.0198          | 0.0233           | 0.0214       | 0.0200          |
| 6                   | 0.0225           | 0.0211       | 0.0198          | 0.0232           | 0.0215       | 0.0199          | 0.0239           | 0.0220       | 0.0202          |
| 8                   | 0.0229           | 0.0215       | 0.0198          | 0.0242           | 0.0226       | 0.0204          | 0.0251           | 0.0234       | 0.0209          |
| 10                  | 0.0234           | 0.0222       | 0.0201          | 0.0252           | 0.0238       | 0.0209          | 0.0264           | 0.0248       | 0.0215          |

| Photon energy [MeV] | <sup>50</sup> Sn |              |                 | <sup>82</sup> Pb |              |                 | <sup>92</sup> U |              |                              |
|---------------------|------------------|--------------|-----------------|------------------|--------------|-----------------|-----------------|--------------|------------------------------|
|                     | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$    | $\mu_K/\rho$ | $\mu_{en}/\rho$              |
| 0.01                | 139.             | 136.         | 136.            | 128              | 127.         | 127.            | 173.            | 171.         | 170.                         |
| 0.015               | 45.2             | 43.7         | 43.6            | 112.0            | 91.7         | 91.7            | 60.2            | 59.6         | 59.4 <i>L<sub>III</sub></i>  |
| 0.02                | 20.0             | 19.8         | 19.8            | 83.3             | 69.2         | 69.1            | 68.3            | 55.5         | 55.5 <i>L<sub>II,I</sub></i> |
| 0.03                | 40.5             | 16.2         | 16.2            | 28.2             | 24.6         | 24.6            | 39.4            | 33.0         | 33.0                         |
| 0.04                | 18.8             | 9.97         | 9.96            | 13.0             | 11.8         | 11.8            | 18.6            | 16.3         | 16.3                         |
| 0.05                | 10.2             | 6.25         | 6.24            | 7.10             | 6.57         | 6.54            | 10.3            | 9.30         | 9.25                         |
| 0.06                | 6.20             | 4.20         | 4.19            | 4.31             | 4.11         | 4.08            | 6.34            | 5.82         | 5.78                         |
| 0.08                | 2.78             | 2.19         | 2.18            | 1.96             | 1.87         | 1.86            | 2.94            | 2.76         | 2.73                         |
| 0.10                | 1.49             | 1.26         | 1.25            | 5.12             | 2.28         | 2.28            | 1.61            | 1.54         | 1.52 <i>K</i>                |
| 0.15                | 0.485            | 0.446        | 0.442           | 1.80             | 1.16         | 1.15            | 2.39            | 1.12         | 1.19                         |
| 0.2                 | 0.226            | 0.211        | 0.209           | 0.869            | 0.637        | 0.629           | 1.15            | 0.712        | 0.704                        |
| 0.3                 | 0.0892           | 0.0853       | 0.0843          | 0.322            | 0.265        | 0.259           | 0.425           | 0.322        | 0.315                        |
| 0.4                 | 0.0550           | 0.0536       | 0.0530          | 0.168            | 0.147        | 0.143           | 0.222           | 0.184        | 0.178                        |
| 0.5                 | 0.0428           | 0.0423       | 0.0416          | 0.108            | 0.0984       | 0.0951          | 0.140           | 0.122        | 0.118                        |
| 0.6                 | 0.0361           | 0.0358       | 0.0353          | 0.0793           | 0.0737       | 0.0710          | 0.100           | 0.0902       | 0.0864                       |
| 0.8                 | 0.0302           | 0.0301       | 0.0294          | 0.0525           | 0.0503       | 0.0481          | 0.0640          | 0.0599       | 0.0569                       |
| 1.0                 | 0.0271           | 0.0270       | 0.0264          | 0.0407           | 0.0396       | 0.0377          | 0.0479          | 0.0458       | 0.0432                       |
| 1.5                 | 0.0239           | 0.0233       | 0.0226          | 0.0303           | 0.0288       | 0.0271          | 0.0337          | 0.0317       | 0.0295                       |
| 2                   | 0.0234           | 0.0220       | 0.0210          | 0.0286           | 0.0259       | 0.0240          | 0.0310          | 0.0278       | 0.0255                       |
| 3                   | 0.0243           | 0.0219       | 0.0205          | 0.0300           | 0.0260       | 0.0234          | 0.0322          | 0.0276       | 0.0246                       |
| 4                   | 0.0259           | 0.0232       | 0.0212          | 0.0324           | 0.0281       | 0.0245          | 0.0346          | 0.0298       | 0.0256                       |
| 5                   | 0.0275           | 0.0247       | 0.0221          | 0.0350           | 0.0306       | 0.0259          | 0.0372          | 0.0324       | 0.0270                       |
| 6                   | 0.0290           | 0.0262       | 0.0230          | 0.0372           | 0.0331       | 0.0272          | 0.0394          | 0.0348       | 0.0281                       |
| 8                   | 0.0319           | 0.0292       | 0.0245          | 0.0411           | 0.0378       | 0.0294          | 0.0433          | 0.0392       | 0.0298                       |
| 10                  | 0.0344           | 0.0319       | 0.0258          | 0.0446           | 0.0419       | 0.0310          | 0.0468          | 0.0432       | 0.0312                       |

TABLE 1.-7 (Continued)

| Photon energy [MeV] | Air          |              |                 | H <sub>2</sub> O |              |                 |
|---------------------|--------------|--------------|-----------------|------------------|--------------|-----------------|
|                     | $\mu_a/\rho$ | $\mu_K/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_K/\rho$ | $\mu_{en}/\rho$ |
| 0.01                | 4.63         | 4.61         | 4.61            | 4.79             |              |                 |
| 0.015               | 1.27         | 1.27         | 1.27            | 1.28             |              |                 |
| 0.02                | 0.512        | 0.511        | 0.511           | 0.512            |              |                 |
| 0.03                | 0.148        |              |                 | 0.149            |              |                 |
| 0.04                | 0.0669       |              |                 | 0.0678           |              |                 |
| 0.05                | 0.0406       |              |                 | 0.0419           |              |                 |
| 0.06                | 0.0305       |              |                 | 0.0320           |              |                 |
| 0.08                | 0.0243       |              |                 | 0.0262           |              |                 |
| 0.10                | 0.0234       |              |                 | 0.0256           |              |                 |
| 0.15                | 0.0250       |              |                 | 0.0277           |              |                 |
| 0.2                 | 0.0268       |              |                 | 0.0297           |              |                 |
| 0.3                 | 0.0288       |              |                 | 0.0319           |              |                 |
| 0.4                 | 0.0295       |              |                 | 0.0328           |              |                 |
| 0.5                 | 0.0297       |              | 0.0296          | 0.0330           |              |                 |
| 0.6                 | 0.0296       |              | 0.0295          | 0.0329           |              |                 |
| 0.8                 | 0.0289       |              | 0.0289          | 0.0321           |              |                 |
| 1.0                 | 0.0280       |              | 0.0278          | 0.0311           |              | 0.0309          |
| 1.5                 | 0.0257       |              | 0.0254          | 0.0285           |              | 0.0282          |
| 2                   | 0.0238       | 0.0236       | 0.0234          | 0.0264           | 0.0262       | 0.0260          |
| 3                   | 0.0212       | 0.0207       | 0.0205          | 0.0234           | 0.0229       | 0.0227          |
| 4                   | 0.0194       | 0.0189       | 0.0186          | 0.0214           | 0.0209       | 0.0206          |
| 5                   | 0.0182       | 0.0178       | 0.0174          | 0.0200           | 0.0195       | 0.0191          |
| 6                   | 0.0174       | 0.0168       | 0.0164          | 0.0190           | 0.0185       | 0.0180          |
| 8                   | 0.0162       | 0.0157       | 0.0152          | 0.0176           | 0.0170       | 0.0166          |
| 10                  | 0.0156       | 0.0151       | 0.0145          | 0.0168           | 0.0162       | 0.0157          |

TABLE 1.-8. Values of  $\mu_a/\rho$ ,  $\mu_K/\rho$ , and  $\mu_{en}/\rho$  extrapolated to the absorption edges from the low-energy and high-energy sides, respectively. Units are  $\text{cm}^2/\text{g}$ .

| Absorption edge | <sup>50</sup> Sn |                     |                     |                     | <sup>82</sup> Pb |                     |                     |                     | <sup>92</sup> U |                     |                     |                     |
|-----------------|------------------|---------------------|---------------------|---------------------|------------------|---------------------|---------------------|---------------------|-----------------|---------------------|---------------------|---------------------|
|                 | [keV]            | $\mu_a/\rho$        | $\mu_K/\rho$        | $\mu_{en}/\rho$     | [keV]            | $\mu_a/\rho$        | $\mu_K/\rho$        | $\mu_{en}/\rho$     | [keV]           | $\mu_a/\rho$        | $\mu_K/\rho$        | $\mu_{en}/\rho$     |
| $L_{III}$ ..... |                  |                     |                     |                     | 13.041           | $\frac{63.9}{162.}$ | $\frac{63.5}{129.}$ | $\frac{63.3}{129.}$ | 17.165          | $\frac{42.6}{103.}$ | $\frac{42.2}{80.1}$ | $\frac{42.1}{80.1}$ |
| $L_{II}$ .....  |                  |                     |                     |                     | 15.205           | $\frac{109.}{142.}$ | $\frac{89.6}{113}$  | $\frac{89.6}{113.}$ | 20.945          | $\frac{60.2}{85.5}$ | $\frac{49.4}{66.9}$ | $\frac{49.4}{66.9}$ |
| $L_I$ .....     |                  |                     |                     |                     | 15.855           | $\frac{126.}{154.}$ | $\frac{102.}{123.}$ | $\frac{102.}{123.}$ | 21.771          | $\frac{77.4}{89.4}$ | $\frac{61.2}{69.6}$ | $\frac{61.1}{69.6}$ |
| $K$ .....       | 29.195           | $\frac{6.74}{43.5}$ | $\frac{6.70}{16.7}$ | $\frac{6.69}{16.7}$ | 88.005           | $\frac{1.51}{7.12}$ | $\frac{1.45}{2.47}$ | $\frac{1.44}{2.47}$ | 115.62          | $\frac{1.09}{4.62}$ | $\frac{1.05}{1.66}$ | $\frac{1.04}{1.66}$ |



TABLE 1.-9. Values of the mass absorption coefficient  $\mu_a/\rho$  and mass energy-absorption coefficient  $\mu_{en}/\rho$  for photon energies 10 to 100 MeV.

Units are  $\text{cm}^2/\text{g}$ .

| Photon energy [MeV] | $^1\text{H}$ |                 | $^7\text{N}$ |                 | $^8\text{O}$ |                 | $^{13}\text{Al}$ |                 | $^{18}\text{Ar}$ |                 |
|---------------------|--------------|-----------------|--------------|-----------------|--------------|-----------------|------------------|-----------------|------------------|-----------------|
|                     | $\mu_a/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_{en}/\rho$ |
| 10                  | 0.0229       | 0.0222          | 0.0154       | 0.0143          | 0.0160       | 0.0148          | 0.0185           | 0.0164          | 0.0201           | 0.0176          |
| 15                  | 0.0188       | 0.0179          | 0.0145       | 0.0131          | 0.0153       | 0.0136          | 0.0187           | 0.0163          | 0.0211           | 0.0183          |
| 20                  | 0.0166       | 0.0156          | 0.0142       | 0.0128          | 0.0152       | 0.0135          | 0.0192           | 0.0162          | 0.0222           | 0.0187          |
| 30                  | 0.0141       | 0.0130          | 0.0142       | 0.0123          | 0.0153       | 0.0131          | 0.0203           | 0.0164          | 0.0240           | 0.0192          |
| 40                  | 0.0129       | 0.0116          | 0.0144       | 0.0121          | 0.0156       | 0.0130          | 0.0212           | 0.0166          | 0.0254           | 0.0192          |
| 50                  | 0.0121       | 0.0107          | 0.0146       | 0.0119          | 0.0160       | 0.0129          | 0.0220           | 0.0164          | 0.0266           | 0.0192          |
| 60                  | 0.0117       | 0.0102          | 0.0149       | 0.0118          | 0.0163       | 0.0129          | 0.0227           | 0.0161          | 0.0276           | 0.0190          |
| 80                  | 0.0111       | 0.0095          | 0.0153       | 0.0118          | 0.0169       | 0.0127          | 0.0238           | 0.0159          | 0.0290           | 0.0188          |
| 100                 | 0.0109       | 0.0092          | 0.0158       | 0.0119          | 0.0174       | 0.0127          | 0.0246           | 0.0156          | 0.0301           | 0.0184          |

| Photon energy [MeV] | $^{26}\text{Fe}$ |                 | $^{82}\text{Pb}$ |                 | Air          |                 | Water        |                 |
|---------------------|------------------|-----------------|------------------|-----------------|--------------|-----------------|--------------|-----------------|
|                     | $\mu_a/\rho$     | $\mu_{en}/\rho$ | $\mu_a/\rho$     | $\mu_{en}/\rho$ | $\mu_a/\rho$ | $\mu_{en}/\rho$ | $\mu_a/\rho$ | $\mu_{en}/\rho$ |
| 10                  | 0.0252           | 0.0212          | 0.0446           | 0.0324          | 0.0156       | 0.0145          | 0.0168       | 0.0155          |
| 15                  | 0.0277           | 0.0223          | 0.0522           | 0.0352          | 0.0148       | 0.0132          | 0.0157       | 0.0141          |
| 20                  | 0.0298           | 0.0230          | 0.0587           | 0.0367          | 0.0145       | 0.0131          | 0.0153       | 0.0136          |
| 30                  | 0.0330           | 0.0236          | 0.0682           | 0.0375          | 0.0146       | 0.0126          | 0.0152       | 0.0131          |
| 40                  | 0.0354           | 0.0235          | 0.0747           | 0.0372          | 0.0148       | 0.0124          | 0.0153       | 0.0128          |
| 50                  | 0.0372           | 0.0234          | 0.0796           | 0.0366          | 0.0151       | 0.0122          | 0.0156       | 0.0126          |
| 60                  | 0.0387           | 0.0230          | 0.0834           | 0.0357          | 0.0154       | 0.0122          | 0.0158       | 0.0125          |
| 80                  | 0.0410           | 0.0233          | 0.0890           | 0.0334          | 0.0159       | 0.0121          | 0.0163       | 0.0125          |
| 100                 | 0.0427           | 0.0217          | 0.0930           | 0.0301          | 0.0163       | 0.0121          | 0.0167       | 0.0124          |

<sup>a</sup> Values of  $\mu_{en}/\rho$  in this table are taken directly from Allison [1961]. Hence the input cross-section data are those of White-Grodstein [1957], and positron annihilation in flight is not taken into account.

## 2. Photon Cross Sections

### 2.1. Scope

This section contains descriptions and tabulations of the individual atomic cross sections for scattering, absorption, and pair production that enter into the computation of the attenuation, energy absorption, and other related coefficients. The information in this report is confined primarily to total cross sections, although some angular distribution information for Compton and Rayleigh scattering is included.<sup>14</sup>

### 2.2. Classification of Interactions

Interactions of photons with matter, by which individual photons are removed or deflected from a primary beam of x- or  $\gamma$ -radiation, may be classified according to:

- (1) The kind of target, e.g., electrons, atoms, or nuclei, with which the photon interacts, and
- (2) The type of event, e.g., scattering, absorption, pair production, etc., which takes place.

Possible interactions are summarized in table 2.-1 (adapted from Fano, Spencer, and Berger [1959]). The relative magnitudes of cross sections for these interactions as functions of energy are shown in figure 2.-1, in which the vertical distance between curves represents the percent contribution of an indicated cross section to the total "electronic" cross section (i.e., excluding photo-nuclear effects).

It is apparent from figure 2.-1 that for attenuations of photons in this energy range the most important interactions are:

- (1) The photoelectric effect,  $\tau_{pe}$ ,
- (2) Compton scattering,  $\sigma_C$ , and
- (3) Electron-positron pair production,  $(\kappa_n + \kappa_e)$ .

Rayleigh scattering,  $\sigma_R$ , is usually of minor importance for the broad beam conditions typically found in shielding but must be known for interpretation of experimental attenuation coefficient data. Two-photon Compton scattering, together with the radiative correction, amounts to less than 1 percent of  $\sigma_C$  below 100 MeV and is included in the total Compton cross section  $\sigma_C$  in figure 2.-1. The photonuclear effect,  $\sigma_{ph.n.}$ , is mostly restricted to the region of the giant resonance around 10 to 30 MeV where, at the resonance peak, it may amount to as much as 10 percent of the total "electronic" cross section.

<sup>14</sup> For further angular distribution data and formulas, reference for Compton scattering can be made to Compton and Allison [1935], Davison and Evans [1952], Nelms [1953], Burton [1953], Evans [1958], Curien [1962], Stinner et al. [1965], and Veigele [1965]; for the atomic photoeffect to Hulberg et al. [1968] and Pratt et al. [1964]; and for electron-positron pair production to Heitler [1954].

TABLE 2.-1. Classification of elementary photon interactions.

Solid-line boxes indicate the major effects contributing to photon attenuation in matter. Dotted-line boxes indicate additional effects which contribute more than 1 percent over particular energy ranges.

| Type of interaction                              | Absorption  | Scattering  |   | Multi-photon effects   |
|--|---|---|---|--|
|  |   | Interaction with:   | Elastic (coherent) (b)  |  |
| (1) Atomic electrons                             | <div style="border: 1px solid black; padding: 5px;">                     Photoelectric effect<br/> <math>\tau_{pe} \begin{cases} \sim Z^4 \text{ (low energy)} \\ \sim Z^5 \text{ (high energy)} \end{cases}</math> </div>  | <div style="border: 1px dotted black; padding: 5px;">                     Rayleigh scattering,<br/> <math>\sigma_R \sim Z^2</math><br/>                     (low energy limit)                 </div> | <div style="border: 1px solid black; padding: 5px;">                     Compton scattering,<br/> <math>\sigma_C \sim Z</math> </div> | <div style="border: 1px dotted black; padding: 5px;">                     Two-photon Compton scattering,<br/> <math>\sim Z</math> </div> |
| (2) Nucleons                                     | <div style="border: 1px dotted black; padding: 5px;">                     Photonuclear reactions<br/>                     (<math>\gamma, n</math>), (<math>\gamma, p</math>), photo-fission, etc.<br/> <math>\sigma_{ph,n} \sim Z</math><br/>                     (<math>E \gtrsim 10 \text{ MeV}</math>)                 </div>  | Elastic nuclear scattering,<br>( $\gamma, \gamma) \sim Z^2$   | Inelastic nuclear scattering,<br>( $\gamma, \gamma')$   |  |
| (3) Electric field surrounding charged particles | <div style="border: 1px solid black; padding: 5px;">                     (1) Electron-positron pair production in field of nucleus,<br/> <math>\kappa_n \sim Z^2</math><br/>                     (<math>E \gtrsim 1.02 \text{ MeV}</math>)<br/>                     (2) Electron-positron pair production in electron field,<br/> <math>\kappa_e \sim Z</math><br/>                     (<math>E \gtrsim 2.04 \text{ MeV}</math>)<br/>                     (3) Nucleon-antinucleon pair production<br/>                     (<math>E \gtrsim 3 \text{ GeV}</math>)                 </div> | Delbrück scattering,<br>$\sim Z^4$  |   |  |
| (4) Mesons                                       | Photomeson production,<br>( $E \gtrsim 150 \text{ MeV}$ )   | Modified<br>( $\gamma, \gamma$ )  |   |  |

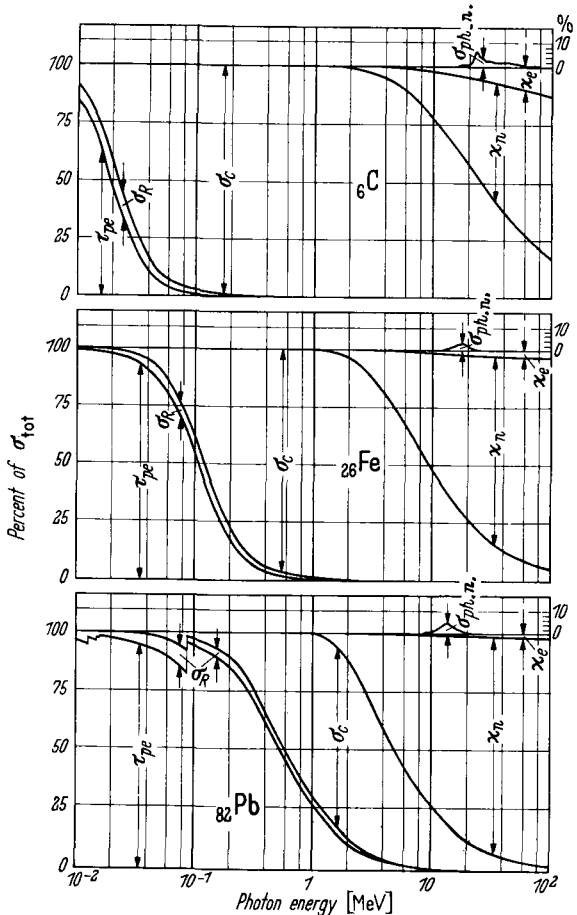


FIGURE 2.-1. Relative contributions of the various photon interactions as functions of energy for carbon, iron, and lead.

In these plots the vertical distance between curves represents the percent contribution of the indicated process to the sum  $\tau_{pe} + \sigma_R + \sigma_C + \kappa_n + \kappa_e$  (see tables in section 3).

The remaining small effects (resonance scattering and Thomson scattering by the nucleus, Compton scattering by nucleons, meson production, resonance scattering associated with meson production, Delbrück scattering and nucleon-antinucleon production) will not be treated here. For a general discussion of these effects, including order of magni-

tude estimates, see Bethe and Ashkin [1953]. Recent photomeson data have been summarized by Crouch et al. [1964], Allaby et al. [1966], Panofsky [1968], and Joos [1968]. We have reproduced in table 2.-2 the photomeson cross section compilation by E. Lohrmann in the review by Joos [1968].

TABLE 2.-2. Meson photoproduction cross sections in  $\mu\text{b}(10^{-30}\text{cm}^2)$ , as summarized by E. Lohrmann in the article by Joos [1968].

| Reaction<br>$\gamma\text{P} \rightarrow$ | Photon energy |            |            |             | References         |
|--|---------------|------------|------------|-------------|--------------------|
|  | 1 GeV         | 2 GeV      | 3 GeV      | 4.5 GeV     |                    |
| $p\pi^0$                                 | 24            | 4.7        | 1.5        | 0.6         | 70, 71, 72, 74     |
| $n\pi^0$                                 | 50            | 5          | 2.2        | 1.0         | 70, 72, 73, 75, 76 |
| $P\rho^0$                                | .....         | 20         | 17         | 17          | 45, 47, 52, 55     |
| $P\omega$                                | .....         | 7          | 4          | 3           | 46, 51, 55         |
| $P\phi$                                  | .....         | $\sim 0.2$ | $\sim 0.3$ | $\sim 0.2$  | 55                 |
| $P\eta$                                  | 6             | $< 1$      | $< 1$      | $< 0.2$     | 51, 55, 78, 79, 80 |
| $PX^0(959)$                              | .....         | $\sim 0.7$ | $\sim 0.2$ | $\sim 0.2$  | 51, 55             |
| $Pf^0$                                   | .....         | .....      | $\sim 0.9$ | $\sim 0.3$  | 52, 55             |
| $\Delta^{++}(1238)\pi^-$                 | 48            | 8          | 4          | 2           | 50, 55, 77, 81, 82 |
| $\Delta^0\pi^+$                          | 2             | .....      | .....      | .....       | 55, 77             |
| $\Delta^{++}\rho^-$                      | .....         | $\sim 4$   | $\sim 2$   | $\sim 1$    | 52, 55, 77         |
| $\Lambda K^+$                            | 2             | $\sim 1$   | $\sim 0.5$ | $\sim 0.25$ | 53, 73, 83, 84     |
| $\Sigma^0 K^+$                           | .....         | $\sim 0.6$ | $\sim 0.2$ | $\sim 0.1$  | 53, 73             |
| $\Sigma^+ K^0$                           | .....         | $< 0.2$    | $< 0.2$    | $< 0.2$     | 53                 |
| $Y^{*0}(1385)K^+$                        | .....         | $\sim 0.5$ | .....      | $\sim 0.2$  | 53                 |
| $Y^{*+}(1385)K^0$                        | .....         | $\sim 0.4$ | .....      | $\sim 0.1$  | 53                 |

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The cross section for photoproduction of nucleon-antinucleon pairs, as discussed by Vdovin [1957], Bushev and Vdovin [1958], Segré [1958], Bertram et al. [1966], and Earles et al. [1967], is three orders of magnitude smaller than that for photomeson production. The threshold for nucleon-antinucleon pair production varies from 3.75 GeV (4 nucleon masses) in the field of a proton at rest down to 3.0 GeV (3.2 nucleon masses) for protons moving in a complex nucleus.

### 2.3. Atomic Photoeffect (Photoelectric Absorption)

In the atomic photoeffect, a photon disappears and an electron is ejected from an atom. The electron carries away all the energy of the absorbed photon, minus the energy binding the electron to the atom. The *K*-shell electrons, which are the most tightly bound, are the most important for this effect in the energy region considered in this report. However, if the photon energy drops below the binding energy of a given shell (see

table 2.-3), an electron from that shell cannot be ejected. Hence, a plot of  $\tau_{pe}$  versus photon energy exhibits the characteristic "absorption edges"<sup>15</sup> which are shown for lead in figure 2.-1.

Although there have been a few direct measurements of  $\tau_{pe}$  or  $\tau_K$  in the region between 0.1 and 3 MeV (see, for example, Latyshev [1947], Seeman [1956], Hultberg and Stockendal [1959], Titus [1959, 1965], Bleeker, Goudsmit, and DeVries [1962], Dowe [1965], and Parthasaradhi et al. [1966]), the best information in the high energy region is at present mostly theoretical.

Most of the theoretical information has been on the *K*-shell component  $\tau_K$  (see, for example, Bethe and Salpeter [1957], Erber [1959], Gavrilá [1959], Pratt [1960a], Nagel [1960], Hultberg et al. [1961],

<sup>15</sup> As a note of caution, it should be mentioned that the high-energy side of an absorption edge exhibits a fine structure (see, for example, Faessler [1955], Sandström [1957], or Azároff [1963]) such that for light elements, where the *K*-edge is well below 10 keV,  $\tau_{pe}$  can oscillate by as much as a factor of five near the edge. However, for the region above 10 keV considered here, the oscillation is less than 10 percent and will be disregarded, for practical purposes, in favor of a smooth extrapolation from the monotonic region back to the theoretical edge.

TABLE 2.-3. *Energies of absorption edges above 10 keV*  
Values are taken from Bearden [1964-1967] except numbers in parentheses, which are from Fine and Hendee [1955].

| Element          | <i>K</i> -edge<br>[keV] | Element           | <i>K</i> -edge<br>[keV] | <i>L</i> <sub>I</sub> - edge<br>[keV] | <i>L</i> <sub>II</sub> - edge<br>[keV] | <i>L</i> <sub>III</sub> - edge<br>[keV] |
|------------------|-------------------------|-------------------|-------------------------|---------------------------------------|--|---|
| <sup>31</sup> Ga | 10.368                  | <sup>66</sup> Dy  | 53.793                  |                                       |  |   |
| <sup>32</sup> Ge | 11.104                  | <sup>67</sup> Ho  | 55.619                  |                                       |  |   |
| <sup>33</sup> As | 11.865                  | <sup>68</sup> Er  | 57.487                  |                                       |  |   |
| <sup>34</sup> Se | 12.654                  | <sup>69</sup> Tm  | 59.38                   | 10.121                                |  |   |
| <sup>35</sup> Br | 13.470                  | <sup>70</sup> Yb  | 61.30                   | 10.490                                |  |   |
| <sup>36</sup> Kr | 14.324                  | <sup>71</sup> Lu  | 63.31                   | 10.874                                | 10.345                                 |   |
| <sup>37</sup> Rb | 15.202                  | <sup>72</sup> Hf  | 65.31                   | 11.274                                | 10.736                                 |   |
| <sup>38</sup> Sr | 16.107                  | <sup>73</sup> Ta  | 67.403                  | 11.682                                | 11.132                                 |   |
| <sup>39</sup> Y  | 17.038                  | <sup>74</sup> W   | 69.508                  | 12.100                                | 11.538                                 | 10.200                                  |
| <sup>40</sup> Zr | 17.999                  | <sup>75</sup> Re  | 71.658                  | 12.530                                | 11.954                                 | 10.531                                  |
| <sup>41</sup> Nb | 18.987                  | <sup>76</sup> Os  | 73.856                  | 12.972                                | 12.381                                 | 10.868                                  |
| <sup>42</sup> Mo | 20.004                  | <sup>77</sup> Ir  | 76.101                  | 13.423                                | 12.820                                 | 11.212                                  |
| <sup>43</sup> Te | 21.047                  | <sup>78</sup> Pt  | 78.381                  | 13.883                                | 13.272                                 | 11.562                                  |
| <sup>44</sup> Ru | 22.119                  | <sup>79</sup> Au  | 80.720                  | 14.354                                | 13.736                                 | 11.921                                  |
| <sup>45</sup> Rh | 23.219                  | <sup>80</sup> Hg  | 83.109                  | 14.842                                | 14.212                                 | 12.286                                  |
| <sup>46</sup> Pd | 24.348                  | <sup>81</sup> Tl  | 85.533                  | 15.343                                | 14.699                                 | 12.660                                  |
| <sup>47</sup> Ag | 25.517                  | <sup>82</sup> Pb  | 88.005                  | 15.855                                | 15.205                                 | 13.041                                  |
| <sup>48</sup> Cd | 26.716                  | <sup>83</sup> Bi  | 90.534                  | 16.376                                | 15.719                                 | 13.426                                  |
| <sup>49</sup> In | 27.942                  | <sup>84</sup> Po  | (93.112)                | (16.935)                              | (16.244)                               | (13.817)                                |
| <sup>50</sup> Sn | 29.195                  | <sup>85</sup> At  | (95.740)                | (17.490)                              | (16.784)                               | (14.215)                                |
| <sup>51</sup> Sb | 30.486                  | <sup>86</sup> Rn  | (98.418)                | (18.058)                              | (17.337)                               | (14.618)                                |
| <sup>52</sup> Te | 31.811                  | <sup>87</sup> Fr  | (101.147)               | (18.638)                              | (17.904)                               | (15.028)                                |
| <sup>53</sup> I  | 33.166                  | <sup>88</sup> Ra  | (103.927)               | 19.236                                | 18.486                                 | 15.444                                  |
| <sup>54</sup> Xe | 34.59                   | <sup>89</sup> Ac  | (106.759)               | (19.842)                              | (19.078)                               | (15.865)                                |
| <sup>55</sup> Cs | 35.987                  | <sup>90</sup> Th  | 109.646                 | 20.464                                | 19.683                                 | 16.299                                  |
| <sup>56</sup> Ba | 37.452                  | <sup>91</sup> Pa  | (112.581)               | (21.102)                              | (20.311)                               | (16.731)                                |
| <sup>57</sup> La | 38.934                  | <sup>92</sup> U   | 115.62                  | 21.771                                | 20.945                                 | 17.165                                  |
| <sup>58</sup> Ce | 40.453                  | <sup>93</sup> Np  | (118.619)               | (21.417)                              | (20.596)                               | (17.614)                                |
| <sup>59</sup> Pr | 42.002                  | <sup>94</sup> Pu  | (121.720)               | 23.109                                | 22.253                                 | 18.054                                  |
| <sup>60</sup> Nd | 43.574                  | <sup>95</sup> Am  | (124.876)               | (23.793)                              | (22.944)                               | (18.525)                                |
| <sup>61</sup> Pm | 45.198                  | <sup>96</sup> Cm  | (128.088)               | (24.503)                              | (23.640)                               | (18.990)                                |
| <sup>62</sup> Sm | 46.849                  | <sup>97</sup> Bk  | (131.357)               | (25.230)                              | (24.352)                               | (19.461)                                |
| <sup>63</sup> Eu | 48.519                  | <sup>98</sup> Cf  | (134.683)               | (25.971)                              | (25.080)                               | (19.938)                                |
| <sup>64</sup> Gd | 50.233                  | <sup>99</sup> E   | (138.067)               | (26.729)                              | (25.824)                               | (20.422)                                |
| <sup>65</sup> Tb | 52.002                  | <sup>100</sup> Fm | (141.510)               | (27.503)                              | (26.584)                               | (20.912)                                |

Pratt et al. [1964], Hall and Sullivan [1966], Gorshkov [1967], Forssner [1968], and Hultberg et al. [1968]), but some calculations including *L*- and higher-shell contributions are now available (see, for example, Pratt [1960b], Gavrilu [1961], Alling and Johnson [1965], Matese and Johnson [1965], Schmickley and Pratt [1967], Brysk and Zerby [1968], and the extensive results by Rakavy and Ron [1967] which include almost all the higher shells and cover the range 1 keV to 2 MeV). Uncertainties in  $\tau_K$  due to screening and other effects are probably about 2 percent over the region from 0.2 to 100 MeV. However, the uncertainty of the total  $\tau_{pe}$  ( $=\tau_K+\tau_L+\tau_M+\dots$ ) is probably more like 3 to 5 percent because of much poorer knowledge of the outer shell contribution, which amounts to as much as  $\frac{1}{4}$  of  $\tau_K$  for the heavier elements.

Extensive theoretical results for the photoeffect in the soft x-ray region (0.1 to 2 keV) are now becoming available (Cooper [1962, 1964], Fano and Cooper [1965], Manson and Cooper [1968], and Fano and Cooper [1968]). The work of these authors is based on the solution of the Schrödinger equation in the dipole approximation, using self-consistent-field wave functions. Numerical results are given for the photoelectric absorption in various outer atomic subshells, with emphasis on the detailed structure of the cross section near threshold. These papers also provide a survey of recent experimental results in the soft x-ray region obtained with synchrotron light and other soft x-ray sources.

In the energy range 10 keV to 0.2 MeV, although the Rakavy-Ron calculations are in considerably better agreement with experiments than are previous theoretical results, present estimates of  $\tau_{pe}$  in this region still rely heavily on high-precision total attenuation coefficient measurements such as those of Hahn [1934], Cuykendall [1936], Jones [1936], Laubert [1941], Bearden [1958, 1966], Deslattes [1958], Wiedenbeck [1962]; McCrary, Plassmann et al. [1967], and others.

From these measurements "experimental" values of  $\tau_{pe}$  are obtained by subtracting theoretical estimates of the scattering cross sections  $\sigma_C^{BD}+\sigma_R$  from the observed values of  $\sigma_{tot}$ .

In the present tabulation in the region 10 keV  $\leq E \leq 100$  keV, we follow the subtraction procedure, using re-evaluated experimental  $\sigma_{tot}$  data and scattering cross sections ( $\sigma_C^{BD}+\sigma_R$ ) from Storm and Israel [1967], except for uranium for which  $\tau_{pe}$  is taken directly from Rakavy and Ron. Values of  $\tau_{pe}$  for tin, tungsten and lead in this energy were taken from a computer-assisted subtraction and analysis in progress (McMaster, Del Grande et al.) and hence constitute a further updating of  $\tau_{pe}$ ,  $\sigma_{tot}$  and related quantities from values given by Hubbell and Berger [1968].

At higher energies we present revised values for  $\tau_{pe}$  which take into account not only the numerical calculations of  $\tau_K$  by Pratt et al. [1964] used by Davisson, but also the extensive  $\tau_K$  calculations by Hultberg et al. [1968]. Although we use the results

of Gavrilu [1959] and Pratt [1960a] in the high energy limit, we ignore, on the advice of Pratt, the extrapolated values of  $\tau_K$  in table 2 in Pratt [1960a] for  $Z/137=0.4$  and 0.6 at energies  $E=2, 3, 5$  and 10 MeV.

As can be seen in table 2.-4,  $\tau_{pe}$  varies over a wide range of magnitudes, decreasing with increasing energy except at the edges and increasing with atomic number. To make interpolation more reliable and convenient, it is important to scale these values in some way. It was found that the product  $\tau_{pe} \cdot (E[\text{MeV}])^3 \cdot Z^{-4.5}$  (above or between absorption edges) varies by less than a factor of three over the range  $Z=1$  to 92 and  $E=10$  to 500 keV, and the product  $\tau_{pe} \cdot E[\text{MeV}] \cdot Z^{-4.5}$  by less than a factor of ten for  $Z=1$  to 92 and  $E=500$  keV to 100 MeV. Values of these products are presented in table 2.-5.

For some purposes, particularly in machine computations, simple empirical formulas are desirable. An empirical formula for the *K*-shell photoeffect above 0.2 MeV is

$$\tau_K \cong Z^5 \sum_{n=1}^4 \frac{a_n + b_n Z}{1 + c_n Z} E^{-p_n} \left[ \frac{\text{b}}{\text{atom}} \right], \quad (2.-1)$$

TABLE 2.-4. Total atomic photoeffect cross section  $\tau_{pe}$  (b/atom), indicating the range of magnitudes

| Photon energy [MeV] | $\tau_{pe}$          |                      |                      |                             |
|---------------------|----------------------|----------------------|----------------------|-----------------------------|
|                     | ${}_6\text{C}$       | ${}_{26}\text{Fe}$   | ${}_{82}\text{Pb}$   |                             |
| 0.01                | $3.93 \cdot 10^1$    | $1.59 \cdot 10^4$    | $4.40 \cdot 10^4$    | <i>K</i> -, <i>L</i> -edges |
| 0.10                | $2.16 \cdot 10^{-2}$ | $1.89 \cdot 10^1$    | $1.76 \cdot 10^3$    |                             |
| 1.0                 | $2.89 \cdot 10^{-5}$ | $3.38 \cdot 10^{-2}$ | $6.39 \cdot 10^0$    |                             |
| 10                  | $1.12 \cdot 10^{-6}$ | $1.19 \cdot 10^{-3}$ | $1.78 \cdot 10^{-1}$ |                             |
| 100                 | $1.01 \cdot 10^{-7}$ | $1.04 \cdot 10^{-4}$ | $1.41 \cdot 10^{-2}$ |                             |

for which the parameters  $a_n, b_n, c_n$  and  $p_n$  are given in table 2.-6. This formula goes to the Pratt [1960a] numerical values in the high energy limit and reproduces the combined experimental and theoretical data fairly well. Deviations from these data over most of the range 0.2 MeV  $\leq E < \infty$  and  $13 \leq Z \leq 92$  are less than 1 to 2 percent, and in no case do they exceed 5 percent over this range. For other empirical formulas see Biggs and Light-hill [1967].

Total  $\tau_{pe}$  values, such as those given in tables 2.-4 and -5, can be obtained approximately by multiplying  $\tau_K$  by the ratios  $\tau_{pe}/\tau_K$  from table 2.-7. Hultberg [1959] suggested that, for practical purposes, this ratio is energy-independent, and the values in table 2.-7 are those derived by Davisson [1965] from the compilation by Kirchner [1930] of experimental *K*-edge data.

For elements  ${}_{1}\text{H}$  through  ${}_{53}\text{I}$  the Davisson-Kirchner ratios agree within 2 percent with the latest *K*-edge ratios in the compilation in progress by

TABLE 2.-5. Scaled values of the total photoelectric cross section  $\tau_{pe}$

| Photon energy [MeV]  | $^1\text{H}^a$   | $^6\text{C}$     | $^{13}\text{Al}$ | $^{20}\text{Ca}$ | $^{26}\text{Fe}$ | $^{29}\text{Cu}$ |
|--|------------------|------------------|------------------|------------------|------------------|------------------|
| $\tau_{pe}$ [b/atom] $\cdot (E[\text{MeV}])^3 \cdot Z^{-4.5} \cdot 10^9$ |                  |                  |                  |                  |                  |                  |
| 0.01   | 9.13             | 12.4             | 11.1             | 8.87             | 6.82             | 6.17             |
| 0.02   | 6.71             | 10.1             | 10.6             | 9.25             | 7.93             | 7.27             |
| 0.03   | 5.59             | 8.50             | 10.1             | 9.13             | 8.29             | 7.83             |
| 0.05   | 4.45             | 7.60             | 9.29             | 8.79             | 8.37             | 8.11             |
| 0.10   | 3.32             | 6.80             | 8.21             | 8.23             | 8.11             | 8.09             |
| 0.20   | 2.62             | 5.77             | 7.40             | 7.91             | 8.00             | 7.98             |
| 0.30   | 2.44             | 5.49             | 7.24             | 7.92             | 8.09             | 8.15             |
| 0.5  | 2.56             | 5.88             | 7.80             | 8.70             | 9.07             | 9.22             |
| $\tau_{pe}$ [b/atom] $\cdot E[\text{MeV}] \cdot Z^{-4.5} \cdot 10^9$     |                  |                  |                  |                  |                  |                  |
| 0.5  | 10.2             | 23.5             | 31.2             | 34.8             | 36.3             | 36.9             |
| 1.0  | 3.98             | 9.10             | 12.3             | 13.8             | 14.6             | 14.8             |
| 2  | 2.36             | 5.42             | 7.26             | 8.11             | 8.42             | 8.56             |
| 3  | 1.99             | 4.55             | 6.03             | 6.67             | 6.89             | 7.00             |
| 5  | 1.75             | 3.97             | 5.22             | 5.70             | 5.86             | 5.91             |
| 10   | 1.58             | 3.53             | 4.64             | 5.02             | 5.11             | 5.12             |
| 100  | 1.43             | 3.19             | 4.11             | 4.41             | 4.45             | 4.46             |
| $\infty$   | 1.41             | 3.15             | 4.04             | 4.33             | 4.37             | 4.39             |
| Photon energy [MeV]  | $^{42}\text{Mo}$ | $^{50}\text{Sn}$ | $^{74}\text{W}$  | $^{82}\text{Pb}$ | $^{92}\text{U}$  | Absorption edges |
| $\tau_{pe}$ [b/atom] $\cdot (E[\text{MeV}])^3 \cdot Z^{-4.5} \cdot 10^9$ |                  |                  |                  |                  |                  |                  |
| 0.01   | 0.663            | 0.619            | 0.108            | 0.108            | 0.0995           | $L_{III}$        |
| 0.02   | 0.730            | 0.714            | 0.615            | 0.560            | 0.314            | $L_{II, I}$      |
| 0.03   | 6.00             | 4.88             | 0.693            | 0.640            | 0.612            |                  |
| 0.05   | 6.74             | 5.70             | 0.779            | 0.744            | 0.740            |                  |
| 0.10   | 7.29             | 6.57             | 4.93             | 4.29             | 0.919            | $K$              |
| 0.20   | 7.66             | 7.28             | 6.06             | 5.70             | 5.21             |                  |
| 0.30   | 8.06             | 7.83             | 6.91             | 6.79             | 6.25             |                  |
| 0.5  | 9.50             | 9.91             | 8.77             | 8.92             | 8.44             |                  |
| $\tau_{pe}$ [b/atom] $\cdot E[\text{MeV}] \cdot Z^{-4.5} \cdot 10^9$     |                  |                  |                  |                  |                  |                  |
| 0.5  | 38.0             | 39.6             | 35.1             | 35.7             | 33.8             |                  |
| 1.0  | 15.5             | 15.6             | 15.0             | 15.6             | 15.1             |                  |
| 2  | 8.77             | 8.73             | 8.25             | 8.64             | 8.26             |                  |
| 3  | 7.10             | 7.11             | 6.49             | 6.70             | 6.51             |                  |
| 5  | 5.92             | 5.86             | 5.19             | 5.30             | 5.11             |                  |
| 10   | 5.04             | 4.93             | 4.28             | 4.35             | 4.19             |                  |
| 100  | 4.30             | 4.16             | 3.56             | 3.44             | 3.49             |                  |
| $\infty$   | 4.22             | 4.11             | 3.50             | 3.39             | 3.44             |                  |

<sup>a</sup>  $^1\text{H}$  has only one  $K$ -shell electron, hence values in this column contain an additional factor of two to allow smooth interpolation to adjacent elements.

TABLE 2.-6. Parameters for empirical fit [eq (2.-1)] to the K-shell photoelectric cross section  $\tau_K$ .

| $n$ | $a_n$                  | $b_n$                   | $c_n$                 | $p_n$ |
|-----|------------------------|-------------------------|-----------------------|-------|
| 1   | $1.6268 \cdot 10^{-9}$ | $-2.683 \cdot 10^{-12}$ | $4.173 \cdot 10^{-2}$ | 1     |
| 2   | $1.5274 \cdot 10^{-9}$ | $-5.110 \cdot 10^{-13}$ | $1.027 \cdot 10^{-2}$ | 2     |
| 3   | $1.1330 \cdot 10^{-9}$ | $-2.177 \cdot 10^{-12}$ | $2.013 \cdot 10^{-2}$ | 3.5   |
| 4   | $-9.12 \cdot 10^{-11}$ | 0                       | 0                     | 4     |

TABLE 2.-7. The experimental ratio  $(\tau_{pe}/\tau_K)_{K-edge}$  as derived from Kirchner [1930] by Davisson [1965].

| Element          | $(\tau_{pe}/\tau_K)_{K-edge}$ | Element          | $(\tau_{pe}/\tau_K)_{K-edge}$ |
|------------------|-------------------------------|------------------|-------------------------------|
| $^1\text{H}$     | 1.00                          | $^{20}\text{Ca}$ | 1.11                          |
| $^4\text{Be}$    | 1.03                          | $^{26}\text{Fe}$ | 1.12                          |
| $^6\text{C}$     | 1.04                          | $^{29}\text{Cu}$ | 1.13                          |
| $^7\text{N}$     | 1.05                          | $^{42}\text{Mo}$ | 1.16                          |
| $^8\text{O}$     | 1.06                          | $^{50}\text{Sn}$ | 1.18                          |
| $^{11}\text{Na}$ | 1.075                         | $^{53}\text{I}$  | 1.19                          |
| $^{12}\text{Mg}$ | 1.08                          | $^{74}\text{W}$  | 1.20                          |
| $^{13}\text{Al}$ | 1.09                          | $^{79}\text{Pt}$ | 1.22                          |
| $^{14}\text{Si}$ | 1.09                          | $^{82}\text{Pb}$ | 1.22                          |
| $^{18}\text{Ar}$ | 1.10                          | $^{92}\text{U}$  | 1.235                         |
| $^{19}\text{P}$  | 1.10                          |                  |                               |

McMaster, Del Grande, et al. For the heavier elements  $^{74}\text{W}$ ,  $^{82}\text{Pb}$ , and  $^{92}\text{U}$  some energy-dependence in the ratio  $\tau_{pe}/\tau_K$  is included, based on the Rakavy-Ron results, from the K-edge to about 1 MeV where the ratio joins smoothly with the values from table 2.-7.

Although not truly a smooth function of  $Z$  because of irregularities in the higher electron shell structure, the ratios in table 2.-7 can be represented with an accuracy of  $\pm 2$  to 3 percent by the empirical fit

$$\tau_{pe}/\tau_K \approx 1 + 0.01481 \ln^2 Z - 0.000788 \ln^3 Z. \quad (2.-2)$$

## 2.4. Scattering

### 2.4.1. Compton Scattering. Klein-Nishina Formula

In Compton scattering, a photon collides with an electron, loses some of its energy and is deflected from its original direction of travel. The basic theory of this effect, assuming the electron to be initially free and at rest, is that of Klein and Nishina [1929]. This theory has been well confirmed experimentally (see, for example, Meitner and Hupfeld [1930], Hofstadter and McIntyre [1949], Cross and Ramsey [1950], French [1965], Sahota et al. [1966], and Gittelmann et al. [1968]). Predictions of this theory have been summarized and extensive tabulations have been given by Nelms [1953], Burton [1953], and Evans [1958, 1968].

Over most of the region in which Compton scattering is a major part of the total cross section, the Klein-Nishina theory is directly applicable. Departures from it occur at low energies because of electron binding effects, and at high energies because of the possibility of emission of an additional pho-

ton (double Compton effect) and radiative corrections associated with emission and reabsorption of virtual photons. These corrections are discussed later in this section.

The relation between photon deflection and energy loss for Compton scattering, assuming the electron to be initially free and stationary, is determined from conservation of momentum and energy between the photon and the recoiling electron (Compton [1923], Debye [1923]). This relation can be expressed as

$$\frac{E'}{E} = \frac{1}{1 + (E/mc^2)(1 - \cos \theta)}, \quad (2.-3)$$

where  $E$  and  $E'$  are the energies of the photon before and after the scattering,  $mc^2$  is the electron rest energy and  $\theta$  is the photon deflection angle.

In transport calculations it is often convenient to use, instead of the energy variable, the wavelength of the photon in Compton units,

$$\lambda = mc^2/E = 0.5110/E [\text{MeV}]. \quad (2.-4)$$

The increase in wavelength associated with a Compton scattering event in these units is

$$\lambda' - \lambda = 1 - \cos \theta, \quad (2.-5)$$

where  $\lambda$  and  $\lambda'$  are the Compton wavelengths of the photon before and after the deflection. The maximum shift in wavelength, occurring for a deflection  $\theta = 180^\circ$ , is two Compton units.

For unpolarized photons the Klein-Nishina angular distribution function per steradian of solid angle  $\Omega$  is

$$\begin{aligned} d\sigma_C^{KN}(\theta)/d\Omega &= \frac{1}{2} r_e^2 [1 + k(1 - \cos \theta)]^{-2} \times \\ &\times \left[ 1 + \cos^2 \theta + \frac{k^2(1 - \cos \theta)^2}{1 + k(1 - \cos \theta)} \right] \left[ \frac{\text{cm}^2/\text{electron}}{\text{steradian}} \right], \end{aligned} \quad (2.-6)$$

in which  $k$  is the reciprocal of the incident photon Compton wavelength

$$k = 1/\lambda = E/mc^2 = E [\text{MeV}]/0.5110. \quad (2.-7)$$

Integration of eq. (2.-6) over all angles gives the total Klein-Nishina cross section

$$\sigma_C^{KN} = 2\pi r_e^2 \left\{ \frac{1+k}{k^2} \left[ \frac{2(1+k)}{1+2k} - \frac{\ln(1+2k)}{k} \right] + \frac{\ln(1+2k)}{2k} - \frac{1+3k}{(1+2k)^2} \right\} \left[ \frac{\text{cm}^2}{\text{electron}} \right]. \quad (2.-8)$$

This formula is not particularly suitable for evaluation of  $\sigma_C^{KN}$  at low energies because of near-cancellation between the logarithmic and purely algebraic terms. For example, using 8-place arithmetic, errors of 1 to 2 percent will occur at 10 to 15 keV. Values of  $\sigma_C^{KN}$  in table 2.-8 were computed in double-precision arithmetic and we believe them correct to the 5 significant figures given.

For  $k \ll 1$ , eq. (2.-8) can be expanded as

$$\sigma_C^{KN} = \frac{8}{3} \pi r_e^2 \frac{1}{(1+2k)^2} \left( 1 + 2k + \frac{6}{5} k^2 - \frac{1}{2} k^3 + \frac{2}{7} k^4 - \frac{6}{35} k^5 + \frac{8}{105} k^6 + \frac{4}{105} k^7 - \dots \right) \left[ \frac{\text{cm}^2}{\text{electron}} \right]. \quad (2.-9)$$

Using only terms through  $k^2$ , the value of  $\sigma_C^{KN}$  from eq. (2.-9) at 10 keV is within 0.001 percent of that from eq. (2.-8). In the low-energy limit ( $k \rightarrow 0$ ) this expression becomes the classical Thomson cross section.<sup>16</sup>

$$\sigma_T = \frac{8}{3} \pi r_e^2 = 0.6652 \cdot 10^{-24} \left[ \frac{\text{cm}^2}{\text{electron}} \right]. \quad (2.-10)$$

For  $k \gg 1$ , a useful approximation is (Heitler [1954]):

$$\sigma_C^{KN} \approx \pi r_e^2 \frac{1+2 \ln(2k)}{2k} \left[ \frac{\text{cm}^2}{\text{electron}} \right] \quad (2.-11)$$

which is equivalent to eq (2.-8) as  $k \rightarrow \infty$ , and gives a result differing by +0.6 percent at 100 MeV and by +0.09 percent at 1000 MeV.

In addition, Hastings [1955] has fitted eq (2.-8) by the empirical formula

$$\sigma_C^{KN} \approx \sigma_C^H = \pi r_e^2 \left( \frac{c_1 \xi + c_2 \xi^2 + c_3 \xi^3}{1 + d_1 \xi + d_2 \xi^2 + d_3 \xi^3} \right) \left[ \frac{\text{cm}^2}{\text{electron}} \right]. \quad (2.-12)$$

where  $\xi = 1/(1+bk)$ . The parameters have the values

$$b = 0.222037$$

$$\begin{array}{ll} c_1 = 1.651035 & d_1 = 12.501332 \\ c_2 = 9.340220 & d_2 = -14.200407 \\ c_3 = -8.325004 & d_3 = 1.699075 \end{array}$$

For photon energies  $0 \leq E \leq 1$  MeV values of  $\sigma_C^H$  are within 0.1 percent of  $\sigma_C^{KN}$ , and for  $E \leq 100$  MeV

<sup>16</sup> However, extrapolation to this limit [ $\sigma_C^{KN}|_{k \rightarrow 0} = \sigma_T$ ] is valid only for a free electron; for bound electrons [ $\sigma_C|_{k \rightarrow 0} = 0$ ].

are within 1.3 percent. However, at 1 GeV values of  $\sigma_C^H$  are less than  $\sigma_C^{KN}$  by 17 percent, and at 100 GeV less by 44 percent.

Also listed in table 2.-8 are values of the Compton energy transfer fraction  $f_C^{KN}$  (for use in computing  $\mu_{\kappa}/\rho$  and  $\mu_a/\rho$  but not  $\mu_{en}/\rho$ ) where

$$f_C^{KN} = a\sigma_C^{KN}/\sigma_C^{KN}. \quad (2.-13)$$

The numerator  $a\sigma_C^{KN}$  is obtained by weighting the right-hand side of eq (2.-6) by the fraction of the photon energy transferred to the recoil electron. This fraction is

$$\frac{k-k'}{k} = \frac{k(1-\cos\theta)}{1+k(1-\cos\theta)} \quad (2.-14)$$

where  $k'$  is the energy of the deflected photon. Combining eq (2.-6) with eq (2.-12) we have

$$\begin{aligned} d_a \sigma_C^{KN}(\theta)/d\Omega &= \frac{1}{2} r_e^2 \frac{k(1-\cos\theta)}{[1+k(1-\cos\theta)]^3} \\ &\times \left[ 1 + \cos^2\theta + \frac{k^2(1-\cos\theta)^2}{1+k(1-\cos\theta)} \right] \left[ \frac{\text{cm}^2/\text{electron}}{\text{steradian}} \right]. \end{aligned} \quad (2.-15)$$

Integration of the right-hand side of eq (2.-15) over all angles yields:

$$\begin{aligned} a\sigma_C^{KN} &= 2\pi r_e^2 \left\{ \frac{2(1+k)^2}{k^2(1+2k)} - \frac{1+3k}{(1+2k)^2} - \frac{(1+k)(2k^2-2k-1)}{k^2(1+2k)^2} \right. \\ &\quad \left. - \frac{4k^2}{3(1+2k)^3} - \left( \frac{1+k}{k^3} - \frac{1}{2k} + \frac{1}{2k^3} \right) \ln(1+2k) \right\} \\ &\quad \left[ \frac{\text{cm}^2}{\text{electron}} \right] \end{aligned} \quad (2.-16)$$

At low photon energies eq (2.-16) suffers from loss of precision similar to that in eq. (2.-8). An expansion of eq (2.-16) useful for  $k \ll 1$  is

$$\begin{aligned} a\sigma_C^{KN} &= \frac{8}{3} \pi r_e^2 \frac{1}{(1+2k)^3} \left( k + \frac{9}{5} k^2 + \frac{3}{2} k^3 \right. \\ &\quad \left. - \frac{13}{35} k^4 + \frac{2}{35} k^5 + \frac{4}{35} k^6 - \frac{4}{15} k^7 + \dots \right) \\ &\quad \left[ \frac{\text{cm}^2}{\text{electron}} \right]. \end{aligned} \quad (2.-17)$$

#### 2.4.2. Electron Binding Corrections to Compton Scattering. Rayleigh Scattering

In gamma ray transport theory and shielding calculations, electron binding effects have usually been either disregarded or treated very approximately by combining them with Rayleigh scattering. The justification for this treatment is that for low- $Z$



TABLE 2.-8. Compton scattering cross section  $\sigma_c$  for a free electron.

These values were evaluated using eq. (2.-8) and modified by the Mork [1968] combined radiative and double-Compton corrections  $\Delta\sigma^M$  here listed.

The average fraction of photon energy transferred to the electron,  $f_c$ , is also listed.

| Photon energy | $\sigma_c^{KN}$ | $\Delta\sigma_c^M$ | $\sigma_c = \sigma_c^{KN} + \Delta\sigma_c^M$ | $f_c^{KN}$ | Photon energy | $\sigma_c^{KN}$ | $\Delta\sigma_c^M$ | $\sigma_c = \sigma_c^{KN} + \Delta\sigma_c^M$ | $f_c^{KN}$ |
|---------------|-----------------|--------------------|---|------------|---------------|-----------------|--------------------|---|------------|
| MeV           | b/electron      | b/electron         | b/electron                                    |            | MeV           | b/electron      | b/electron         | b/electron                                    |            |
| 0.010         | 0.64039         | (0.00000)          | (0.6404)                                      | 0.01876    | 40            | 0.017462        | 0.00012            | 0.01758                                       | 0.76004    |
| .015          | .62888          | (.00001)           | (.6289)                                       | .02758     | 50            | .014565         | .00011             | .01468  | .76922     |
| .02           | .61791          | (.00001)           | (.6179)                                       | .03605     | 60            | .012541         | .00010             | .01264  | .77624     |
| .03           | .59742          | (.00002)           | (.5974)                                       | .05204     | 80            | .0098806        | .000090            | .009970                                       | .78650     |
| .04           | .57867          | (.00002)           | (.5787)                                       | .06688     | 100           | .0081976        | .000082            | .008280                                       | .79385     |
| .05           | .56144          | (.00003)           | (.5615)                                       | .08071     | 150           | .0058182        | .000075            | .005893                                       | .80600     |
| .06           | .54555          | (.00003)           | (.5456)                                       | .09363     | 200           | .0045506        | .000070            | .004620                                       | .81379     |
| .08           | .51722          | (.00004)           | (.5173)                                       | .11713     | 300           | .0032086        | .000067            | .003276                                       | .82378     |
| .10           | .49269          | (.00005)           | (.4927)                                       | .13800     | 400           | .0024992        | .000066            | .002565                                       | .83024     |
| .15           | .44355          | (.00007)           | (.4436)                                       | .18156     | 500           | .0020568        | .000067            | .002124                                       | .83493     |
| .2            | .40643          | (.00008)           | (.4065)                                       | .21635     | 600           | .0017531        | .000065            | .001818                                       | .83858     |
| .3            | .35340          | (.00010)           | (.3535)                                       | .26965     | 800           | .0013609        | .000059            | .001420                                       | .84402     |
| .4            | .31664          | (.00013)           | (.3168)                                       | .30962     | 1000          | .0011174        | .000051            | .001168                                       | .84799     |
| .5            | .28913          | (.00014)           | (.2893)                                       | .34136     | 1500          | .00077951       | (.0000362)         | (.0008158)                                    | .85471     |
| .6            | .26747          | (.00016)           | (.2676)                                       | .36751     | 2000          | .00060303       | (.0000283)         | (.0006314)                                    | .85913     |
| .8            | .23493          | (.00018)           | (.2351)                                       | .40866     | 3000          | .00041929       | (.0000197)         | (.0004390)                                    | .86492     |
| 1.0           | .21118          | (.00020)           | (.2114)                                       | .44004     | 4000          | .00032365       | (.0000152)         | (.0003389)                                    | .86874     |
| 1.5           | .17156          | (.00023)           | (.1718)                                       | .49468     | 5000          | .00026462       | (.0000124)         | (.0002771)                                    | .87156     |
| 2.0           | .14634          | (.00024)           | (.1466)                                       | .53084     | 6000          | .00022439       | (.0000105)         | (.0002349)                                    | .87378     |
| 3.0           | .11508          | (.00024)           | (.1153)                                       | .57732     | 8000          | .00017288       | (.0000081)         | (.0001810)                                    | .87713     |
| 4             | .095963         | .00024             | .09620  | .60693     | 10 000        | .00014115       | (.0000066)         | (.0001478)                                    | .87960     |
| 5             | .082856         | .00022             | .08308  | .62799     | 15 000        | .000097550      | (.00000458)        | (.0001021)                                    | .88386     |
| 6             | .073221         | .00020             | .07342  | .64400     | 20 000        | .000074997      | (.00000352)        | (.00007852)                                   | .88670     |
| 8             | .059877         | .00018             | .06006  | .66720     | 30 000        | .000051721      | (.00000243)        | (.00005415)                                   | .89047     |
| 10            | .050983         | .00017             | .05115  | .68356     | 40 000        | .000039708      | (.00000187)        | (.00004157)                                   | .89300     |
| 15            | .037708         | .00015             | .03786  | .71004     | 50 000        | .000032335      | (.00000152)        | (.00003385)                                   | .89488     |
| 20            | .030246         | .00014             | .03039  | .72656     | 60 000        | .000027333      | (.00000128)        | (.00002862)                                   | .89637     |
| 30            | .021995         | .00013             | .02212  | .74713     | 80 000        | .000020958      | (.00000099)        | (.00002194)                                   | .89864     |
|               |                 |                    |   |            | 100 000       | .000017051      | (.00000080)        | (.00001785)                                   | .90033     |

elements the *K*-shell binding energies are low in comparison with the photon energies considered, while for high-*Z* materials with substantial *K*-shell binding energies these electrons are a small fraction of the total.

The scattering of 0.662-MeV photons by *K*-shell electrons of various heavy atoms has been measured by Motz and Missoni [1961], Sujkowski and Nagel [1961], and Varma and Eswaran [1962]. The ratio of the observed differential cross section  $d\sigma_c^K(\theta)/d\Omega$  to the Klein-Nishina differential cross section  $d\sigma_c^{KN}(\theta)/d\Omega$  [eq (2.-6)] for tin and gold is given in figure 2.-2, based on data of Motz and Missoni. It is seen that for small angles the effect of binding is to decrease the cross section, whereas for large angles an increase occurs. The decrease and increase tend to compensate each other, so that for the cases shown in figure 2.-2 the integrated cross sections  $\sigma_c$  and  $\sigma_c^{KN}$  [eq (2.-8)] agree within experimental error. Similar measurements by Dowe [1965] on thallium *K*-shell electrons suggest such compensation may extend down to 0.122 MeV.

The usual Klein-Nishina cross section, which assumes that the target electron is free and at rest, has been generalized by Jauch and Rohrlich [1955] to the case where the electron is free but in motion.

Motz and Missoni used this generalized theory to interpret their data at large angles. Their results, obtained by averaging over the appropriate electron velocity distributions, are shown as the solid curves in figure 2.-2.

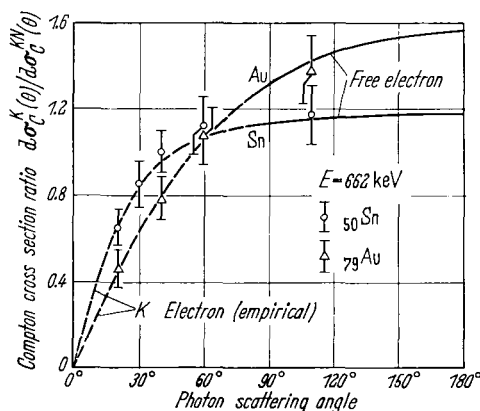


FIGURE 2.-2. Ratio of observed Compton scattering from *K*-shell electrons (Motz and Missoni [1961]) to Klein-Nishina theory, eq. (2.-6).

The solid curves are extrapolations (by Motz and Missoni) to  $\theta = 180^\circ$  using the theory of Jauch and Rohrlich [1955] which considers electron velocities.

The binding corrections have usually been treated in the impulse approximation, taking into account not only the  $K$ -shell, but all the atomic electrons. This involves applying a multiplicative correction, the so-called "incoherent scattering function,"  $S(q, Z)$ , to the differential Klein-Nishina formula [eq. (2.-6)]

$$d\sigma_c(\theta)/d\Omega = S(q, Z) d\sigma_c^N(\theta)/d\Omega. \quad (2.-18)$$

The momentum transfer  $q$  is related to the photon energies and deflection angle  $\theta$  according to

$$q = \sqrt{k^2 + k'^2 - 2kk' \cos \theta}, \quad (2.-19)$$

or, using eq (2.-3),

$$q = 2k \sin \frac{\theta}{2} \cdot \sqrt{1 + (k^2 + 2k) \sin^2 \theta / (1 + 2k \sin^2 \theta)}, \quad (2.-20)$$

where  $q$  is in  $mc$  units and  $k$  and  $k'$  are the photon energies (in  $mc^2$  units) before and after the deflection. Since binding effects are important mainly for small momentum transfers, the approximation  $k - k' \approx 0$  is usually made, so that

$$q \approx 2k \sin \frac{\theta}{2} \quad (2.-21)$$

The incoherent scattering function  $S(q, Z)$  represents the probability that an atom be raised to any excited or ionized state as a result of a sudden impulsive action which imparts a recoil momentum  $q$  to an atomic electron. For  $K$ -shell electrons only,  $S(q, Z)$  would correspond to the ratios shown in figure 2.-2.

Rayleigh scattering is a process by which photons are scattered by bound atomic electrons and in which the atom is neither ionized nor excited. The scattering from different parts of the atomic charge distribution is then "coherent," i.e., there are interference effects.

This process occurs mostly at low energies and for high  $Z$  materials, in the same region where electron binding effects influence the Compton scattering cross section. Indeed, if each atomic electron contributed independently to the cross section, the onset of Rayleigh scattering for low momentum transfer would exactly compensate for the reduction of Compton scattering due to binding. However, the various atomic electrons contribute coherently to Rayleigh scattering, greatly increasing the probability for the process.

We shall restrict the following discussion to Rayleigh scattering in the narrower sense, in which the coherence extends only over the  $Z$  electrons of individual atoms. This coherence can also extend to electrons of different atoms to give more striking

interference effects, such as Bragg-law diffraction by crystal lattices.

Experimental studies of Rayleigh scattering have been made by Moon [1950], Storruste [1950], Wilson [1951], Mann [1956], Schopper [1957], Storruste and Tjóm [1958], Anand, Singh, and Sood [1963, 1964], and Nath and Ghose [1964]. In interpreting these measured data, one must also take into account other, much less probable, elastic or quasi-elastic scattering processes, such as Thomson scattering by the nucleus, nuclear resonance scattering, and Delbrück scattering (see sec. 2.2.), in addition to Rayleigh scattering. Theoretical information on these processes, including constructive interference effects between the different processes, has been summarized by Moon [1950] and by Jauch and Rohrlich [1955].

Detailed Rayleigh scattering calculations have been made by Levinger [1952] for  $K$ -shell electrons of tin, and by Brown et al. [1954-1957] for  $K$ -shell electrons of mercury. In practice, it is necessary to consider the charge distribution of all  $Z$  electrons at once. This can be done approximately through use of an "atomic form factor"  $F(q, Z)$  based on the Thomas-Fermi, Hartree, or other model of the atom. The square of this form factor,  $[F(q, Z)]^2$ , is the probability that the  $Z$  electrons of an atom take up a recoil momentum,  $q$ , without absorbing any energy. In this process  $q$  is well-represented by (eq (2.-21) since it is assumed that  $k - k' = 0$ . The above probability  $[F(q, Z)]^2$ , is combined with the low-energy limiting form of the Klein-Nishina differential formula [eq (2.-6)] to give the differential Rayleigh scattering cross section for unpolarized photons:

$$d\sigma_R(\theta)/d\Omega = \frac{r_e^2}{2} (1 + \cos^2 \theta) [F(q, Z)]^2 \left[ \frac{\text{cm}^2/\text{atom}}{\text{steradian}} \right]. \quad (2.-22)$$

Calculations of  $S(q, Z)$  and  $F(q, Z)$  depend on knowledge of the atomic wave functions; they can be done analytically for hydrogen and, for other atoms, in various approximations based on the Thomas-Fermi, Hartree, or other models. The procedures used in such calculations have been discussed by White-Grodstein [1957] for  $S(q, Z)$  and by Nelms and Oppenheimer [1955] for  $F(q, Z)$ .

Evaluations of  $\sigma_c^{BP}$  have until recently used  $S(q, Z)$  values based on the Thomas-Fermi model.<sup>17</sup> However, Cromer and Mann [1967] have now provided Hartree-Fock  $S(q, Z)$  data for the 39 spherically symmetric atoms. Corresponding Hartree-model tabulations of  $F(q, Z)$  have been given by Hanson et al. [1964] and by Cromer and Waber [1965].

<sup>17</sup> In addition to the Grodstein [1957] (and Davison [1965]) results, extensive evaluations of  $\sigma_c^{BP}$  based on the Thomas-Fermi model have been given by Brown [1966b]  $1 \leq Z \leq 100$ , 1 keV to MeV and by Veigele [1965]:  $1 \leq Z \leq 106$ , 0.1 keV to 1 MeV.

Storm and Israel [1967] have used  $S(q, Z)$  values of Cromer and Mann (and additional data from Cromer) and  $F(q, Z)$  values from Hanson et al. to calculate  $\sigma_c^{BD}$  and  $\sigma_R$  (integrating over equations (2.-18) and (2.-22), respectively) for all elements  $Z=1$  to 100 and energies ranging up from 1 keV. Figure 2.-3 shows ratios of these values of  $\sigma_c^{BD}$  (excluding interpolated values) to values given by the Klein-Nishina formula [eq (2.-8)] for photon energies of 1, 10, and 100 keV.

Cumulative angular distributions of  $\sigma_R$ , based on values of  $F(q, Z)$  from Nelms and Oppenheim [1955], are displayed in figure 2.-4 for C, Fe, and Hg. At high energies it is seen that Rayleigh scattering is confined to small angles (at 1 MeV more than half the photons are scattered by less than  $5^\circ$ ). At low energies, particularly for high- $Z$  materials, the angular distribution is much broader. Here, however, the Rayleigh scattering cross section is small in comparison with photoelectric absorption. On the basis of these considerations, Rayleigh scattering is frequently disregarded in gamma ray transport theory and shielding calculations (Fano, Spencer, and Berger [1959], Goldstein and Wilkins [1954]).

Rayleigh scattering can, however, be of importance in interpreting "narrow beam" attenuation coefficient measurements, depending on the angular resolution of the apparatus. A useful sim-

ple criterion for judging the angular spread of Rayleigh scattering is (Moon [1950], Evans [1958]):

$$\theta_c = 2 \arcsin \left[ \frac{0.0133Z^{1/3}}{E[\text{MeV}]} \right], \quad (2.-23)$$

where  $\theta_c$  is the opening half-angle of a cone containing at least 75 percent of the Rayleigh-scattered photons (see also fig. 2.-4).

The sum  $(\sigma_c^{BD} + \sigma_R)$ , rather than  $\sigma_c^{BD}$  and  $\sigma_R$  individually, has been tabulated in previous compilations (White-Grodstein [1957] and Davisson [1965]), because this sum is less sensitive to errors from approximations in the theory. In this report, since present theory still relies on the impulse approximation and neglects initial motion of the electrons, we retain the White-Grodstein format in our tables in section 3. That is, in tables 3.-1 to 3.-36 we list the sum  $(\sigma_c^{BD} + \sigma_R)$  (or "scattering, with coherent" in the notation of White-Grodstein and Davisson), in which  $\sigma_c^{BD}$  and  $\sigma_R$  are the values given by Storm and Israel [1967]. Also, in table 2.-9 we give these results in the form of a percentage correction to the total "without coherent" cross section,  $\sigma_{\text{tot}}$ , given in table 1.-4, viz

$$\frac{(\sigma_c^{BD} + \sigma_R) - \sigma_c^{KN}}{\sigma_{\text{tot}}} \times 100\%. \quad (2.-24)$$

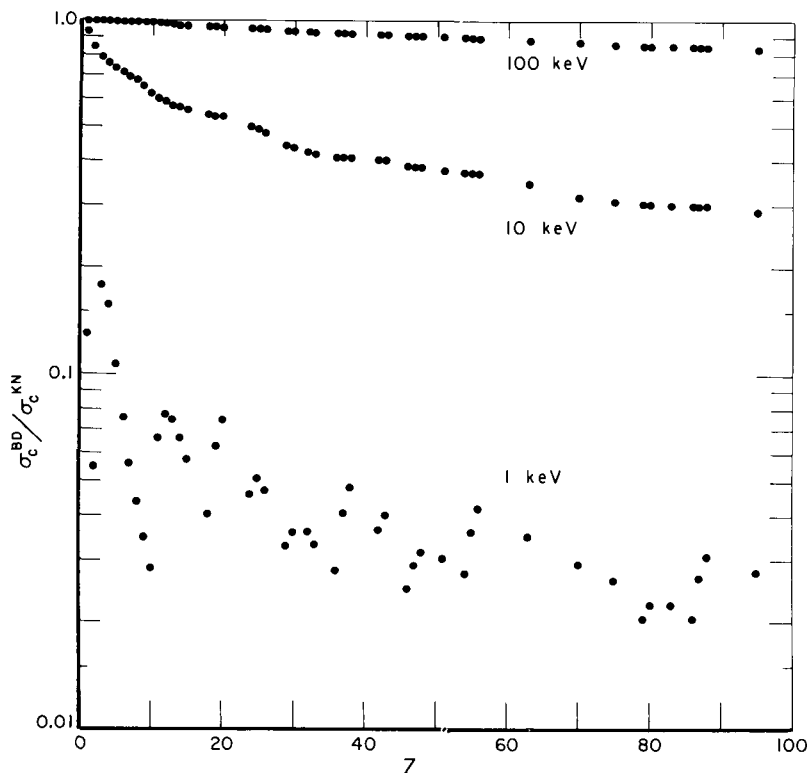


FIGURE 2.-3. Ratio of the bound-electron Compton collision cross section,  $\sigma_c^{BD}$  calculated by Storm and Israel [1967] to that for free electrons,  $\sigma_c^{KN}$ , evaluated from the Klein-Nishina formula.

At energies above 100 keV the sum ( $\sigma_C^{BD} + \sigma_R$ ) given by Storm and Israel (based entirely on the Hartree model) is within 1 percent of that given by

White-Grodstein and Davisson (based mostly on the Thomas-Fermi model). However, between 10 and 100 keV there are differences of as much as 10 percent in either direction.

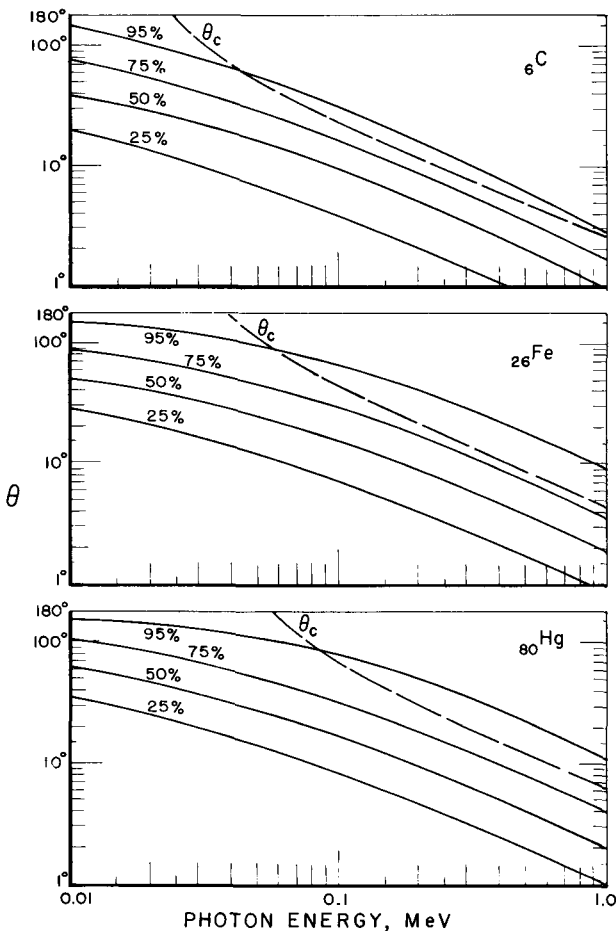


FIGURE 2-4. Opening half-angle,  $\theta$ , of cone containing 25 percent, 50 percent, 75 percent, and 95 percent, respectively, of photons Rayleigh-scattered from C, Fe, and Hg. The function  $\theta_c$  (Eq. 2.-23) is included for comparison.

### 2.4.3. Radiative Corrections. Double Compton Effect

The radiative correction (of the order 1/137) is associated with emission and reabsorption of virtual photons whereas in the double Compton effect an additional real photon, usually very low in energy, is emitted.

Because of the predominance of pair production at high energies, experimental data on these effects are difficult to obtain and the existing experiments by Cavanagh [1952], Bracci et al. [1956], Theus and Beach [1957], and Burdet [1963] have large uncertainties. Hence, the information is primarily theoretical and has only recently become sufficiently quantitative for inclusion in tabulations. We have relied on the recent theoretical results of Mork [1968] who made a calculation combining the radiative correction  $\sigma(\text{rad. corr.})$  with the cross section  $\sigma(\text{double Compt.})$  for the double Compton effect.

The differential formulas (Brown and Feynman [1952], Mandl and Skyrme [1952]) for the two effects each contain an "infrared divergence." These divergencies are of opposite sign, and in the combined calculation they cancel each other to give a physically meaningful result.

The Mork correction, which must be added to the Klein-Nishina cross section,

$$\Delta\sigma_C^M = \sigma(\text{double Compt.}) + \sigma(\text{rad. corr.}) \quad (2.-25)$$

is given in table 2.-8 separately and in the combination with  $\sigma_C^M$ . It is seen that the contribution of  $\Delta\sigma_C^M$  to  $\sigma_C$  is  $\sim 0.25$  percent at 4 MeV, rising to  $\sim 1$  percent at 100 MeV and  $\sim 5$  percent at 1000 MeV.

TABLE 2.-9. Percentage by which  $\sigma_{\text{tot}}$  or  $\mu/\rho$  is increased if coherent scattering effects are included. Based on data by Storm and Israel [1967] taking into account Rayleigh scattering and the effect of electron binding on Compton scattering

| Photon energy [MeV] | $1\text{H}$ | $6\text{C}$ | $13\text{Al}$ | $20\text{Ca}$ | $26\text{Fe}$ | $29\text{Cu}$ | $42\text{Mo}$ | $50\text{Sn}$ | $74\text{W}$ | $82\text{Pb}$ | $92\text{U}$ | Absorption edges |
|---------------------|-------------|-------------|---------------|---------------|---------------|---------------|---------------|---------------|--------------|---------------|--------------|------------------|
| 0.01                | -2          | 5.2         | 1.9           | 0.9           | 0.7           | 0.6           | 2.6           | 1.8           | 4.8          | 3.8           | 3.1          | $L_{III}$ edge   |
| 0.02                | -1          | 10.7        | 5.3           | 2.7           | 1.9           | 1.7           | 8.0           | 5.8           | 3.0          | 2.7           | 3.7          |                  |
| 0.03                | 0           | 9.0         | 8.4           | 4.6           | 3.2           | 2.8           | 1.8           | 1.6           | 5.2          | 4.5           | 3.7          | $K$ edge         |
| 0.05                | 0           | 4.7         | 10.6          | 7.9           | 5.7           | 5.1           | 3.2           | 2.8           | 9.4          | 8.1           | 6.6          |                  |
| 0.10                | 0           | 1.4         | 5.8           | 8.4           | 8.2           | 8.0           | 5.9           | 5.0           | 3.4          | 3.3           | 11.7         |                  |
| 0.20                | 0           | 0.5         | 2.0           | 3.8           | 5.0           | 6.0           | 7.2           | 6.9           | 5.3          | 4.9           | 4.4          |                  |
| 0.30                | 0           | < 0.5       | 1.0           | 2.0           | 3.1           | 3.6           | 5.8           | 6.2           | 5.8          | 5.4           | 5.0          |                  |
| 0.50                | 0           | < 0.5       | < 0.5         | 0.9           | 1.3           | 1.7           | 2.8           | 3.8           | 5.0          | 4.8           | 4.7          |                  |
| 1.0                 | 0           | < 0.5       | < 0.5         | < 0.5         | < 0.5         | 0.5           | 1.1           | 1.2           | 2.2          | 2.6           | 2.8          |                  |
| 2.0                 | 0           | < 0.5       | < 0.5         | < 0.5         | < 0.5         | < 0.5         | < 0.5         | < 0.5         | 0.8          | 1.1           | 0.9          |                  |
| 3.0                 | 0           | < 0.5       | < 0.5         | < 0.5         | < 0.5         | < 0.5         | < 0.5         | < 0.5         | < 0.5        | < 0.5         | 0.6          |                  |

## 2.5. Electron-Positron Pair Production

### 2.5.1. General Discussion

In this effect, which is the most likely photon interaction at high energies, a photon disappears in the field of a charged particle, and an electron-positron pair appears. The cross section  $\kappa_n$  for pair production in the field of a nucleus varies as

$$\kappa_n \sim Z^2. \quad (2.-26)$$

The cross section  $\kappa_e$  in the field of all the atomic electrons varies as  $Z$  times the square of the unit charge, or,

$$\kappa_e \sim Z, \quad (2.-27)$$

and is of minor importance except for the lowest- $Z$  materials. The ratio  $\kappa_e/\kappa_n$  can be set equal to  $\eta/Z$  where  $\eta$  is a slowly varying function of  $Z$  and  $E$ , generally close to one, and will be discussed later in this section.

There have been a number of experimental studies in which the  $\kappa_n$  and  $\kappa_e$  cross sections have been isolated to some extent. For  $\kappa_n$  data see, for example, the results by Standil and Shkolnik [1958], Singh et al. [1959], Rao et al. [1968], Plimpton and Hammer [1963], Yamazaki and Hollander [1965], and Titus and Levy [1966], and for  $\kappa_e$  data, the results of Criegee [1960], Sandhu

et al. [1962], and Frei et al. [1964]. Earlier results for both cross sections have been summarized by Davisson [1965]. There are additional data which depend on subtraction of the Compton cross section  $\sigma_c^N$  from measured total cross sections  $\sigma_{tot}$  (see, for example, Jones [1959, 1960], Wyckoff and Koch [1960]), but the recent Mork correction  $\Delta\sigma_c^N$  to  $\sigma_c^N$  requires slight revisions in these estimates. These data still leave wide gaps or contain substantial uncertainties. For tabulations we rely heavily on theory, as discussed in the remainder of this section.

### 2.5.2. Pair Production in the Field of the Nucleus

The threshold for this effect is equal to the combined rest energies of the created pair  $2mc^2$  ( $=1.022$  MeV). The cross section rises monotonically from zero at threshold, varying approximately linearly with  $E$ , until it levels off near 50 MeV for high- $Z$  materials and at higher energies for low- $Z$  materials. At 100, 1000 and 10,000 MeV the cross section is roughly 75 percent, 95 percent, and 99 percent, respectively, of its high-energy limiting value.

The values of  $\kappa_n$  we present in table 2.-10 and in section 3 have been revised to incorporate new screening calculations by Sörenssen [1965, 1966] and the Mork-Olsen [1965] radiative correction. However, it is useful to describe first the procedures and sources of information for the well-established

TABLE 2.-10. Scaled cross section  $\kappa_n/Z^2$  for pair production in the field of the nucleus, based on  $\kappa_n^{BH}$  (Born) evaluated by Maximon [1968], screening (Hartree-Fock-Slater) estimates by Sörenssen [1965, 1966], the Mork-Olsen [1965] radiative correction, and corrections to the Born approximation by empirical adjustment of the Coulomb correction.

Units are [b/atom]/ $Z^2$ . For unscaled  $\kappa_n$  values up to 100 GeV, see tables in section 3.

| Photon energy [MeV] | ${}_1\text{H}$       | ${}_6\text{C}$       | ${}_{13}\text{Al}$   | ${}_{20}\text{Ca}$   | ${}_{26}\text{Fe}$   | ${}_{29}\text{Cu}$   |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1.022               | 0                    | 0                    | 0                    | 0                    | 0                    | 0                    |
| 1.5                 | $4.35 \cdot 10^{-5}$ | $4.37 \cdot 10^{-5}$ | $4.45 \cdot 10^{-5}$ | $4.62 \cdot 10^{-5}$ | $4.81 \cdot 10^{-5}$ | $4.92 \cdot 10^{-5}$ |
| 2                   | $1.79 \cdot 10^{-4}$ | $1.79 \cdot 10^{-4}$ | $1.81 \cdot 10^{-4}$ | $1.84 \cdot 10^{-4}$ | $1.88 \cdot 10^{-4}$ | $1.90 \cdot 10^{-4}$ |
| 3                   | $5.12 \cdot 10^{-4}$ | $5.11 \cdot 10^{-4}$ | $5.13 \cdot 10^{-4}$ | $5.16 \cdot 10^{-4}$ | $5.19 \cdot 10^{-4}$ | $5.21 \cdot 10^{-4}$ |
| 5                   | $1.11 \cdot 10^{-3}$ | $1.11 \cdot 10^{-3}$ | $1.11 \cdot 10^{-3}$ | $1.11 \cdot 10^{-3}$ | $1.10 \cdot 10^{-3}$ | $1.10 \cdot 10^{-3}$ |
| 10                  | $2.15 \cdot 10^{-3}$ | $2.14 \cdot 10^{-3}$ | $2.12 \cdot 10^{-3}$ | $2.10 \cdot 10^{-3}$ | $2.09 \cdot 10^{-3}$ | $2.08 \cdot 10^{-3}$ |
| 20                  | $3.30 \cdot 10^{-3}$ | $3.28 \cdot 10^{-3}$ | $3.23 \cdot 10^{-3}$ | $3.20 \cdot 10^{-3}$ | $3.17 \cdot 10^{-3}$ | $3.15 \cdot 10^{-3}$ |
| 30                  | $3.99 \cdot 10^{-3}$ | $3.95 \cdot 10^{-3}$ | $3.88 \cdot 10^{-3}$ | $3.84 \cdot 10^{-3}$ | $3.79 \cdot 10^{-3}$ | $3.78 \cdot 10^{-3}$ |
| 50                  | $4.87 \cdot 10^{-3}$ | $4.76 \cdot 10^{-3}$ | $4.67 \cdot 10^{-3}$ | $4.60 \cdot 10^{-3}$ | $4.54 \cdot 10^{-3}$ | $4.52 \cdot 10^{-3}$ |
| 100                 | $6.05 \cdot 10^{-3}$ | $5.76 \cdot 10^{-3}$ | $5.61 \cdot 10^{-3}$ | $5.50 \cdot 10^{-3}$ | $5.42 \cdot 10^{-3}$ | $5.39 \cdot 10^{-3}$ |
| Photon energy [MeV] | ${}_{42}\text{Mo}$   | ${}_{50}\text{Sn}$   | ${}_{74}\text{W}$    | ${}_{82}\text{Pb}$   | ${}_{92}\text{U}$    |                      |
| 1.022               | 0                    | 0                    | 0                    | 0                    | 0                    |                      |
| 1.5                 | $5.55 \cdot 10^{-5}$ | $6.01 \cdot 10^{-5}$ | $7.67 \cdot 10^{-5}$ | $8.27 \cdot 10^{-5}$ | $9.03 \cdot 10^{-5}$ |                      |
| 2                   | $2.02 \cdot 10^{-4}$ | $2.10 \cdot 10^{-4}$ | $2.42 \cdot 10^{-4}$ | $2.53 \cdot 10^{-4}$ | $2.68 \cdot 10^{-4}$ |                      |
| 3                   | $5.33 \cdot 10^{-4}$ | $5.42 \cdot 10^{-4}$ | $5.74 \cdot 10^{-4}$ | $5.86 \cdot 10^{-4}$ | $6.01 \cdot 10^{-4}$ |                      |
| 5                   | $1.10 \cdot 10^{-3}$ | $1.10 \cdot 10^{-3}$ | $1.09 \cdot 10^{-3}$ | $1.08 \cdot 10^{-3}$ | $1.08 \cdot 10^{-3}$ |                      |
| 10                  | $2.03 \cdot 10^{-3}$ | $1.99 \cdot 10^{-3}$ | $1.87 \cdot 10^{-3}$ | $1.83 \cdot 10^{-3}$ | $1.77 \cdot 10^{-3}$ |                      |
| 20                  | $3.06 \cdot 10^{-3}$ | $3.00 \cdot 10^{-3}$ | $2.79 \cdot 10^{-3}$ | $2.72 \cdot 10^{-3}$ | $2.62 \cdot 10^{-3}$ |                      |
| 30                  | $3.67 \cdot 10^{-3}$ | $3.59 \cdot 10^{-3}$ | $3.35 \cdot 10^{-3}$ | $3.27 \cdot 10^{-3}$ | $3.16 \cdot 10^{-3}$ |                      |
| 50                  | $4.38 \cdot 10^{-3}$ | $4.29 \cdot 10^{-3}$ | $4.00 \cdot 10^{-3}$ | $3.90 \cdot 10^{-3}$ | $3.78 \cdot 10^{-3}$ |                      |
| 100                 | $5.20 \cdot 10^{-3}$ | $5.08 \cdot 10^{-3}$ | $4.74 \cdot 10^{-3}$ | $4.63 \cdot 10^{-3}$ | $4.48 \cdot 10^{-3}$ |                      |

White-Grodstein [1957] compilation, and then note how the present evaluation differs.

White-Grodstein used as an initial approximation the Bethe-Heitler theory done in the Born approximation (Bethe and Heitler [1934], Heitler and Sauter [1933], and Racah [1934, 1935]). In the energy region  $E < 5$  MeV, where screening effects are negligible, cross section values for an unscreened nucleus were obtained from a formula of Hough [1948], which fits the Bethe-Heitler results to 0.1 percent. For  $E \gg 5$  MeV the differential Bethe-Heitler formula, including screening based on the Thomas-Fermi model of the atom (Bethe and Heitler [1934, eq (36)], also Bethe and Ashkin [1953, eq (114)]), was integrated numerically over the energy distribution between the pair particles to obtain  $\kappa_n^{BH}(\text{Born})$ .

Corrections to the Born approximation values were applied at all energies. These corrections were derived from:

- (1) Calculations of Jaeger and Hulme in the energy range  $E < 5$  MeV,
- (2) Calculations of Davies, Bethe and Maximon for  $E \gg 5$  MeV, and
- (3) Experimental data.

The results of Jaeger and Hulme [1936] and Jaeger [1936, 1941] were obtained by numerical solution of the Dirac equation and indicate considerable departures from the Born approximation near threshold, especially for high- $Z$  elements. For example, for tin at  $3 mc^2$  ( $= 1.533$  MeV) the ratio of their result to that from formulas based on the Born approximation is 1.30, while for lead at  $3mc^2$  this ratio is 1.97, dropping to 1.24 at  $5.2mc^2$  ( $= 2.66$  MeV).<sup>18</sup>

The calculation of Davies, Bethe, and Maximon [1954] for an unscreened nucleus went beyond the Born approximation, using Sommerfeld-Maue [1935] wave functions rather than plane waves. Their results lead to the appearance of a negative Coulomb correction

$$-\Delta\kappa_n^{DBM} = -\frac{28}{9} \frac{Z^2 r_e^2}{137} f(Z), \quad (2.-28)$$

where  $f(Z)$  may be evaluated from the sum

$$f(Z) = a^2 [(1+a^2)^{-1} + 0.20206 - 0.0369 a^2 + 0.0083 a^4 - 0.002 a^6 + \dots], \quad (2.-29)$$

in which

$$a = Z/137.$$

In their approximation (neglect of terms of order  $\ln k/k$  and  $1/k$ ) the Coulomb correction remains the same whether screening is absent, partial, or complete.

In her tabulations in the energy range  $E < 5$  MeV, White-Grodstein used the Hough formula to calculate  $\kappa_n^{BH}(\text{Born})$  and then applied graphically-interpolated values of the Jaeger-Hulme correction. In the range  $E > 5$  MeV she fitted the relevant corrections by a semi-empirical formula

$$\kappa_n(\text{White-Grodstein}) = \kappa_n^{BH}(\text{Born}) - \Delta\kappa_n^{DBM} + b^2 \frac{\ln k}{k}, \quad (2.-30)$$

where the terms  $\kappa_n^{BH}(\text{Born})$  and  $-\Delta\kappa_n^{DBM}$  were computed as explained above. The additional term  $b^2(\ln k)/k$  was adjusted to give better agreement with experimental data, particularly those of Colgate [1952] and Paul [1954] and to provide a smooth transition to the low-energy results of Jaeger and Hulme.

In the present revision, use was made of a slightly different semiempirical formula

$$\kappa_n = [\kappa_n^{BH}(\text{Born, unscreened}) - s^{HFS}] \cdot [1 + \Delta(\text{rad. corr.}) - \Delta(\text{empirical})] \cdot \Delta\kappa_n^{DBM}, \quad (2.-31)$$

which, although not necessarily more accurate than eq. (2.-30), covers the entire energy range from threshold to the high energy limit. Values of  $\kappa_n$  computed using eq (2.-31) are presented in table 2.-10 in the scaled form  $\kappa_n/Z^2$  for ease of interpolation.

New data taken into account in this revision are:

- (a) the near-threshold expressions by Maximon [1968] of  $\kappa_n^{BH}$  (Born, unscreened) as given in equations (2.-34) and (2.-36),
- (b) the screening correction  $s^{HFS}$  (in table 2.-13) calculated by Sørensen [1965, 1966] using Hartree-Fock-Slater wave functions (Hanson et al. [1964]) for  $0 \leq q \leq 0.3$  and the Thomas-Fermi model of the atom for  $0.3 \leq q \leq 8.0$  where  $q$  is momentum transfer in  $mc$  units,
- (c) the radiative correction of Mork and Olsen [1965] given in table 2.-11, and
- (d) an empirical correction to the Born approximation entered as an energy-dependent correction factor (given in table 2.-11) applied to the high-energy Coulomb correction  $\Delta\kappa_n^{DBM}$  given in table 2.-12, since both corrections vary approximately as  $Z^4$  and are large and of opposite sign near threshold.<sup>19</sup> The latter correction takes into account additional  $\kappa_n$  experimental data including measurements by Standil and Shkolnik [1958] and Titus and Levy [1966], and total attenuation data by Barkan [1956], Hübel, Röh, and Scheer [1959] and Barlett and Donahue [1965].

<sup>18</sup> Recently Øverbø [1967] has extended the Jaeger-Hulme results to include 8 elements  $eC$  through  ${}_{82}\text{U}$  and energies ranging from  $2.001 mc^2$  (1.0225 MeV) to  $6.5 mc^2$  (3.32 MeV).

<sup>19</sup> Maximon has derived an energy dependence (see table 2.-11) for the Coulomb correction, giving the modified correction  $[1 - (2/7)(9k^{-1} - 6k^{-2} + 4k^{-3})] \cdot \Delta\kappa_n^{DBM}$ , as quoted by Koch [1964] and Sørensen [1965, 1966], which goes to zero at threshold. However, this improved Coulomb correction still results in a negative theoretical cross section near threshold if no empirical correction term is added.

TABLE 2.-11. Energy-dependent parameters used for evaluating  $\kappa_n$ .

| Photon energy [MeV] | $\kappa_n^{BH}$ (Born) [b/atom]/ $Z^2$ | Mork-Olsen radiative correction factor [1+ $\Delta$ (rad. corr.)] | Empirical multiplier for Coulomb correction | Theoretical multiplier for Coulomb correction |
|---------------------|--|---|---|---|
| 1.022               | 0                                      | 1.000   | 0   | 0   |
| 1.5                 | $4.30 \cdot 10^{-5}$                   | (1.011)   | -0.0677                                     | 0.2778  |
| 2                   | $1.772 \cdot 10^{-4}$                  | (1.012)   | -0.1286                                     | 0.4359  |
| 3                   | $5.055 \cdot 10^{-4}$                  | (1.012)   | -0.1356                                     | 0.6061  |
| 4                   | $8.205 \cdot 10^{-4}$                  | (1.013)   | -0.0639                                     | 0.6971  |
| 5                   | $1.100 \cdot 10^{-3}$                  | (1.013)   | +0.0204                                     | 0.7539  |
| 6                   | $1.350 \cdot 10^{-3}$                  | (1.013)   | 0.1216                                      | 0.7927  |
| 8                   | $1.775 \cdot 10^{-3}$                  | (1.013)   | 0.305                                       | 0.8425  |
| 10                  | $2.127 \cdot 10^{-3}$                  | 1.012   | 0.450                                       | 0.8729  |
| 15                  | $2.792 \cdot 10^{-3}$                  | 1.012   | 0.655                                       | 0.9144  |
| 20                  | $3.278 \cdot 10^{-3}$                  | 1.011   | 0.740                                       | 0.9354  |
| 30                  | $3.977 \cdot 10^{-3}$                  | 1.011   | 0.824                                       | 0.9567  |
| 40                  | $4.479 \cdot 10^{-3}$                  | 1.011   | 0.871                                       | 0.9674  |
| 50                  | $4.872 \cdot 10^{-3}$                  | 1.011   | 0.900                                       | 0.9739  |
| 60                  | $5.194 \cdot 10^{-3}$                  | 1.011   | 0.924                                       | 0.9782  |
| 80                  | $5.705 \cdot 10^{-3}$                  | 1.010   | 0.954                                       | 0.9837  |
| 100                 | $6.102 \cdot 10^{-3}$                  | 1.010   | 0.976                                       | 0.9869  |

 TABLE 2.-12. Davies-Bethe-Maximon [1954] high-energy Coulomb correction,  $-\Delta\kappa_n^{DBM}$ , divided by  $Z^2$ . Units are [b/atom]/ $Z^2$ .

| Z  | $-\Delta\kappa_n^{DBM}/Z^2$ | Z  | $-\Delta\kappa_n^{DBM}/Z^2$ |
|----|-----------------------------|----|-----------------------------|
| 1  | $-1.15 \cdot 10^{-7}$       | 18 | $-3.684 \cdot 10^{-5}$      |
| 4  | $-1.84 \cdot 10^{-6}$       | 19 | $-4.097 \cdot 10^{-5}$      |
| 5  | $-2.88 \cdot 10^{-6}$       | 20 | $-4.532 \cdot 10^{-5}$      |
| 6  | $-4.15 \cdot 10^{-6}$       | 26 | $-7.566 \cdot 10^{-5}$      |
| 7  | $-5.64 \cdot 10^{-6}$       | 29 | $-9.344 \cdot 10^{-5}$      |
| 8  | $-7.36 \cdot 10^{-6}$       | 42 | $-1.884 \cdot 10^{-4}$      |
| 11 | $-1.388 \cdot 10^{-5}$      | 50 | $-2.591 \cdot 10^{-4}$      |
| 12 | $-1.651 \cdot 10^{-5}$      | 53 | $-2.876 \cdot 10^{-4}$      |
| 13 | $-1.935 \cdot 10^{-5}$      | 74 | $-5.078 \cdot 10^{-4}$      |
| 14 | $-2.241 \cdot 10^{-5}$      | 82 | $-5.977 \cdot 10^{-4}$      |
| 15 | $-2.569 \cdot 10^{-5}$      | 92 | $-7.119 \cdot 10^{-4}$      |
| 16 | $-2.919 \cdot 10^{-5}$      |    |                             |

The differential Bethe-Heitler Born-approximation cross section, in the high-energy approximation and for partial screening, can be approximated by use of a simple and convenient formula derived by Bernstein [1950]. In this approximation the Bethe-Heitler screening functions  $\varphi_1$  and  $\varphi_2$  (based on the Thomas-Fermi atom) are assumed to be equal, and  $\varphi_1$  is fitted by an analytic expression to better than 2 percent. In terms of the photon energy  $k$  and the outgoing electron kinetic energy  $T$ , both in  $mc^2$  units, the resulting formula is

$$\begin{aligned}
 & d\kappa_n^{BH} \text{ (Born)}/dT \\
 & \approx \frac{4Z^2 r_e^2}{137} \ln(183 Z^{-1/3}) \frac{1}{k} \left[ 1 - u \frac{T+1}{k} + u \left( \frac{T+1}{k} \right)^2 \right] \\
 & \times \left[ 1 - \frac{Kk}{(T+1)(k-T-1)} \right]^{-1}, \quad (2.-32)
 \end{aligned}$$

where

$$u = \frac{4}{3} + [9 \ln(183 Z^{-1/3})]^{-1}$$

and

$$K = 255 Z^{-1/3} / (15.6 - \frac{4}{3} \ln Z).$$

This formula can be integrated analytically to give the total pair production cross section:

$$\begin{aligned}
 \kappa_n^{BH} \text{ (Born)} & \approx \frac{4Z^2 r_e^2}{137} \ln(183 Z^{-1/3}) \left[ \left( 1 - \frac{2}{k} \right) \right. \\
 & \times \left( 1 + \frac{uK}{k} \right) - \frac{u}{6} - \frac{2}{k} + \frac{u}{k^2} - \frac{2u}{3k^3} - \frac{2K}{k} \\
 & \left. \times \frac{\left( 1 + \frac{uK}{k} \right)}{\sqrt{1 + \frac{4K}{k}}} \ln \frac{\sqrt{1 + \frac{4K}{k}} + 1 - \frac{2}{k}}{\sqrt{1 + \frac{4K}{k}} - 1 + \frac{2}{k}} \right]. \quad (2.-33)
 \end{aligned}$$

If the Bernstein formula (2.-33) is inserted into eq (2.-31) we obtain values of  $\kappa_n$  which agree with those in table 2.-10 and with experimental data to ~ 5 percent over the energy range  $E \geq 5$  MeV for  $Z \geq 29$ . For lighter materials this agreement is restricted to higher energies: e.g., for carbon the Bernstein result is lower by ~ 20 percent over the range 5 to 20 MeV but agrees within ~ 5 percent for  $E > 50$  MeV. However, for these materials the addition of the contribution of Compton scattering results in total photon inter-

TABLE 2.-13. Sörensen [1965, 1966] screening (Hartree-Fock-Slater) corrections,  $s^{\text{HFS}}$ , to be subtracted from  $\kappa_n^{\text{BH}}$  (Born) divided by  $Z^2$ .

Since  $s^{\text{HFS}}$  is not a smoothly varying function of  $Z$  near  $\mu\text{H}$ , values of  $s^{\text{HFS}}/Z^2$  for 2, 3, and 4 are included. Values below 10 MeV are extrapolated. Units are [b/atom]/ $Z^2$ .

| Photon energy [MeV] | ${}_1\text{H}$       | ${}_2\text{He}$      | ${}_3\text{Li}$      | ${}_4\text{Be}$      | ${}_6\text{C}$       | ${}_{13}\text{Al}$   | ${}_{20}\text{Ca}$   |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1.022               | 0                    | 0                    | 0                    | 0                    | 0                    | 0                    | 0                    |
| 1.5                 | —                    | —                    | $1.0 \cdot 10^{-7}$  | $1.0 \cdot 10^{-7}$  | $1.0 \cdot 10^{-7}$  | $3.0 \cdot 10^{-7}$  | $4.0 \cdot 10^{-7}$  |
| 2                   | —                    | $3.0 \cdot 10^{-7}$  | $3.0 \cdot 10^{-7}$  | $3.0 \cdot 10^{-7}$  | $4.0 \cdot 10^{-7}$  | $6.0 \cdot 10^{-7}$  | $8.0 \cdot 10^{-7}$  |
| 3                   | $2.0 \cdot 10^{-7}$  | $8.0 \cdot 10^{-7}$  | $9.0 \cdot 10^{-7}$  | $1.0 \cdot 10^{-6}$  | $1.1 \cdot 10^{-6}$  | $1.6 \cdot 10^{-6}$  | $2.3 \cdot 10^{-6}$  |
| 5                   | $8.0 \cdot 10^{-7}$  | $2.1 \cdot 10^{-6}$  | $2.3 \cdot 10^{-6}$  | $2.6 \cdot 10^{-6}$  | $3.3 \cdot 10^{-6}$  | $5.0 \cdot 10^{-6}$  | $6.6 \cdot 10^{-6}$  |
| 10                  | $4.0 \cdot 10^{-5}$  | $6.2 \cdot 10^{-6}$  | $6.7 \cdot 10^{-6}$  | $7.5 \cdot 10^{-6}$  | $9.4 \cdot 10^{-6}$  | $2.01 \cdot 10^{-5}$ | $2.71 \cdot 10^{-5}$ |
| 20                  | $1.51 \cdot 10^{-5}$ | $1.65 \cdot 10^{-5}$ | $1.75 \cdot 10^{-5}$ | $2.07 \cdot 10^{-5}$ | $3.07 \cdot 10^{-5}$ | $6.60 \cdot 10^{-4}$ | $8.10 \cdot 10^{-4}$ |
| 30                  | $2.87 \cdot 10^{-5}$ | $2.82 \cdot 10^{-5}$ | $3.11 \cdot 10^{-5}$ | $4.30 \cdot 10^{-5}$ | $6.60 \cdot 10^{-5}$ | $1.20 \cdot 10^{-4}$ | $1.47 \cdot 10^{-4}$ |
| 50                  | $5.28 \cdot 10^{-5}$ | $5.46 \cdot 10^{-5}$ | $8.20 \cdot 10^{-5}$ | $1.10 \cdot 10^{-4}$ | $1.57 \cdot 10^{-4}$ | $2.38 \cdot 10^{-4}$ | $2.85 \cdot 10^{-4}$ |
| 100                 | $1.10 \cdot 10^{-4}$ | $1.82 \cdot 10^{-4}$ | $2.70 \cdot 10^{-4}$ | $3.30 \cdot 10^{-4}$ | $3.94 \cdot 10^{-4}$ | $5.32 \cdot 10^{-4}$ | $6.19 \cdot 10^{-4}$ |

| Photon energy [MeV] | ${}_{26}\text{Fe}$   | ${}_{29}\text{Cu}$   | ${}_{42}\text{Mo}$   | ${}_{50}\text{Sn}$   | ${}_{74}\text{W}$    | ${}_{82}\text{Pb}$   | ${}_{92}\text{U}$    |
|---------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| 1.022               | 0                    | 0                    | 0                    | 0                    | 0                    | 0                    | 0                    |
| 1.5                 | $5.0 \cdot 10^{-7}$  | $6.0 \cdot 10^{-7}$  | $8.0 \cdot 10^{-7}$  | $9.0 \cdot 10^{-7}$  | $1.2 \cdot 10^{-6}$  | $1.3 \cdot 10^{-6}$  | $1.4 \cdot 10^{-6}$  |
| 2                   | $1.1 \cdot 10^{-6}$  | $1.3 \cdot 10^{-6}$  | $1.9 \cdot 10^{-6}$  | $2.2 \cdot 10^{-6}$  | $2.8 \cdot 10^{-6}$  | $2.8 \cdot 10^{-6}$  | $2.9 \cdot 10^{-6}$  |
| 3                   | $2.9 \cdot 10^{-6}$  | $3.2 \cdot 10^{-6}$  | $4.3 \cdot 10^{-6}$  | $4.9 \cdot 10^{-6}$  | $6.1 \cdot 10^{-6}$  | $6.4 \cdot 10^{-6}$  | $6.8 \cdot 10^{-6}$  |
| 5                   | $8.0 \cdot 10^{-6}$  | $8.6 \cdot 10^{-6}$  | $1.11 \cdot 10^{-5}$ | $1.25 \cdot 10^{-5}$ | $1.57 \cdot 10^{-5}$ | $1.67 \cdot 10^{-5}$ | $1.79 \cdot 10^{-5}$ |
| 10                  | $3.05 \cdot 10^{-5}$ | $3.17 \cdot 10^{-5}$ | $3.85 \cdot 10^{-5}$ | $4.32 \cdot 10^{-5}$ | $5.40 \cdot 10^{-5}$ | $5.65 \cdot 10^{-4}$ | $5.91 \cdot 10^{-5}$ |
| 20                  | $9.10 \cdot 10^{-5}$ | $9.43 \cdot 10^{-5}$ | $1.14 \cdot 10^{-4}$ | $1.24 \cdot 10^{-4}$ | $1.50 \cdot 10^{-4}$ | $1.56 \cdot 10^{-4}$ | $1.66 \cdot 10^{-4}$ |
| 30                  | $1.64 \cdot 10^{-4}$ | $1.68 \cdot 10^{-4}$ | $1.98 \cdot 10^{-4}$ | $2.17 \cdot 10^{-4}$ | $2.55 \cdot 10^{-4}$ | $2.66 \cdot 10^{-4}$ | $2.76 \cdot 10^{-4}$ |
| 50                  | $3.11 \cdot 10^{-4}$ | $3.20 \cdot 10^{-4}$ | $3.73 \cdot 10^{-4}$ | $4.00 \cdot 10^{-4}$ | $4.59 \cdot 10^{-4}$ | $4.78 \cdot 10^{-4}$ | $4.96 \cdot 10^{-4}$ |
| 100                 | $6.64 \cdot 10^{-4}$ | $6.76 \cdot 10^{-4}$ | $7.76 \cdot 10^{-4}$ | $8.20 \cdot 10^{-4}$ | $9.20 \cdot 10^{-4}$ | $9.41 \cdot 10^{-4}$ | $9.74 \cdot 10^{-4}$ |

action cross sections  $\sigma_{\text{tot}}$  which agree with those in table 1.-4 within 5 percent.

This differential Bethe-Heitler Born-approximate cross section, without the high energy approximation and with screening disregarded, has been integrated analytically by Racah [1934, 1936] and Jost, Luttinger, and Slotnick [1950], but the resulting expression contains double and single integrals over elliptic functions. Recently Maximon [1968] has derived two series expansions for this expression, which he integrated to give the total cross section  $\kappa_n^{\text{BH}}$ (Born, unscreened). The resulting two series, which converge rapidly at low and high energies, respectively, are:

(a) For  $E \leq 2$  MeV:

$$\kappa_n^{\text{BH}}(\text{Born, unscreened}) = \frac{Z^2 r_e^2}{137} \cdot \frac{2\pi}{3} \cdot \left(\frac{k-2}{k}\right)^3 \times \left[1 + \frac{1}{2}\rho + \frac{23}{40}\rho^2 + \frac{11}{60}\rho^3 + \frac{29}{960}\rho^4 + \dots\right] \quad (2.-34)$$

where

$$\rho = \frac{2k-4}{2+k+2\sqrt{2k}} \quad (2.-35)$$

(b) For  $E \geq 2$  MeV:

$$\begin{aligned} \kappa_n^{\text{BH}}(\text{Born, unscreened}) &= \frac{Z^2 r_e^2}{137} \left\{ \frac{28}{9} \ln(2k) - \frac{218}{27} \right. \\ &+ \left(\frac{2}{k}\right)^2 \left[ 6 \ln(2k) - \frac{7}{2} + \frac{2}{3} \ln^3(2k) - \ln^2(2k) \right. \\ &\left. \left. - \frac{1}{3} \pi^2 \ln(2k) + 2\zeta(3) + \frac{\pi^2}{6} \right] \right. \\ &\left. - \left(\frac{2}{k}\right)^4 \left[ \frac{3}{16} \ln(2k) + \frac{1}{8} \right] \right. \\ &\left. - \left(\frac{2}{k}\right)^6 \left[ \frac{29}{9 \cdot 256} \ln(2k) - \frac{77}{27 \cdot 512} \right] + \dots \right\} \quad (2.-36) \end{aligned}$$

where

$$\zeta(3) = \sum_{n=1}^{\infty} \frac{1}{n^3} = 1.2020569 \dots \quad (2.-37)$$

These two expansions (2.-34) and (2.-36), using only the terms given here, provide values of  $\kappa_n^{\text{BH}}$ (Born, unscreened) accurate to within 0.01 per-



cent over the entire energy range from threshold to arbitrarily high energies.

In addition, Jost, Luttinger, and Slotnick [1950] have extended their derivation to the case of arbitrary screening. They obtained a formula differential in the momentum transfer which includes screening effects in terms of the atomic form factor  $F(q, Z)$  and which can be numerically integrated to obtain the total cross section  $\kappa_n$ .

### 2.5.3. Pair Production in the Field of an Electron

This effect has a threshold of  $4 mc^2$  ( $=2.044$  MeV) as required by the sharing, in this case, of the photon energy and momentum with the target electron as well as the created electron-positron pair. The resulting trajectories of the two electrons and the positron appear as a three-pronged track in a cloud chamber or photographic emulsion, hence the name "triplet production" often given to the process.

An exact theoretical treatment should include the following effects:

- (1) atomic binding of the target electron,
- (2) screening by the other atomic electrons and by the field of the nucleus,
- (3) retardation which occurs when the atomic electron recoil velocity is not negligible in comparison with the velocity of light.
- (4) the  $\gamma-e$  interaction of the incident photon with the atomic electron (i.e., virtual Compton scattering in which the scattered photon gives rise to an electron-positron pair),
- (5) exchange terms resulting from the indistinguishability of the two electrons, and
- (6) the radiative corrections.

No one treatment has included all six of these effects, so numerical values are usually obtained from a combination of one or more of the following three principal theories, all of which employ the Born approximation.

Wheeler and Lamb [1939] used the high energy approximation and included the above effects (1) and (2). Ghizzetti [1947] and Borsellino<sup>20</sup> [1947] included only (3), but Suh and Bethe [1959] have shown that at high energies their neglect of exchange (5) is unimportant. Votruba [1948] included (3), (4) and (5), but his differential cross sections are so complex that until very recently the required integrations to obtain the total cross section have been done only crudely. However, Mork [1967] has now integrated the Votruba expressions numerically, and his results are shown in table 2.-14 in the form of an energy-dependent correction  $\Delta$  (triplet) to be

TABLE 2.-14. The Mork [1967] correction to the Borsellino-Ghizzetti  $\kappa_e$  result, obtained by numerical integration of the Votruba differential expressions.

| Photon energy [MeV] | $\Delta$ (triplet) |
|---------------------|--------------------|
| 2.044               | 0.215              |
| 2.5                 | 0.608              |
| 3                   | 0.765              |
| 4                   | 0.895              |
| 5                   | 0.932              |
| 6                   | 0.959              |
| 8                   | 0.996              |
| 10                  | 1.0                |

applied to the Borsellino-Ghizzetti result between threshold and 10 MeV.

Additional theoretical studies of triplet production have been made by Watson [1947], Nemirovsky [1947, 1948], Reyntjens [1957], Kopylov et al. [1964], Kaufman [1964], and Knasel [1968]. The most comprehensive survey of the theory is that of Joseph and Rohrlich [1958], and more recent results have been summarized by Gates et al. [1960, 1962], Koch [1964], Davisson [1965], and Olsen [1968].

In the present tabulation we use values of  $\kappa_e$  obtained by combining the Borsellino-Ghizzetti cross section  $\kappa_e^{BG}$  (using the Ghizzetti expansion which includes terms through  $k^{-7}$ ), the Mork-Votruba correction  $\Delta$  (triplet), the Wheeler-Lamb screened cross section  $\kappa_e^{WL}$  in the high-energy and Thomas-Fermi approximations, the Bethe-Heitler unscreened nuclear-field cross section  $\kappa_n^{BH}$ , and the Mork-Olsen radiative correction here assumed to have the value 1.01. From threshold to 10 MeV, where screening is negligible, we used the combination

$$\kappa_e = \kappa_e^{BH} \cdot \Delta(\text{triplet}) \cdot 1.01 \quad (2.-38)$$

for the cross section per electron. At higher energies, as suggested by Mork, we used the combination

$$\kappa_e = \{ \kappa_e^{WL} - [ \kappa_n^{BH}(1H) - \kappa_e^{BG} ] \} \cdot 1.01. \quad (2.-39)$$

The Ghizzetti [1947] expansion for  $\kappa_e^{BG}$  is reproduced here for convenience:

$$\begin{aligned} \kappa_e^{BG} = & \frac{r_e^2}{137} \left\{ \frac{28}{9} \ln(2k) - \frac{218}{27} \right. \\ & + \frac{1}{k} \left[ -\frac{4}{3} \ln^3(2k) + 3 \ln^2(2k) \right. \\ & \left. \left. - \frac{60 + 16a}{3} \ln(2k) + \frac{123 + 12a + 16b}{3} \right] \right\} \\ & + \left( \frac{1}{k} \right)^2 \left\{ \frac{8}{3} \ln^3(2k) - 4 \ln^2(2k) \right. \\ & \left. \left. + \frac{51 + 32a}{3} \ln(2k) - \frac{123 + 32a + 64b}{6} \right] \right\} \end{aligned}$$

<sup>20</sup> Mork has pointed out that the Borsellino result is identifiable as the leading terms of the series solution in eq (2.-40) by Ghizzetti [1947], and that the last Borsellino term should read  $-21.51$ , rather than  $+21.51$ , giving

$$\begin{aligned} \kappa_e (\text{Borsellino corrected}) = & \frac{r_e^2}{137} \left\{ \frac{28}{9} \ln(2k) - \frac{218}{27} \right. \\ & \left. - \frac{1}{k} \left[ \frac{4}{3} \ln^3(2k) - 3 \ln^2(2k) + 6.84 \ln(2k) - 21.51 \right] \right\} \end{aligned}$$

for the cross section per electron.

$$\begin{aligned}
& + \left(\frac{1}{k}\right)^3 \left[ \ln^2(2k) - \frac{53}{9} \ln(2k) - \frac{2915 - 288a}{216} \right] \\
& + \left(\frac{1}{k}\right)^4 \left[ -\frac{49}{18} \ln(2k) - \frac{115}{432} \right] \\
& + \left(\frac{1}{k}\right)^5 \left[ -\frac{77}{36} \ln(2k) + \frac{10831}{8640} \right] \\
& + \left(\frac{1}{k}\right)^6 \left[ -\frac{641}{300} \ln(2k) + \frac{64573}{36000} \right] \\
& + \left(\frac{1}{k}\right)^7 \left[ -\frac{4423}{1800} \ln(2k) + \frac{394979}{216000} \right] \\
& + \dots \} \tag{2.-40}
\end{aligned}$$

in which the constants

$$\begin{aligned}
a &= -2.46740 \text{ and} \\
b &= -1.80310
\end{aligned}$$

are evaluations of definite integrals over a series expansion given by Ghizzetti. In addition, to make the results join smoothly and to correct for the Wheeler-Lamb high-energy approximation, we mul-

tiplied the results from eq (2.-39) by the ratio of these two results for hydrogen. This ratio [eq (2.-38) divided by eq (2.-39)] varies from 0.857 at 10 MeV to 0.997 at 100 MeV.

Values of  $\kappa_e$  from eqs (2.-38) and (-39), given explicitly in the tables in section 3, are also given in table 2.-15 in terms of the scaled ratio

$$\eta = Z \cdot (\kappa_e/\kappa_n) \tag{2.-41}$$

for purposes of interpolation. The total pair production cross section can thus be reconstructed from tables 2.-10 and -15 as

$$\kappa = \kappa_n + \kappa_e = Z(Z + \eta)(\kappa_n/Z^2). \tag{2.-42}$$

The values in table 2.-15 can be represented to within 5 percent from 10 to 100 MeV and within  $\pm 2$  percent from 20 to 80 MeV by the empirical formula

$$\eta \approx \frac{3+a}{9} \ln\left(\frac{k}{2}\right) - 0.00635 \ln^3\left(\frac{k}{2}\right), \tag{2.-43}$$

in which

$$a = Z/137,$$

TABLE 2.-15. Values of  $\eta = Z \cdot (\kappa_e/\kappa_n)$  relating the triplet cross section  $\kappa_e$  to that for nuclear-field pair production.

Here,  $\kappa_e$  is the Borsellino [1947]-Ghizzetti [1947] unscreened result corrected for exchange and for  $\gamma$ - $e$  interaction near threshold by Mork [1967], for screening using the Wheeler-Lamb [1939] results, and includes a radiative correction factor of 1.01. Using table 2.-10,  $\kappa(\text{total}) = Z(Z + \eta)(\kappa_n/Z^2)$ . For explicit values of  $\kappa_e$  up to 100 GeV, see tables in section 3.

| Photon energy [MeV] | ${}^1\text{H}$                       | ${}^6\text{C}$ | ${}^{13}\text{Al}$ | ${}^{20}\text{Ca}$ | ${}^{26}\text{Fe}$ | ${}^{29}\text{Cu}$ |
|---------------------|--------------------------------------|----------------|--------------------|--------------------|--------------------|--------------------|
|                     | $\eta = Z \cdot (\kappa_e/\kappa_n)$ |                |                    |                    |                    |                    |
| 2.044               | 0                                    | 0              | 0                  | 0                  | 0                  | 0                  |
| 3                   | 0.0786                               | 0.0787         | 0.0785             | 0.0781             | 0.0775             | 0.0773             |
| 4                   | 0.199                                | 0.200          | 0.199              | 0.199              | 0.199              | 0.199              |
| 5                   | 0.292                                | 0.292          | 0.293              | 0.293              | 0.294              | 0.294              |
| 10                  | 0.543                                | 0.545          | 0.550              | 0.555              | 0.559              | 0.562              |
| 20                  | 0.707                                | 0.711          | 0.721              | 0.729              | 0.737              | 0.741              |
| 30                  | 0.779                                | 0.787          | 0.801              | 0.811              | 0.819              | 0.820              |
| 50                  | 0.849                                | 0.868          | 0.883              | 0.888              | 0.890              | 0.891              |
| 100                 | 0.920                                | 0.956          | 0.963              | 0.966              | 0.968              | 0.968              |

| Photon energy [MeV] | ${}^{42}\text{Mo}$                   | ${}^{50}\text{Sn}$ | ${}^{74}\text{W}$ | ${}^{82}\text{Pb}$ | ${}^{92}\text{U}$ |
|---------------------|--------------------------------------|--------------------|-------------------|--------------------|-------------------|
|                     | $\eta = Z \cdot (\kappa_e/\kappa_n)$ |                    |                   |                    |                   |
| 2.044               | 0                                    | 0                  | 0                 | 0                  | 0                 |
| 3                   | 0.0755                               | 0.0742             | 0.0700            | 0.0687             | 0.0669            |
| 4                   | 0.198                                | 0.197              | 0.194             | 0.193              | 0.191             |
| 5                   | 0.295                                | 0.296              | 0.298             | 0.299              | 0.300             |
| 10                  | 0.575                                | 0.586              | 0.624             | 0.639              | 0.658             |
| 20                  | 0.761                                | 0.773              | 0.819             | 0.837              | 0.861             |
| 30                  | 0.833                                | 0.844              | 0.886             | 0.901              | 0.923             |
| 50                  | 0.903                                | 0.912              | 0.954             | 0.973              | 0.994             |
| 100                 | 0.983                                | 0.994              | 1.034             | 1.048              | 1.068             |

and  $k$  is the photon energy in  $mc^2$  units. Below 10 MeV,  $\kappa_e$  is less than 2 percent of  $\sigma_{\text{tot}}$ , and experimental estimates (see, for example, the recent results of Frei, Staub, and Stüssi [1964]) still contain uncertainties too large for confirmation of present theory.

## 2.6. Photonuclear Absorption

This effect consists of nuclear interactions initiated by the absorption of a photon. The most likely result of such an interaction is the emission of a single neutron, but one must also consider the emission of charged particles, gamma rays, or more than one neutron. Available experimental and theoretical information on such interactions is discussed in review articles by DeSabbata [1957, 1959], Levinger [1960], Fuller and Hayward [1962], Hayward [1963], Brenig [1965], and Danos and Fuller [1965].

The most characteristic feature of the cross section for nuclear absorption of photons is the "giant resonance." This is a broad peak in the absorption cross section centered at about 24 MeV for light nuclei, decreasing in energy with increasing mass number to about 12 MeV for the heaviest stable nuclei. The width "Γ" (energy difference between the points at which the cross section drops to one half its maximum value) varies from about 3 MeV to 9 MeV depending on the detailed properties of individual nuclei.

When studied with finer resolution the gross "resonance" is found to have considerable sub-structure. A prominent feature of this sub-structure, for nuclei having large permanent deformations, is a splitting of the giant resonance into two main peaks. In general, those nuclei having either large permanent deformations or large "dynamic deformations" (resulting from the vibrational nature of the nuclear ground state) have their giant resonances spread over the widest energy range.

Table 2.-16 gives the gross parameters of the giant resonance for a representative group of nuclei throughout the periodic table. From these parameters the giant resonance can be approximately reconstructed by assuming that it has the shape of a Lorentz line (see, e.g., Fuller and Hayward [1962], eq. (2.5), p. 117):

$$\sigma_{\text{ph. n.}}(E) \approx \sigma_0 \frac{E^2 \Gamma^2}{(E_0^2 - E^2)^2 + E^2 \Gamma^2} \quad (2.-44)$$

As indicated in table 2.-16, the magnitude of the photonuclear absorption cross section, even at the resonance peak energy,  $E_0$ , is small in comparison with the sum of the competing "electronic" cross sections discussed in sections 2.3 to 2.5, and in no case contributes more than 10 percent to the total cross section. However, photonuclear absorption can be of considerable importance in shielding and irradiation technology whenever photon energies

are present which exceed reaction threshold energies such as those indicated in table 2.-16.

In shielding technology (see, e.g., NBS Handbook 97 [1964] and Hubbell and Spencer [1964]) nuclear absorption of photons is important because neutrons are produced in a large fraction of the reactions (about 40 to 100 percent probability depending on the photon energy and the mass number of the particular nucleus). These neutrons are usually far more penetrating than the incident photons. Of importance in irradiation technology (see, e.g.,

TABLE 2.-16. Photonuclear giant resonance cross section parameters.<sup>1</sup>

| Nucleus           | Threshold energies |             | $E_0$ , energy at $\sigma_{\text{ph. n.}}$ peak | $\sigma_0$ , value of $\sigma_{\text{ph. n.}}$ at peak | Γ, peak width at half-max. | Percent of "electronic" cross section at $E_0$ | Refs. <sup>2</sup> |
|-------------------|--------------------|-------------|---|--|----------------------------|--|--------------------|
|                   | (γ, n)             | (γ, p)      |   |  |                            |  |                    |
| <sup>12</sup> C   | MeV<br>18.7        | MeV<br>16.0 | MeV<br><sup>3</sup> 23.                         | b/atom<br><sup>4</sup> 0.018                           | MeV<br>3.6                 | %<br>5.9                                       | 63 Bu 3            |
| <sup>27</sup> Al  | 13.1               | 8.3         | <sup>3</sup> 21.5                               | <sup>4</sup> .038                                      | 9.0                        | 3.9  | 64 Do 2            |
| <sup>40</sup> Ca  | 15.7               | 8.3         | <sup>3</sup> 20.5                               | <sup>4</sup> .100                                      | 4.5                        | 5.2  | 66 Do 2            |
| <sup>63</sup> Cu  | 10.8               | 6.1         | 17.0  | <sup>5</sup> .070                                      | 8.0                        | 2.0  | 64 Fu 1            |
| <sup>90</sup> Zr  | 12.0               | 8.4         | 17.0  | <sup>5</sup> .180                                      | 4.5                        | 3.0  | 67 Be 2            |
| <sup>127</sup> I  | 9.1                | 6.2         | 15.2  | <sup>5</sup> .210                                      | 5.7                        | 2.3  | 66 Br 1            |
| <sup>165</sup> Ho | 8.0                | 6.1         | <sup>3</sup> 14.0                               | <sup>6</sup> .220                                      | 8.5                        | 1.7  | 65 Am 1            |
| <sup>181</sup> Ta | 7.6                | 6.2         | <sup>3</sup> 14.0                               | <sup>6</sup> .280                                      | 6.5                        | 1.8  | 63 Br 1            |
| <sup>208</sup> Pb | 7.4                | 8.0         | 13.6  | <sup>5</sup> .495                                      | 3.8                        | 2.7  | 64 Ha 2            |
| <sup>235</sup> U  | 6.1                | 7.6         | <sup>3</sup> 12.2                               | <sup>7</sup> .500                                      | 7.0                        | 2.4  | 64 Bo 3            |

<sup>1</sup> This table was supplied by E. G. Fuller.

- <sup>2</sup> References (as given in the Photonuclear Data Index):
- 63 Br 1 Bramblett, R. L., Caldwell, J. T., Auchampaugh, G. F., Fultz S. C.; Phys. Rev. **129**, 2723 (1963).
  - 63 Bu 3 Burgov, N. A., Danilyan, G. V., Dolbilkin, B. S., Lazareva, L. E., Nikolaev, F. A.; Zhur. Eksp. i Teoret. Fiz. **45**, 1693 (1963); Soviet Phys. JETP **18**, 1159 (1964).
  - 64 Bo 3 Bowman, C. D., Auchampaugh, G. F., Fultz, S. C.; Phys. Rev. **133**, B676 (1964).
  - 64 Do 2 Dolbilkin, B. S., Zapevalov, V. A., Korin, V. I., Lazareva, L. E., Nikolaev, F. A.; PICNS-64 1060 (1964).
  - 64 Fu 1 Fultz, S. C., Bramblett, R. L., Caldwell, J. T., Harvey, R. R.; Phys. Rev. **133**, B1149 (1964).
  - 64 Ha 2 Harvey, R. R., Caldwell, J. T., Bramblett, R. L., Fultz, S. C.; Phys. Rev. **136**, B126-131 (1964).
  - 65 Am 1 Ambler, E., Fuller, E. G., Marshak, H.; Phys. Rev. **138**, B117 (1965).
  - 66 Br 1 Bramblett, R. L., Caldwell, J. T., Berman, B. L., Harvey, R. R., Fultz, S. C.; Phys. Rev. **148**, B1198 (1966).
  - 66 Do 2 Dolbilkin, B. S., Zapevalov, V. A., Korin, V. I., Lazareva, L. E., Nikolaev, F. A.; Izv. Akad. Nauk fiz. **30**, 349 (1966); Bull. Acad. Sci. USSR-Phys. **30**, 354 (1966).
  - 67 Be 2 Berman, B. L., Caldwell, J. T., Harvey, R. R., Kelly, M. A., Bramblett, R. L., Fultz, S. C.; Phys. Rev. **162**, 1098 (1967).

<sup>3</sup> Cross section has structure. Energy given is approximate mean energy for photon absorption.

<sup>4</sup> Total nuclear absorption cross section at  $E_0$ .

<sup>5</sup> Maximum absorption cross section resulting in production of neutrons. For these nuclei this is a good approximation to the total nuclear absorption cross section.

<sup>6</sup> Deformed nuclei. Absorption cross section has two peaks. Comments under footnote 5 apply.

<sup>7</sup> Includes photofission cross section. Comments under footnotes 5 and 6 apply.

Manowitz et al. [1964] and DeProost et al. [1966]) as well as in shielding is the radioactivity which results from the photodisintegration of the nucleus in which the photon was absorbed or from the capture in other nuclei of the reaction products.

An initial attempt at a systematic photonuclear cross section compilation (in the form of graphs) has been made by Hunt et al. [1963] for use in food irradiator design studies. Parameters describing gross features of measured cross sections for photonuclear reactions have been tabulated by Goryachev [1964].

However, the best source of data for individual nuclei is at present the technical literature. Avail-

able data in the literature can be located by means of the NBS Photonuclear Data Index (Baggett et al. [1966] and Collins et al. [1967]) which is an annotated index and bibliography of references containing experimental data on photonuclear reactions. Each index entry gives specific quantitative data about the type of information available in each reference. The source of data used to compile this index is the NBS Photonuclear Data File. This file consists of data sheets containing abstracts of the significant data (both numerical and graphical) from each reference. These data sheets, as well as a reprint collection of all references abstracted, are on deposit at the Photonuclear Data Center at the National Bureau of Standards.

### 3. Tabulation of Cross Sections for Elements and Compounds

This section contains photon interaction cross sections and attenuation coefficients as described in sections 1 and 2. The data are presented by element, following the format of White-Grodstein [1957] and Davisson [1965] except that total cross sections are given in barns/atom in addition to the mass attenuation coefficient in  $\text{cm}^2/\text{g}$ . Similar data (all in  $\text{cm}^2/\text{g}$ ) for some compounds and mixtures of interest in dosimetry (Evans [1968]) have been added.

In tables 3.-1 to 3.-23 the first column lists the photon energy in MeV. In this and in other columns the sign and following two digits at the end of each entry indicate the power of ten by which the preceding part of the entry is to be multiplied. A pair of successive identical energies, the second of which is preceded by K, L<sub>1</sub>, L<sub>2</sub>, or L<sub>3</sub>, marks the presence of an "absorption edge" discontinuity in the photoelectric and total cross section columns.

The second column, labeled "scattering, with coherent," is the sum ( $\sigma_C^{BD} + \sigma_R$ ) of the Compton (incoherent) collision cross section corrected for electron binding and the Rayleigh (coherent) scattering cross section. This sum is based on values calculated by Storm and Israel [1967] (see sec. 2.4.2). The third column, labeled "scattering, without coherent," is the free-electron Compton collision cross section ( $Z \times \sigma_C$ ) [b/atom]

where  $\sigma_C$ , including the Mork [1968] radiative and double-Compton corrections  $\Delta\sigma_C^M$ , is given in table 2.-8.

The fourth column, labeled "photoelectric," is the photoeffect cross section  $\tau_{pe}$  derived from experimental and theoretical values by procedures described in section 2.3. The fifth column, labeled "pair production in field of nucleus," contains values of  $\kappa_n$  from eq (2.-31), and the sixth column, labeled "pair production in field of electrons," contains values of  $\kappa_e$  from eqs (2.-38) and (2.-39).

The seventh and eighth columns, labeled "total, with coherent" and "total, without coherent," are sums  $\sigma_{\text{tot}}$  over columns 2, 4, 5, and 6, and over columns 3, 4, 5, and 6, respectively. The conversion factor at the bottom of each page (also in table 1.-1) has been used to convert the total cross section values (b/atom) in columns 7 and 8 into the corresponding mass attenuation coefficients  $\mu/\rho$  ( $\text{cm}^2/\text{g}$ ) in columns 9 and 10. Values of  $\mu/\rho$  in the last column are identical with those in table 1.-4. Estimates of uncertainties for various ranges of  $E$  and  $Z$  are given in section 1.4.

Tables 3.-24 to 3.-36 for compounds and mixtures were derived from values in tables 3.-1 to 3.-23 using eq (1.-6) and the fractions-by-weight  $w_i$  in table 1.-3. Possible errors from use of the "mixture rule" as employed here are discussed in the last paragraph of section 1.3.

**Table 3.-1. HYDROGEN, Z=1**

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total                   |                         |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|-------------------------|-------------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent           | Without coherent        |
| <i>MeV</i>    | <i>b/atom</i> | <i>b/atom</i>    | <i>b/atom</i>  | <i>b/atom</i>   | <i>b/atom</i>  | <i>b/atom</i> | <i>b/atom</i>    | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> |
| 1.00-02       | 6.39-01       | 6.40-01          | 4.57-03        |                 |                | 6.44-01       | 6.45-01          | 3.85-01                 | 3.85-01                 |
| 1.50-02       | 6.28-01       | 6.29-01          | 1.13-03        |                 |                | 6.30-01       | 6.30-01          | 3.76-01                 | 3.76-01                 |
| 2.00-02       | 6.17-01       | 6.18-01          | 4.19-04        |                 |                | 6.18-01       | 6.18-01          | 3.69-01                 | 3.69-01                 |
| 3.00-02       |               | 5.97-01          | 1.03-04        |                 |                |               | 5.98-01          |                         | 3.57-01                 |
| 4.00-02       |               | 5.79-01          | 3.84-05        |                 |                |               | 5.79-01          |                         | 3.46-01                 |
| 5.00-02       |               | 5.61-01          | 1.78-05        |                 |                |               | 5.61-01          |                         | 3.35-01                 |
| 6.00-02       |               | 5.46-01          | 9.51-06        |                 |                |               | 5.46-01          |                         | 3.26-01                 |
| 8.00-02       |               | 5.17-01          | 3.55-06        |                 |                |               | 5.17-01          |                         | 3.09-01                 |
| 1.00-01       |               | 4.93-01          | 1.66-06        |                 |                |               | 4.93-01          |                         | 2.94-01                 |
| 1.50-01       |               | 4.44-01          | 4.23-07        |                 |                |               | 4.44-01          |                         | 2.65-01                 |
| 2.00-01       |               | 4.06-01          | 1.64-07        |                 |                |               | 4.06-01          |                         | 2.43-01                 |
| 3.00-01       |               | 3.53-01          | 4.51-08        |                 |                |               | 3.53-01          |                         | 2.11-01                 |
| 4.00-01       |               | 3.17-01          | 1.91-08        |                 |                |               | 3.17-01          |                         | 1.89-01                 |
| 5.00-01       |               | 2.89-01          | 1.02-08        |                 |                |               | 2.89-01          |                         | 1.73-01                 |
| 6.00-01       |               | 2.67-01          | 6.35-09        |                 |                |               | 2.68-01          |                         | 1.60-01                 |
| 8.00-01       |               | 2.35-01          | 3.20-09        |                 |                |               | 2.35-01          |                         | 1.40-01                 |
| 1.00+00       |               | 2.11-01          | 1.99-09        |                 |                |               | 2.11-01          |                         | 1.26-01                 |
| 1.50+00       |               | 1.72-01          | 9.25-10        | 4.43-05         |                |               | 1.72-01          |                         | 1.03-01                 |
| 2.00+00       |               | 1.46-01          | 5.90-10        | 1.77-04         |                |               | 1.46-01          |                         | 8.75-02                 |
| 3.00+00       |               | 1.15-01          | 3.32-10        | 5.11-04         | 4.02-05        |               | 1.16-01          |                         | 6.91-02                 |
| 4.00+00       |               | 9.62-02          | 2.28-10        | 8.30-04         | 1.65-04        |               | 9.72-02          |                         | 5.81-02                 |
| 5.00+00       |               | 8.31-02          | 1.75-10        | 1.11-03         | 3.25-04        |               | 8.45-02          |                         | 5.05-02                 |
| 6.00+00       |               | 7.34-02          | 1.40-10        | 1.36-03         | 4.99-04        |               | 7.53-02          |                         | 4.50-02                 |
| 8.00+00       |               | 6.01-02          | 1.00-10        | 1.79-03         | 8.54-04        |               | 6.27-02          |                         | 3.75-02                 |
| 1.00+01       |               | 5.11-02          | 7.89-11        | 2.14-03         | 1.17-03        |               | 5.45-02          |                         | 3.25-02                 |
| 1.50+01       |               | 3.79-02          |                | 2.79-03         | 1.82-03        |               | 4.25-02          |                         | 2.54-02                 |
| 2.00+01       |               | 3.04-02          |                | 3.28-03         | 2.33-03        |               | 3.60-02          |                         | 2.15-02                 |
| 3.00+01       |               | 2.21-02          |                | 3.97-03         | 3.11-03        |               | 2.92-02          |                         | 1.74-02                 |
| 4.00+01       |               | 1.76-02          |                | 4.46-03         | 3.68-03        |               | 2.57-02          |                         | 1.54-02                 |
| 5.00+01       |               | 1.47-02          |                | 4.85-03         | 4.14-03        |               | 2.37-02          |                         | 1.41-02                 |
| 6.00+01       |               | 1.26-02          |                | 5.17-03         | 4.51-03        |               | 2.23-02          |                         | 1.33-02                 |
| 8.00+01       |               | 9.97-03          |                | 5.66-03         | 5.10-03        |               | 2.07-02          |                         | 1.24-02                 |
| 1.00+02       |               | 8.28-03          |                | 6.04-03         | 5.56-03        |               | 1.99-02          |                         | 1.19-02                 |
| 1.50+02       |               | 5.89-03          |                | 6.69-03         | 6.39-03        |               | 1.90-02          |                         | 1.13-02                 |
| 2.00+02       |               | 4.62-03          |                | 7.12-03         | 6.95-03        |               | 1.87-02          |                         | 1.12-02                 |
| 3.00+02       |               | 3.28-03          |                | 7.65-03         | 7.70-03        |               | 1.86-02          |                         | 1.11-02                 |
| 4.00+02       |               | 2.56-03          |                | 7.97-03         | 8.20-03        |               | 1.87-02          |                         | 1.12-02                 |
| 5.00+02       |               | 2.12-03          |                | 8.19-03         | 8.55-03        |               | 1.89-02          |                         | 1.13-02                 |
| 6.00+02       |               | 1.82-03          |                | 8.35-03         | 8.82-03        |               | 1.90-02          |                         | 1.13-02                 |
| 8.00+02       |               | 1.42-03          |                | 8.57-03         | 9.21-03        |               | 1.92-02          |                         | 1.15-02                 |
| 1.00+03       |               | 1.17-03          |                | 8.71-03         | 9.47-03        |               | 1.94-02          |                         | 1.16-02                 |
| 1.50+03       |               | 8.16-04          |                | 8.93-03         | 9.88-03        |               | 1.96-02          |                         | 1.17-02                 |
| 2.00+03       |               | 6.31-04          |                | 9.04-03         | 1.01-02        |               | 1.98-02          |                         | 1.18-02                 |
| 3.00+03       |               | 4.39-04          |                | 9.16-03         | 1.04-02        |               | 2.00-02          |                         | 1.20-02                 |
| 4.00+03       |               | 3.39-04          |                | 9.24-03         | 1.06-02        |               | 2.01-02          |                         | 1.20-02                 |
| 5.00+03       |               | 2.77-04          |                | 9.27-03         | 1.06-02        |               | 2.02-02          |                         | 1.21-02                 |
| 6.00+03       |               | 2.35-04          |                | 9.31-03         | 1.07-02        |               | 2.03-02          |                         | 1.21-02                 |
| 8.00+03       |               | 1.81-04          |                | 9.35-03         | 1.08-02        |               | 2.03-02          |                         | 1.22-02                 |
| 1.00+04       |               | 1.48-04          |                | 9.37-03         | 1.09-02        |               | 2.04-02          |                         | 1.22-02                 |
| 1.50+04       |               | 1.02-04          |                | 9.41-03         | 1.09-02        |               | 2.05-02          |                         | 1.22-02                 |
| 2.00+04       |               | 7.85-05          |                | 9.43-03         | 1.10-02        |               | 2.05-02          |                         | 1.23-02                 |
| 3.00+04       |               | 5.41-05          |                | 9.45-03         | 1.10-02        |               | 2.06-02          |                         | 1.23-02                 |
| 4.00+04       |               | 4.16-05          |                | 9.46-03         | 1.11-02        |               | 2.06-02          |                         | 1.23-02                 |
| 5.00+04       |               | 3.39-05          |                | 9.47-03         | 1.11-02        |               | 2.06-02          |                         | 1.23-02                 |
| 6.00+04       |               | 2.86-05          |                | 9.47-03         | 1.11-02        |               | 2.06-02          |                         | 1.23-02                 |
| 8.00+04       |               | 2.19-05          |                | 9.48-03         | 1.11-02        |               | 2.06-02          |                         | 1.23-02                 |
| 1.00+05       |               | 1.78-05          |                | 9.48-03         | 1.11-02        |               | 2.06-02          |                         | 1.23-02                 |

(b/atom) x .597500 = cm<sup>2</sup>/g

**Table 3.-2. BERYLLIUM, Z=4**

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total                   |                         |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|-------------------------|-------------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent           | Without coherent        |
| <i>MeV</i>    | <i>b/atom</i> | <i>b/atom</i>    | <i>b/atom</i>  | <i>b/atom</i>   | <i>b/atom</i>  | <i>b/atom</i> | <i>b/atom</i>    | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> |
| 1.00-02       | 3.42+00       | 2.56+00          | 5.46+00        |                 |                | 8.88+00       | 8.02+00          | 5.93-01                 | 5.36-01                 |
| 1.50-02       | 3.01+00       | 2.52+00          | 1.49+00        |                 |                | 4.50+00       | 4.01+00          | 3.00-01                 | 2.68-01                 |
| 2.00-02       | 2.78+00       | 2.47+00          | 6.12-01        |                 |                | 3.39+00       | 3.08+00          | 2.27-01                 | 2.06-01                 |
| 3.00-02       | 2.54+00       | 2.39+00          | 1.68-01        |                 |                | 2.70+00       | 2.56+00          | 1.81-01                 | 1.71-01                 |
| 4.00-02       | 2.40+00       | 2.31+00          | 6.45-02        |                 |                | 2.47+00       | 2.38+00          | 1.65-01                 | 1.59-01                 |
| 5.00-02       | 2.31+00       | 2.25+00          | 3.06-02        |                 |                | 2.34+00       | 2.28+00          | 1.56-01                 | 1.52-01                 |
| 6.00-02       | 2.23+00       | 2.18+00          | 1.67-02        |                 |                | 2.24+00       | 2.20+00          | 1.50-01                 | 1.47-01                 |
| 8.00-02       | 2.09+00       | 2.07+00          | 6.44-03        |                 |                | 2.10+00       | 2.08+00          | 1.40-01                 | 1.39-01                 |
| 1.00-01       | 1.99+00       | 1.97+00          | 3.04-03        |                 |                | 1.99+00       | 1.97+00          | 1.33-01                 | 1.32-01                 |
| 1.50-01       | 1.78+00       | 1.77+00          | 8.01-04        |                 |                | 1.78+00       | 1.77+00          | 1.19-01                 | 1.19-01                 |
| 2.00-01       |               | 1.63+00          | 3.15-04        |                 |                |               | 1.63+00          |                         | 1.09-01                 |
| 3.00-01       |               | 1.41+00          | 8.83-05        |                 |                |               | 1.41+00          |                         | 9.45-02                 |
| 4.00-01       |               | 1.27+00          | 3.76-05        |                 |                |               | 1.27+00          |                         | 8.47-02                 |
| 5.00-01       |               | 1.16+00          | 2.01-05        |                 |                |               | 1.16+00          |                         | 7.73-02                 |
| 6.00-01       |               | 1.07+00          | 1.26-05        |                 |                |               | 1.07+00          |                         | 7.15-02                 |
| 8.00-01       |               | 9.40-01          | 6.32-06        |                 |                |               | 9.41-01          |                         | 6.29-02                 |
| 1.00+00       |               | 8.45-01          | 3.91-06        |                 |                |               | 8.46-01          |                         | 5.65-02                 |
| 1.50+00       |               | 6.87-01          | 1.83-06        | 7.10-04         |                |               | 6.88-01          |                         | 4.60-02                 |
| 2.00+00       |               | 5.86-01          | 1.16-06        | 2.84-03         |                |               | 5.89-01          |                         | 3.94-02                 |
| 3.00+00       |               | 4.61-01          | 6.55-07        | 8.17-03         | 1.61-04        |               | 4.70-01          |                         | 3.14-02                 |
| 4.00+00       |               | 3.85-01          | 4.48-07        | 1.33-02         | 6.61-04        |               | 3.99-01          |                         | 2.66-02                 |
| 5.00+00       |               | 3.32-01          | 3.44-07        | 1.78-02         | 1.30-03        |               | 3.51-01          |                         | 2.35-02                 |
| 6.00+00       |               | 2.94-01          | 2.75-07        | 2.18-02         | 2.00-03        |               | 3.17-01          |                         | 2.12-02                 |
| 8.00+00       |               | 2.40-01          | 1.97-07        | 2.86-02         | 3.42-03        |               | 2.72-01          |                         | 1.82-02                 |
| 1.00+01       |               | 2.05-01          | 1.55-07        | 3.41-02         | 4.67-03        |               | 2.43-01          |                         | 1.63-02                 |
| 1.50+01       |               | 1.51-01          |                | 4.46-02         | 7.27-03        |               | 2.03-01          |                         | 1.36-02                 |
| 2.00+01       |               | 1.21-01          |                | 5.23-02         | 9.34-03        |               | 1.83-01          |                         | 1.22-02                 |
| 3.00+01       |               | 8.85-02          |                | 6.32-02         | 1.24-02        |               | 1.64-01          |                         | 1.10-02                 |
| 4.00+01       |               | 7.03-02          |                | 7.09-02         | 1.47-02        |               | 1.56-01          |                         | 1.04-02                 |
| 5.00+01       |               | 5.87-02          |                | 7.67-02         | 1.66-02        |               | 1.52-01          |                         | 1.02-02                 |
| 6.00+01       |               | 5.06-02          |                | 8.12-02         | 1.80-02        |               | 1.50-01          |                         | 1.00-02                 |
| 8.00+01       |               | 3.99-02          |                | 8.81-02         | 2.04-02        |               | 1.48-01          |                         | 9.91-03                 |
| 1.00+02       |               | 3.31-02          |                | 9.31-02         | 2.22-02        |               | 1.48-01          |                         | 9.92-03                 |
| 1.50+02       |               | 2.36-02          |                | 1.01-01         | 2.53-02        |               | 1.50-01          |                         | 1.00-02                 |
| 2.00+02       |               | 1.85-02          |                | 1.07-01         | 2.74-02        |               | 1.52-01          |                         | 1.02-02                 |
| 3.00+02       |               | 1.31-02          |                | 1.13-01         | 3.02-02        |               | 1.56-01          |                         | 1.04-02                 |
| 4.00+02       |               | 1.03-02          |                | 1.17-01         | 3.20-02        |               | 1.59-01          |                         | 1.06-02                 |
| 5.00+02       |               | 8.49-03          |                | 1.20-01         | 3.33-02        |               | 1.61-01          |                         | 1.08-02                 |
| 6.00+02       |               | 7.27-03          |                | 1.21-01         | 3.43-02        |               | 1.63-01          |                         | 1.09-02                 |
| 8.00+02       |               | 5.68-03          |                | 1.24-01         | 3.59-02        |               | 1.66-01          |                         | 1.11-02                 |
| 1.00+03       |               | 4.67-03          |                | 1.26-01         | 3.69-02        |               | 1.68-01          |                         | 1.12-02                 |
| 1.50+03       |               | 3.26-03          |                | 1.28-01         | 3.87-02        |               | 1.70-01          |                         | 1.14-02                 |
| 2.00+03       |               | 2.52-03          |                | 1.30-01         | 3.98-02        |               | 1.72-01          |                         | 1.15-02                 |
| 3.00+03       |               | 1.76-03          |                | 1.31-01         | 4.11-02        |               | 1.74-01          |                         | 1.16-02                 |
| 4.00+03       |               | 1.35-03          |                | 1.32-01         | 4.19-02        |               | 1.75-01          |                         | 1.17-02                 |
| 5.00+03       |               | 1.11-03          |                | 1.33-01         | 4.24-02        |               | 1.76-01          |                         | 1.18-02                 |
| 6.00+03       |               | 9.40-04          |                | 1.33-01         | 4.28-02        |               | 1.77-01          |                         | 1.18-02                 |
| 8.00+03       |               | 7.24-04          |                | 1.34-01         | 4.32-02        |               | 1.77-01          |                         | 1.19-02                 |
| 1.00+04       |               | 5.91-04          |                | 1.34-01         | 4.35-02        |               | 1.78-01          |                         | 1.19-02                 |
| 1.50+04       |               | 4.08-04          |                | 1.34-01         | 4.38-02        |               | 1.79-01          |                         | 1.19-02                 |
| 2.00+04       |               | 3.14-04          |                | 1.35-01         | 4.40-02        |               | 1.79-01          |                         | 1.20-02                 |
| 3.00+04       |               | 2.17-04          |                | 1.35-01         | 4.42-02        |               | 1.79-01          |                         | 1.20-02                 |
| 4.00+04       |               | 1.66-04          |                | 1.35-01         | 4.43-02        |               | 1.79-01          |                         | 1.20-02                 |
| 5.00+04       |               | 1.35-04          |                | 1.35-01         | 4.44-02        |               | 1.79-01          |                         | 1.20-02                 |
| 6.00+04       |               | 1.14-04          |                | 1.35-01         | 4.44-02        |               | 1.80-01          |                         | 1.20-02                 |
| 8.00+04       |               | 8.78-05          |                | 1.35-01         | 4.44-02        |               | 1.80-01          |                         | 1.20-02                 |
| 1.00+05       |               | 7.14-05          |                | 1.35-01         | 4.45-02        |               | 1.80-01          |                         | 1.20-02                 |

(b/atom) x .066830 = cm<sup>2</sup>/g

Table 3.-3. BORON, Z=5

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total                   |                         |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|-------------------------|-------------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent           | Without coherent        |
| <i>MeV</i>    | <i>b/atom</i> | <i>b/atom</i>    | <i>b/atom</i>  | <i>b/atom</i>   | <i>b/atom</i>  | <i>b/atom</i> | <i>b/atom</i>    | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> |
| 1.00-02       | 4.61+00       | 3.20+00          | 1.63+01        |                 |                | 2.09+01       | 1.95+01          | 1.16+00                 | 1.09+00                 |
| 1.50-02       | 3.95+00       | 3.14+00          | 4.36+00        |                 |                | 8.31+00       | 7.50+00          | 4.63-01                 | 4.18-01                 |
| 2.00-02       | 3.61+00       | 3.09+00          | 1.68+00        |                 |                | 5.29+00       | 4.77+00          | 2.95-01                 | 2.66-01                 |
| 3.00-02       | 3.25+00       | 2.99+00          | 4.52-01        |                 |                | 3.70+00       | 3.44+00          | 2.06-01                 | 1.92-01                 |
| 4.00-02       | 3.04+00       | 2.89+00          | 1.84-01        |                 |                | 3.23+00       | 3.08+00          | 1.80-01                 | 1.71-01                 |
| 5.00-02       | 2.91+00       | 2.81+00          | 8.80-02        |                 |                | 3.00+00       | 2.89+00          | 1.67-01                 | 1.61-01                 |
| 6.00-02       | 2.80+00       | 2.73+00          | 4.86-02        |                 |                | 2.85+00       | 2.78+00          | 1.59-01                 | 1.55-01                 |
| 8.00-02       | 2.63+00       | 2.59+00          | 1.89-02        |                 |                | 2.64+00       | 2.60+00          | 1.47-01                 | 1.45-01                 |
| 1.00-01       | 2.49+00       | 2.46+00          | 8.97-03        |                 |                | 2.50+00       | 2.47+00          | 1.39-01                 | 1.38-01                 |
| 1.50-01       | 2.23+00       | 2.22+00          | 2.38-03        |                 |                | 2.23+00       | 2.22+00          | 1.24-01                 | 1.24-01                 |
| 2.00-01       | 2.04+00       | 2.03+00          | 9.41-04        |                 |                | 2.04+00       | 2.03+00          | 1.14-01                 | 1.13-01                 |
| 3.00-01       | 1.77+00       | 1.77+00          | 2.65-04        |                 |                | 1.77+00       | 1.77+00          | 9.84-02                 | 9.85-02                 |
| 4.00-01       |               | 1.58+00          | 1.13-04        |                 |                |               | 1.58+00          |                         | 8.83-02                 |
| 5.00-01       |               | 1.45+00          | 6.05-05        |                 |                |               | 1.45+00          |                         | 8.06-02                 |
| 6.00-01       |               | 1.34+00          | 3.77-05        |                 |                |               | 1.34+00          |                         | 7.45-02                 |
| 8.00-01       |               | 1.18+00          | 1.90-05        |                 |                |               | 1.18+00          |                         | 6.55-02                 |
| 1.00+00       |               | 1.06+00          | 1.18-05        |                 |                |               | 1.06+00          |                         | 5.89-02                 |
| 1.50+00       |               | 8.59-01          | 5.51-06        | 1.11-03         |                |               | 8.60-01          |                         | 4.79-02                 |
| 2.00+00       |               | 7.33-01          | 3.51-06        | 4.44-03         |                |               | 7.37-01          |                         | 4.11-02                 |
| 3.00+00       |               | 5.77-01          | 1.97-06        | 1.28-02         | 2.01-04        |               | 5.90-01          |                         | 3.28-02                 |
| 4.00+00       |               | 4.81-01          | 1.35-06        | 2.07-02         | 8.26-04        |               | 5.03-01          |                         | 2.80-02                 |
| 5.00+00       |               | 4.15-01          | 1.03-06        | 2.78-02         | 1.62-03        |               | 4.45-01          |                         | 2.48-02                 |
| 6.00+00       |               | 3.67-01          | 8.23-07        | 3.40-02         | 2.50-03        |               | 4.04-01          |                         | 2.25-02                 |
| 8.00+00       |               | 3.00-01          | 5.89-07        | 4.46-02         | 4.27-03        |               | 3.49-01          |                         | 1.95-02                 |
| 1.00+01       |               | 2.56-01          | 4.63-07        | 5.32-02         | 5.84-03        |               | 3.15-01          |                         | 1.75-02                 |
| 1.50+01       |               | 1.89-01          |                | 6.96-02         | 9.09-03        |               | 2.68-01          |                         | 1.49-02                 |
| 2.00+01       |               | 1.52-01          |                | 8.16-02         | 1.17-02        |               | 2.45-01          |                         | 1.37-02                 |
| 3.00+01       |               | 1.11-01          |                | 9.85-02         | 1.55-02        |               | 2.25-01          |                         | 1.25-02                 |
| 4.00+01       |               | 8.79-02          |                | 1.10-01         | 1.84-02        |               | 2.17-01          |                         | 1.21-02                 |
| 5.00+01       |               | 7.34-02          |                | 1.19-01         | 2.07-02        |               | 2.13-01          |                         | 1.19-02                 |
| 6.00+01       |               | 6.32-02          |                | 1.26-01         | 2.26-02        |               | 2.12-01          |                         | 1.18-02                 |
| 8.00+01       |               | 4.98-02          |                | 1.37-01         | 2.55-02        |               | 2.12-01          |                         | 1.18-02                 |
| 1.00+02       |               | 4.14-02          |                | 1.45-01         | 2.77-02        |               | 2.14-01          |                         | 1.19-02                 |
| 1.50+02       |               | 2.95-02          |                | 1.57-01         | 3.15-02        |               | 2.18-01          |                         | 1.22-02                 |
| 2.00+02       |               | 2.31-02          |                | 1.66-01         | 3.40-02        |               | 2.23-01          |                         | 1.24-02                 |
| 3.00+02       |               | 1.64-02          |                | 1.76-01         | 3.74-02        |               | 2.29-01          |                         | 1.28-02                 |
| 4.00+02       |               | 1.28-02          |                | 1.82-01         | 3.96-02        |               | 2.34-01          |                         | 1.30-02                 |
| 5.00+02       |               | 1.06-02          |                | 1.86-01         | 4.13-02        |               | 2.37-01          |                         | 1.32-02                 |
| 6.00+02       |               | 9.09-03          |                | 1.89-01         | 4.25-02        |               | 2.40-01          |                         | 1.34-02                 |
| 8.00+02       |               | 7.10-03          |                | 1.93-01         | 4.43-02        |               | 2.44-01          |                         | 1.36-02                 |
| 1.00+03       |               | 5.84-03          |                | 1.95-01         | 4.56-02        |               | 2.47-01          |                         | 1.37-02                 |
| 1.50+03       |               | 4.08-03          |                | 1.99-01         | 4.76-02        |               | 2.51-01          |                         | 1.40-02                 |
| 2.00+03       |               | 3.16-03          |                | 2.01-01         | 4.89-02        |               | 2.53-01          |                         | 1.41-02                 |
| 3.00+03       |               | 2.19-03          |                | 2.04-01         | 5.05-02        |               | 2.56-01          |                         | 1.43-02                 |
| 4.00+03       |               | 1.69-03          |                | 2.05-01         | 5.14-02        |               | 2.58-01          |                         | 1.44-02                 |
| 5.00+03       |               | 1.38-03          |                | 2.06-01         | 5.21-02        |               | 2.59-01          |                         | 1.44-02                 |
| 6.00+03       |               | 1.17-03          |                | 2.06-01         | 5.25-02        |               | 2.60-01          |                         | 1.45-02                 |
| 8.00+03       |               | 9.05-04          |                | 2.07-01         | 5.31-02        |               | 2.61-01          |                         | 1.45-02                 |
| 1.00+04       |               | 7.39-04          |                | 2.07-01         | 5.34-02        |               | 2.61-01          |                         | 1.46-02                 |
| 1.50+04       |               | 5.11-04          |                | 2.08-01         | 5.40-02        |               | 2.63-01          |                         | 1.46-02                 |
| 2.00+04       |               | 3.93-04          |                | 2.08-01         | 5.43-02        |               | 2.63-01          |                         | 1.47-02                 |
| 3.00+04       |               | 2.71-04          |                | 2.09-01         | 5.46-02        |               | 2.64-01          |                         | 1.47-02                 |
| 4.00+04       |               | 2.08-04          |                | 2.09-01         | 5.48-02        |               | 2.64-01          |                         | 1.47-02                 |
| 5.00+04       |               | 1.69-04          |                | 2.09-01         | 5.49-02        |               | 2.64-01          |                         | 1.47-02                 |
| 6.00+04       |               | 1.43-04          |                | 2.09-01         | 5.49-02        |               | 2.64-01          |                         | 1.47-02                 |
| 8.00+04       |               | 1.10-04          |                | 2.09-01         | 5.50-02        |               | 2.64-01          |                         | 1.47-02                 |
| 1.00+05       |               | 8.93-05          |                | 2.09-01         | 5.51-02        |               | 2.64-01          |                         | 1.47-02                 |

(b/atom) x .055710 = cm<sup>2</sup>/g

**Table 3.-4. CARBON, Z=6**

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 6.11+00       | 3.84+00          | 3.93+01        |                 |                | 4.54+01       | 4.31+01          | 2.28+00            | 2.17+00            |
| 1.50-02       | 5.06+00       | 3.77+00          | 1.06+01        |                 |                | 1.57+01       | 1.44+01          | 7.87-01            | 7.22-01            |
| 2.00-02       | 4.53+00       | 3.71+00          | 4.01+00        |                 |                | 8.54+00       | 7.72+00          | 4.29-01            | 3.88-01            |
| 3.00-02       | 4.00+00       | 3.58+00          | 9.99-01        |                 |                | 5.00+00       | 4.58+00          | 2.51-01            | 2.30-01            |
| 4.00-02       | 3.73+00       | 3.47+00          | 3.79-01        |                 |                | 4.10+00       | 3.85+00          | 2.06-01            | 1.93-01            |
| 5.00-02       | 3.54+00       | 3.37+00          | 1.93-01        |                 |                | 3.73+00       | 3.56+00          | 1.87-01            | 1.79-01            |
| 6.00-02       | 3.39+00       | 3.27+00          | 1.15-01        |                 |                | 3.51+00       | 3.39+00          | 1.76-01            | 1.70-01            |
| 8.00-02       | 3.17+00       | 3.10+00          | 4.50-02        |                 |                | 3.21+00       | 3.15+00          | 1.61-01            | 1.58-01            |
| 1.00-01       | 3.00+00       | 2.96+00          | 2.16-02        |                 |                | 3.02+00       | 2.98+00          | 1.52-01            | 1.50-01            |
| 1.50-01       | 2.69+00       | 2.66+00          | 5.75-03        |                 |                | 2.69+00       | 2.67+00          | 1.35-01            | 1.34-01            |
| 2.00-01       | 2.45+00       | 2.44+00          | 2.29-03        |                 |                | 2.45+00       | 2.44+00          | 1.23-01            | 1.23-01            |
| 3.00-01       | 2.13+00       | 2.12+00          | 6.46-04        |                 |                | 2.13+00       | 2.12+00          | 1.07-01            | 1.07-01            |
| 4.00-01       | 1.90+00       | 1.90+00          | 2.77-04        |                 |                | 1.91+00       | 1.90+00          | 9.57-02            | 9.55-02            |
| 5.00-01       |               | 1.74+00          | 1.49-04        |                 |                |               | 1.74+00          | 8.72-02            | 8.72-02            |
| 6.00-01       |               | 1.61+00          | 9.27-05        |                 |                |               | 1.61+00          | 8.07-02            | 8.07-02            |
| 8.00-01       |               | 1.41+00          | 4.68-05        |                 |                |               | 1.41+00          | 7.09-02            | 7.09-02            |
| 1.00+00       |               | 1.27+00          | 2.89-05        |                 |                |               | 1.27+00          | 6.37-02            | 6.37-02            |
| 1.50+00       |               | 1.03+00          | 1.35-05        | 1.60-03         |                |               | 1.03+00          | 5.19-02            | 5.19-02            |
| 2.00+00       |               | 8.79-01          | 8.61-06        | 6.40-03         |                |               | 8.86-01          | 4.45-02            | 4.45-02            |
| 3.00+00       |               | 6.92-01          | 4.82-06        | 1.84-02         | 2.41-04        |               | 7.11-01          | 3.57-02            | 3.57-02            |
| 4.00+00       |               | 5.77-01          | 3.29-06        | 2.98-02         | 9.91-04        |               | 6.08-01          | 3.05-02            | 3.05-02            |
| 5.00+00       |               | 4.98-01          | 2.52-06        | 4.00-02         | 1.95-03        |               | 5.40-01          | 2.71-02            | 2.71-02            |
| 6.00+00       |               | 4.40-01          | 2.01-06        | 4.90-02         | 3.00-03        |               | 4.93-01          | 2.47-02            | 2.47-02            |
| 8.00+00       |               | 3.60-01          | 1.44-06        | 6.42-02         | 5.12-03        |               | 4.30-01          | 2.16-02            | 2.16-02            |
| 1.00+01       |               | 3.07-01          | 1.12-06        | 7.66-02         | 7.01-03        |               | 3.90-01          | 1.96-02            | 1.96-02            |
| 1.50+01       |               | 2.27-01          |                | 1.00-01         | 1.09-02        |               | 3.38-01          | 1.70-02            | 1.70-02            |
| 2.00+01       |               | 1.82-01          |                | 1.17-01         | 1.40-02        |               | 3.14-01          | 1.58-02            | 1.58-02            |
| 3.00+01       |               | 1.33-01          |                | 1.41-01         | 1.87-02        |               | 2.93-01          | 1.47-02            | 1.47-02            |
| 4.00+01       |               | 1.05-01          |                | 1.58-01         | 2.21-02        |               | 2.86-01          | 1.44-02            | 1.44-02            |
| 5.00+01       |               | 8.80-02          |                | 1.71-01         | 2.48-02        |               | 2.84-01          | 1.42-02            | 1.42-02            |
| 6.00+01       |               | 7.59-02          |                | 1.81-01         | 2.71-02        |               | 2.84-01          | 1.43-02            | 1.43-02            |
| 8.00+01       |               | 5.98-02          |                | 1.96-01         | 3.06-02        |               | 2.86-01          | 1.44-02            | 1.44-02            |
| 1.00+02       |               | 4.97-02          |                | 2.07-01         | 3.31-02        |               | 2.90-01          | 1.46-02            | 1.46-02            |
| 1.50+02       |               | 3.54-02          |                | 2.26-01         | 3.76-02        |               | 2.99-01          | 1.50-02            | 1.50-02            |
| 2.00+02       |               | 2.77-02          |                | 2.37-01         | 4.06-02        |               | 3.06-01          | 1.53-02            | 1.53-02            |
| 3.00+02       |               | 1.96-02          |                | 2.51-01         | 4.46-02        |               | 3.16-01          | 1.59-02            | 1.59-02            |
| 4.00+02       |               | 1.54-02          |                | 2.60-01         | 4.72-02        |               | 3.22-01          | 1.62-02            | 1.62-02            |
| 5.00+02       |               | 1.27-02          |                | 2.65-01         | 4.91-02        |               | 3.27-01          | 1.64-02            | 1.64-02            |
| 6.00+02       |               | 1.09-02          |                | 2.69-01         | 5.05-02        |               | 3.31-01          | 1.66-02            | 1.66-02            |
| 8.00+02       |               | 8.52-03          |                | 2.75-01         | 5.26-02        |               | 3.36-01          | 1.69-02            | 1.69-02            |
| 1.00+03       |               | 7.01-03          |                | 2.78-01         | 5.40-02        |               | 3.40-01          | 1.71-02            | 1.71-02            |
| 1.50+03       |               | 4.89-03          |                | 2.84-01         | 5.64-02        |               | 3.45-01          | 1.73-02            | 1.73-02            |
| 2.00+03       |               | 3.79-03          |                | 2.87-01         | 5.79-02        |               | 3.48-01          | 1.75-02            | 1.75-02            |
| 3.00+03       |               | 2.64-03          |                | 2.90-01         | 5.98-02        |               | 3.52-01          | 1.77-02            | 1.77-02            |
| 4.00+03       |               | 2.03-03          |                | 2.92-01         | 6.08-02        |               | 3.54-01          | 1.78-02            | 1.78-02            |
| 5.00+03       |               | 1.66-03          |                | 2.93-01         | 6.15-02        |               | 3.56-01          | 1.79-02            | 1.79-02            |
| 6.00+03       |               | 1.41-03          |                | 2.93-01         | 6.20-02        |               | 3.57-01          | 1.79-02            | 1.79-02            |
| 8.00+03       |               | 1.09-03          |                | 2.94-01         | 6.26-02        |               | 3.58-01          | 1.80-02            | 1.80-02            |
| 1.00+04       |               | 8.87-04          |                | 2.95-01         | 6.30-02        |               | 3.59-01          | 1.80-02            | 1.80-02            |
| 1.50+04       |               | 6.13-04          |                | 2.96-01         | 6.36-02        |               | 3.60-01          | 1.81-02            | 1.81-02            |
| 2.00+04       |               | 4.71-04          |                | 2.96-01         | 6.40-02        |               | 3.61-01          | 1.81-02            | 1.81-02            |
| 3.00+04       |               | 3.25-04          |                | 2.97-01         | 6.43-02        |               | 3.62-01          | 1.82-02            | 1.82-02            |
| 4.00+04       |               | 2.49-04          |                | 2.97-01         | 6.45-02        |               | 3.62-01          | 1.82-02            | 1.82-02            |
| 5.00+04       |               | 2.03-04          |                | 2.97-01         | 6.46-02        |               | 3.62-01          | 1.82-02            | 1.82-02            |
| 6.00+04       |               | 1.72-04          |                | 2.97-01         | 6.47-02        |               | 3.62-01          | 1.82-02            | 1.82-02            |
| 8.00+04       |               | 1.32-04          |                | 2.98-01         | 6.48-02        |               | 3.63-01          | 1.82-02            | 1.82-02            |
| 1.00+05       |               | 1.07-04          |                | 2.98-01         | 6.49-02        |               | 3.63-01          | 1.82-02            | 1.82-02            |

(b/atom) x .050240 = cm<sup>2</sup>/g



Table 3.-5. NITROGEN, Z = 7

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 8.03+00       | 4.48+00          | 7.86+01        |                 |                | 8.66+01       | 8.31+01          | 3.73+00            | 3.57+00            |
| 1.50-02       | 6.38+00       | 4.40+00          | 2.10+01        |                 |                | 2.74+01       | 2.54+01          | 1.18+00            | 1.09+00            |
| 2.00-02       | 5.60+00       | 4.33+00          | 8.26+00        |                 |                | 1.39+01       | 1.26+01          | 5.96-01            | 5.41-01            |
| 3.00-02       | 4.83+00       | 4.18+00          | 2.23+00        |                 |                | 7.06+00       | 6.41+00          | 3.04-01            | 2.76-01            |
| 4.00-02       | 4.44+00       | 4.05+00          | 8.78-01        |                 |                | 5.31+00       | 4.93+00          | 2.29-01            | 2.12-01            |
| 5.00-02       | 4.18+00       | 3.93+00          | 4.25-01        |                 |                | 4.61+00       | 4.35+00          | 1.98-01            | 1.87-01            |
| 6.00-02       | 4.00+00       | 3.82+00          | 2.38-01        |                 |                | 4.24+00       | 4.06+00          | 1.82-01            | 1.74-01            |
| 8.00-02       | 3.73+00       | 3.62+00          | 9.40-02        |                 |                | 3.82+00       | 3.72+00          | 1.64-01            | 1.60-01            |
| 1.00-01       | 3.52+00       | 3.45+00          | 4.54-02        |                 |                | 3.56+00       | 3.49+00          | 1.53-01            | 1.50-01            |
| 1.50-01       | 3.13+00       | 3.11+00          | 1.22-02        |                 |                | 3.15+00       | 3.12+00          | 1.35-01            | 1.34-01            |
| 2.00-01       | 2.86+00       | 2.85+00          | 4.85-03        |                 |                | 2.86+00       | 2.85+00          | 1.23-01            | 1.23-01            |
| 3.00-01       | 2.48+00       | 2.48+00          | 1.38-03        |                 |                | 2.49+00       | 2.48+00          | 1.07-01            | 1.06-01            |
| 4.00-01       |               | 2.22+00          | 5.89-04        |                 |                |               | 2.22+00          |                    | 9.54-02            |
| 5.00-01       |               | 2.03+00          | 3.16-04        |                 |                |               | 2.03+00          |                    | 8.71-02            |
| 6.00-01       |               | 1.87+00          | 1.97-04        |                 |                |               | 1.87+00          |                    | 8.05-02            |
| 8.00-01       |               | 1.65+00          | 9.94-05        |                 |                |               | 1.65+00          |                    | 7.08-02            |
| 1.00+00       |               | 1.48+00          | 6.15-05        |                 |                |               | 1.48+00          |                    | 6.36-02            |
| 1.50+00       |               | 1.20+00          | 2.88-05        | 2.19-03         |                |               | 1.21+00          |                    | 5.18-02            |
| 2.00+00       |               | 1.03+00          | 1.84-05        | 8.71-03         |                |               | 1.03+00          |                    | 4.45-02            |
| 3.00+00       |               | 8.07-01          | 1.03-05        | 2.50-02         | 2.82-04        |               | 8.33-01          |                    | 3.58-02            |
| 4.00+00       |               | 6.73-01          | 6.99-06        | 4.06-02         | 1.16-03        |               | 7.15-01          |                    | 3.07-02            |
| 5.00+00       |               | 5.81-01          | 5.36-06        | 5.44-02         | 2.27-03        |               | 6.38-01          |                    | 2.74-02            |
| 6.00+00       |               | 5.14-01          | 4.27-06        | 6.67-02         | 3.50-03        |               | 5.84-01          |                    | 2.51-02            |
| 8.00+00       |               | 4.20-01          | 3.06-06        | 8.73-02         | 5.98-03        |               | 5.14-01          |                    | 2.21-02            |
| 1.00+01       |               | 3.58-01          | 2.39-06        | 1.04-01         | 8.17-03        |               | 4.70-01          |                    | 2.02-02            |
| 1.50+01       |               | 2.65-01          |                | 1.36-01         | 1.27-02        |               | 4.14-01          |                    | 1.78-02            |
| 2.00+01       |               | 2.13-01          |                | 1.59-01         | 1.63-02        |               | 3.88-01          |                    | 1.67-02            |
| 3.00+01       |               | 1.55-01          |                | 1.92-01         | 2.18-02        |               | 3.68-01          |                    | 1.58-02            |
| 4.00+01       |               | 1.23-01          |                | 2.14-01         | 2.58-02        |               | 3.63-01          |                    | 1.56-02            |
| 5.00+01       |               | 1.03-01          |                | 2.32-01         | 2.90-02        |               | 3.63-01          |                    | 1.56-02            |
| 6.00+01       |               | 8.85-02          |                | 2.45-01         | 3.16-02        |               | 3.65-01          |                    | 1.57-02            |
| 8.00+01       |               | 6.98-02          |                | 2.66-01         | 3.56-02        |               | 3.71-01          |                    | 1.60-02            |
| 1.00+02       |               | 5.97-02          |                | 2.81-01         | 3.85-02        |               | 3.79-01          |                    | 1.63-02            |
| 1.50+02       |               | 4.13-02          |                | 3.06-01         | 4.37-02        |               | 3.91-01          |                    | 1.68-02            |
| 2.00+02       |               | 3.23-02          |                | 3.21-01         | 4.71-02        |               | 4.01-01          |                    | 1.72-02            |
| 3.00+02       |               | 2.29-02          |                | 3.40-01         | 5.17-02        |               | 4.14-01          |                    | 1.78-02            |
| 4.00+02       |               | 1.79-02          |                | 3.51-01         | 5.47-02        |               | 4.23-01          |                    | 1.82-02            |
| 5.00+02       |               | 1.49-02          |                | 3.58-01         | 5.68-02        |               | 4.30-01          |                    | 1.85-02            |
| 6.00+02       |               | 1.27-02          |                | 3.63-01         | 5.84-02        |               | 4.35-01          |                    | 1.87-02            |
| 8.00+02       |               | 9.94-03          |                | 3.70-01         | 6.08-02        |               | 4.41-01          |                    | 1.90-02            |
| 1.00+03       |               | 8.18-03          |                | 3.75-01         | 6.24-02        |               | 4.46-01          |                    | 1.92-02            |
| 1.50+03       |               | 5.71-03          |                | 3.82-01         | 6.51-02        |               | 4.53-01          |                    | 1.95-02            |
| 2.00+03       |               | 4.42-03          |                | 3.86-01         | 6.68-02        |               | 4.57-01          |                    | 1.96-02            |
| 3.00+03       |               | 3.07-03          |                | 3.90-01         | 6.89-02        |               | 4.62-01          |                    | 1.99-02            |
| 4.00+03       |               | 2.37-03          |                | 3.92-01         | 7.00-02        |               | 4.64-01          |                    | 2.00-02            |
| 5.00+03       |               | 1.94-03          |                | 3.93-01         | 7.07-02        |               | 4.66-01          |                    | 2.00-02            |
| 6.00+03       |               | 1.64-03          |                | 3.94-01         | 7.13-02        |               | 4.67-01          |                    | 2.01-02            |
| 8.00+03       |               | 1.27-03          |                | 3.95-01         | 7.20-02        |               | 4.69-01          |                    | 2.02-02            |
| 1.00+04       |               | 1.03-03          |                | 3.96-01         | 7.24-02        |               | 4.70-01          |                    | 2.02-02            |
| 1.50+04       |               | 7.15-04          |                | 3.97-01         | 7.31-02        |               | 4.71-01          |                    | 2.03-02            |
| 2.00+04       |               | 5.50-04          |                | 3.98-01         | 7.34-02        |               | 4.72-01          |                    | 2.03-02            |
| 3.00+04       |               | 3.79-04          |                | 3.99-01         | 7.38-02        |               | 4.73-01          |                    | 2.03-02            |
| 4.00+04       |               | 2.91-04          |                | 3.99-01         | 7.40-02        |               | 4.73-01          |                    | 2.03-02            |
| 5.00+04       |               | 2.37-04          |                | 3.99-01         | 7.41-02        |               | 4.73-01          |                    | 2.04-02            |
| 6.00+04       |               | 2.00-04          |                | 3.99-01         | 7.42-02        |               | 4.74-01          |                    | 2.04-02            |
| 8.00+04       |               | 1.54-04          |                | 3.99-01         | 7.43-02        |               | 4.74-01          |                    | 2.04-02            |
| 1.00+05       |               | 1.25-04          |                | 3.99-01         | 7.43-02        |               | 4.74-01          |                    | 2.04-02            |

(b/atom) x .043000 = cm<sup>2</sup>/g

Table 3.-6. OXYGEN, Z=8

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total                   |                         |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|-------------------------|-------------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent           | Without coherent        |
| <i>MeV</i>    | <i>b/atom</i> | <i>b/atom</i>    | <i>b/atom</i>  | <i>b/atom</i>   | <i>b/atom</i>  | <i>b/atom</i> | <i>b/atom</i>    | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> |
| 1.00-02       | 1.06+01       | 5.12+00          | 1.43+02        |                 |                | 1.54+02       | 1.48+02          | 5.78+00                 | 5.58+00                 |
| 1.50-02       | 8.00+00       | 5.03+00          | 3.81+01        |                 |                | 4.61+01       | 4.31+01          | 1.74+00                 | 1.62+00                 |
| 2.00-02       | 6.84+00       | 4.94+00          | 1.51+01        |                 |                | 2.19+01       | 2.00+01          | 8.26-01                 | 7.54-01                 |
| 3.00-02       | 5.74+00       | 4.78+00          | 4.13+00        |                 |                | 9.87+00       | 8.91+00          | 3.72-01                 | 3.35-01                 |
| 4.00-02       | 5.20+00       | 4.63+00          | 1.64+00        |                 |                | 6.84+00       | 6.27+00          | 2.57-01                 | 2.36-01                 |
| 5.00-02       | 4.87+00       | 4.49+00          | 8.00-01        |                 |                | 5.67+00       | 5.29+00          | 2.13-01                 | 1.99-01                 |
| 6.00-02       | 4.63+00       | 4.36+00          | 4.48-01        |                 |                | 5.08+00       | 4.81+00          | 1.91-01                 | 1.81-01                 |
| 8.00-02       | 4.29+00       | 4.14+00          | 1.78-01        |                 |                | 4.47+00       | 4.32+00          | 1.68-01                 | 1.62-01                 |
| 1.00-01       | 4.05+00       | 3.94+00          | 8.54-02        |                 |                | 4.13+00       | 4.03+00          | 1.56-01                 | 1.52-01                 |
| 1.50-01       | 3.60+00       | 3.55+00          | 2.32-02        |                 |                | 3.62+00       | 3.57+00          | 1.36-01                 | 1.34-01                 |
| 2.00-01       | 3.27+00       | 3.25+00          | 9.30-03        |                 |                | 3.28+00       | 3.26+00          | 1.24-01                 | 1.23-01                 |
| 3.00-01       | 2.84+00       | 2.83+00          | 2.65-03        |                 |                | 2.84+00       | 2.83+00          | 1.07-01                 | 1.07-01                 |
| 4.00-01       | 2.54+00       | 2.53+00          | 1.13-03        |                 |                | 2.54+00       | 2.54+00          | 9.57-02                 | 9.54-02                 |
| 5.00-01       | 2.32+00       | 2.31+00          | 6.11-04        |                 |                | 2.32+00       | 2.31+00          | 8.73-02                 | 8.71-02                 |
| 6.00-01       | 2.15+00       | 2.14+00          | 3.82-04        |                 |                | 2.15+00       | 2.14+00          | 8.08-02                 | 8.06-02                 |
| 8.00-01       |               | 1.88+00          | 1.92-04        |                 |                |               | 1.88+00          |                         | 7.08-02                 |
| 1.00+00       |               | 1.69+00          | 1.19-04        |                 |                |               | 1.69+00          |                         | 6.37-02                 |
| 1.50+00       |               | 1.37+00          | 5.57-05        | 2.86-03         |                |               | 1.38+00          |                         | 5.18-02                 |
| 2.00+00       |               | 1.17+00          | 3.54-05        | 1.14-02         |                |               | 1.18+00          |                         | 4.46-02                 |
| 3.00+00       |               | 9.23-01          | 1.98-05        | 3.27-02         | 3.22-04        |               | 9.56-01          |                         | 3.60-02                 |
| 4.00+00       |               | 7.69-01          | 1.35-05        | 5.30-02         | 1.32-03        |               | 8.24-01          |                         | 3.10-02                 |
| 5.00+00       |               | 6.65-01          | 1.03-05        | 7.11-02         | 2.60-03        |               | 7.38-01          |                         | 2.78-02                 |
| 6.00+00       |               | 5.87-01          | 8.22-06        | 8.70-02         | 3.99-03        |               | 6.78-01          |                         | 2.55-02                 |
| 8.00+00       |               | 4.80-01          | 5.88-06        | 1.14-01         | 6.83-03        |               | 6.01-01          |                         | 2.26-02                 |
| 1.00+01       |               | 4.09-01          | 4.61-06        | 1.36-01         | 9.34-03        |               | 5.54-01          |                         | 2.09-02                 |
| 1.50+01       |               | 3.03-01          |                | 1.77-01         | 1.45-02        |               | 4.95-01          |                         | 1.86-02                 |
| 2.00+01       |               | 2.43-01          |                | 2.08-01         | 1.87-02        |               | 4.69-01          |                         | 1.77-02                 |
| 3.00+01       |               | 1.77-01          |                | 2.50-01         | 2.49-02        |               | 4.52-01          |                         | 1.70-02                 |
| 4.00+01       |               | 1.41-01          |                | 2.79-01         | 2.95-02        |               | 4.49-01          |                         | 1.69-02                 |
| 5.00+01       |               | 1.17-01          |                | 3.01-01         | 3.31-02        |               | 4.52-01          |                         | 1.70-02                 |
| 6.00+01       |               | 1.01-01          |                | 3.19-01         | 3.61-02        |               | 4.56-01          |                         | 1.72-02                 |
| 8.00+01       |               | 7.98-02          |                | 3.46-01         | 4.05-02        |               | 4.66-01          |                         | 1.75-02                 |
| 1.00+02       |               | 6.62-02          |                | 3.65-01         | 4.39-02        |               | 4.75-01          |                         | 1.79-02                 |
| 1.50+02       |               | 4.72-02          |                | 3.97-01         | 4.97-02        |               | 4.94-01          |                         | 1.86-02                 |
| 2.00+02       |               | 3.70-02          |                | 4.17-01         | 5.36-02        |               | 5.08-01          |                         | 1.91-02                 |
| 3.00+02       |               | 2.62-02          |                | 4.40-01         | 5.87-02        |               | 5.25-01          |                         | 1.98-02                 |
| 4.00+02       |               | 2.05-02          |                | 4.54-01         | 6.21-02        |               | 5.37-01          |                         | 2.02-02                 |
| 5.00+02       |               | 1.70-02          |                | 4.63-01         | 6.44-02        |               | 5.45-01          |                         | 2.05-02                 |
| 6.00+02       |               | 1.45-02          |                | 4.70-01         | 6.62-02        |               | 5.51-01          |                         | 2.07-02                 |
| 8.00+02       |               | 1.14-02          |                | 4.79-01         | 6.88-02        |               | 5.59-01          |                         | 2.10-02                 |
| 1.00+03       |               | 9.34-03          |                | 4.84-01         | 7.07-02        |               | 5.65-01          |                         | 2.12-02                 |
| 1.50+03       |               | 6.53-03          |                | 4.93-01         | 7.37-02        |               | 5.73-01          |                         | 2.16-02                 |
| 2.00+03       |               | 5.05-03          |                | 4.98-01         | 7.56-02        |               | 5.78-01          |                         | 2.18-02                 |
| 3.00+03       |               | 3.51-03          |                | 5.02-01         | 7.78-02        |               | 5.84-01          |                         | 2.20-02                 |
| 4.00+03       |               | 2.71-03          |                | 5.05-01         | 7.90-02        |               | 5.87-01          |                         | 2.21-02                 |
| 5.00+03       |               | 2.22-03          |                | 5.07-01         | 7.98-02        |               | 5.89-01          |                         | 2.22-02                 |
| 6.00+03       |               | 1.88-03          |                | 5.08-01         | 8.04-02        |               | 5.90-01          |                         | 2.22-02                 |
| 8.00+03       |               | 1.45-03          |                | 5.09-01         | 8.11-02        |               | 5.92-01          |                         | 2.23-02                 |
| 1.00+04       |               | 1.18-03          |                | 5.10-01         | 8.16-02        |               | 5.93-01          |                         | 2.23-02                 |
| 1.50+04       |               | 8.17-04          |                | 5.12-01         | 8.23-02        |               | 5.95-01          |                         | 2.24-02                 |
| 2.00+04       |               | 6.28-04          |                | 5.12-01         | 8.27-02        |               | 5.96-01          |                         | 2.24-02                 |
| 3.00+04       |               | 4.33-04          |                | 5.13-01         | 8.31-02        |               | 5.97-01          |                         | 2.25-02                 |
| 4.00+04       |               | 3.33-04          |                | 5.13-01         | 8.33-02        |               | 5.97-01          |                         | 2.25-02                 |
| 5.00+04       |               | 2.71-04          |                | 5.14-01         | 8.34-02        |               | 5.97-01          |                         | 2.25-02                 |
| 6.00+04       |               | 2.29-04          |                | 5.14-01         | 8.35-02        |               | 5.98-01          |                         | 2.25-02                 |
| 8.00+04       |               | 1.75-04          |                | 5.14-01         | 8.37-02        |               | 5.98-01          |                         | 2.25-02                 |
| 1.00+05       |               | 1.43-04          |                | 5.14-01         | 8.38-02        |               | 5.98-01          |                         | 2.25-02                 |

(b/atom) x .037640 = cm<sup>2</sup>/g

Table 3.-7. SODIUM, Z=11

| Photon energy. | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|----------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|                | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV            | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02        | 2.19+01       | 7.04+00          | 5.69+02        |                 |                | 5.91+02       | 5.76+02          | 1.55+01            | 1.51+01            |
| 1.50-02        | 1.49+01       | 6.92+00          | 1.60+02        |                 |                | 1.75+02       | 1.67+02          | 4.58+00            | 4.37+00            |
| 2.00-02        | 1.18+01       | 6.80+00          | 6.48+01        |                 |                | 7.66+01       | 7.16+01          | 2.01+00            | 1.88+00            |
| 3.00-02        | 9.11+00       | 6.57+00          | 1.78+01        |                 |                | 2.69+01       | 2.44+01          | 7.05-01            | 6.39-01            |
| 4.00-02        | 7.90+00       | 6.37+00          | 7.18+00        |                 |                | 1.51+01       | 1.35+01          | 3.95-01            | 3.55-01            |
| 5.00-02        | 7.19+00       | 6.18+00          | 3.53+00        |                 |                | 1.07+01       | 0.97+01          | 2.81-01            | 2.54-01            |
| 6.00-02        | 6.73+00       | 6.00+00          | 1.99+00        |                 |                | 8.72+00       | 7.99+00          | 2.28-01            | 2.09-01            |
| 8.00-02        | 6.11+00       | 5.69+00          | 7.92-01        |                 |                | 6.90+00       | 6.48+00          | 1.81-01            | 1.70-01            |
| 1.00-01        | 5.69+00       | 5.42+00          | 3.85-01        |                 |                | 6.08+00       | 5.80+00          | 1.59-01            | 1.52-01            |
| 1.50-01        | 5.01+00       | 4.88+00          | 1.06-01        |                 |                | 5.11+00       | 4.99+00          | 1.34-01            | 1.31-01            |
| 2.00-01        | 4.54+00       | 4.47+00          | 4.29-02        |                 |                | 4.58+00       | 4.51+00          | 1.20-01            | 1.18-01            |
| 3.00-01        | 3.92+00       | 3.89+00          | 1.24-02        |                 |                | 3.93+00       | 3.90+00          | 1.03-01            | 1.02-01            |
| 4.00-01        | 3.50+00       | 3.48+00          | 5.31-03        |                 |                | 3.50+00       | 3.49+00          | 9.18-02            | 9.14-02            |
| 5.00-01        | 3.19+00       | 3.18+00          | 2.86-03        |                 |                | 3.19+00       | 3.18+00          | 8.36-02            | 8.34-02            |
| 6.00-01        | 2.95+00       | 2.94+00          | 1.78-03        |                 |                | 2.95+00       | 2.95+00          | 7.74-02            | 7.72-02            |
| 8.00-01        |               | 2.59+00          | 9.01-04        |                 |                |               | 2.59+00          |                    | 6.78-02            |
| 1.00+00        |               | 2.33+00          | 5.58-04        |                 |                |               | 2.33+00          |                    | 6.09-02            |
| 1.50+00        |               | 1.89+00          | 2.61-04        | 5.46-03         |                |               | 1.90+00          |                    | 4.97-02            |
| 2.00+00        |               | 1.61+00          | 1.67-04        | 2.16-02         |                |               | 1.63+00          |                    | 4.28-02            |
| 3.00+00        |               | 1.27+00          | 9.25-05        | 6.19-02         | 4.43-04        |               | 1.33+00          |                    | 3.49-02            |
| 4.00+00        |               | 1.06+00          | 6.28-05        | 1.00-01         | 1.82-03        |               | 1.16+00          |                    | 3.04-02            |
| 5.00+00        |               | 9.14-01          | 4.79-05        | 1.34-01         | 3.57-03        |               | 1.05+00          |                    | 2.76-02            |
| 6.00+00        |               | 8.08-01          | 3.82-05        | 1.64-01         | 5.49-03        |               | 9.77-01          |                    | 2.56-02            |
| 8.00+00        |               | 6.61-01          | 2.73-05        | 2.15-01         | 9.40-03        |               | 8.85-01          |                    | 2.32-02            |
| 1.00+01        |               | 5.63-01          | 2.14-05        | 2.56-01         | 1.28-02        |               | 8.31-01          |                    | 2.18-02            |
| 1.50+01        |               | 4.16-01          |                | 3.34-01         | 2.00-02        |               | 7.70-01          |                    | 2.02-02            |
| 2.00+01        |               | 3.34-01          |                | 3.90-01         | 2.57-02        |               | 7.50-01          |                    | 1.96-02            |
| 3.00+01        |               | 2.43-01          |                | 4.69-01         | 3.42-02        |               | 7.47-01          |                    | 1.96-02            |
| 4.00+01        |               | 1.93-01          |                | 5.24-01         | 4.05-02        |               | 7.58-01          |                    | 1.99-02            |
| 5.00+01        |               | 1.61-01          |                | 5.65-01         | 4.55-02        |               | 7.72-01          |                    | 2.02-02            |
| 6.00+01        |               | 1.39-01          |                | 5.98-01         | 4.94-02        |               | 7.87-01          |                    | 2.06-02            |
| 8.00+01        |               | 1.10-01          |                | 6.47-01         | 5.53-02        |               | 8.12-01          |                    | 2.13-02            |
| 1.00+02        |               | 9.11-02          |                | 6.82-01         | 5.98-02        |               | 8.33-01          |                    | 2.18-02            |
| 1.50+02        |               | 6.48-02          |                | 7.39-01         | 6.75-02        |               | 8.72-01          |                    | 2.28-02            |
| 2.00+02        |               | 5.08-02          |                | 7.74-01         | 7.27-02        |               | 8.97-01          |                    | 2.35-02            |
| 3.00+02        |               | 3.60-02          |                | 8.14-01         | 7.95-02        |               | 9.30-01          |                    | 2.44-02            |
| 4.00+02        |               | 2.82-02          |                | 8.38-01         | 8.38-02        |               | 9.50-01          |                    | 2.49-02            |
| 5.00+02        |               | 2.34-02          |                | 8.53-01         | 8.69-02        |               | 9.64-01          |                    | 2.52-02            |
| 6.00+02        |               | 2.00-02          |                | 8.65-01         | 8.92-02        |               | 9.74-01          |                    | 2.55-02            |
| 8.00+02        |               | 1.56-02          |                | 8.79-01         | 9.26-02        |               | 9.79-01          |                    | 2.59-02            |
| 1.00+03        |               | 1.28-02          |                | 8.88-01         | 9.50-02        |               | 9.96-01          |                    | 2.61-02            |
| 1.50+03        |               | 8.97-03          |                | 9.03-01         | 9.89-02        |               | 1.01+00          |                    | 2.65-02            |
| 2.00+03        |               | 6.94-03          |                | 9.10-01         | 1.01-01        |               | 1.02+00          |                    | 2.67-02            |
| 3.00+03        |               | 4.83-03          |                | 9.18-01         | 1.04-01        |               | 1.03+00          |                    | 2.69-02            |
| 4.00+03        |               | 3.73-03          |                | 9.23-01         | 1.05-01        |               | 1.03+00          |                    | 2.70-02            |
| 5.00+03        |               | 3.05-03          |                | 9.26-01         | 1.06-01        |               | 1.04+00          |                    | 2.71-02            |
| 6.00+03        |               | 2.58-03          |                | 9.28-01         | 1.07-01        |               | 1.04+00          |                    | 2.72-02            |
| 8.00+03        |               | 1.99-03          |                | 9.30-01         | 1.08-01        |               | 1.04+00          |                    | 2.72-02            |
| 1.00+04        |               | 1.63-03          |                | 9.31-01         | 1.08-01        |               | 1.04+00          |                    | 2.73-02            |
| 1.50+04        |               | 1.12-03          |                | 9.34-01         | 1.09-01        |               | 1.04+00          |                    | 2.74-02            |
| 2.00+04        |               | 8.64-04          |                | 9.36-01         | 1.10-01        |               | 1.05+00          |                    | 2.74-02            |
| 3.00+04        |               | 5.96-04          |                | 9.36-01         | 1.10-01        |               | 1.05+00          |                    | 2.74-02            |
| 4.00+04        |               | 4.57-04          |                | 9.37-01         | 1.10-01        |               | 1.05+00          |                    | 2.75-02            |
| 5.00+04        |               | 3.72-04          |                | 9.38-01         | 1.11-01        |               | 1.05+00          |                    | 2.75-02            |
| 6.00+04        |               | 3.15-04          |                | 9.38-01         | 1.11-01        |               | 1.05+00          |                    | 2.75-02            |
| 8.00+04        |               | 2.41-04          |                | 9.38-01         | 1.11-01        |               | 1.05+00          |                    | 2.75-02            |
| 1.00+05        |               | 1.96-04          |                | 9.38-01         | 1.11-01        |               | 1.05+00          |                    | 2.75-02            |

(b/atom) x .026200 = cm<sup>2</sup>/g

Table 3.-8. MAGNESIUM, Z=12

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total                   |                         |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|-------------------------|-------------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent           | Without coherent        |
| <i>MeV</i>    | <i>b/atom</i> | <i>b/atom</i>    | <i>b/atom</i>  | <i>b/atom</i>   | <i>b/atom</i>  | <i>b/atom</i> | <i>b/atom</i>    | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> |
| 1.00-02       | 2.60+01       | 7.68+00          | 8.13+02        |                 |                | 8.39+02       | 8.21+02          | 2.08+01                 | 2.03+01                 |
| 1.50-02       | 1.75+01       | 7.55+00          | 2.34+02        |                 |                | 2.52+02       | 2.42+02          | 6.23+00                 | 5.98+00                 |
| 2.00-02       | 1.37+01       | 7.41+00          | 9.60+01        |                 |                | 1.10+02       | 1.03+02          | 2.72+00                 | 2.56+00                 |
| 3.00-02       | 1.03+01       | 7.17+00          | 2.67+01        |                 |                | 3.70+01       | 3.39+01          | 9.18-01                 | 8.39-01                 |
| 4.00-02       | 8.87+00       | 6.94+00          | 1.07+01        |                 |                | 1.96+01       | 1.76+01          | 4.85-01                 | 4.37-01                 |
| 5.00-02       | 8.02+00       | 6.74+00          | 5.28+00        |                 |                | 1.33+01       | 1.20+01          | 3.29-01                 | 2.98-01                 |
| 6.00-02       | 7.46+00       | 6.55+00          | 2.97+00        |                 |                | 1.04+01       | 9.52+00          | 2.58-01                 | 2.36-01                 |
| 8.00-02       | 6.73+00       | 6.21+00          | 1.19+00        |                 |                | 7.92+00       | 7.40+00          | 1.96-01                 | 1.83-01                 |
| 1.00-01       | 6.25+00       | 5.91+00          | 5.81-01        |                 |                | 6.83+00       | 6.49+00          | 1.69-01                 | 1.61-01                 |
| 1.50-01       | 5.48+00       | 5.32+00          | 1.60-01        |                 |                | 5.64+00       | 5.48+00          | 1.40-01                 | 1.36-01                 |
| 2.00-01       | 4.96+00       | 4.88+00          | 6.48-02        |                 |                | 5.03+00       | 4.94+00          | 1.25-01                 | 1.22-01                 |
| 3.00-01       | 4.28+00       | 4.24+00          | 1.87-02        |                 |                | 4.30+00       | 4.26+00          | 1.06-01                 | 1.06-01                 |
| 4.00-01       | 3.82+00       | 3.80+00          | 8.08-03        |                 |                | 3.83+00       | 3.81+00          | 9.49-02                 | 9.44-02                 |
| 5.00-01       | 3.48+00       | 3.47+00          | 4.35-03        |                 |                | 3.49+00       | 3.48+00          | 8.64-02                 | 8.61-02                 |
| 6.00-01       | 3.22+00       | 3.21+00          | 2.72-03        |                 |                | 3.22+00       | 3.21+00          | 7.97-02                 | 7.96-02                 |
| 8.00-01       | 2.83+00       | 2.82+00          | 1.37-03        |                 |                | 2.83+00       | 2.82+00          | 7.01-02                 | 6.99-02                 |
| 1.00+00       | 2.54+00       | 2.54+00          | 8.50-04        |                 |                | 2.54+00       | 2.54+00          | 6.28-02                 | 6.29-02                 |
| 1.50+00       |               | 2.06+00          | 3.99-04        | 6.52-03         |                |               | 2.07+00          |                         | 5.12-02                 |
| 2.00+00       |               | 1.76+00          | 2.53-04        | 2.58-02         |                |               | 1.79+00          |                         | 4.42-02                 |
| 3.00+00       |               | 1.38+00          | 1.40-04        | 7.36-02         | 4.83-04        |               | 1.46+00          |                         | 3.61-02                 |
| 4.00+00       |               | 1.15+00          | 9.53-05        | 1.19-01         | 1.98-03        |               | 1.28+00          |                         | 3.16-02                 |
| 5.00+00       |               | 9.97-01          | 7.27-05        | 1.60-01         | 3.89-03        |               | 1.16+00          |                         | 2.87-02                 |
| 6.00+00       |               | 8.81-01          | 5.79-05        | 1.95-01         | 5.99-03        |               | 1.08+00          |                         | 2.68-02                 |
| 8.00+00       |               | 7.21-01          | 4.14-05        | 2.55-01         | 1.02-02        |               | 9.86-01          |                         | 2.44-02                 |
| 1.00+01       |               | 6.14-01          | 3.23-05        | 3.04-01         | 1.40-02        |               | 9.32-01          |                         | 2.31-02                 |
| 1.50+01       |               | 4.54-01          |                | 3.96-01         | 2.18-02        |               | 8.73-01          |                         | 2.16-02                 |
| 2.00+01       |               | 3.65-01          |                | 4.63-01         | 2.80-02        |               | 8.56-01          |                         | 2.12-02                 |
| 3.00+01       |               | 2.66-01          |                | 5.57-01         | 3.73-02        |               | 8.60-01          |                         | 2.13-02                 |
| 4.00+01       |               | 2.11-01          |                | 6.22-01         | 4.42-02        |               | 8.77-01          |                         | 2.17-02                 |
| 5.00+01       |               | 1.76-01          |                | 6.71-01         | 4.95-02        |               | 8.97-01          |                         | 2.22-02                 |
| 6.00+01       |               | 1.52-01          |                | 7.10-01         | 5.37-02        |               | 9.15-01          |                         | 2.27-02                 |
| 8.00+01       |               | 1.20-01          |                | 7.67-01         | 6.02-02        |               | 9.47-01          |                         | 2.35-02                 |
| 1.00+02       |               | 9.93-02          |                | 8.09-01         | 6.50-02        |               | 9.73-01          |                         | 2.41-02                 |
| 1.50+02       |               | 7.07-02          |                | 8.76-01         | 7.34-02        |               | 1.02+00          |                         | 2.53-02                 |
| 2.00+02       |               | 5.54-02          |                | 9.16-01         | 7.91-02        |               | 1.05+00          |                         | 2.60-02                 |
| 3.00+02       |               | 3.93-02          |                | 9.64-01         | 8.63-02        |               | 1.09+00          |                         | 2.70-02                 |
| 4.00+02       |               | 3.08-02          |                | 9.91-01         | 9.10-02        |               | 1.11+00          |                         | 2.76-02                 |
| 5.00+02       |               | 2.55-02          |                | 1.01+00         | 9.43-02        |               | 1.13+00          |                         | 2.80-02                 |
| 6.00+02       |               | 2.18-02          |                | 1.02+00         | 9.67-02        |               | 1.14+00          |                         | 2.83-02                 |
| 8.00+02       |               | 1.70-02          |                | 1.04+00         | 1.00-01        |               | 1.16+00          |                         | 2.87-02                 |
| 1.00+03       |               | 1.40-02          |                | 1.05+00         | 1.03-01        |               | 1.17+00          |                         | 2.90-02                 |
| 1.50+03       |               | 9.79-03          |                | 1.07+00         | 1.07-01        |               | 1.18+00          |                         | 2.93-02                 |
| 2.00+03       |               | 7.58-03          |                | 1.08+00         | 1.10-01        |               | 1.19+00          |                         | 2.96-02                 |
| 3.00+03       |               | 5.27-03          |                | 1.09+00         | 1.12-01        |               | 1.20+00          |                         | 2.98-02                 |
| 4.00+03       |               | 4.07-03          |                | 1.09+00         | 1.14-01        |               | 1.21+00          |                         | 3.00-02                 |
| 5.00+03       |               | 3.33-03          |                | 1.10+00         | 1.15-01        |               | 1.21+00          |                         | 3.01-02                 |
| 6.00+03       |               | 2.82-03          |                | 1.10+00         | 1.16-01        |               | 1.22+00          |                         | 3.02-02                 |
| 8.00+03       |               | 2.17-03          |                | 1.10+00         | 1.17-01        |               | 1.22+00          |                         | 3.02-02                 |
| 1.00+04       |               | 1.77-03          |                | 1.10+00         | 1.17-01        |               | 1.22+00          |                         | 3.03-02                 |
| 1.50+04       |               | 1.23-03          |                | 1.11+00         | 1.18-01        |               | 1.23+00          |                         | 3.03-02                 |
| 2.00+04       |               | 9.42-04          |                | 1.11+00         | 1.18-01        |               | 1.23+00          |                         | 3.04-02                 |
| 3.00+04       |               | 6.50-04          |                | 1.11+00         | 1.19-01        |               | 1.23+00          |                         | 3.04-02                 |
| 4.00+04       |               | 4.99-04          |                | 1.11+00         | 1.19-01        |               | 1.23+00          |                         | 3.05-02                 |
| 5.00+04       |               | 4.06-04          |                | 1.11+00         | 1.19-01        |               | 1.23+00          |                         | 3.05-02                 |
| 6.00+04       |               | 3.43-04          |                | 1.11+00         | 1.20-01        |               | 1.23+00          |                         | 3.05-02                 |
| 8.00+04       |               | 2.63-04          |                | 1.11+00         | 1.20-01        |               | 1.23+00          |                         | 3.05-02                 |
| 1.00+05       |               | 2.14-04          |                | 1.11+00         | 1.20-01        |               | 1.23+00          |                         | 3.05-02                 |

(b/atom) x .024770 = cm<sup>2</sup>/g

Table 3.-9. ALUMINUM, Z=13

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.04+01       | 8.32+00          | 1.15+03        |                 |                | 1.18+03       | 1.16+03          | 2.63+01            | 2.58+01            |
| 1.50-02       | 2.03+01       | 8.17+00          | 3.35+02        |                 |                | 3.55+02       | 3.43+02          | 7.93+00            | 7.66+00            |
| 2.00-02       | 1.57+01       | 8.03+00          | 1.37+02        |                 |                | 1.53+02       | 1.45+02          | 3.41+00            | 3.24+00            |
| 3.00-02       | 1.17+01       | 7.77+00          | 3.85+01        |                 |                | 5.02+01       | 4.63+01          | 1.12+00            | 1.03+00            |
| 4.00-02       | 9.89+00       | 7.52+00          | 1.55+01        |                 |                | 2.54+01       | 2.30+01          | 5.67-01            | 5.14-01            |
| 5.00-02       | 8.88+00       | 7.30+00          | 7.65+00        |                 |                | 1.65+01       | 1.49+01          | 3.69-01            | 3.34-01            |
| 6.00-02       | 8.22+00       | 7.09+00          | 4.33+00        |                 |                | 1.25+01       | 1.14+01          | 2.80-01            | 2.55-01            |
| 8.00-02       | 7.38+00       | 6.72+00          | 1.73+00        |                 |                | 9.11+00       | 8.45+00          | 2.03-01            | 1.89-01            |
| 1.00-01       | 6.83+00       | 6.41+00          | 8.45-01        |                 |                | 7.67+00       | 7.25+00          | 1.71-01            | 1.62-01            |
| 1.50-01       | 5.96+00       | 5.77+00          | 2.33-01        |                 |                | 6.19+00       | 6.00+00          | 1.38-01            | 1.34-01            |
| 2.00-01       | 5.39+00       | 5.28+00          | 9.53-02        |                 |                | 5.49+00       | 5.38+00          | 1.22-01            | 1.20-01            |
| 3.00-01       | 4.64+00       | 4.60+00          | 2.76-02        |                 |                | 4.67+00       | 4.62+00          | 1.04-01            | 1.03-01            |
| 4.00-01       | 4.14+00       | 4.12+00          | 1.19-02        |                 |                | 4.15+00       | 4.13+00          | 9.27-02            | 9.22-02            |
| 5.00-01       | 3.78+00       | 3.76+00          | 6.43-03        |                 |                | 3.78+00       | 3.77+00          | 8.44-02            | 8.41-02            |
| 6.00-01       | 3.49+00       | 3.48+00          | 4.02-03        |                 |                | 3.49+00       | 3.48+00          | 7.80-02            | 7.77-02            |
| 8.00-01       | 3.06+00       | 3.06+00          | 2.04-03        |                 |                | 3.06+00       | 3.06+00          | 6.84-02            | 6.83-02            |
| 1.00+00       | 2.75+00       | 2.75+00          | 1.26-03        |                 |                | 2.75+00       | 2.75+00          | 6.13-02            | 6.14-02            |
| 1.50+00       |               | 2.23+00          | 5.89-04        | 7.68-03         |                |               | 2.24+00          | 5.00-02            | 5.00-02            |
| 2.00+00       |               | 1.91+00          | 3.73-04        | 3.03-02         |                |               | 1.94+00          | 4.32-02            | 4.32-02            |
| 3.00+00       |               | 1.50+00          | 2.07-04        | 8.65-02         | 5.23-04        |               | 1.59+00          | 3.54-02            | 3.54-02            |
| 4.00+00       |               | 1.25+00          | 1.41-04        | 1.40-01         | 2.15-03        |               | 1.39+00          | 3.11-02            | 3.11-02            |
| 5.00+00       |               | 1.08+00          | 1.07-04        | 1.87-01         | 4.22-03        |               | 1.27+00          | 2.84-02            | 2.84-02            |
| 6.00+00       |               | 9.54-01          | 8.53-05        | 2.29-01         | 6.49-03        |               | 1.19+00          | 2.66-02            | 2.66-02            |
| 8.00+00       |               | 7.81-01          | 6.09-05        | 2.99-01         | 1.11-02        |               | 1.09+00          | 2.44-02            | 2.44-02            |
| 1.00+01       |               | 6.65-01          | 4.76-05        | 3.57-01         | 1.52-02        |               | 1.04+00          | 2.31-02            | 2.31-02            |
| 1.50+01       |               | 4.92-01          |                | 4.65-01         | 2.36-02        |               | 9.80-01          | 2.19-02            | 2.19-02            |
| 2.00+01       |               | 3.95-01          |                | 5.43-01         | 3.03-02        |               | 9.68-01          | 2.16-02            | 2.16-02            |
| 3.00+01       |               | 2.88-01          |                | 6.52-01         | 4.04-02        |               | 9.81-01          | 2.19-02            | 2.19-02            |
| 4.00+01       |               | 2.29-01          |                | 7.29-01         | 4.79-02        |               | 1.01+00          | 2.24-02            | 2.24-02            |
| 5.00+01       |               | 1.91-01          |                | 7.86-01         | 5.36-02        |               | 1.03+00          | 2.30-02            | 2.30-02            |
| 6.00+01       |               | 1.64-01          |                | 8.31-01         | 5.81-02        |               | 1.05+00          | 2.35-02            | 2.35-02            |
| 8.00+01       |               | 1.30-01          |                | 8.98-01         | 6.51-02        |               | 1.09+00          | 2.44-02            | 2.44-02            |
| 1.00+02       |               | 1.08-01          |                | 9.46-01         | 7.03-02        |               | 1.12+00          | 2.51-02            | 2.51-02            |
| 1.50+02       |               | 7.66-02          |                | 1.02+00         | 7.93-02        |               | 1.18+00          | 2.63-02            | 2.63-02            |
| 2.00+02       |               | 6.01-02          |                | 1.07+00         | 8.53-02        |               | 1.21+00          | 2.71-02            | 2.71-02            |
| 3.00+02       |               | 4.26-02          |                | 1.13+00         | 9.31-02        |               | 1.26+00          | 2.82-02            | 2.82-02            |
| 4.00+02       |               | 3.33-02          |                | 1.16+00         | 9.81-02        |               | 1.29+00          | 2.88-02            | 2.88-02            |
| 5.00+02       |               | 2.76-02          |                | 1.18+00         | 1.02-01        |               | 1.31+00          | 2.92-02            | 2.92-02            |
| 6.00+02       |               | 2.36-02          |                | 1.19+00         | 1.04-01        |               | 1.32+00          | 2.95-02            | 2.95-02            |
| 8.00+02       |               | 1.85-02          |                | 1.22+00         | 1.08-01        |               | 1.34+00          | 3.00-02            | 3.00-02            |
| 1.00+03       |               | 1.52-02          |                | 1.23+00         | 1.11-01        |               | 1.35+00          | 3.02-02            | 3.02-02            |
| 1.50+03       |               | 1.06-02          |                | 1.25+00         | 1.15-01        |               | 1.37+00          | 3.07-02            | 3.07-02            |
| 2.00+03       |               | 8.21-03          |                | 1.26+00         | 1.18-01        |               | 1.38+00          | 3.09-02            | 3.09-02            |
| 3.00+03       |               | 5.71-03          |                | 1.27+00         | 1.21-01        |               | 1.40+00          | 3.12-02            | 3.12-02            |
| 4.00+03       |               | 4.40-03          |                | 1.28+00         | 1.22-01        |               | 1.40+00          | 3.13-02            | 3.13-02            |
| 5.00+03       |               | 3.60-03          |                | 1.28+00         | 1.23-01        |               | 1.41+00          | 3.14-02            | 3.14-02            |
| 6.00+03       |               | 3.05-03          |                | 1.28+00         | 1.24-01        |               | 1.41+00          | 3.15-02            | 3.15-02            |
| 8.00+03       |               | 2.35-03          |                | 1.29+00         | 1.25-01        |               | 1.41+00          | 3.16-02            | 3.16-02            |
| 1.00+04       |               | 1.92-03          |                | 1.29+00         | 1.26-01        |               | 1.42+00          | 3.16-02            | 3.16-02            |
| 1.50+04       |               | 1.33-03          |                | 1.29+00         | 1.27-01        |               | 1.42+00          | 3.17-02            | 3.17-02            |
| 2.00+04       |               | 1.02-03          |                | 1.29+00         | 1.27-01        |               | 1.42+00          | 3.17-02            | 3.17-02            |
| 3.00+04       |               | 7.04-04          |                | 1.30+00         | 1.28-01        |               | 1.42+00          | 3.18-02            | 3.18-02            |
| 4.00+04       |               | 5.40-04          |                | 1.30+00         | 1.28-01        |               | 1.43+00          | 3.18-02            | 3.18-02            |
| 5.00+04       |               | 4.40-04          |                | 1.30+00         | 1.28-01        |               | 1.43+00          | 3.18-02            | 3.18-02            |
| 6.00+04       |               | 3.72-04          |                | 1.30+00         | 1.28-01        |               | 1.43+00          | 3.18-02            | 3.18-02            |
| 8.00+04       |               | 2.85-04          |                | 1.30+00         | 1.28-01        |               | 1.43+00          | 3.18-02            | 3.18-02            |
| 1.00+05       |               | 2.32-04          |                | 1.30+00         | 1.28-01        |               | 1.43+00          | 3.19-02            | 3.19-02            |

(b/atom) x .022320 = cm<sup>2</sup>/g

**Table 3.-10. SILICON, Z=14**

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.50+01       | 8.97+00          | 1.56+03        |                 |                | 1.59+03       | 1.57+03          | 3.42+01            | 3.36+01            |
| 1.50-02       | 2.34+01       | 8.80+00          | 4.56+02        |                 |                | 4.79+02       | 4.65+02          | 1.03+01            | 9.97+00            |
| 2.00-02       | 1.78+01       | 8.65+00          | 1.87+02        |                 |                | 2.05+02       | 1.96+02          | 4.39+00            | 4.19+00            |
| 3.00-02       | 1.31+01       | 8.36+00          | 5.29+01        |                 |                | 6.60+01       | 6.13+01          | 1.41+00            | 1.31+00            |
| 4.00-02       | 1.10+01       | 8.10+00          | 2.15+01        |                 |                | 3.25+01       | 2.96+01          | 6.96-01            | 6.35-01            |
| 5.00-02       | 9.79+00       | 7.86+00          | 1.06+01        |                 |                | 2.04+01       | 1.85+01          | 4.37-01            | 3.96-01            |
| 6.00-02       | 9.01+00       | 7.64+00          | 6.00+00        |                 |                | 1.50+01       | 1.36+01          | 3.22-01            | 2.92-01            |
| 8.00-02       | 8.04+00       | 7.24+00          | 2.42+00        |                 |                | 1.05+01       | 9.66+00          | 2.24-01            | 2.07-01            |
| 1.00-01       | 7.41+00       | 6.90+00          | 1.19+00        |                 |                | 8.60+00       | 8.09+00          | 1.84-01            | 1.73-01            |
| 1.50-01       | 6.44+00       | 6.21+00          | 3.29-01        |                 |                | 6.77+00       | 6.54+00          | 1.45-01            | 1.40-01            |
| 2.00-01       | 5.82+00       | 5.69+00          | 1.34-01        |                 |                | 5.96+00       | 5.82+00          | 1.28-01            | 1.25-01            |
| 3.00-01       | 5.01+00       | 4.95+00          | 3.91-02        |                 |                | 5.05+00       | 4.99+00          | 1.08-01            | 1.07-01            |
| 4.00-01       | 4.47+00       | 4.43+00          | 1.69-02        |                 |                | 4.49+00       | 4.45+00          | 9.62-02            | 9.54-02            |
| 5.00-01       | 4.07+00       | 4.05+00          | 9.15-03        |                 |                | 4.08+00       | 4.06+00          | 8.75-02            | 8.70-02            |
| 6.00-01       | 3.76+00       | 3.75+00          | 5.72-03        |                 |                | 3.77+00       | 3.75+00          | 8.08-02            | 8.05-02            |
| 8.00-01       | 3.29+00       | 3.29+00          | 3.29-03        |                 |                | 3.30+00       | 3.29+00          | 7.07-02            | 7.06-02            |
| 1.00+00       |               | 2.96+00          | 1.79-03        |                 |                |               | 2.96+00          |                    | 6.35-02            |
| 1.50+00       |               | 2.40+00          | 8.36-04        | 8.94-03         |                |               | 2.41+00          |                    | 5.18-02            |
| 2.00+00       |               | 2.05+00          | 5.30-04        | 3.52-02         |                |               | 2.09+00          |                    | 4.48-02            |
| 3.00+00       |               | 1.61+00          | 2.93-04        | 1.00-01         | 5.63-04        |               | 1.72+00          |                    | 3.68-02            |
| 4.00+00       |               | 1.35+00          | 1.99-04        | 1.62-01         | 2.31-03        |               | 1.51+00          |                    | 3.24-02            |
| 5.00+00       |               | 1.16+00          | 1.42-04        | 2.17-01         | 4.54-03        |               | 1.38+00          |                    | 2.97-02            |
| 6.00+00       |               | 1.03+00          | 1.21-04        | 2.67-01         | 6.99-03        |               | 1.30+00          |                    | 2.79-02            |
| 8.00+00       |               | 8.41-01          | 8.61-05        | 3.47-01         | 1.20-02        |               | 1.20+00          |                    | 2.57-02            |
| 1.00+01       |               | 7.16-01          | 6.74-05        | 4.13-01         | 1.63-02        |               | 1.15+00          |                    | 2.46-02            |
| 1.50+01       |               | 5.30-01          |                | 5.38-01         | 2.55-02        |               | 1.09+00          |                    | 2.34-02            |
| 2.00+01       |               | 4.25-01          |                | 6.28-01         | 3.27-02        |               | 1.09+00          |                    | 2.33-02            |
| 3.00+01       |               | 3.10-01          |                | 7.55-01         | 4.35-02        |               | 1.11+00          |                    | 2.38-02            |
| 4.00+01       |               | 2.46-01          |                | 8.43-01         | 5.16-02        |               | 1.14+00          |                    | 2.45-02            |
| 5.00+01       |               | 2.05-01          |                | 9.13-01         | 5.76-02        |               | 1.18+00          |                    | 2.52-02            |
| 6.00+01       |               | 1.77-01          |                | 9.61-01         | 6.25-02        |               | 1.20+00          |                    | 2.57-02            |
| 8.00+01       |               | 1.40-01          |                | 1.04+00         | 6.99-02        |               | 1.25+00          |                    | 2.67-02            |
| 1.00+02       |               | 1.16-01          |                | 1.09+00         | 7.55-02        |               | 1.28+00          |                    | 2.75-02            |
| 1.50+02       |               | 8.25-02          |                | 1.18+00         | 8.51-02        |               | 1.35+00          |                    | 2.89-02            |
| 2.00+02       |               | 6.47-02          |                | 1.24+00         | 9.16-02        |               | 1.39+00          |                    | 2.99-02            |
| 3.00+02       |               | 4.58-02          |                | 1.30+00         | 9.98-02        |               | 1.54+00          |                    | 3.10-02            |
| 4.00+02       |               | 3.59-02          |                | 1.34+00         | 1.05-01        |               | 1.48+00          |                    | 3.17-02            |
| 5.00+02       |               | 2.97-02          |                | 1.36+00         | 1.09-01        |               | 1.50+00          |                    | 3.22-02            |
| 6.00+02       |               | 2.55-02          |                | 1.38+00         | 1.12-01        |               | 1.52+00          |                    | 3.25-02            |
| 8.00+02       |               | 1.99-02          |                | 1.40+00         | 1.16-01        |               | 1.54+00          |                    | 3.30-02            |
| 1.00+03       |               | 1.63-02          |                | 1.42+00         | 1.19-01        |               | 1.55+00          |                    | 3.33-02            |
| 1.50+03       |               | 1.14-02          |                | 1.44+00         | 1.23-01        |               | 1.58+00          |                    | 3.38-02            |
| 2.00+03       |               | 8.84-03          |                | 1.45+00         | 1.26-01        |               | 1.59+00          |                    | 3.41-02            |
| 3.00+03       |               | 6.15-03          |                | 1.47+00         | 1.29-01        |               | 1.60+00          |                    | 3.44-02            |
| 4.00+03       |               | 4.74-03          |                | 1.47+00         | 1.31-01        |               | 1.61+00          |                    | 3.45-02            |
| 5.00+03       |               | 3.88-03          |                | 1.48+00         | 1.32-01        |               | 1.61+00          |                    | 3.46-02            |
| 6.00+03       |               | 3.29-03          |                | 1.48+00         | 1.33-01        |               | 1.62+00          |                    | 3.47-02            |
| 8.00+03       |               | 2.53-03          |                | 1.49+00         | 1.34-01        |               | 1.62+00          |                    | 3.48-02            |
| 1.00+04       |               | 2.07-03          |                | 1.49+00         | 1.34-01        |               | 1.63+00          |                    | 3.48-02            |
| 1.50+04       |               | 1.43-03          |                | 1.49+00         | 1.35-01        |               | 1.63+00          |                    | 3.49-02            |
| 2.00+04       |               | 1.10-03          |                | 1.49+00         | 1.36-01        |               | 1.63+00          |                    | 3.50-02            |
| 3.00+04       |               | 7.58-04          |                | 1.50+00         | 1.36-01        |               | 1.63+00          |                    | 3.50-02            |
| 4.00+04       |               | 5.82-04          |                | 1.50+00         | 1.37-01        |               | 1.64+00          |                    | 3.51-02            |
| 5.00+04       |               | 4.74-04          |                | 1.50+00         | 1.37-01        |               | 1.64+00          |                    | 3.51-02            |
| 6.00+04       |               | 4.01-04          |                | 1.50+00         | 1.37-01        |               | 1.64+00          |                    | 3.51-02            |
| 8.00+04       |               | 3.07-04          |                | 1.50+00         | 1.37-01        |               | 1.64+00          |                    | 3.51-02            |
| 1.00+05       |               | 2.50-04          |                | 1.50+00         | 1.37-01        |               | 1.64+00          |                    | 3.51-02            |

(b/atom) x .021440 = cm<sup>2</sup>/g

Table 3.-11. PHOSPHORUS, Z=15

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.99+01       | 9.61+00          | 2.06+03        |                 |                | 2.10+03       | 2.07+03          | 4.08+01            | 4.02+01            |
| 1.50-02       | 2.66+01       | 9.43+00          | 6.10+02        |                 |                | 6.37+02       | 6.19+02          | 1.24+01            | 1.20+01            |
| 2.00-02       | 2.02+01       | 9.27+00          | 2.53+02        |                 |                | 2.73+02       | 2.62+02          | 5.31+00            | 5.10+00            |
| 3.00-02       | 1.46+01       | 8.96+00          | 7.10+01        |                 |                | 8.56+01       | 8.00+01          | 1.66+00            | 1.55+00            |
| 4.00-02       | 1.21+01       | 8.68+00          | 2.89+01        |                 |                | 4.10+01       | 3.76+01          | 7.97-01            | 7.31-01            |
| 5.00-02       | 1.07+01       | 8.42+00          | 1.44+01        |                 |                | 2.51+01       | 2.28+01          | 4.89-01            | 4.44-01            |
| 6.00-02       | 9.84+00       | 8.18+00          | 8.16+00        |                 |                | 1.80+01       | 1.63+01          | 3.50-01            | 3.18-01            |
| 8.00-02       | 8.71+00       | 7.76+00          | 3.31+00        |                 |                | 1.20+01       | 1.11+01          | 2.34-01            | 2.15-01            |
| 1.00-01       | 8.00+00       | 7.39+00          | 1.61+00        |                 |                | 9.61+00       | 9.00+00          | 1.87-01            | 1.75-01            |
| 1.50-01       | 6.93+00       | 6.65+00          | 4.53-01        |                 |                | 7.39+00       | 7.11+00          | 1.44-01            | 1.38-01            |
| 2.00-01       | 6.25+00       | 6.10+00          | 1.85-01        |                 |                | 6.44+00       | 6.28+00          | 1.25-01            | 1.22-01            |
| 3.00-01       | 5.38+00       | 5.30+00          | 5.41-02        |                 |                | 5.43+00       | 5.36+00          | 1.06-01            | 1.04-01            |
| 4.00-01       | 4.79+00       | 4.75+00          | 2.35-02        |                 |                | 4.81+00       | 4.78+00          | 9.36-02            | 9.28-02            |
| 5.00-01       | 4.36+00       | 4.34+00          | 1.27-02        |                 |                | 4.37+00       | 4.35+00          | 8.50-02            | 8.46-02            |
| 6.00-01       | 4.03+00       | 4.01+00          | 7.95-03        |                 |                | 4.03+00       | 4.02+00          | 7.84-02            | 7.82-02            |
| 8.00-01       | 3.54+00       | 3.53+00          | 4.01-03        |                 |                | 3.54+00       | 3.53+00          | 6.88-02            | 6.86-02            |
| 1.00+00       |               | 3.17+00          | 2.49-03        |                 |                |               | 3.17+00          |                    | 6.17-02            |
| 1.50+00       |               | 2.58+00          | 1.17-03        | 1.03-02         |                |               | 2.59+00          |                    | 5.03-02            |
| 2.00+00       |               | 2.20+00          | 7.36-04        | 4.05-02         |                |               | 2.24+00          |                    | 4.36-02            |
| 3.00+00       |               | 1.73+00          | 4.07-04        | 1.15-01         | 6.04-04        |               | 1.85+00          |                    | 3.59-02            |
| 4.00+00       |               | 1.44+00          | 2.76-04        | 1.86-01         | 2.48-03        |               | 1.63+00          |                    | 3.17-02            |
| 5.00+00       |               | 1.25+00          | 2.11-04        | 2.49-01         | 4.87-03        |               | 1.50+00          |                    | 2.92-02            |
| 6.00+00       |               | 1.10+00          | 1.67-04        | 3.04-01         | 7.49-03        |               | 1.41+00          |                    | 2.75-02            |
| 8.00+00       |               | 9.01-01          | 1.19-04        | 3.98-01         | 1.28-02        |               | 1.31+00          |                    | 2.55-02            |
| 1.00+01       |               | 7.67-01          | 9.32-05        | 4.73-01         | 1.75-02        |               | 1.26+00          |                    | 2.45-02            |
| 1.50+01       |               | 5.68-01          |                | 6.16-01         | 2.73-02        |               | 1.21+00          |                    | 2.36-02            |
| 2.00+01       |               | 4.56-01          |                | 7.20-01         | 3.50-02        |               | 1.21+00          |                    | 2.35-02            |
| 3.00+01       |               | 3.32-01          |                | 8.66-01         | 4.66-02        |               | 1.24+00          |                    | 2.42-02            |
| 4.00+01       |               | 2.64-01          |                | 9.67-01         | 5.52-02        |               | 1.29+00          |                    | 2.50-02            |
| 5.00+01       |               | 2.20-01          |                | 1.04+00         | 6.17-02        |               | 1.32+00          |                    | 2.57-02            |
| 6.00+01       |               | 1.90-01          |                | 1.10+00         | 6.68-02        |               | 1.36+00          |                    | 2.64-02            |
| 8.00+01       |               | 1.50-01          |                | 1.19+00         | 7.47-02        |               | 1.41+00          |                    | 2.74-02            |
| 1.00+02       |               | 1.24-01          |                | 1.25+00         | 8.06-02        |               | 1.45+00          |                    | 2.83-02            |
| 1.50+02       |               | 8.84-02          |                | 1.35+00         | 9.09-02        |               | 1.53+00          |                    | 2.98-02            |
| 2.00+02       |               | 6.93-02          |                | 1.41+00         | 9.78-02        |               | 1.58+00          |                    | 3.07-02            |
| 3.00+02       |               | 4.91-02          |                | 1.49+00         | 1.06-01        |               | 1.64+00          |                    | 3.19-02            |
| 4.00+02       |               | 3.85-02          |                | 1.53+00         | 1.12-01        |               | 1.68+00          |                    | 3.27-02            |
| 5.00+02       |               | 3.18-02          |                | 1.56+00         | 1.16-01        |               | 1.71+00          |                    | 3.32-02            |
| 6.00+02       |               | 2.73-02          |                | 1.58+00         | 1.19-01        |               | 1.72+00          |                    | 3.35-02            |
| 8.00+02       |               | 2.13-02          |                | 1.60+00         | 1.23-01        |               | 1.75+00          |                    | 3.40-02            |
| 1.00+03       |               | 1.75-02          |                | 1.62+00         | 1.26-01        |               | 1.77+00          |                    | 3.44-02            |
| 1.50+03       |               | 1.22-02          |                | 1.65+00         | 1.31-01        |               | 1.79+00          |                    | 3.48-02            |
| 2.00+03       |               | 9.47-03          |                | 1.66+00         | 1.34-01        |               | 1.81+00          |                    | 3.51-02            |
| 3.00+03       |               | 6.58-03          |                | 1.68+00         | 1.37-01        |               | 1.82+00          |                    | 3.54-02            |
| 4.00+03       |               | 5.08-03          |                | 1.69+00         | 1.39-01        |               | 1.83+00          |                    | 3.56-02            |
| 5.00+03       |               | 4.16-03          |                | 1.69+00         | 1.40-01        |               | 1.84+00          |                    | 3.57-02            |
| 6.00+03       |               | 3.52-03          |                | 1.70+00         | 1.41-01        |               | 1.84+00          |                    | 3.58-02            |
| 8.00+03       |               | 2.71-03          |                | 1.70+00         | 1.42-01        |               | 1.85+00          |                    | 3.59-02            |
| 1.00+04       |               | 2.22-03          |                | 1.70+00         | 1.43-01        |               | 1.85+00          |                    | 3.59-02            |
| 1.50+04       |               | 1.53-03          |                | 1.71+00         | 1.44-01        |               | 1.85+00          |                    | 3.60-02            |
| 2.00+04       |               | 1.18-03          |                | 1.71+00         | 1.44-01        |               | 1.86+00          |                    | 3.61-02            |
| 3.00+04       |               | 8.12-04          |                | 1.71+00         | 1.45-01        |               | 1.86+00          |                    | 3.61-02            |
| 4.00+04       |               | 6.24-04          |                | 1.71+00         | 1.45-01        |               | 1.86+00          |                    | 3.61-02            |
| 5.00+04       |               | 5.08-04          |                | 1.71+00         | 1.45-01        |               | 1.86+00          |                    | 3.62-02            |
| 6.00+04       |               | 4.29-04          |                | 1.71+00         | 1.45-01        |               | 1.86+00          |                    | 3.62-02            |
| 8.00+04       |               | 3.29-04          |                | 1.71+00         | 1.46-01        |               | 1.86+00          |                    | 3.62-02            |
| 1.00+05       |               | 2.68-04          |                | 1.72+00         | 1.46-01        |               | 1.86+00          |                    | 3.62-02            |

(b/atom) x .019440 = cm<sup>2</sup>/g

**Table 3.-12. SULFUR, Z=16**

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 4.52+01       | 1.02+01          | 2.67+03        |                 |                | 2.72+03       | 2.68+03          | 5.10+01            | 5.03+01            |
| 1.50-02       | 3.03+01       | 1.01+01          | 8.00+02        |                 |                | 8.30+02       | 8.10+02          | 1.56+01            | 1.52+01            |
| 2.00-02       | 2.28+01       | 9.89+00          | 3.32+02        |                 |                | 3.55+02       | 3.42+02          | 6.66+00            | 6.42+00            |
| 3.00-02       | 1.62+01       | 9.56+00          | 9.40+01        |                 |                | 1.10+02       | 1.04+02          | 2.07+00            | 1.94+00            |
| 4.00-02       | 1.33+01       | 9.26+00          | 3.82+01        |                 |                | 5.15+01       | 4.75+01          | 9.68-01            | 8.91-01            |
| 5.00-02       | 1.17+01       | 8.98+00          | 1.91+01        |                 |                | 3.08+01       | 2.81+01          | 5.79-01            | 5.27-01            |
| 6.00-02       | 1.07+01       | 8.73+00          | 1.08+01        |                 |                | 2.15+01       | 1.95+01          | 4.04-01            | 3.67-01            |
| 8.00-02       | 9.41+00       | 8.28+00          | 4.40+00        |                 |                | 1.38+01       | 1.27+01          | 2.59-01            | 2.38-01            |
| 1.00-01       | 8.61+00       | 7.88+00          | 2.16+00        |                 |                | 1.08+01       | 1.00+01          | 2.02-01            | 1.89-01            |
| 1.50-01       | 7.43+00       | 7.10+00          | 6.10-01        |                 |                | 8.04+00       | 7.71+00          | 1.51-01            | 1.45-01            |
| 2.00-01       | 6.69+00       | 6.50+00          | 2.51-01        |                 |                | 6.94+00       | 6.75+00          | 1.30-01            | 1.27-01            |
| 3.00-01       | 5.73+00       | 5.66+00          | 7.35-02        |                 |                | 5.81+00       | 5.73+00          | 1.09-01            | 1.08-01            |
| 4.00-01       | 5.11+00       | 5.07+00          | 3.19-02        |                 |                | 5.14+00       | 5.10+00          | 9.66-02            | 9.58-02            |
| 5.00-01       | 4.66+00       | 4.63+00          | 1.73-02        |                 |                | 4.67+00       | 4.65+00          | 8.78-02            | 8.72-02            |
| 6.00-01       | 4.30+00       | 4.28+00          | 1.08-02        |                 |                | 4.31+00       | 4.29+00          | 8.10-02            | 8.06-02            |
| 8.00-01       | 3.77+00       | 3.76+00          | 5.48-03        |                 |                | 3.77+00       | 3.77+00          | 7.09-02            | 7.08-02            |
| 1.00+00       | 3.39+00       | 3.38+00          | 3.39-03        |                 |                | 3.40+00       | 3.39+00          | 6.38-02            | 6.36-02            |
| 1.50+00       | 2.74+00       | 2.75+00          | 1.59-03        | 1.18-02         |                | 2.76+00       | 2.76+00          | 5.18-02            | 5.19-02            |
| 2.00+00       |               | 2.34+00          | 1.00-03        | 4.62-02         |                |               | 2.39+00          |                    | 4.49-02            |
| 3.00+00       |               | 1.84+00          | 5.53-04        | 1.31-01         | 6.44-04        |               | 1.98+00          |                    | 3.71-02            |
| 4.00+00       |               | 1.54+00          | 3.74-04        | 2.12-01         | 2.64-03        |               | 1.75+00          |                    | 3.29-02            |
| 5.00+00       |               | 1.33+00          | 2.86-04        | 2.83-01         | 5.19-03        |               | 1.62+00          |                    | 3.04-02            |
| 6.00+00       |               | 1.17+00          | 2.27-04        | 3.46-01         | 7.99-03        |               | 1.53+00          |                    | 2.87-02            |
| 8.00+00       |               | 9.61-01          | 1.62-04        | 4.52-01         | 1.37-02        |               | 1.43+00          |                    | 2.68-02            |
| 1.00+01       |               | 8.18-01          | 1.26-04        | 5.38-01         | 1.87-02        |               | 1.38+00          |                    | 2.58-02            |
| 1.50+01       |               | 6.06-01          |                | 7.00-01         | 2.91-02        |               | 1.34+00          |                    | 2.51-02            |
| 2.00+01       |               | 4.86-01          |                | 8.18-01         | 3.73-02        |               | 1.34+00          |                    | 2.52-02            |
| 3.00+01       |               | 3.54-01          |                | 9.83-01         | 4.98-02        |               | 1.39+00          |                    | 2.61-02            |
| 4.00+01       |               | 2.81-01          |                | 1.10+00         | 5.88-02        |               | 1.44+00          |                    | 2.70-02            |
| 5.00+01       |               | 2.35-01          |                | 1.18+00         | 6.57-02        |               | 1.48+00          |                    | 2.78-02            |
| 6.00+01       |               | 2.02-01          |                | 1.25+00         | 7.11-02        |               | 1.52+00          |                    | 2.86-02            |
| 8.00+01       |               | 1.60-01          |                | 1.35+00         | 7.95-02        |               | 1.59+00          |                    | 2.98-02            |
| 1.00+02       |               | 1.33-01          |                | 1.42+00         | 8.58-02        |               | 1.64+00          |                    | 3.07-02            |
| 1.50+02       |               | 9.43-02          |                | 1.53+00         | 9.67-02        |               | 1.72+00          |                    | 3.24-02            |
| 2.00+02       |               | 7.39-02          |                | 1.60+00         | 1.04-01        |               | 1.78+00          |                    | 3.34-02            |
| 3.00+02       |               | 5.24-02          |                | 1.68+00         | 1.13-01        |               | 1.85+00          |                    | 3.48-02            |
| 4.00+02       |               | 4.10-02          |                | 1.73+00         | 1.19-01        |               | 1.89+00          |                    | 3.56-02            |
| 5.00+02       |               | 3.40-02          |                | 1.77+00         | 1.23-01        |               | 1.92+00          |                    | 3.61-02            |
| 6.00+02       |               | 2.91-02          |                | 1.79+00         | 1.26-01        |               | 1.95+00          |                    | 3.65-02            |
| 8.00+02       |               | 2.27-02          |                | 1.82+00         | 1.31-01        |               | 1.97+00          |                    | 3.70-02            |
| 1.00+03       |               | 1.87-02          |                | 1.84+00         | 1.34-01        |               | 1.99+00          |                    | 3.74-02            |
| 1.50+03       |               | 1.30-02          |                | 1.87+00         | 1.39-01        |               | 2.02+00          |                    | 3.80-02            |
| 2.00+03       |               | 1.01-02          |                | 1.89+00         | 1.42-01        |               | 2.04+00          |                    | 3.83-02            |
| 3.00+03       |               | 7.02-03          |                | 1.90+00         | 1.45-01        |               | 2.06+00          |                    | 3.86-02            |
| 4.00+03       |               | 5.42-03          |                | 1.91+00         | 1.47-01        |               | 2.06+00          |                    | 3.88-02            |
| 5.00+03       |               | 4.43-03          |                | 1.92+00         | 1.49-01        |               | 2.07+00          |                    | 3.89-02            |
| 6.00+03       |               | 3.76-03          |                | 1.92+00         | 1.49-01        |               | 2.08+00          |                    | 3.90-02            |
| 8.00+03       |               | 2.90-03          |                | 1.93+00         | 1.50-01        |               | 2.08+00          |                    | 3.91-02            |
| 1.00+04       |               | 2.37-03          |                | 1.93+00         | 1.51-01        |               | 2.08+00          |                    | 3.91-02            |
| 1.50+04       |               | 1.63-03          |                | 1.94+00         | 1.52-01        |               | 2.09+00          |                    | 3.92-02            |
| 2.00+04       |               | 1.26-03          |                | 1.94+00         | 1.53-01        |               | 2.09+00          |                    | 3.93-02            |
| 3.00+04       |               | 8.66-04          |                | 1.94+00         | 1.53-01        |               | 2.09+00          |                    | 3.93-02            |
| 4.00+04       |               | 6.65-04          |                | 1.94+00         | 1.54-01        |               | 2.10+00          |                    | 3.94-02            |
| 5.00+04       |               | 5.42-04          |                | 1.94+00         | 1.54-01        |               | 2.10+00          |                    | 3.94-02            |
| 6.00+04       |               | 4.58-04          |                | 1.94+00         | 1.54-01        |               | 2.10+00          |                    | 3.94-02            |
| 8.00+04       |               | 3.51-04          |                | 1.94+00         | 1.54-01        |               | 2.10+00          |                    | 3.94-02            |
| 1.00+05       |               | 2.86-04          |                | 1.94+00         | 1.54-01        |               | 2.10+00          |                    | 3.94-02            |

(b/atom) x .018780 = cm<sup>2</sup>/g



Table 3.-13. ARGON, Z=18

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 5.66+01       | 1.15+01          | 4.22+03        |                 |                | 4.28+03       | 4.23+03          | 6.45+01            | 6.38+01            |
| 1.50-02       | 3.84+01       | 1.13+01          | 1.28+03        |                 |                | 1.32+03       | 1.29+03          | 1.99+01            | 1.95+01            |
| 2.00-02       | 2.87+01       | 1.11+01          | 5.37+02        |                 |                | 5.66+02       | 5.48+02          | 8.53+00            | 8.27+00            |
| 3.00-02       | 1.97+01       | 1.08+01          | 1.54+02        |                 |                | 1.74+02       | 1.65+02          | 2.62+00            | 2.48+00            |
| 4.00-02       | 1.59+01       | 1.04+01          | 6.34+01        |                 |                | 7.93+01       | 7.38+01          | 1.20+00            | 1.11+00            |
| 5.00-02       | 1.38+01       | 1.01+01          | 3.17+01        |                 |                | 4.55+01       | 4.18+01          | 6.87-01            | 6.30-01            |
| 6.00-02       | 1.25+01       | 9.82+00          | 1.80+01        |                 |                | 3.05+01       | 2.78+01          | 4.60-01            | 4.20-01            |
| 8.00-02       | 1.09+01       | 9.31+00          | 7.40+00        |                 |                | 1.83+01       | 1.67+01          | 2.75-01            | 2.52-01            |
| 1.00-01       | 9.87+00       | 8.87+00          | 3.65+00        |                 |                | 1.35+01       | 1.25+01          | 2.04-01            | 1.89-01            |
| 1.50-01       | 8.44+00       | 7.98+00          | 1.05+00        |                 |                | 9.49+00       | 9.03+00          | 1.43-01            | 1.36-01            |
| 2.00-01       | 7.58+00       | 7.32+00          | 4.34-01        |                 |                | 8.01+00       | 7.75+00          | 1.21-01            | 1.17-01            |
| 3.00-01       | 6.48+00       | 6.36+00          | 1.28-01        |                 |                | 6.61+00       | 6.49+00          | 9.96-02            | 9.79-02            |
| 4.00-01       | 5.77+00       | 5.70+00          | 5.57-02        |                 |                | 5.82+00       | 5.76+00          | 8.78-02            | 8.68-02            |
| 5.00-01       | 5.24+00       | 5.21+00          | 3.01-02        |                 |                | 5.27+00       | 5.24+00          | 7.95-02            | 7.90-02            |
| 6.00-01       | 4.84+00       | 4.82+00          | 1.89-02        |                 |                | 4.86+00       | 4.84+00          | 7.33-02            | 7.29-02            |
| 8.00-01       | 4.24+00       | 4.23+00          | 9.60-03        |                 |                | 4.25+00       | 4.24+00          | 6.41-02            | 6.40-02            |
| 1.00+00       | 3.82+00       | 3.80+00          | 5.95-03        |                 |                | 3.82+00       | 3.81+00          | 5.76-02            | 5.75-02            |
| 1.50+00       | 3.10+00       | 3.09+00          | 2.77-03        | 1.51-02         |                | 3.11+00       | 3.11+00          | 4.70-02            | 4.69-02            |
| 2.00+00       |               | 2.64+00          | 1.75-03        | 5.88-02         |                |               | 2.70+00          |                    | 4.07-02            |
| 3.00+00       |               | 2.08+00          | 9.66-04        | 1.66-01         | 7.24-04        |               | 2.24+00          |                    | 3.38-02            |
| 4.00+00       |               | 1.73+00          | 6.52-04        | 2.68-01         | 2.97-03        |               | 2.00+00          |                    | 3.02-02            |
| 5.00+00       |               | 1.49+00          | 4.96-04        | 3.58-01         | 5.84-03        |               | 1.86+00          |                    | 2.80-02            |
| 6.00+00       |               | 1.32+00          | 3.94-04        | 4.38-01         | 8.98-03        |               | 1.77+00          |                    | 2.67-02            |
| 8.00+00       |               | 1.08+00          | 2.81-04        | 5.71-01         | 1.54-02        |               | 1.67+00          |                    | 2.51-02            |
| 1.00+01       |               | 9.21-01          | 2.19-04        | 6.79-01         | 2.10-02        |               | 1.62+00          |                    | 2.44-02            |
| 1.50+01       |               | 6.81-01          |                | 8.84-01         | 3.27-02        |               | 1.60+00          |                    | 2.41-02            |
| 2.00+01       |               | 5.47-01          |                | 1.03+00         | 4.20-02        |               | 1.62+00          |                    | 2.44-02            |
| 3.00+01       |               | 3.98-01          |                | 1.24+00         | 5.60-02        |               | 1.69+00          |                    | 2.55-02            |
| 4.00+01       |               | 3.16-01          |                | 1.38+00         | 6.60-02        |               | 1.76+00          |                    | 2.66-02            |
| 5.00+01       |               | 2.64-01          |                | 1.49+00         | 7.36-02        |               | 1.83+00          |                    | 2.75-02            |
| 6.00+01       |               | 2.28-01          |                | 1.57+00         | 7.98-02        |               | 1.88+00          |                    | 2.84-02            |
| 8.00+01       |               | 1.79-01          |                | 1.69+00         | 8.90-02        |               | 1.96+00          |                    | 2.96-02            |
| 1.00+02       |               | 1.49-01          |                | 1.78+00         | 9.60-02        |               | 2.03+00          |                    | 3.06-02            |
| 1.50+02       |               | 1.06-01          |                | 1.94+00         | 1.08-01        |               | 2.16+00          |                    | 3.25-02            |
| 2.00+02       |               | 8.32-02          |                | 2.02+00         | 1.16-01        |               | 2.22+00          |                    | 3.34-02            |
| 3.00+02       |               | 5.89-02          |                | 2.12+00         | 1.26-01        |               | 2.31+00          |                    | 3.48-02            |
| 4.00+02       |               | 4.62-02          |                | 2.18+00         | 1.33-01        |               | 2.36+00          |                    | 3.56-02            |
| 5.00+02       |               | 3.82-02          |                | 2.22+00         | 1.37-01        |               | 2.39+00          |                    | 3.61-02            |
| 6.00+02       |               | 3.27-02          |                | 2.25+00         | 1.41-01        |               | 2.42+00          |                    | 3.65-02            |
| 8.00+02       |               | 2.56-02          |                | 2.29+00         | 1.46-01        |               | 2.46+00          |                    | 3.71-02            |
| 1.00+03       |               | 2.10-02          |                | 2.31+00         | 1.49-01        |               | 2.48+00          |                    | 3.75-02            |
| 1.50+03       |               | 1.47-02          |                | 2.35+00         | 1.55-01        |               | 2.52+00          |                    | 3.80-02            |
| 2.00+03       |               | 1.14-02          |                | 2.37+00         | 1.58-01        |               | 2.54+00          |                    | 3.82-02            |
| 3.00+03       |               | 7.90-03          |                | 2.39+00         | 1.62-01        |               | 2.56+00          |                    | 3.86-02            |
| 4.00+03       |               | 6.10-03          |                | 2.40+00         | 1.64-01        |               | 2.57+00          |                    | 3.87-02            |
| 5.00+03       |               | 4.99-03          |                | 2.41+00         | 1.65-01        |               | 2.58+00          |                    | 3.89-02            |
| 6.00+03       |               | 4.23-03          |                | 2.41+00         | 1.66-01        |               | 2.58+00          |                    | 3.89-02            |
| 8.00+03       |               | 3.26-03          |                | 2.42+00         | 1.67-01        |               | 2.59+00          |                    | 3.91-02            |
| 1.00+04       |               | 2.66-03          |                | 2.42+00         | 1.68-01        |               | 2.60+00          |                    | 3.91-02            |
| 1.50+04       |               | 1.84-03          |                | 2.43+00         | 1.69-01        |               | 2.60+00          |                    | 3.92-02            |
| 2.00+04       |               | 1.41-03          |                | 2.43+00         | 1.69-01        |               | 2.60+00          |                    | 3.93-02            |
| 3.00+04       |               | 9.75-04          |                | 2.44+00         | 1.70-01        |               | 2.61+00          |                    | 3.93-02            |
| 4.00+04       |               | 7.48-04          |                | 2.44+00         | 1.70-01        |               | 2.61+00          |                    | 3.93-02            |
| 5.00+04       |               | 6.09-04          |                | 2.44+00         | 1.71-01        |               | 2.61+00          |                    | 3.93-02            |
| 6.00+04       |               | 5.15-04          |                | 2.44+00         | 1.71-01        |               | 2.61+00          |                    | 3.94-02            |
| 8.00+04       |               | 3.95-04          |                | 2.44+00         | 1.71-01        |               | 2.61+00          |                    | 3.94-02            |
| 1.00+05       |               | 3.21-04          |                | 2.44+00         | 1.71-01        |               | 2.61+00          |                    | 3.94-02            |

(b/atom) x .015080 = cm<sup>2</sup>/g

Table 3.-14. POTASSIUM, Z=19

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 6.22+01       | 1.22+01          | 5.19+03        |                 |                | 5.25+03       | 5.20+03          | 8.09+01            | 8.01+01            |
| 1.50-02       | 4.25+01       | 1.19+01          | 1.58+03        |                 |                | 1.63+03       | 1.60+03          | 2.50+01            | 2.46+01            |
| 2.00-02       | 3.17+01       | 1.17+01          | 6.69+02        |                 |                | 7.01+02       | 6.81+02          | 1.08+01            | 1.05+01            |
| 3.00-02       | 2.17+01       | 1.13+01          | 1.93+02        |                 |                | 2.14+02       | 2.04+02          | 3.30+00            | 3.14+00            |
| 4.00-02       | 1.73+01       | 1.10+01          | 7.94+01        |                 |                | 9.67+01       | 9.04+01          | 1.49+00            | 1.39+00            |
| 5.00-02       | 1.49+01       | 1.07+01          | 3.98+01        |                 |                | 5.47+01       | 5.05+01          | 8.43-01            | 7.77-01            |
| 6.00-02       | 1.35+01       | 1.04+01          | 2.29+01        |                 |                | 3.64+01       | 3.33+01          | 5.60-01            | 5.12-01            |
| 8.00-02       | 1.16+01       | 9.83+00          | 9.40+00        |                 |                | 2.10+01       | 1.92+01          | 3.24-01            | 2.96-01            |
| 1.00-01       | 1.05+01       | 9.36+00          | 4.65+00        |                 |                | 1.52+01       | 1.40+01          | 2.33-01            | 2.16-01            |
| 1.50-01       | 8.95+00       | 8.43+00          | 1.34+00        |                 |                | 1.03+01       | 9.77+00          | 1.58-01            | 1.50-01            |
| 2.00-01       | 8.02+00       | 7.72+00          | 5.57-01        |                 |                | 8.58+00       | 8.28+00          | 1.32-01            | 1.28-01            |
| 3.00-01       | 6.85+00       | 6.72+00          | 1.64-01        |                 |                | 7.01+00       | 6.88+00          | 1.08-01            | 1.06-01            |
| 4.00-01       | 6.09+00       | 6.02+00          | 7.17-02        |                 |                | 6.16+00       | 6.09+00          | 9.49-02            | 9.38-02            |
| 5.00-01       | 5.54+00       | 5.50+00          | 3.89-02        |                 |                | 5.58+00       | 5.53+00          | 8.59-02            | 8.52-02            |
| 6.00-01       | 5.12+00       | 5.08+00          | 2.44-02        |                 |                | 5.14+00       | 5.11+00          | 7.92-02            | 7.87-02            |
| 8.00-01       | 4.48+00       | 4.47+00          | 1.24-02        |                 |                | 4.49+00       | 4.48+00          | 6.92-02            | 6.90-02            |
| 1.00+00       | 4.03+00       | 4.02+00          | 7.68-03        |                 |                | 4.04+00       | 4.02+00          | 6.21-02            | 6.20-02            |
| 1.50+00       | 3.27+00       | 3.26+00          | 3.58-03        | 1.69-02         |                | 3.29+00       | 3.28+00          | 5.06-02            | 5.06-02            |
| 2.00+00       |               | 2.78+00          | 2.26-03        | 6.56-02         |                |               | 2.85+00          | 4.39-02            | 4.39-02            |
| 3.00+00       |               | 2.19+00          | 1.24-03        | 1.86-01         | 7.65-04        |               | 2.38+00          | 3.66-02            | 3.66-02            |
| 4.00+00       |               | 1.83+00          | 8.39-04        | 2.99-01         | 3.14-03        |               | 2.13+00          | 3.28-02            | 3.28-02            |
| 5.00+00       |               | 1.58+00          | 6.38-04        | 3.99-01         | 6.17-03        |               | 1.98+00          | 3.06-02            | 3.06-02            |
| 6.00+00       |               | 1.39+00          | 5.06-04        | 4.87-01         | 9.49-03        |               | 1.89+00          | 2.91-02            | 2.91-02            |
| 8.00+00       |               | 1.14+00          | 3.60-04        | 6.35-01         | 1.62-02        |               | 1.79+00          | 2.76-02            | 2.76-02            |
| 1.00+01       |               | 9.72-01          | 2.80-04        | 7.56-01         | 2.22-02        |               | 1.75+00          | 2.70-02            | 2.70-02            |
| 1.50+01       |               | 7.19-01          |                | 9.83-01         | 3.46-02        |               | 1.74+00          | 2.68-02            | 2.68-02            |
| 2.00+01       |               | 5.77-01          |                | 1.15+00         | 4.43-02        |               | 1.77+00          | 2.73-02            | 2.73-02            |
| 3.00+01       |               | 4.20-01          |                | 1.38+00         | 5.91-02        |               | 1.86+00          | 2.86-02            | 2.86-02            |
| 4.00+01       |               | 3.34-01          |                | 1.54+00         | 6.96-02        |               | 1.94+00          | 2.99-02            | 2.99-02            |
| 5.00+01       |               | 2.79-01          |                | 1.65+00         | 7.76-02        |               | 2.01+00          | 3.10-02            | 3.10-02            |
| 6.00+01       |               | 2.40-01          |                | 1.75+00         | 8.40-02        |               | 2.07+00          | 3.19-02            | 3.19-02            |
| 8.00+01       |               | 1.89-01          |                | 1.88+00         | 9.38-02        |               | 2.17+00          | 3.34-02            | 3.34-02            |
| 1.00+02       |               | 1.57-01          |                | 1.98+00         | 1.01-01        |               | 2.24+00          | 3.45-02            | 3.45-02            |
| 1.50+02       |               | 1.12-01          |                | 2.16+00         | 1.14-01        |               | 2.39+00          | 3.68-02            | 3.68-02            |
| 2.00+02       |               | 8.78-02          |                | 2.24+00         | 1.22-01        |               | 2.45+00          | 3.77-02            | 3.77-02            |
| 3.00+02       |               | 6.22-02          |                | 2.36+00         | 1.33-01        |               | 2.55+00          | 3.93-02            | 3.93-02            |
| 4.00+02       |               | 4.87-02          |                | 2.42+00         | 1.40-01        |               | 2.61+00          | 4.02-02            | 4.02-02            |
| 5.00+02       |               | 4.03-02          |                | 2.46+00         | 1.44-01        |               | 2.65+00          | 4.08-02            | 4.08-02            |
| 6.00+02       |               | 3.45-02          |                | 2.50+00         | 1.48-01        |               | 2.68+00          | 4.12-02            | 4.12-02            |
| 8.00+02       |               | 2.70-02          |                | 2.54+00         | 1.53-01        |               | 2.72+00          | 4.19-02            | 4.19-02            |
| 1.00+03       |               | 2.22-02          |                | 2.57+00         | 1.57-01        |               | 2.75+00          | 4.23-02            | 4.23-02            |
| 1.50+03       |               | 1.55-02          |                | 2.61+00         | 1.63-01        |               | 2.79+00          | 4.29-02            | 4.29-02            |
| 2.00+03       |               | 1.20-02          |                | 2.63+00         | 1.66-01        |               | 2.80+00          | 4.32-02            | 4.32-02            |
| 3.00+03       |               | 8.34-03          |                | 2.65+00         | 1.70-01        |               | 2.83+00          | 4.36-02            | 4.36-02            |
| 4.00+03       |               | 6.44-03          |                | 2.66+00         | 1.72-01        |               | 2.84+00          | 4.38-02            | 4.38-02            |
| 5.00+03       |               | 5.26-03          |                | 2.67+00         | 1.73-01        |               | 2.85+00          | 4.39-02            | 4.39-02            |
| 6.00+03       |               | 4.46-03          |                | 2.68+00         | 1.74-01        |               | 2.86+00          | 4.40-02            | 4.40-02            |
| 8.00+03       |               | 3.44-03          |                | 2.69+00         | 1.75-01        |               | 2.87+00          | 4.41-02            | 4.41-02            |
| 1.00+04       |               | 2.81-03          |                | 2.69+00         | 1.76-01        |               | 2.87+00          | 4.42-02            | 4.42-02            |
| 1.50+04       |               | 1.94-03          |                | 2.70+00         | 1.77-01        |               | 2.88+00          | 4.43-02            | 4.43-02            |
| 2.00+04       |               | 1.49-03          |                | 2.70+00         | 1.78-01        |               | 2.88+00          | 4.43-02            | 4.43-02            |
| 3.00+04       |               | 1.03-03          |                | 2.70+00         | 1.78-01        |               | 2.88+00          | 4.44-02            | 4.44-02            |
| 4.00+04       |               | 7.90-04          |                | 2.71+00         | 1.79-01        |               | 2.89+00          | 4.45-02            | 4.45-02            |
| 5.00+04       |               | 6.43-04          |                | 2.71+00         | 1.79-01        |               | 2.89+00          | 4.45-02            | 4.45-02            |
| 6.00+04       |               | 5.44-04          |                | 2.71+00         | 1.79-01        |               | 2.89+00          | 4.45-02            | 4.45-02            |
| 8.00+04       |               | 4.17-04          |                | 2.71+00         | 1.79-01        |               | 2.89+00          | 4.45-02            | 4.45-02            |
| 1.00+05       |               | 3.39-04          |                | 2.71+00         | 1.79-01        |               | 2.89+00          | 4.45-02            | 4.45-02            |

(b/atom) x .015400 = cm<sup>2</sup>/g

Table 3.-15. CALCIUM, Z=20

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 6.78+01       | 1.28+01          | 6.35+03        |                 |                | 6.42+03       | 6.36+03          | 9.65+01            | 9.56+01            |
| 1.50-02       | 4.68+01       | 1.26+01          | 1.96+03        |                 |                | 2.00+03       | 1.97+03          | 3.01+01            | 2.96+01            |
| 2.00-02       | 3.49+01       | 1.24+01          | 8.27+02        |                 |                | 8.62+02       | 8.39+02          | 1.30+01            | 1.26+01            |
| 3.00-02       | 2.36+01       | 1.19+01          | 2.42+02        |                 |                | 2.66+02       | 2.54+02          | 3.99+00            | 3.82+00            |
| 4.00-02       | 1.87+01       | 1.16+01          | 9.98+01        |                 |                | 1.19+02       | 1.11+02          | 1.78+00            | 1.67+00            |
| 5.00-02       | 1.61+01       | 1.12+01          | 5.03+01        |                 |                | 6.64+01       | 6.15+01          | 9.98-01            | 9.25-01            |
| 6.00-02       | 1.44+01       | 1.09+01          | 2.87+01        |                 |                | 4.31+01       | 3.96+01          | 6.48-01            | 5.95-01            |
| 8.00-02       | 1.24+01       | 1.03+01          | 1.19+01        |                 |                | 2.43+01       | 2.22+01          | 3.65-01            | 3.34-01            |
| 1.00-01       | 1.12+01       | 9.85+00          | 5.89+00        |                 |                | 1.71+01       | 1.57+01          | 2.56-01            | 2.37-01            |
| 1.50-01       | 9.47+00       | 8.87+00          | 1.70+00        |                 |                | 1.12+01       | 1.06+01          | 1.68-01            | 1.59-01            |
| 2.00-01       | 8.47+00       | 8.13+00          | 7.09-01        |                 |                | 9.17+00       | 8.84+00          | 1.38-01            | 1.33-01            |
| 3.00-01       | 7.22+00       | 7.07+00          | 2.10-01        |                 |                | 7.43+00       | 7.28+00          | 1.12-01            | 1.09-01            |
| 4.00-01       | 6.42+00       | 6.33+00          | 9.19-02        |                 |                | 6.51+00       | 6.43+00          | 9.79-02            | 9.66-02            |
| 5.00-01       | 5.84+00       | 5.79+00          | 4.98-02        |                 |                | 5.89+00       | 5.84+00          | 8.85-02            | 8.78-02            |
| 6.00-01       | 5.39+00       | 5.35+00          | 3.13-02        |                 |                | 5.42+00       | 5.38+00          | 8.14-02            | 8.09-02            |
| 8.00-01       | 4.72+00       | 4.70+00          | 1.59-02        |                 |                | 4.74+00       | 4.72+00          | 7.12-02            | 7.09-02            |
| 1.00+00       | 4.24+00       | 4.23+00          | 9.87-03        |                 |                | 4.25+00       | 4.24+00          | 6.39-02            | 6.37-02            |
| 1.50+00       | 3.44+00       | 3.44+00          | 4.58-03        | 1.88-02         |                | 3.46+00       | 3.46+00          | 5.20-02            | 5.20-02            |
| 2.00+00       | 2.93+00       | 2.93+00          | 2.90-03        | 7.30-02         |                | 3.01+00       | 3.01+00          | 4.53-02            | 4.52-02            |
| 3.00+00       |               | 2.31+00          | 1.59-03        | 2.06-01         | 8.05-04        |               | 2.51+00          |                    | 3.78-02            |
| 4.00+00       |               | 1.92+00          | 1.07-03        | 3.31-01         | 3.30-03        |               | 2.26+00          |                    | 3.40-02            |
| 5.00+00       |               | 1.66+00          | 8.16-04        | 4.42-01         | 6.49-03        |               | 2.11+00          |                    | 3.17-02            |
| 6.00+00       |               | 1.47+00          | 6.46-04        | 5.40-01         | 9.98-03        |               | 2.02+00          |                    | 3.03-02            |
| 8.00+00       |               | 1.20+00          | 4.60-04        | 7.03-01         | 1.71-02        |               | 1.92+00          |                    | 2.89-02            |
| 1.00+01       |               | 1.02+00          | 3.59-04        | 8.36-01         | 2.33-02        |               | 1.88+00          |                    | 2.83-02            |
| 1.50+01       |               | 7.57-01          |                | 1.09+00         | 3.64-02        |               | 1.88+00          |                    | 2.83-02            |
| 2.00+01       |               | 6.08-01          |                | 1.27+00         | 4.67-02        |               | 1.92+00          |                    | 2.89-02            |
| 3.00+01       |               | 4.42-01          |                | 1.52+00         | 6.22-02        |               | 2.03+00          |                    | 3.05-02            |
| 4.00+01       |               | 3.52-01          |                | 1.70+00         | 7.32-02        |               | 2.12+00          |                    | 3.19-02            |
| 5.00+01       |               | 2.93-01          |                | 1.83+00         | 8.16-02        |               | 2.20+00          |                    | 3.31-02            |
| 6.00+01       |               | 2.53-01          |                | 1.93+00         | 8.83-02        |               | 2.27+00          |                    | 3.42-02            |
| 8.00+01       |               | 1.99-01          |                | 2.08+00         | 9.85-02        |               | 2.38+00          |                    | 3.58-02            |
| 1.00+02       |               | 1.66-01          |                | 2.19+00         | 1.06-01        |               | 2.46+00          |                    | 3.70-02            |
| 1.50+02       |               | 1.18-01          |                | 2.39+00         | 1.20-01        |               | 2.62+00          |                    | 3.94-02            |
| 2.00+02       |               | 9.24-02          |                | 2.48+00         | 1.28-01        |               | 2.70+00          |                    | 4.05-02            |
| 3.00+02       |               | 6.55-02          |                | 2.60+00         | 1.39-01        |               | 2.81+00          |                    | 4.22-02            |
| 4.00+02       |               | 5.13-02          |                | 2.67+00         | 1.46-01        |               | 2.87+00          |                    | 4.32-02            |
| 5.00+02       |               | 4.25-02          |                | 2.72+00         | 1.51-01        |               | 2.92+00          |                    | 4.38-02            |
| 6.00+02       |               | 3.64-02          |                | 2.76+00         | 1.55-01        |               | 2.95+00          |                    | 4.43-02            |
| 8.00+02       |               | 2.84-02          |                | 2.81+00         | 1.60-01        |               | 2.99+00          |                    | 4.50-02            |
| 1.00+03       |               | 2.34-02          |                | 2.84+00         | 1.64-01        |               | 3.03+00          |                    | 4.55-02            |
| 1.50+03       |               | 1.63-02          |                | 2.88+00         | 1.70-01        |               | 3.07+00          |                    | 4.61-02            |
| 2.00+03       |               | 1.26-02          |                | 2.90+00         | 1.74-01        |               | 3.09+00          |                    | 4.64-02            |
| 3.00+03       |               | 8.78-03          |                | 2.93+00         | 1.78-01        |               | 3.12+00          |                    | 4.68-02            |
| 4.00+03       |               | 6.78-03          |                | 2.94+00         | 1.80-01        |               | 3.13+00          |                    | 4.70-02            |
| 5.00+03       |               | 5.54-03          |                | 2.95+00         | 1.81-01        |               | 3.14+00          |                    | 4.72-02            |
| 6.00+03       |               | 4.70-03          |                | 2.96+00         | 1.82-01        |               | 3.14+00          |                    | 4.73-02            |
| 8.00+03       |               | 3.62-03          |                | 2.97+00         | 1.83-01        |               | 3.15+00          |                    | 4.74-02            |
| 1.00+04       |               | 2.96-03          |                | 2.97+00         | 1.84-01        |               | 3.16+00          |                    | 4.75-02            |
| 1.50+04       |               | 2.04-03          |                | 2.98+00         | 1.85-01        |               | 3.17+00          |                    | 4.76-02            |
| 2.00+04       |               | 1.57-03          |                | 2.98+00         | 1.86-01        |               | 3.17+00          |                    | 4.77-02            |
| 3.00+04       |               | 1.08-03          |                | 2.99+00         | 1.86-01        |               | 3.17+00          |                    | 4.77-02            |
| 4.00+04       |               | 8.31-04          |                | 2.99+00         | 1.87-01        |               | 3.18+00          |                    | 4.77-02            |
| 5.00+04       |               | 6.77-04          |                | 2.99+00         | 1.87-01        |               | 3.18+00          |                    | 4.78-02            |
| 6.00+04       |               | 5.72-04          |                | 2.99+00         | 1.87-01        |               | 3.18+00          |                    | 4.78-02            |
| 8.00+04       |               | 4.39-04          |                | 2.99+00         | 1.87-01        |               | 3.18+00          |                    | 4.78-02            |
| 1.00+05       |               | 3.57-04          |                | 2.99+00         | 1.87-01        |               | 3.18+00          |                    | 4.78-02            |

(b/atom) x .015030 = cm<sup>2</sup>/g

Table 3.-16. IRON, Z=26

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 1.23+02       | 1.67+01          | 1.59+04        |                 |                | 1.60+04       | 1.59+04          | 1.73+02            | 1.72+02            |
| 1.50-02       | 8.05+01       | 1.63+01          | 5.15+03        |                 |                | 5.23+03       | 5.17+03          | 5.64+01            | 5.57+01            |
| 2.00-02       | 5.98+01       | 1.61+01          | 2.31+03        |                 |                | 2.37+03       | 2.33+03          | 2.55+01            | 2.51+01            |
| 3.00-02       | 3.89+01       | 1.55+01          | 7.15+02        |                 |                | 7.54+02       | 7.31+02          | 8.13+00            | 7.88+00            |
| 4.00-02       | 2.94+01       | 1.50+01          | 3.06+02        |                 |                | 3.35+02       | 3.21+02          | 3.62+00            | 3.46+00            |
| 5.00-02       | 2.43+01       | 1.46+01          | 1.56+02        |                 |                | 1.80+02       | 1.71+02          | 1.94+00            | 1.84+00            |
| 6.00-02       | 2.12+01       | 1.42+01          | 9.04+01        |                 |                | 1.12+02       | 1.05+02          | 1.20+00            | 1.13+00            |
| 8.00-02       | 1.76+01       | 1.34+01          | 3.76+01        |                 |                | 5.52+01       | 5.10+01          | 5.95-01            | 5.50-01            |
| 1.00-01       | 1.54+01       | 1.28+01          | 1.89+01        |                 |                | 3.43+01       | 3.17+01          | 3.70-01            | 3.42-01            |
| 1.50-01       | 1.27+01       | 1.15+01          | 5.52+00        |                 |                | 1.82+01       | 1.71+01          | 1.96-01            | 1.84-01            |
| 2.00-01       | 1.12+01       | 1.06+01          | 2.33+00        |                 |                | 1.35+01       | 1.29+01          | 1.46-01            | 1.39-01            |
| 3.00-01       | 9.50+00       | 9.19+00          | 6.98-01        |                 |                | 1.02+01       | 9.89+00          | 1.10-01            | 1.07-01            |
| 4.00-01       | 8.41+00       | 8.24+00          | 3.09-01        |                 |                | 8.72+00       | 8.54+00          | 9.40-02            | 9.21-02            |
| 5.00-01       | 7.62+00       | 7.52+00          | 1.69-01        |                 |                | 7.79+00       | 7.69+00          | 8.40-02            | 8.29-02            |
| 6.00-01       | 7.03+00       | 6.96+00          | 1.07-01        |                 |                | 7.14+00       | 7.06+00          | 7.69-02            | 7.62-02            |
| 8.00-01       | 6.15+00       | 6.11+00          | 5.44-02        |                 |                | 6.21+00       | 6.17+00          | 6.69-02            | 6.65-02            |
| 1.00+00       | 5.52+00       | 5.50+00          | 3.38-02        |                 |                | 5.55+00       | 5.53+00          | 5.99-02            | 5.96-02            |
| 1.50+00       | 4.48+00       | 4.47+00          | 1.56-02        | 3.32-02         |                | 4.53+00       | 4.51+00          | 4.88-02            | 4.87-02            |
| 2.00+00       |               | 3.81+00          | 9.81-03        | 1.26-01         |                |               | 3.95+00          |                    | 4.25-02            |
| 3.00+00       |               | 3.00+00          | 5.35-03        | 3.50-01         | 1.05-03        |               | 3.35+00          |                    | 3.62-02            |
| 4.00+00       |               | 2.50+00          | 3.61-03        | 5.61-01         | 4.30-03        |               | 3.07+00          |                    | 3.31-02            |
| 5.00+00       |               | 2.16+00          | 2.73-03        | 7.46-01         | 8.44-03        |               | 2.92+00          |                    | 3.14-02            |
| 6.00+00       |               | 1.91+00          | 2.16-03        | 9.08-01         | 1.30-02        |               | 2.83+00          |                    | 3.05-02            |
| 8.00+00       |               | 1.56+00          | 1.53-03        | 1.18+00         | 2.22-02        |               | 2.77+00          |                    | 2.98-02            |
| 1.00+01       |               | 1.33+00          | 1.19-03        | 1.40+00         | 3.04-02        |               | 2.76+00          |                    | 2.98-02            |
| 1.50+01       |               | 9.84-01          | 7.00-04        | 1.82+00         | 4.73-02        |               | 2.85+00          |                    | 3.07-02            |
| 2.00+01       |               | 7.90-01          | 5.00-04        | 2.13+00         | 6.07-02        |               | 2.98+00          |                    | 3.21-02            |
| 3.00+01       |               | 5.75-01          |                | 2.55+00         | 8.06-02        |               | 3.20+00          |                    | 3.45-02            |
| 4.00+01       |               | 4.57-01          |                | 2.84+00         | 9.45-02        |               | 3.39+00          |                    | 3.65-02            |
| 5.00+01       |               | 3.81-01          |                | 3.06+00         | 1.05-01        |               | 3.54+00          |                    | 3.82-02            |
| 6.00+01       |               | 3.29-01          |                | 3.22+00         | 1.13-01        |               | 3.67+00          |                    | 3.95-02            |
| 8.00+01       |               | 2.59-01          |                | 3.48+00         | 1.27-01        |               | 3.86+00          |                    | 4.16-02            |
| 1.00+02       |               | 2.15-01          |                | 3.65+00         | 1.36-01        |               | 4.01+00          |                    | 4.32-02            |
| 1.50+02       |               | 1.53-01          |                | 3.94+00         | 1.53-01        |               | 4.25+00          |                    | 4.58-02            |
| 2.00+02       |               | 1.20-01          |                | 4.12+00         | 1.64-01        |               | 4.40+00          |                    | 4.75-02            |
| 3.00+02       |               | 8.51-02          |                | 4.32+00         | 1.78-01        |               | 4.58+00          |                    | 4.94-02            |
| 4.00+02       |               | 6.67-02          |                | 4.44+00         | 1.86-01        |               | 4.69+00          |                    | 5.06-02            |
| 5.00+02       |               | 5.52-02          |                | 4.52+00         | 1.92-01        |               | 4.77+00          |                    | 5.14-02            |
| 6.00+02       |               | 4.73-02          |                | 4.57+00         | 1.97-01        |               | 4.82+00          |                    | 5.19-02            |
| 8.00+02       |               | 3.69-02          |                | 4.65+00         | 2.04-01        |               | 4.89+00          |                    | 5.27-02            |
| 1.00+03       |               | 3.04-02          |                | 4.69+00         | 2.09-01        |               | 4.93+00          |                    | 5.32-02            |
| 1.50+03       |               | 2.12-02          |                | 4.77+00         | 2.16-01        |               | 5.00+00          |                    | 5.39-02            |
| 2.00+03       |               | 1.64-02          |                | 4.80+00         | 2.20-01        |               | 5.04+00          |                    | 5.43-02            |
| 3.00+03       |               | 1.14-02          |                | 4.84+00         | 2.24-01        |               | 5.08+00          |                    | 5.48-02            |
| 4.00+03       |               | 8.81-03          |                | 4.86+00         | 2.26-01        |               | 5.10+00          |                    | 5.50-02            |
| 5.00+03       |               | 7.20-03          |                | 4.88+00         | 2.28-01        |               | 5.11+00          |                    | 5.51-02            |
| 6.00+03       |               | 6.11-03          |                | 4.89+00         | 2.29-01        |               | 5.13+00          |                    | 5.52-02            |
| 8.00+03       |               | 4.71-03          |                | 4.90+00         | 2.31-01        |               | 5.14+00          |                    | 5.54-02            |
| 1.00+04       |               | 3.84-03          |                | 4.91+00         | 2.31-01        |               | 5.14+00          |                    | 5.55-02            |
| 1.50+04       |               | 2.66-03          |                | 4.92+00         | 2.33-01        |               | 5.16+00          |                    | 5.56-02            |
| 2.00+04       |               | 2.04-03          |                | 4.93+00         | 2.33-01        |               | 5.16+00          |                    | 5.56-02            |
| 3.00+04       |               | 1.41-03          |                | 4.93+00         | 2.34-01        |               | 5.17+00          |                    | 5.57-02            |
| 4.00+04       |               | 1.08-03          |                | 4.93+00         | 2.35-01        |               | 5.17+00          |                    | 5.57-02            |
| 5.00+04       |               | 8.80-04          |                | 4.94+00         | 2.35-01        |               | 5.17+00          |                    | 5.58-02            |
| 6.00+04       |               | 7.44-04          |                | 4.94+00         | 2.35-01        |               | 5.17+00          |                    | 5.58-02            |
| 8.00+04       |               | 5.70-04          |                | 4.94+00         | 2.35-01        |               | 5.17+00          |                    | 5.58-02            |
| 1.00+05       |               | 4.64-04          |                | 4.94+00         | 2.36-01        |               | 5.17+00          |                    | 5.58-02            |

(b/atom) x .010780 = cm<sup>2</sup>/g

Table 3.-17. COPPER, Z=29

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 1.66+02       | 1.86+01          | 2.35+04        |                 |                | 2.37+04       | 2.35+04          | 2.24+02            | 2.23+02            |
| 1.50-02       | 1.06+02       | 1.82+01          | 7.72+03        |                 |                | 7.83+03       | 7.74+03          | 7.42+01            | 7.33+01            |
| 2.00-02       | 7.70+01       | 1.79+01          | 3.46+03        |                 |                | 3.54+03       | 3.48+03          | 3.35+01            | 3.30+01            |
| 3.00-02       | 4.92+01       | 1.73+01          | 1.11+03        |                 |                | 1.15+03       | 1.12+03          | 1.09+01            | 1.06+01            |
| 4.00-02       | 3.64+01       | 1.68+01          | 4.80+02        |                 |                | 5.16+02       | 4.97+02          | 4.89+00            | 4.71+00            |
| 5.00-02       | 2.96+01       | 1.63+01          | 2.47+02        |                 |                | 2.77+02       | 2.63+02          | 2.62+00            | 2.50+00            |
| 6.00-02       | 2.55+01       | 1.58+01          | 1.45+02        |                 |                | 1.71+02       | 1.61+02          | 1.62+00            | 1.52+00            |
| 8.00-02       | 2.07+01       | 1.50+01          | 6.08+01        |                 |                | 8.14+01       | 7.58+01          | 7.72-01            | 7.18-01            |
| 1.00-01       | 1.79+01       | 1.43+01          | 3.08+01        |                 |                | 4.87+01       | 4.51+01          | 4.61-01            | 4.27-01            |
| 1.50-01       | 1.45+01       | 1.29+01          | 9.04+00        |                 |                | 2.36+01       | 2.19+01          | 2.23-01            | 2.08-01            |
| 2.00-01       | 1.27+01       | 1.18+01          | 3.80+00        |                 |                | 1.65+01       | 1.56+01          | 1.57-01            | 1.48-01            |
| 3.00-01       | 1.07+01       | 1.02+01          | 1.15+00        |                 |                | 1.18+01       | 1.14+01          | 1.12-01            | 1.08-01            |
| 4.00-01       | 9.42+00       | 9.19+00          | 5.12-01        |                 |                | 9.93+00       | 9.70+00          | 9.41-02            | 9.19-02            |
| 5.00-01       | 8.54+00       | 8.39+00          | 2.81-01        |                 |                | 8.82+00       | 8.67+00          | 8.36-02            | 8.22-02            |
| 6.00-01       | 7.86+00       | 7.76+00          | 1.77-01        |                 |                | 8.04+00       | 7.94+00          | 7.62-02            | 7.52-02            |
| 8.00-01       | 6.87+00       | 6.82+00          | 9.11-02        |                 |                | 6.96+00       | 6.91+00          | 6.60-02            | 6.55-02            |
| 1.00+00       | 6.16+00       | 6.13+00          | 5.65-02        |                 |                | 6.22+00       | 6.19+00          | 5.89-02            | 5.86-02            |
| 1.50+00       | 4.99+00       | 4.98+00          | 2.61-02        | 4.23-02         |                | 5.06+00       | 5.05+00          | 4.80-02            | 4.79-02            |
| 2.00+00       | 4.25+00       | 4.25+00          | 1.63-02        | 1.58-01         |                | 4.43+00       | 4.43+00          | 4.20-02            | 4.19-02            |
| 3.00+00       | 3.35+00       | 3.34+00          | 8.88-03        | 4.38-01         | 1.17-03        | 3.79+00       | 3.79+00          | 3.60-02            | 3.59-02            |
| 4.00+00       |               | 2.79+00          | 5.96-03        | 6.98-01         | 4.79-03        |               | 3.50+00          |                    | 3.32-02            |
| 5.00+00       |               | 2.41+00          | 4.50-03        | 9.28-01         | 9.41-03        |               | 3.35+00          |                    | 3.18-02            |
| 6.00+00       |               | 2.13+00          | 3.56-03        | 1.13+00         | 1.45-02        |               | 3.28+00          |                    | 3.10-02            |
| 8.00+00       |               | 1.74+00          | 2.52-03        | 1.46+00         | 2.48-02        |               | 3.23+00          |                    | 3.06-02            |
| 1.00+01       |               | 1.48+00          | 1.95-03        | 1.74+00         | 3.39-02        |               | 3.25+00          |                    | 3.08-02            |
| 1.50+01       |               | 1.10+00          | 1.20-03        | 2.25+00         | 5.27-02        |               | 3.41+00          |                    | 3.23-02            |
| 2.00+01       |               | 8.81-01          | 9.00-04        | 2.63+00         | 6.77-02        |               | 3.58+00          |                    | 3.39-02            |
| 3.00+01       |               | 6.41-01          | 6.00-04        | 3.15+00         | 8.97-02        |               | 3.89+00          |                    | 3.68-02            |
| 4.00+01       |               | 5.10-01          | 4.00-04        | 3.51+00         | 1.05-01        |               | 4.13+00          |                    | 3.91-02            |
| 5.00+01       |               | 4.25-01          |                | 3.78+00         | 1.17-01        |               | 4.32+00          |                    | 4.10-02            |
| 6.00+01       |               | 3.67-01          |                | 3.99+00         | 1.26-01        |               | 4.48+00          |                    | 4.25-02            |
| 8.00+01       |               | 2.89-01          |                | 4.30+00         | 1.41-01        |               | 4.73+00          |                    | 4.48-02            |
| 1.00+02       |               | 2.40-01          |                | 4.52+00         | 1.51-01        |               | 4.91+00          |                    | 4.65-02            |
| 1.50+02       |               | 1.71-01          |                | 4.87+00         | 1.70-01        |               | 5.21+00          |                    | 4.94-02            |
| 2.00+02       |               | 1.34-01          |                | 5.08+00         | 1.82-01        |               | 5.39+00          |                    | 5.11-02            |
| 3.00+02       |               | 9.50-02          |                | 5.32+00         | 1.97-01        |               | 5.61+00          |                    | 5.32-02            |
| 4.00+02       |               | 7.44-02          |                | 5.46+00         | 2.06-01        |               | 5.74+00          |                    | 5.44-02            |
| 5.00+02       |               | 6.16-02          |                | 5.55+00         | 2.13-01        |               | 5.83+00          |                    | 5.52-02            |
| 6.00+02       |               | 5.27-02          |                | 5.62+00         | 2.18-01        |               | 5.89+00          |                    | 5.58-02            |
| 8.00+02       |               | 4.12-02          |                | 5.71+00         | 2.25-01        |               | 5.97+00          |                    | 5.66-02            |
| 1.00+03       |               | 3.39-02          |                | 5.77+00         | 2.30-01        |               | 6.03+00          |                    | 5.72-02            |
| 1.50+03       |               | 2.37-02          |                | 5.85+00         | 2.38-01        |               | 6.11+00          |                    | 5.79-02            |
| 2.00+03       |               | 1.83-02          |                | 5.89+00         | 2.42-01        |               | 6.15+00          |                    | 5.83-02            |
| 3.00+03       |               | 1.27-02          |                | 5.94+00         | 2.47-01        |               | 6.20+00          |                    | 5.88-02            |
| 4.00+03       |               | 9.83-03          |                | 5.97+00         | 2.49-01        |               | 6.23+00          |                    | 5.90-02            |
| 5.00+03       |               | 8.03-03          |                | 5.98+00         | 2.51-01        |               | 6.24+00          |                    | 5.91-02            |
| 6.00+03       |               | 6.81-03          |                | 5.99+00         | 2.52-01        |               | 6.25+00          |                    | 5.93-02            |
| 8.00+03       |               | 5.25-03          |                | 6.01+00         | 2.54-01        |               | 6.26+00          |                    | 5.94-02            |
| 1.00+04       |               | 4.29-03          |                | 6.01+00         | 2.55-01        |               | 6.27+00          |                    | 5.95-02            |
| 1.50+04       |               | 2.96-03          |                | 6.03+00         | 2.56-01        |               | 6.29+00          |                    | 5.96-02            |
| 2.00+04       |               | 2.28-03          |                | 6.03+00         | 2.57-01        |               | 6.29+00          |                    | 5.96-02            |
| 3.00+04       |               | 1.57-03          |                | 6.05+00         | 2.58-01        |               | 6.31+00          |                    | 5.98-02            |
| 4.00+04       |               | 1.21-03          |                | 6.05+00         | 2.58-01        |               | 6.31+00          |                    | 5.98-02            |
| 5.00+04       |               | 9.82-04          |                | 6.05+00         | 2.58-01        |               | 6.31+00          |                    | 5.98-02            |
| 6.00+04       |               | 8.30-04          |                | 6.05+00         | 2.58-01        |               | 6.31+00          |                    | 5.98-02            |
| 8.00+04       |               | 6.36-04          |                | 6.05+00         | 2.59-01        |               | 6.31+00          |                    | 5.98-02            |
| 1.00+05       |               | 5.18-04          |                | 6.05+00         | 2.59-01        |               | 6.31+00          |                    | 5.98-02            |

(b/atom) x .009478 = cm<sup>2</sup>/g

Table 3.-18. MOLYBDENUM, Z=42

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |         |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|---------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |         |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |         |
| K             | 1.00-02       | 3.77+02          | 2.69+01        | 1.34+04         |                |               | 1.37+04          | 1.34+04            | 8.62+01            | 8.40+01 |
|               | 1.50-02       | 2.46+02          | 2.64+01        | 4.24+03         |                |               | 4.49+03          | 4.27+03            | 2.82+01            | 2.68+01 |
|               | 2.00-02       | 1.74+02          | 2.59+01        | 1.84+03         |                |               | 2.01+03          | 1.87+03            | 1.26+01            | 1.17+01 |
|               | 2.00-02       | 1.74+02          | 2.59+01        | 1.28+04         |                |               | 1.30+04          | 1.29+04            | 8.17+01            | 8.08+01 |
|               | 3.00-02       | 1.07+02          | 2.51+01        | 4.48+03         |                |               | 4.59+03          | 4.51+03            | 2.88+01            | 2.83+01 |
|               | 4.00-02       | 7.64+01          | 2.43+01        | 2.04+03         |                |               | 2.12+03          | 2.07+03            | 1.33+01            | 1.30+01 |
|               | 5.00-02       | 5.94+01          | 2.36+01        | 1.09+03         |                |               | 1.15+03          | 1.11+03            | 7.20+00            | 6.97+00 |
|               | 6.00-02       | 4.90+01          | 2.29+01        | 6.54+02         |                |               | 7.03+02          | 6.77+02            | 4.41+00            | 4.25+00 |
|               | 8.00-02       | 3.71+01          | 2.17+01        | 2.85+02         |                |               | 3.22+02          | 3.06+02            | 2.02+00            | 1.92+00 |
|               | 1.00-01       | 3.06+01          | 2.07+01        | 1.47+02         |                |               | 1.78+02          | 1.68+02            | 1.11+00            | 1.05+00 |
|               | 1.50-01       | 2.32+01          | 1.86+01        | 4.50+01         |                |               | 6.82+01          | 6.36+01            | 4.28-01            | 3.99-01 |
|               | 2.00-01       | 1.97+01          | 1.71+01        | 1.93+01         |                |               | 3.90+01          | 3.64+01            | 2.45-01            | 2.28-01 |
|               | 3.00-01       | 1.60+01          | 1.48+01        | 6.02+00         |                |               | 2.21+01          | 2.09+01            | 1.39-01            | 1.31-01 |
|               | 4.00-01       | 1.39+01          | 1.33+01        | 2.74+00         |                |               | 1.67+01          | 1.60+01            | 1.05-01            | 1.01-01 |
|               | 5.00-01       | 1.25+01          | 1.22+01        | 1.53+00         |                |               | 1.41+01          | 1.37+01            | 8.83-02            | 8.59-02 |
|               | 6.00-01       | 1.16+01          | 1.12+01        | 9.80-01         |                |               | 1.25+01          | 1.22+01            | 7.88-02            | 7.67-02 |
| 8.00-01       | 1.00+01       | 9.88+00          | 5.04-01        |                 |                | 1.05+01       | 1.04+01          | 6.61-02            | 6.52-02            |         |
| 1.00+00       | 8.97+00       | 8.88+00          | 3.13-01        |                 |                | 9.29+00       | 9.19+00          | 5.83-02            | 5.77-02            |         |
| 1.50+00       | 7.25+00       | 7.21+00          | 1.43-01        | 9.99-02         |                | 7.49+00       | 7.46+00          | 4.70-02            | 4.68-02            |         |
| 2.00+00       | 6.17+00       | 6.16+00          | 8.84-02        | 3.54-01         |                | 6.62+00       | 6.60+00          | 4.15-02            | 4.14-02            |         |
| 3.00+00       | 4.84+00       | 4.84+00          | 4.77-02        | 9.40-01         | 1.69-03        | 5.83+00       | 5.83+00          | 3.66-02            | 3.66-02            |         |
| 4.00+00       | 4.05+00       | 4.04+00          | 3.18-02        | 1.47+00         | 6.94-03        | 5.56+00       | 5.55+00          | 3.49-02            | 3.48-02            |         |
| 5.00+00       | 3.50+00       | 3.49+00          | 2.39-02        | 1.94+00         | 1.36-02        | 5.47+00       | 5.47+00          | 3.44-02            | 3.43-02            |         |
| 6.00+00       |               | 3.08+00          | 1.88-02        | 2.34+00         | 2.10-02        |               | 5.46+00          |                    | 3.43-02            |         |
| 8.00+00       |               | 2.52+00          | 1.31-02        | 3.01+00         | 3.59-02        |               | 5.58+00          |                    | 3.50-02            |         |
| 1.00+01       |               | 2.15+00          | 1.02-02        | 3.55+00         | 4.90-02        |               | 5.76+00          |                    | 3.62-02            |         |
| 1.50+01       |               | 1.59+00          | 6.39-03        | 4.59+00         | 7.64-02        |               | 6.27+00          |                    | 3.93-02            |         |
| 2.00+01       |               | 1.28+00          | 4.65-03        | 5.36+00         | 9.78-02        |               | 6.74+00          |                    | 4.23-02            |         |
| 3.00+01       |               | 9.29-01          | 3.01-03        | 6.43+00         | 1.28-01        |               | 7.49+00          |                    | 4.70-02            |         |
| 4.00+01       |               | 7.38-01          | 2.22-03        | 7.15+00         | 1.50-01        |               | 8.04+00          |                    | 5.05-02            |         |
| 5.00+01       |               | 6.16-01          | 1.76-03        | 7.69+00         | 1.66-01        |               | 8.47+00          |                    | 5.32-02            |         |
| 6.00+01       |               | 5.31-01          | 1.46-03        | 8.10+00         | 1.79-01        |               | 8.82+00          |                    | 5.53-02            |         |
| 8.00+01       |               | 4.19-01          | 1.08-03        | 8.72+00         | 1.99-01        |               | 9.34+00          |                    | 5.86-02            |         |
| 1.00+02       |               | 3.48-01          | 8.65-04        | 9.14+00         | 2.15-01        |               | 9.71+00          |                    | 6.09-02            |         |
| 1.50+02       |               | 2.48-01          |                | 9.83+00         | 2.40-01        |               | 1.03+01          |                    | 6.48-02            |         |
| 2.00+02       |               | 1.94-01          |                | 1.02+01         | 2.56-01        |               | 1.07+01          |                    | 6.72-02            |         |
| 3.00+02       |               | 1.38-01          |                | 1.07+01         | 2.76-01        |               | 1.12+01          |                    | 7.00-02            |         |
| 4.00+02       |               | 1.08-01          |                | 1.10+01         | 2.89-01        |               | 1.14+01          |                    | 7.16-02            |         |
| 5.00+02       |               | 8.92-02          |                | 1.12+01         | 2.97-01        |               | 1.16+01          |                    | 7.27-02            |         |
| 6.00+02       |               | 7.63-02          |                | 1.13+01         | 3.04-01        |               | 1.17+01          |                    | 7.35-02            |         |
| 8.00+02       |               | 5.96-02          |                | 1.15+01         | 3.14-01        |               | 1.19+01          |                    | 7.45-02            |         |
| 1.00+03       |               | 4.91-02          |                | 1.16+01         | 3.20-01        |               | 1.20+01          |                    | 7.53-02            |         |
| 1.50+03       |               | 3.43-02          |                | 1.18+01         | 3.30-01        |               | 1.21+01          |                    | 7.62-02            |         |
| 2.00+03       |               | 2.65-02          |                | 1.19+01         | 3.35-01        |               | 1.22+01          |                    | 7.67-02            |         |
| 3.00+03       |               | 1.84-02          |                | 1.20+01         | 3.41-01        |               | 1.23+01          |                    | 7.73-02            |         |
| 4.00+03       |               | 1.42-02          |                | 1.20+01         | 3.44-01        |               | 1.24+01          |                    | 7.77-02            |         |
| 5.00+03       |               | 1.16-02          |                | 1.20+01         | 3.46-01        |               | 1.24+01          |                    | 7.79-02            |         |
| 6.00+03       |               | 9.87-03          |                | 1.21+01         | 3.48-01        |               | 1.24+01          |                    | 7.80-02            |         |
| 8.00+03       |               | 7.60-03          |                | 1.21+01         | 3.50-01        |               | 1.24+01          |                    | 7.81-02            |         |
| 1.00+04       |               | 6.21-03          |                | 1.21+01         | 3.51-01        |               | 1.25+01          |                    | 7.83-02            |         |
| 1.50+04       |               | 4.29-03          |                | 1.22+01         | 3.53-01        |               | 1.25+01          |                    | 7.85-02            |         |
| 2.00+04       |               | 3.30-03          |                | 1.22+01         | 3.54-01        |               | 1.25+01          |                    | 7.85-02            |         |
| 3.00+04       |               | 2.27-03          |                | 1.22+01         | 3.55-01        |               | 1.25+01          |                    | 7.86-02            |         |
| 4.00+04       |               | 1.75-03          |                | 1.22+01         | 3.55-01        |               | 1.25+01          |                    | 7.86-02            |         |
| 5.00+04       |               | 1.42-03          |                | 1.22+01         | 3.55-01        |               | 1.25+01          |                    | 7.86-02            |         |
| 6.00+04       |               | 1.20-03          |                | 1.22+01         | 3.56-01        |               | 1.25+01          |                    | 7.87-02            |         |
| 8.00+04       |               | 9.22-04          |                | 1.22+01         | 3.56-01        |               | 1.25+01          |                    | 7.88-02            |         |
| 1.00+05       |               | 7.50-04          |                | 1.22+01         | 3.56-01        |               | 1.25+01          |                    | 7.88-02            |         |

(b/atom) x .006277 = cm<sup>2</sup>/g

Table 3.-19. TIN, Z=50

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| K             |               |                  |                |                 |                |               |                  |                    |                    |
| 1.00-02       | 5.38+02       | 3.20+01          | 2.73+04        |                 |                | 2.79+04       | 2.74+04          | 1.41+02            | 1.39+02            |
| 1.50-02       | 3.60+02       | 3.14+01          | 8.91+03        |                 |                | 9.27+03       | 8.94+03          | 4.70+01            | 4.53+01            |
| 2.00-02       | 2.59+02       | 3.09+01          | 3.95+03        |                 |                | 4.21+03       | 3.98+03          | 2.13+01            | 2.02+01            |
| 2.92-02       | 1.61+02       | 2.99+01          | 1.33+03        |                 |                | 1.49+03       | 1.36+03          | 7.54+00            | 6.88+00            |
| 2.92-02       | 1.61+02       | 2.99+01          | 8.57+03        |                 |                | 8.73+03       | 8.60+03          | 4.43+01            | 4.37+01            |
| 3.00-02       | 1.56+02       | 2.99+01          | 7.98+03        |                 |                | 8.14+03       | 8.01+03          | 4.13+01            | 4.07+01            |
| 4.00-02       | 1.10+02       | 2.89+01          | 3.70+03        |                 |                | 3.81+03       | 3.73+03          | 1.94+01            | 1.89+01            |
| 5.00-02       | 8.44+01       | 2.81+01          | 2.02+03        |                 |                | 2.10+03       | 2.04+03          | 1.07+01            | 1.04+01            |
| 6.00-02       | 6.85+01       | 2.73+01          | 1.22+03        |                 |                | 1.29+03       | 1.25+03          | 6.53+00            | 6.32+00            |
| 8.00-02       | 5.02+01       | 2.59+01          | 5.45+02        |                 |                | 5.95+02       | 5.71+02          | 3.02+00            | 2.90+00            |
| 1.00-01       | 4.05+01       | 2.46+01          | 2.90+02        |                 |                | 3.31+02       | 3.15+02          | 1.68+00            | 1.60+00            |
| 1.50-01       | 2.96+01       | 2.22+01          | 9.15+01        |                 |                | 1.21+02       | 1.14+02          | 6.14-01            | 5.77-01            |
| 2.00-01       | 2.45+01       | 2.03+01          | 4.02+01        |                 |                | 6.47+01       | 6.06+01          | 3.28-01            | 3.07-01            |
| 3.00-01       | 1.96+01       | 1.77+01          | 1.28+01        |                 |                | 3.24+01       | 3.05+01          | 1.64-01            | 1.55-01            |
| 4.00-01       | 1.69+01       | 1.58+01          | 5.93+00        |                 |                | 2.28+01       | 2.18+01          | 1.16-01            | 1.10-01            |
| 5.00-01       | 1.51+01       | 1.45+01          | 3.50+00        |                 |                | 1.86+01       | 1.80+01          | 9.46-02            | 9.11-02            |
| 6.00-01       | 1.39+01       | 1.34+01          | 2.20+00        |                 |                | 1.61+01       | 1.56+01          | 8.16-02            | 7.91-02            |
| 8.00-01       | 1.20+01       | 1.18+01          | 1.15+00        |                 |                | 1.32+01       | 1.29+01          | 6.69-02            | 6.55-02            |
| 1.00+00       | 1.07+01       | 1.06+01          | 6.90-01        |                 |                | 1.14+01       | 1.13+01          | 5.78-02            | 5.71-02            |
| 1.50+00       | 8.65+00       | 8.59+00          | 3.13-01        | 1.53-01         |                | 9.12+00       | 9.06+00          | 4.63-02            | 4.59-02            |
| 2.00+00       | 7.36+00       | 7.33+00          | 1.93-01        | 5.23-01         |                | 8.08+00       | 8.04+00          | 4.10-02            | 4.08-02            |
| 3.00+00       | 5.77+00       | 5.77+00          | 1.05-01        | 1.35+00         | 2.01-03        | 7.24+00       | 7.23+00          | 3.67-02            | 3.67-02            |
| 4.00+00       | 4.82+00       | 4.81+00          | 6.93-02        | 2.10+00         | 8.26-03        | 7.00+00       | 6.98+00          | 3.55-02            | 3.54-02            |
| 5.00+00       | 4.16+00       | 4.15+00          | 5.18-02        | 2.74+00         | 1.62-02        | 6.97+00       | 6.96+00          | 3.54-02            | 3.53-02            |
| 6.00+00       | 3.68+00       | 3.67+00          | 4.05-02        | 3.29+00         | 2.50-02        | 7.03+00       | 7.03+00          | 3.57-02            | 3.57-02            |
| 8.00+00       |               | 3.00+00          | 2.83-02        | 4.21+00         | 4.27-02        |               | 7.28+00          |                    | 3.69-02            |
| 1.00+01       |               | 2.56+00          | 2.18-02        | 4.95+00         | 5.84-02        |               | 7.58+00          |                    | 3.85-02            |
| 1.50+01       |               | 1.89+00          | 1.37-02        | 6.38+00         | 9.09-02        |               | 8.37+00          |                    | 4.25-02            |
| 2.00+01       |               | 1.52+00          | 9.94-03        | 7.44+00         | 1.16-01        |               | 9.08+00          |                    | 4.61-02            |
| 3.00+01       |               | 1.11+00          | 6.41-03        | 8.92+00         | 1.52-01        |               | 1.02+01          |                    | 5.17-02            |
| 4.00+01       |               | 8.79-01          | 4.73-03        | 9.92+00         | 1.77-01        |               | 1.10+01          |                    | 5.57-02            |
| 5.00+01       |               | 7.34-01          | 3.75-03        | 1.07+01         | 1.96-01        |               | 1.16+01          |                    | 5.88-02            |
| 6.00+01       |               | 6.32-01          | 3.10-03        | 1.12+01         | 2.11-01        |               | 1.21+01          |                    | 6.13-02            |
| 8.00+01       |               | 4.98-01          | 2.31-03        | 1.21+01         | 2.35-01        |               | 1.28+01          |                    | 6.51-02            |
| 1.00+02       |               | 4.14-01          | 1.84-03        | 1.27+01         | 2.52-01        |               | 1.33+01          |                    | 6.77-02            |
| 1.50+02       |               | 2.95-01          |                | 1.36+01         | 2.81-01        |               | 1.42+01          |                    | 7.21-02            |
| 2.00+02       |               | 2.31-01          |                | 1.42+01         | 3.00-01        |               | 1.47+01          |                    | 7.48-02            |
| 3.00+02       |               | 1.64-01          |                | 1.49+01         | 3.23-01        |               | 1.54+01          |                    | 7.80-02            |
| 4.00+02       |               | 1.28-01          |                | 1.53+01         | 3.38-01        |               | 1.57+01          |                    | 7.98-02            |
| 5.00+02       |               | 1.06-01          |                | 1.55+01         | 3.48-01        |               | 1.60+01          |                    | 8.10-02            |
| 6.00+02       |               | 9.09-02          |                | 1.57+01         | 3.56-01        |               | 1.61+01          |                    | 8.19-02            |
| 8.00+02       |               | 7.10-02          |                | 1.59+01         | 3.67-01        |               | 1.64+01          |                    | 8.31-02            |
| 1.00+03       |               | 5.84-02          |                | 1.61+01         | 3.74-01        |               | 1.65+01          |                    | 8.38-02            |
| 1.50+03       |               | 4.08-02          |                | 1.63+01         | 3.84-01        |               | 1.67+01          |                    | 8.49-02            |
| 2.00+03       |               | 3.16-02          |                | 1.64+01         | 3.90-01        |               | 1.69+01          |                    | 8.56-02            |
| 3.00+03       |               | 2.19-02          |                | 1.66+01         | 3.97-01        |               | 1.70+01          |                    | 8.62-02            |
| 4.00+03       |               | 1.69-02          |                | 1.66+01         | 4.00-01        |               | 1.70+01          |                    | 8.65-02            |
| 5.00+03       |               | 1.38-02          |                | 1.67+01         | 4.03-01        |               | 1.71+01          |                    | 8.67-02            |
| 6.00+03       |               | 1.17-02          |                | 1.67+01         | 4.04-01        |               | 1.71+01          |                    | 8.68-02            |
| 8.00+03       |               | 9.05-03          |                | 1.67+01         | 4.06-01        |               | 1.72+01          |                    | 8.70-02            |
| 1.00+04       |               | 7.39-03          |                | 1.68+01         | 4.08-01        |               | 1.72+01          |                    | 8.71-02            |
| 1.50+04       |               | 5.11-03          |                | 1.68+01         | 4.10-01        |               | 1.72+01          |                    | 8.73-02            |
| 2.00+04       |               | 3.93-03          |                | 1.68+01         | 4.11-01        |               | 1.72+01          |                    | 8.74-02            |
| 3.00+04       |               | 2.71-03          |                | 1.68+01         | 4.12-01        |               | 1.73+01          |                    | 8.75-02            |
| 4.00+04       |               | 2.08-03          |                | 1.68+01         | 4.12-01        |               | 1.73+01          |                    | 8.76-02            |
| 5.00+04       |               | 1.69-03          |                | 1.69+01         | 4.13-01        |               | 1.73+01          |                    | 8.77-02            |
| 6.00+04       |               | 1.43-03          |                | 1.69+01         | 4.13-01        |               | 1.73+01          |                    | 8.77-02            |
| 8.00+04       |               | 1.10-03          |                | 1.69+01         | 4.13-01        |               | 1.73+01          |                    | 8.77-02            |
| 1.00+05       |               | 8.93-03          |                | 1.69+01         | 4.14-01        |               | 1.73+01          |                    | 8.77-02            |

(b/atom) x .005074 = cm<sup>2</sup>/g

Table 3.-20. IODINE, Z=53

| Photon energy | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|---------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|               | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV           | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| K             |               |                  |                |                 |                |               |                  |                    |                    |
| 1.00-02       | 6.07+02       | 3.39+01          | 3.33+04        |                 |                | 3.39+04       | 3.33+04          | 1.61+02            | 1.58+02            |
| 1.50-02       | 4.05+02       | 3.33+01          | 1.12+04        |                 |                | 1.16+04       | 1.13+04          | 5.52+01            | 5.34+01            |
| 2.00-02       | 2.94+02       | 3.28+01          | 5.18+03        |                 |                | 5.47+03       | 5.21+03          | 2.60+01            | 2.47+01            |
| 3.00-02       | 1.77+02       | 3.17+01          | 1.65+03        |                 |                | 1.83+03       | 1.68+03          | 8.67+00            | 7.98+00            |
| 3.32-02       | 1.56+02       | 3.13+01          | 1.24+03        |                 |                | 1.40+03       | 1.27+03          | 6.62+00            | 6.03+00            |
| 3.32-02       | 1.56+02       | 3.13+01          | 7.52+03        |                 |                | 7.68+03       | 7.55+03          | 3.64+01            | 3.58+01            |
| 4.00-02       | 1.23+02       | 3.07+01          | 4.66+03        |                 |                | 4.79+03       | 4.69+03          | 2.27+01            | 2.23+01            |
| 5.00-02       | 9.48+01       | 2.98+01          | 2.57+03        |                 |                | 2.66+03       | 2.60+03          | 1.26+01            | 1.23+01            |
| 6.00-02       | 7.69+01       | 2.89+01          | 1.56+03        |                 |                | 1.64+03       | 1.59+03          | 7.78+00            | 7.55+00            |
| 8.00-02       | 5.58+01       | 2.74+01          | 7.14+02        |                 |                | 7.69+02       | 7.41+02          | 3.65+00            | 3.52+00            |
| 1.00-01       | 4.46+01       | 2.61+01          | 3.77+02        |                 |                | 4.22+02       | 4.03+02          | 2.00+00            | 1.91+00            |
| 1.50-01       | 3.21+01       | 2.35+01          | 1.18+02        |                 |                | 1.50+02       | 1.42+02          | 7.14-01            | 6.74-01            |
| 2.00-01       | 2.64+01       | 2.15+01          | 5.21+01        |                 |                | 7.85+01       | 7.36+01          | 3.72-01            | 3.49-01            |
| 3.00-01       | 2.09+01       | 1.87+01          | 1.66+01        |                 |                | 3.76+01       | 3.53+01          | 1.78-01            | 1.68-01            |
| 4.00-01       | 1.80+01       | 1.68+01          | 7.71+00        |                 |                | 2.57+01       | 2.45+01          | 1.22-01            | 1.16-01            |
| 5.00-01       | 1.62+01       | 1.53+01          | 4.40+00        |                 |                | 2.06+01       | 1.97+01          | 9.76-02            | 9.36-02            |
| 6.00-01       | 1.48+01       | 1.42+01          | 2.83+00        |                 |                | 1.76+01       | 1.70+01          | 8.35-02            | 8.07-02            |
| 8.00-01       | 1.28+01       | 1.25+01          | 1.46+00        |                 |                | 1.42+01       | 1.39+01          | 6.76-02            | 6.61-02            |
| 1.00+00       | 1.13+01       | 1.12+01          | 9.11-01        |                 |                | 1.23+01       | 1.21+01          | 5.81-02            | 5.75-02            |
| 1.50+00       | 9.18+00       | 9.10+00          | 4.13-01        | 1.78-01         |                | 9.77+00       | 9.70+00          | 4.64-02            | 4.60-02            |
| 2.00+00       | 7.80+00       | 7.77+00          | 2.54-01        | 5.98-01         |                | 8.65+00       | 8.62+00          | 4.11-02            | 4.09-02            |
| 3.00+00       | 6.12+00       | 6.11+00          | 1.36-01        | 1.53+00         | 2.13-03        | 7.79+00       | 7.78+00          | 3.70-02            | 3.69-02            |
| 4.00+00       | 5.12+00       | 5.10+00          | 8.97-02        | 2.36+00         | 8.76-03        | 7.57+00       | 7.56+00          | 3.59-02            | 3.59-02            |
| 5.00+00       | 4.41+00       | 4.40+00          | 6.70-02        | 3.08+00         | 1.72-02        | 7.57+00       | 7.56+00          | 3.59-02            | 3.59-02            |
| 6.00+00       | 3.90+00       | 3.89+00          | 5.25-02        | 3.69+00         | 2.65-02        | 7.66+00       | 7.66+00          | 3.64-02            | 3.63-02            |
| 8.00+00       |               | 3.18+00          | 3.66-02        | 4.70+00         | 4.53-02        |               | 7.96+00          |                    | 3.78-02            |
| 1.00+01       |               | 2.71+00          | 2.82-02        | 5.52+00         | 6.19-02        |               | 8.32+00          |                    | 3.95-02            |
| 1.50+01       |               | 2.01+00          | 1.76-02        | 7.10+00         | 9.64-02        |               | 9.22+00          |                    | 4.38-02            |
| 2.00+01       |               | 1.61+00          | 1.28-02        | 8.29+00         | 1.23-01        |               | 1.00+01          |                    | 4.76-02            |
| 3.00+01       |               | 1.17+00          | 8.25-03        | 9.95+00         | 1.60-01        |               | 1.13+01          |                    | 5.36-02            |
| 4.00+01       |               | 9.32-01          | 6.09-03        | 1.11+01         | 1.87-01        |               | 1.22+01          |                    | 5.78-02            |
| 5.00+01       |               | 7.78-01          | 4.83-03        | 1.19+01         | 2.07-01        |               | 1.29+01          |                    | 6.11-02            |
| 6.00+01       |               | 6.70-01          | 3.99-03        | 1.25+01         | 2.23-01        |               | 1.34+01          |                    | 6.37-02            |
| 8.00+01       |               | 5.28-01          | 2.97-03        | 1.35+01         | 2.48-01        |               | 1.42+01          |                    | 6.76-02            |
| 1.00+02       |               | 4.39-01          | 2.37-03        | 1.41+01         | 2.66-01        |               | 1.48+01          |                    | 7.04-02            |
| 1.50+02       |               | 3.12-01          |                | 1.52+01         | 2.97-01        |               | 1.58+01          |                    | 7.50-02            |
| 2.00+02       |               | 2.45-01          |                | 1.58+01         | 3.16-01        |               | 1.64+01          |                    | 7.78-02            |
| 3.00+02       |               | 1.74-01          |                | 1.66+01         | 3.40-01        |               | 1.71+01          |                    | 8.11-02            |
| 4.00+02       |               | 1.36-01          |                | 1.70+01         | 3.56-01        |               | 1.75+01          |                    | 8.30-02            |
| 5.00+02       |               | 1.12-01          |                | 1.73+01         | 3.67-01        |               | 1.77+01          |                    | 8.42-02            |
| 6.00+02       |               | 9.63-02          |                | 1.75+01         | 3.75-01        |               | 1.79+01          |                    | 8.51-02            |
| 8.00+02       |               | 7.52-02          |                | 1.78+01         | 3.86-01        |               | 1.82+01          |                    | 8.64-02            |
| 1.00+03       |               | 6.19-02          |                | 1.79+01         | 3.94-01        |               | 1.84+01          |                    | 8.71-02            |
| 1.50+03       |               | 4.32-02          |                | 1.82+01         | 4.05-01        |               | 1.86+01          |                    | 8.84-02            |
| 2.00+03       |               | 3.35-02          |                | 1.83+01         | 4.11-01        |               | 1.88+01          |                    | 8.90-02            |
| 3.00+03       |               | 2.33-02          |                | 1.84+01         | 4.17-01        |               | 1.89+01          |                    | 8.96-02            |
| 4.00+03       |               | 1.80-02          |                | 1.85+01         | 4.21-01        |               | 1.90+01          |                    | 9.00-02            |
| 5.00+03       |               | 1.47-02          |                | 1.86+01         | 4.23-01        |               | 1.90+01          |                    | 9.02-02            |
| 6.00+03       |               | 1.24-02          |                | 1.86+01         | 4.25-01        |               | 1.90+01          |                    | 9.04-02            |
| 8.00+03       |               | 9.59-03          |                | 1.86+01         | 4.27-01        |               | 1.91+01          |                    | 9.05-02            |
| 1.00+04       |               | 7.83-03          |                | 1.87+01         | 4.29-01        |               | 1.91+01          |                    | 9.06-02            |
| 1.50+04       |               | 5.41-03          |                | 1.87+01         | 4.31-01        |               | 1.91+01          |                    | 9.08-02            |
| 2.00+04       |               | 4.16-03          |                | 1.87+01         | 4.32-01        |               | 1.92+01          |                    | 9.10-02            |
| 3.00+04       |               | 2.87-03          |                | 1.88+01         | 4.33-01        |               | 1.92+01          |                    | 9.11-02            |
| 4.00+04       |               | 2.20-03          |                | 1.88+01         | 4.33-01        |               | 1.92+01          |                    | 9.11-02            |
| 5.00+04       |               | 1.79-03          |                | 1.88+01         | 4.34-01        |               | 1.92+01          |                    | 9.11-02            |
| 6.00+04       |               | 1.52-03          |                | 1.88+01         | 4.34-01        |               | 1.92+01          |                    | 9.12-02            |
| 8.00+04       |               | 1.16-03          |                | 1.88+01         | 4.34-01        |               | 1.92+01          |                    | 9.12-02            |
| 1.00+05       |               | 9.46-04          |                | 1.88+01         | 4.35-01        |               | 1.92+01          |                    | 9.12-02            |

(b/atom) x .004746 = cm<sup>2</sup>/g



Table 3.-21. TUNGSTEN, Z = 74

| Photon energy  | Scattering     |                  | Photo-electric | Pair production |                | Total         |                  | Total                   |                         |         |         |
|----------------|----------------|------------------|----------------|-----------------|----------------|---------------|------------------|-------------------------|-------------------------|---------|---------|
|                | With coherent  | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent           | Without coherent        |         |         |
| <i>MeV</i>     | <i>b/atom</i>  | <i>b/atom</i>    | <i>b/atom</i>  | <i>b/atom</i>   | <i>b/atom</i>  | <i>b/atom</i> | <i>b/atom</i>    | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> |         |         |
| L <sub>3</sub> | 1.00-02        | 1.38+03          | 4.74+01        | 2.78+04         |                |               | 2.92+04          | 2.78+04                 | 9.55+01                 | 9.12+01 |         |
|                | 1.02-02        | 1.35+03          | 4.74+01        | 2.63+04         |                |               | 2.77+04          | 2.64+04                 | 9.07+01                 | 8.64+01 |         |
|                | 1.02-02        | 1.35+03          | 4.74+01        | 7.04+04         |                |               | 7.18+04          | 7.05+04                 | 2.35+02                 | 2.31+02 |         |
|                | 1.15-02        | 1.20+03          | 4.71+01        | 5.06+04         |                |               | 5.17+04          | 5.06+04                 | 1.70+02                 | 1.66+02 |         |
|                | L <sub>2</sub> | 1.15-02          | 1.20+03        | 4.71+01         | 7.05+04        |               |                  | 7.17+04                 | 7.05+04                 | 2.35+02 | 2.31+02 |
|                |                | 1.21-02          | 1.14+03        | 4.70+01         | 6.17+04        |               |                  | 6.29+04                 | 6.18+04                 | 2.06+02 | 2.02+02 |
|                |                | 1.21-02          | 1.14+03        | 4.70+01         | 7.45+04        |               |                  | 7.56+04                 | 7.45+04                 | 2.48+02 | 2.44+02 |
|                | L <sub>1</sub> | 1.50-02          | 8.99+02        | 4.65+01         | 4.25+04        |               |                  | 4.34+04                 | 4.25+04                 | 1.42+02 | 1.39+02 |
|                |                | 2.00-02          | 6.39+02        | 4.57+01         | 1.98+04        |               |                  | 2.05+04                 | 1.99+04                 | 6.70+01 | 6.51+01 |
| 3.00-02        |                | 3.88+02          | 4.42+01        | 6.62+03         |                |               | 7.01+03          | 6.67+03                 | 2.30+01                 | 2.18+01 |         |
| 4.00-02        |                | 2.65+02          | 4.28+01        | 3.00+03         |                |               | 3.26+03          | 3.04+03                 | 1.07+01                 | 9.97+00 |         |
| 5.00-02        |                | 1.96+02          | 4.16+01        | 1.61+03         |                |               | 1.80+03          | 1.65+03                 | 5.91+00                 | 5.40+00 |         |
| 6.00-02        |                | 1.54+02          | 4.04+01        | 9.61+02         |                |               | 1.12+03          | 1.00+03                 | 3.65+00                 | 3.28+00 |         |
| K              | 6.95-02        | 1.28+02          | 3.93+01        | 6.32+02         |                |               | 7.60+02          | 6.71+02                 | 2.49+00                 | 2.20+00 |         |
|                | 6.95-02        | 1.28+02          | 3.93+01        | 3.33+03         |                |               | 3.46+03          | 3.37+03                 | 1.13+01                 | 1.10+01 |         |
|                | 8.00-02        | 1.07+02          | 3.83+01        | 2.30+03         |                |               | 2.41+03          | 2.34+03                 | 7.89+00                 | 7.66+00 |         |
|                | 1.00-01        | 8.13+01          | 3.65+01        | 1.27+03         |                |               | 1.35+03          | 1.31+03                 | 4.43+00                 | 4.29+00 |         |
|                | 1.50-01        | 5.38+01          | 3.28+01        | 4.26+02         |                |               | 4.80+02          | 4.59+02                 | 1.57+00                 | 1.50+00 |         |
|                | 2.00-01        | 4.20+01          | 3.01+01        | 1.95+02         |                |               | 2.37+02          | 2.25+02                 | 7.77-01                 | 7.38-01 |         |
| 3.00-01        | 3.15+01        | 2.62+01          | 6.60+01        |                 |                | 9.75+01       | 9.22+01          | 3.20-01                 | 3.02-01                 |         |         |
| 4.00-01        | 2.65+01        | 2.34+01          | 3.14+01        |                 |                | 5.79+01       | 5.48+01          | 1.90-01                 | 1.80-01                 |         |         |
| 5.00-01        | 2.34+01        | 2.14+01          | 1.81+01        |                 |                | 4.15+01       | 3.95+01          | 1.36-01                 | 1.29-01                 |         |         |
| 6.00-01        | 2.12+01        | 1.98+01          | 1.17+01        |                 |                | 3.29+01       | 3.15+01          | 1.08-01                 | 1.03-01                 |         |         |
| 8.00-01        | 1.82+01        | 1.74+01          | 6.20+00        |                 |                | 2.44+01       | 2.36+01          | 7.99-02                 | 7.73-02                 |         |         |
| 1.00+00        | 1.61+01        | 1.56+01          | 3.88+00        |                 |                | 2.00+01       | 1.95+01          | 6.54-02                 | 6.39-02                 |         |         |
| 1.50+00        | 1.30+01        | 1.27+01          | 1.77+00        | 4.28-01         |                | 1.52+01       | 1.49+01          | 4.97-02                 | 4.88-02                 |         |         |
| 2.00+00        | 1.09+01        | 1.08+01          | 1.06+00        | 1.32+00         |                | 1.33+01       | 1.32+01          | 4.37-02                 | 4.34-02                 |         |         |
| 3.00+00        | 8.57+00        | 8.53+00          | 5.58-01        | 3.15+00         | 2.98-03        | 1.23+01       | 1.22+01          | 4.02-02                 | 4.01-02                 |         |         |
| 4.00+00        | 7.16+00        | 7.12+00          | 3.62-01        | 4.67+00         | 1.22-02        | 1.22+01       | 1.22+01          | 4.00-02                 | 3.98-02                 |         |         |
| 5.00+00        | 6.17+00        | 6.15+00          | 2.68-01        | 5.96+00         | 2.40-02        | 1.24+01       | 1.24+01          | 4.07-02                 | 4.06-02                 |         |         |
| 6.00+00        | 5.45+00        | 5.43+00          | 2.08-01        | 7.02+00         | 3.69-02        | 1.27+01       | 1.27+01          | 4.16-02                 | 4.16-02                 |         |         |
| 8.00+00        | 4.45+00        | 4.44+00          | 1.44-01        | 8.76+00         | 6.32-02        | 1.34+01       | 1.34+01          | 4.39-02                 | 4.39-02                 |         |         |
| 1.00+01        | 3.80+00        | 3.78+00          | 1.10-01        | 1.02+01         | 8.64-02        | 1.42+01       | 1.41+01          | 4.64-02                 | 4.63-02                 |         |         |
| 1.50+01        |                | 2.80+00          | 6.88-02        | 1.30+01         | 1.34-01        |               | 1.60+01          |                         | 5.24-02                 |         |         |
| 2.00+01        |                | 2.25+00          | 4.97-02        | 1.51+01         | 1.69-01        |               | 1.76+01          |                         | 5.77-02                 |         |         |
| 3.00+01        |                | 1.64+00          | 3.20-02        | 1.84+01         | 2.19-01        |               | 2.01+01          |                         | 6.59-02                 |         |         |
| 4.00+01        |                | 1.30+00          | 2.36-02        | 2.03+01         | 2.55-01        |               | 2.19+01          |                         | 7.16-02                 |         |         |
| 5.00+01        |                | 1.09+00          | 1.87-02        | 2.18+01         | 2.83-01        |               | 2.32+01          |                         | 7.60-02                 |         |         |
| 6.00+01        |                | 9.35-01          | 1.55-02        | 2.30+01         | 3.05-01        |               | 2.42+01          |                         | 7.94-02                 |         |         |
| 8.00+01        |                | 7.38-01          | 1.15-02        | 2.47+01         | 3.38-01        |               | 2.58+01          |                         | 8.45-02                 |         |         |
| 1.00+02        |                | 6.13-01          | 9.20-03        | 2.59+01         | 3.62-01        |               | 2.69+01          |                         | 8.81-02                 |         |         |
| 1.50+02        |                | 4.36-01          |                | 2.78+01         | 4.02-01        |               | 2.87+01          |                         | 9.39-02                 |         |         |
| 2.00+02        |                | 3.42-01          |                | 2.90+01         | 4.27-01        |               | 2.98+01          |                         | 9.76-02                 |         |         |
| 3.00+02        |                | 2.42-01          |                | 3.03+01         | 4.59-01        |               | 3.11+01          |                         | 1.02-01                 |         |         |
| 4.00+02        |                | 1.90-01          |                | 3.11+01         | 4.80-01        |               | 3.18+01          |                         | 1.04-01                 |         |         |
| 5.00+02        |                | 1.57-01          |                | 3.16+01         | 4.94-01        |               | 3.23+01          |                         | 1.06-01                 |         |         |
| 6.00+02        |                | 1.34-01          |                | 3.20+01         | 5.04-01        |               | 3.26+01          |                         | 1.07-01                 |         |         |
| 8.00+02        |                | 1.05-01          |                | 3.24+01         | 5.18-01        |               | 3.31+01          |                         | 1.08-01                 |         |         |
| 1.00+03        |                | 8.64-02          |                | 3.27+01         | 5.27-01        |               | 3.34+01          |                         | 1.09-01                 |         |         |
| 1.50+03        |                | 6.04-02          |                | 3.32+01         | 5.40-01        |               | 3.38+01          |                         | 1.11-01                 |         |         |
| 2.00+03        |                | 4.67-02          |                | 3.34+01         | 5.48-01        |               | 3.40+01          |                         | 1.11-01                 |         |         |
| 3.00+03        |                | 3.25-02          |                | 3.37+01         | 5.56-01        |               | 3.43+01          |                         | 1.12-01                 |         |         |
| 4.00+03        |                | 2.51-02          |                | 3.38+01         | 5.60-01        |               | 3.44+01          |                         | 1.13-01                 |         |         |
| 5.00+03        |                | 2.05-02          |                | 3.39+01         | 5.63-01        |               | 3.45+01          |                         | 1.13-01                 |         |         |
| 6.00+03        |                | 1.74-02          |                | 3.40+01         | 5.65-01        |               | 3.45+01          |                         | 1.13-01                 |         |         |
| 8.00+03        |                | 1.34-02          |                | 3.40+01         | 5.68-01        |               | 3.46+01          |                         | 1.13-01                 |         |         |
| 1.00+04        |                | 1.09-02          |                | 3.41+01         | 5.70-01        |               | 3.47+01          |                         | 1.14-01                 |         |         |
| 1.50+04        |                | 7.56-03          |                | 3.41+01         | 5.72-01        |               | 3.47+01          |                         | 1.14-01                 |         |         |
| 2.00+04        |                | 5.81-03          |                | 3.42+01         | 5.73-01        |               | 3.48+01          |                         | 1.14-01                 |         |         |
| 3.00+04        |                | 4.01-03          |                | 3.42+01         | 5.75-01        |               | 3.48+01          |                         | 1.14-01                 |         |         |
| 4.00+04        |                | 3.08-03          |                | 3.42+01         | 5.76-01        |               | 3.48+01          |                         | 1.14-01                 |         |         |
| 5.00+04        |                | 2.51-03          |                | 3.43+01         | 5.76-01        |               | 3.48+01          |                         | 1.14-01                 |         |         |
| 6.00+04        |                | 2.12-03          |                | 3.43+01         | 5.76-01        |               | 3.48+01          |                         | 1.14-01                 |         |         |
| 8.00+04        |                | 1.62-03          |                | 3.43+01         | 5.77-01        |               | 3.48+01          |                         | 1.14-01                 |         |         |
| 1.00+05        |                | 1.32-03          |                | 3.43+01         | 5.77-01        |               | 3.48+01          |                         | 1.14-01                 |         |         |

(b/atom) x .003276 = cm<sup>2</sup>/g

Table 3.-22. LEAD, Z=82

| Photon energy  | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|----------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|                | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV            | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| L <sub>3</sub> | 1.00-02       | 1.73+03          | 5.25+01        | 4.40+04         |                | 4.57+04       | 4.41+04          | 1.33+02            | 1.28+02            |
|                | 1.30-02       | 1.34+03          | 5.19+01        | 2.20+04         |                | 2.33+04       | 2.20+04          | 6.78+01            | 6.41+01            |
|                | 1.30-02       | 1.34+03          | 5.19+01        | 5.58+04         |                | 5.71+04       | 5.59+04          | 1.66+02            | 1.62+02            |
|                | 1.50-02       | 1.15+03          | 5.16+01        | 3.84+04         |                | 3.96+04       | 3.85+04          | 1.15+02            | 1.12+02            |
|                | 1.52-02       | 1.13+03          | 5.15+01        | 3.75+04         |                | 3.86+04       | 3.76+04          | 1.12+02            | 1.09+02            |
|                | 1.52-02       | 1.13+03          | 5.15+01        | 4.90+04         |                | 5.01+04       | 4.91+04          | 1.46+02            | 1.43+02            |
| L <sub>2</sub> | 1.59-02       | 1.08+03          | 5.14+01        | 4.35+04         |                | 4.46+04       | 4.36+04          | 1.30+02            | 1.27+02            |
|                | 1.59-02       | 1.08+03          | 5.14+01        | 5.29+04         |                | 5.40+04       | 5.29+04          | 1.57+02            | 1.54+02            |
| L <sub>1</sub> | 2.00-02       | 8.17+02          | 5.07+01        | 2.86+04         |                | 2.95+04       | 2.87+04          | 8.57+01            | 8.34+01            |
|                | 3.00-02       | 4.91+02          | 4.90+01        | 9.71+03         |                | 1.02+04       | 9.76+03          | 2.97+01            | 2.84+01            |
| K              | 4.00-02       | 3.36+02          | 4.75+01        | 4.47+03         |                | 4.81+03       | 4.52+03          | 1.40+01            | 1.31+01            |
|                | 5.00-02       | 2.48+02          | 4.60+01        | 2.44+03         |                | 2.68+03       | 2.48+03          | 7.81+00            | 7.22+00            |
|                | 6.00-02       | 1.94+02          | 4.47+01        | 1.48+03         |                | 1.67+03       | 1.52+03          | 4.87+00            | 4.43+00            |
|                | 8.00-02       | 1.32+02          | 4.24+01        | 6.70+02         |                | 8.03+02       | 7.13+02          | 2.33+00            | 2.07+00            |
|                | 8.80-02       | 1.16+02          | 4.16+01        | 5.15+02         |                | 6.31+02       | 5.56+02          | 1.83+00            | 1.62+00            |
|                | 8.80-02       | 1.16+02          | 4.16+01        | 2.45+03         |                | 2.56+03       | 2.49+03          | 7.45+00            | 7.23+00            |
|                | 1.00-01       | 9.93+01          | 4.04+01        | 1.76+03         |                | 1.86+03       | 1.80+03          | 5.40+00            | 5.23+00            |
|                | 1.50-01       | 6.39+01          | 3.64+01        | 6.14+02         |                | 6.78+02       | 6.51+02          | 1.97+00            | 1.89+00            |
|                | 2.00-01       | 4.92+01          | 3.33+01        | 2.92+02         |                | 3.41+02       | 3.25+02          | 9.91-01            | 9.45-01            |
|                | 3.00-01       | 3.61+01          | 2.90+01        | 1.03+02         |                | 1.39+02       | 1.32+02          | 4.04-01            | 3.83-01            |
|                | 4.00-01       | 3.00+01          | 2.60+01        | 4.96+01         |                | 7.96+01       | 7.56+01          | 2.31-01            | 2.20-01            |
|                | 5.00-01       | 2.63+01          | 2.37+01        | 2.92+01         |                | 5.55+01       | 5.29+01          | 1.61-01            | 1.54-01            |
| 6.00-01        | 2.37+01       | 2.19+01          | 1.92+01        |                 | 4.29+01        | 4.11+01       | 1.25-01          | 1.20-01            |                    |
| 8.00-01        | 2.03+01       | 1.93+01          | 1.02+01        |                 | 3.04+01        | 2.95+01       | 8.85-02          | 8.56-02            |                    |
| 1.00+00        | 1.79+01       | 1.73+01          | 6.39+00        |                 | 2.43+01        | 2.37+01       | 7.08-02          | 6.90-02            |                    |
| 1.50+00        | 1.43+01       | 1.41+01          | 2.89+00        | 5.66-01         | 1.78+01        | 1.75+01       | 5.17-02          | 5.10-02            |                    |
| 2.00+00        | 1.22+01       | 1.20+01          | 1.77+00        | 1.70+00         | 1.57+01        | 1.55+01       | 4.55-02          | 4.50-02            |                    |
| 3.00+00        | 9.51+00       | 9.46+00          | 9.14-01        | 3.94+00         | 3.30-03        | 1.44+01       | 1.43+01          | 4.18-02            | 4.16-02            |
| 4.00+00        | 7.94+00       | 7.89+00          | 5.89-01        | 5.77+00         | 1.35-02        | 1.43+01       | 1.43+01          | 4.16-02            | 4.14-02            |
| 5.00+00        | 6.84+00       | 6.81+00          | 4.34-01        | 7.30+00         | 2.66-02        | 1.46+01       | 1.46+01          | 4.24-02            | 4.24-02            |
| 6.00+00        | 6.04+00       | 6.02+00          | 3.36-01        | 8.54+00         | 4.09-02        | 1.50+01       | 1.49+01          | 4.35-02            | 4.34-02            |
| 8.00+00        | 4.93+00       | 4.92+00          | 2.31-01        | 1.05+01         | 7.00-02        | 1.58+01       | 1.58+01          | 4.59-02            | 4.59-02            |
| 1.00+01        | 4.20+00       | 4.19+00          | 1.78-01        | 1.22+01         | 9.57-02        | 1.67+01       | 1.67+01          | 4.84-02            | 4.84-02            |
| 1.50+01        |               | 3.10+00          | 1.12-01        | 1.55+01         | 1.48-01        |               | 1.89+01          |                    | 5.48-02            |
| 2.00+01        |               | 2.49+00          | 8.10-02        | 1.81+01         | 1.86-01        |               | 2.09+01          |                    | 6.06-02            |
| 3.00+01        |               | 1.81+00          | 5.20-02        | 2.18+01         | 2.42-01        |               | 2.39+01          |                    | 6.96-02            |
| 4.00+01        |               | 1.44+00          | 3.80-02        | 2.43+01         | 2.81-01        |               | 2.60+01          |                    | 7.57-02            |
| 5.00+01        |               | 1.20+00          | 3.00-02        | 2.61+01         | 3.11-01        |               | 2.77+01          |                    | 8.04-02            |
| 6.00+01        |               | 1.04+00          | 2.50-02        | 2.75+01         | 3.35-01        |               | 2.89+01          |                    | 8.41-02            |
| 8.00+01        |               | 8.18-01          | 1.80-02        | 2.96+01         | 3.71-01        |               | 3.08+01          |                    | 8.96-02            |
| 1.00+02        |               | 6.79-01          | 1.41-02        | 3.10+01         | 3.97-01        |               | 3.21+01          |                    | 9.34-02            |
| 1.50+02        |               | 4.83-01          |                | 3.33+01         | 4.41-01        |               | 3.43+01          |                    | 9.96-02            |
| 2.00+02        |               | 3.79-01          |                | 3.48+01         | 4.68-01        |               | 3.56+01          |                    | 1.03-01            |
| 3.00+02        |               | 2.69-01          |                | 3.64+01         | 5.03-01        |               | 3.71+01          |                    | 1.08-01            |
| 4.00+02        |               | 2.10-01          |                | 3.73+01         | 5.25-01        |               | 3.80+01          |                    | 1.11-01            |
| 5.00+02        |               | 1.74-01          |                | 3.79+01         | 5.40-01        |               | 3.86+01          |                    | 1.12-01            |
| 6.00+02        |               | 1.49-01          |                | 3.83+01         | 5.51-01        |               | 3.90+01          |                    | 1.13-01            |
| 8.00+02        |               | 1.16-01          |                | 3.89+01         | 5.66-01        |               | 3.96+01          |                    | 1.15-01            |
| 1.00+03        |               | 9.58-02          |                | 3.92+01         | 5.76-01        |               | 3.99+01          |                    | 1.16-01            |
| 1.50+03        |               | 6.69-02          |                | 3.98+01         | 5.90-01        |               | 4.04+01          |                    | 1.18-01            |
| 2.00+03        |               | 5.18-02          |                | 4.00+01         | 5.98-01        |               | 4.07+01          |                    | 1.18-01            |
| 3.00+03        |               | 3.60-02          |                | 4.04+01         | 6.07-01        |               | 4.10+01          |                    | 1.19-01            |
| 4.00+03        |               | 2.78-02          |                | 4.05+01         | 6.12-01        |               | 4.12+01          |                    | 1.20-01            |
| 5.00+03        |               | 2.27-02          |                | 4.06+01         | 6.15-01        |               | 4.13+01          |                    | 1.20-01            |
| 6.00+03        |               | 1.93-02          |                | 4.07+01         | 6.17-01        |               | 4.13+01          |                    | 1.20-01            |
| 8.00+03        |               | 1.48-02          |                | 4.08+01         | 6.20-01        |               | 4.14+01          |                    | 1.20-01            |
| 1.00+04        |               | 1.21-02          |                | 4.09+01         | 6.21-01        |               | 4.15+01          |                    | 1.21-01            |
| 1.50+04        |               | 8.37-03          |                | 4.09+01         | 6.24-01        |               | 4.16+01          |                    | 1.21-01            |
| 2.00+04        |               | 6.44-03          |                | 4.10+01         | 6.25-01        |               | 4.16+01          |                    | 1.21-01            |
| 3.00+04        |               | 4.44-03          |                | 4.10+01         | 6.27-01        |               | 4.16+01          |                    | 1.21-01            |
| 4.00+04        |               | 3.41-03          |                | 4.10+01         | 6.28-01        |               | 4.17+01          |                    | 1.21-01            |
| 5.00+04        |               | 2.78-03          |                | 4.11+01         | 6.28-01        |               | 4.17+01          |                    | 1.21-01            |
| 6.00+04        |               | 2.35-03          |                | 4.11+01         | 6.28-01        |               | 4.17+01          |                    | 1.21-01            |
| 8.00+04        |               | 1.80-03          |                | 4.11+01         | 6.29-01        |               | 4.17+01          |                    | 1.21-01            |
| 1.00+05        |               | 1.46-03          |                | 4.11+01         | 6.29-01        |               | 4.17+01          |                    | 1.21-01            |

(b/atom) x .002907 = cm<sup>2</sup>/g

Table 3.-23. URANIUM, Z=92

| Photon energy  | Scattering    |                  | Photo-electric | Pair production |                | Total         |                  | Total              |                    |
|----------------|---------------|------------------|----------------|-----------------|----------------|---------------|------------------|--------------------|--------------------|
|                | With coherent | Without coherent |                | Nuclear field   | Electron field | With coherent | Without coherent | With coherent      | Without coherent   |
| MeV            | b/atom        | b/atom           | b/atom         | b/atom          | b/atom         | b/atom        | b/atom           | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| L <sub>3</sub> | 1.00-02       | 2.17+03          | 5.89+01        | 6.84+04         |                | 7.05+04       | 6.84+04          | 1.78+02            | 1.73+02            |
|                | 1.50-02       | 1.47+03          | 5.79+01        | 2.38+04         |                | 2.53+04       | 2.38+04          | 6.39+01            | 6.03+01            |
|                | 1.72-02       | 1.27+03          | 5.74+01        | 1.68+04         |                | 1.81+04       | 1.69+04          | 4.58+01            | 4.28+01            |
|                | 1.72-02       | 1.27+03          | 5.74+01        | 4.06+04         |                | 4.19+04       | 4.07+04          | 1.06+02            | 1.03+02            |
|                | 2.00-02       | 1.07+03          | 5.68+01        | 2.70+04         |                | 2.81+04       | 2.71+04          | 7.10+01            | 6.85+01            |
|                | 2.09-02       | 1.01+03          | 5.67+01        | 2.38+04         |                | 2.48+04       | 2.38+04          | 6.27+01            | 6.03+01            |
|                | 2.09-02       | 1.01+03          | 5.67+01        | 3.38+04         |                | 3.48+04       | 3.38+04          | 8.80+01            | 8.56+01            |
|                | 2.18-02       | 9.61+02          | 5.65+01        | 3.06+04         |                | 3.15+04       | 3.06+04          | 7.98+01            | 7.75+01            |
| L <sub>2</sub> | 2.18-02       | 9.61+02          | 5.65+01        | 3.53+04         |                | 3.63+04       | 3.54+04          | 9.18+01            | 8.95+01            |
|                | 3.00-02       | 6.36+02          | 5.50+01        | 1.56+04         |                | 1.62+04       | 1.56+04          | 4.10+01            | 3.96+01            |
|                | 4.00-02       | 4.36+02          | 5.32+01        | 7.35+03         |                | 7.79+03       | 7.40+03          | 1.97+01            | 1.87+01            |
|                | 5.00-02       | 3.22+02          | 5.16+01        | 4.07+03         |                | 4.39+03       | 4.12+03          | 1.11+01            | 1.04+01            |
|                | 6.00-02       | 2.51+02          | 5.02+01        | 2.50+03         |                | 2.75+03       | 2.55+03          | 6.96+00            | 6.45+00            |
|                | 8.00-02       | 1.68+02          | 4.76+01        | 1.16+03         |                | 1.32+03       | 1.20+03          | 3.35+00            | 3.04+00            |
|                | 1.00-01       | 1.25+02          | 4.53+01        | 6.31+02         |                | 7.56+02       | 6.77+02          | 1.91+00            | 1.71+00            |
|                | 1.16-01       | 1.05+02          | 4.38+01        | 4.26+02         |                | 5.31+02       | 4.70+02          | 1.34+00            | 1.19+00            |
| K              | 1.16-01       | 1.05+02          | 4.38+01        | 1.82+03         |                | 1.92+03       | 1.86+03          | 4.86+00            | 4.71+00            |
|                | 1.50-01       | 7.80+01          | 4.08+01        | 9.36+02         |                | 1.01+03       | 9.77+02          | 2.56+00            | 2.47+00            |
|                | 2.00-01       | 5.88+01          | 3.74+01        | 4.48+02         |                | 5.07+02       | 4.85+02          | 1.28+00            | 1.23+00            |
|                | 3.00-01       | 4.21+01          | 3.25+01        | 1.59+02         |                | 2.01+02       | 1.92+02          | 5.09-01            | 4.85-01            |
|                | 4.00-01       | 3.45+01          | 2.91+01        | 7.87+01         |                | 1.13+02       | 1.08+02          | 2.86-01            | 2.73-01            |
|                | 5.00-01       | 3.01+01          | 2.66+01        | 4.64+01         |                | 7.65+01       | 7.30+01          | 1.93-01            | 1.85-01            |
|                | 6.00-01       | 2.70+01          | 2.46+01        | 3.06+01         |                | 5.76+01       | 5.52+01          | 1.46-01            | 1.40-01            |
|                | 8.00-01       | 2.29+01          | 2.16+01        | 1.65+01         |                | 3.94+01       | 3.81+01          | 9.97-02            | 9.64-02            |
| 1.00+00        | 2.03+01       | 1.94+01          | 1.04+01        |                 | 3.07+01        | 2.98+01       | 7.76-02          | 7.54-02            |                    |
| 1.50+00        | 1.61+01       | 1.58+01          | 4.73+00        | 7.77-01         | 2.17+01        | 2.13+01       | 5.48-02          | 5.39-02            |                    |
| 2.00+00        | 1.37+01       | 1.35+01          | 2.84+00        | 2.26+00         | 1.88+01        | 1.86+01       | 4.75-02          | 4.70-02            |                    |
| 3.00+00        | 1.07+01       | 1.06+01          | 1.49+00        | 5.09+00         | 3.70-03        | 1.73+01       | 1.72+01          | 4.38-02            | 4.35-02            |
| 4.00+00        | 8.91+00       | 8.85+00          | 9.58-01        | 7.32+00         | 1.52-02        | 1.72+01       | 1.71+01          | 4.35-02            | 4.34-02            |
| 5.00+00        | 7.68+00       | 7.64+00          | 7.02-01        | 9.16+00         | 2.99-02        | 1.76+01       | 1.75+01          | 4.45-02            | 4.44-02            |
| 6.00+00        | 6.78+00       | 6.75+00          | 5.43-01        | 1.06+01         | 4.59-02        | 1.80+01       | 1.80+01          | 4.55-02            | 4.54-02            |
| 8.00+00        | 5.55+00       | 5.52+00          | 3.75-01        | 1.30+01         | 7.86-02        | 1.90+01       | 1.89+01          | 4.80-02            | 4.79-02            |
| 1.00+01        | 4.72+00       | 4.71+00          | 2.88-01        | 1.49+01         | 1.07-01        | 2.00+01       | 2.00+01          | 5.06-02            | 5.06-02            |
| 1.50+01        |               | 3.48+00          | 1.80-01        | 1.88+01         | 1.65-01        |               | 2.27+01          |                    | 5.73-02            |
| 2.00+01        |               | 2.80+00          | 1.31-01        | 2.20+01         | 2.08-01        |               | 2.51+01          |                    | 6.36-02            |
| 3.00+01        |               | 2.04+00          | 8.50-02        | 2.66+01         | 2.69-01        |               | 2.90+01          |                    | 7.33-02            |
| 4.00+01        |               | 1.62+00          | 6.20-02        | 2.96+01         | 3.13-01        |               | 3.16+01          |                    | 7.99-02            |
| 5.00+01        |               | 1.35+00          | 5.00-02        | 3.18+01         | 3.46-01        |               | 3.36+01          |                    | 8.50-02            |
| 6.00+01        |               | 1.16+00          | 4.00-02        | 3.36+01         | 3.73-01        |               | 3.51+01          |                    | 8.89-02            |
| 8.00+01        |               | 9.17-01          | 3.00-02        | 3.61+01         | 4.12-01        |               | 3.75+01          |                    | 9.48-02            |
| 1.00+02        |               | 7.62-01          | 2.40-02        | 3.77+01         | 4.41-01        |               | 3.89+01          |                    | 9.84-02            |
| 1.50+02        |               | 5.42-01          |                | 4.07+01         | 4.89-01        |               | 4.17+01          |                    | 1.06-01            |
| 2.00+02        |               | 4.25-01          |                | 4.24+01         | 5.19-01        |               | 4.34+01          |                    | 1.10-01            |
| 3.00+02        |               | 3.01-01          |                | 4.44+01         | 5.57-01        |               | 4.53+01          |                    | 1.15-01            |
| 4.00+02        |               | 2.36-01          |                | 4.56+01         | 5.81-01        |               | 4.64+01          |                    | 1.17-01            |
| 5.00+02        |               | 1.95-01          |                | 4.63+01         | 5.98-01        |               | 4.71+01          |                    | 1.19-01            |
| 6.00+02        |               | 1.67-01          |                | 4.69+01         | 6.09-01        |               | 4.76+01          |                    | 1.21-01            |
| 8.00+02        |               | 1.31-01          |                | 4.75+01         | 6.25-01        |               | 4.83+01          |                    | 1.22-01            |
| 1.00+03        |               | 1.07-01          |                | 4.80+01         | 6.36-01        |               | 4.88+01          |                    | 1.23-01            |
| 1.50+03        |               | 7.50-02          |                | 4.87+01         | 6.51-01        |               | 4.94+01          |                    | 1.25-01            |
| 2.00+03        |               | 5.81-02          |                | 4.90+01         | 6.60-01        |               | 4.97+01          |                    | 1.26-01            |
| 3.00+03        |               | 4.04-02          |                | 4.94+01         | 6.69-01        |               | 5.01+01          |                    | 1.27-01            |
| 4.00+03        |               | 3.12-02          |                | 4.96+01         | 6.74-01        |               | 5.03+01          |                    | 1.27-01            |
| 5.00+03        |               | 2.55-02          |                | 4.97+01         | 6.78-01        |               | 5.04+01          |                    | 1.28-01            |
| 6.00+03        |               | 2.16-02          |                | 4.98+01         | 6.80-01        |               | 5.05+01          |                    | 1.28-01            |
| 8.00+03        |               | 1.67-02          |                | 5.00+01         | 6.83-01        |               | 5.07+01          |                    | 1.28-01            |
| 1.00+04        |               | 1.36-02          |                | 5.00+01         | 6.85-01        |               | 5.07+01          |                    | 1.28-01            |
| 1.50+04        |               | 9.40-03          |                | 5.01+01         | 6.88-01        |               | 5.08+01          |                    | 1.29-01            |
| 2.00+04        |               | 7.22-03          |                | 5.02+01         | 6.89-01        |               | 5.09+01          |                    | 1.29-01            |
| 3.00+04        |               | 4.98-03          |                | 5.02+01         | 6.91-01        |               | 5.09+01          |                    | 1.29-01            |
| 4.00+04        |               | 3.83-03          |                | 5.03+01         | 6.92-01        |               | 5.10+01          |                    | 1.29-01            |
| 5.00+04        |               | 3.11-03          |                | 5.03+01         | 6.92-01        |               | 5.10+01          |                    | 1.29-01            |
| 6.00+04        |               | 2.63-03          |                | 5.03+01         | 6.92-01        |               | 5.10+01          |                    | 1.29-01            |
| 8.00+04        |               | 2.02-03          |                | 5.03+01         | 6.93-01        |               | 5.10+01          |                    | 1.29-01            |
| 1.00+05        |               | 1.64-03          |                | 5.04+01         | 6.93-01        |               | 5.11+01          |                    | 1.29-01            |

(b/atom) x .002530 = cm<sup>2</sup>/g

Table 3.-24. WATER, H<sub>2</sub>O

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.97-01            | 2.14-01            | 4.78+00            |                    |                    | 5.18+00            | 4.99+00            |
| 1.50-02       | 3.09-01            | 2.10-01            | 1.27+00            |                    |                    | 1.58+00            | 1.48+00            |
| 2.00-02       | 2.70-01            | 2.07-01            | 5.05-01            |                    |                    | 7.75-01            | 7.11-01            |
| 3.00-02       | 2.32-01            | 2.00-01            | 1.38-01            |                    |                    | 3.70-01            | 3.38-01            |
| 4.00-02       | 2.13-01            | 1.93-01            | 5.48-02            |                    |                    | 2.67-01            | 2.48-01            |
| 5.00-02       | 2.00-01            | 1.88-01            | 2.67-02            |                    |                    | 2.27-01            | 2.14-01            |
| 6.00-02       | 1.91-01            | 1.82-01            | 1.50-02            |                    |                    | 2.06-01            | 1.97-01            |
| 8.00-02       | 1.78-01            | 1.73-01            | 5.95-03            |                    |                    | 1.84-01            | 1.79-01            |
| 1.00-01       | 1.68-01            | 1.65-01            | 2.85-03            |                    |                    | 1.71-01            | 1.68-01            |
| 1.50-01       | 1.50-01            | 1.48-01            | 7.76-04            |                    |                    | 1.51-01            | 1.49-01            |
| 2.00-01       | 1.37-01            | 1.36-01            | 3.11-04            |                    |                    | 1.37-01            | 1.36-01            |
| 3.00-01       | 1.19-01            | 1.18-01            | 8.86-05            |                    |                    | 1.19-01            | 1.18-01            |
| 4.00-01       | 1.06-01            | 1.06-01            | 3.78-05            |                    |                    | 1.06-01            | 1.06-01            |
| 5.00-01       | 9.68-02            | 9.67-02            | 2.04-05            |                    |                    | 9.68-02            | 9.67-02            |
| 6.00-01       | 8.96-02            | 8.95-02            | 1.28-05            |                    |                    | 8.96-02            | 8.95-02            |
| 8.00-01       |                    | 7.86-02            | 6.42-06            |                    |                    |                    | 7.86-02            |
| 1.00+00       |                    | 7.06-02            | 3.98-06            |                    |                    |                    | 7.07-02            |
| 1.50+00       |                    | 5.74-02            | 1.86-06            | 9.86-05            |                    |                    | 5.75-02            |
| 2.00+00       |                    | 4.90-02            | 1.18-06            | 3.93-04            |                    |                    | 4.94-02            |
| 3.00+00       |                    | 3.85-02            | 6.62-07            | 1.13-03            | 1.34-05            |                    | 3.97-02            |
| 4.00+00       |                    | 3.22-02            | 4.51-07            | 1.83-03            | 5.52-05            |                    | 3.40-02            |
| 5.00+00       |                    | 2.78-02            | 3.44-07            | 2.45-03            | 1.09-04            |                    | 3.03-02            |
| 6.00+00       |                    | 2.45-02            | 2.75-07            | 3.00-03            | 1.67-04            |                    | 2.77-02            |
| 8.00+00       |                    | 2.01-02            | 1.97-07            | 3.93-03            | 2.86-04            |                    | 2.43-02            |
| 1.00+01       |                    | 1.71-02            | 1.54-07            | 4.69-03            | 3.90-04            |                    | 2.22-02            |
| 1.50+01       |                    | 1.27-02            |                    | 6.11-03            | 6.08-04            |                    | 1.94-02            |
| 2.00+01       |                    | 1.02-02            |                    | 7.16-03            | 7.80-04            |                    | 1.81-02            |
| 3.00+01       |                    | 7.40-03            |                    | 8.63-03            | 1.04-03            |                    | 1.71-02            |
| 4.00+01       |                    | 5.88-03            |                    | 9.63-03            | 1.23-03            |                    | 1.67-02            |
| 5.00+01       |                    | 4.91-03            |                    | 1.04-02            | 1.38-03            |                    | 1.67-02            |
| 6.00+01       |                    | 4.22-03            |                    | 1.10-02            | 1.51-03            |                    | 1.67-02            |
| 8.00+01       |                    | 3.33-03            |                    | 1.19-02            | 1.70-03            |                    | 1.70-02            |
| 1.00+02       |                    | 2.77-03            |                    | 1.26-02            | 1.84-03            |                    | 1.72-02            |
| 1.50+02       |                    | 1.97-03            |                    | 1.37-02            | 2.09-03            |                    | 1.78-02            |
| 2.00+02       |                    | 1.54-03            |                    | 1.44-02            | 2.26-03            |                    | 1.82-02            |
| 3.00+02       |                    | 1.09-03            |                    | 1.52-02            | 2.48-03            |                    | 1.88-02            |
| 4.00+02       |                    | 8.57-04            |                    | 1.57-02            | 2.62-03            |                    | 1.92-02            |
| 5.00+02       |                    | 7.10-04            |                    | 1.60-02            | 2.73-03            |                    | 1.95-02            |
| 6.00+02       |                    | 6.08-04            |                    | 1.63-02            | 2.80-03            |                    | 1.97-02            |
| 8.00+02       |                    | 4.75-04            |                    | 1.66-02            | 2.92-03            |                    | 2.00-02            |
| 1.00+03       |                    | 3.90-04            |                    | 1.68-02            | 3.00-03            |                    | 2.02-02            |
| 1.50+03       |                    | 2.73-04            |                    | 1.71-02            | 3.12-03            |                    | 2.05-02            |
| 2.00+03       |                    | 2.11-04            |                    | 1.72-02            | 3.20-03            |                    | 2.06-02            |
| 3.00+03       |                    | 1.47-04            |                    | 1.74-02            | 3.30-03            |                    | 2.08-02            |
| 4.00+03       |                    | 1.13-04            |                    | 1.75-02            | 3.35-03            |                    | 2.10-02            |
| 5.00+03       |                    | 9.26-05            |                    | 1.76-02            | 3.38-03            |                    | 2.10-02            |
| 6.00+03       |                    | 7.86-05            |                    | 1.76-02            | 3.40-03            |                    | 2.11-02            |
| 8.00+03       |                    | 6.05-05            |                    | 1.77-02            | 3.43-03            |                    | 2.11-02            |
| 1.00+04       |                    | 4.94-05            |                    | 1.77-02            | 3.45-03            |                    | 2.12-02            |
| 1.50+04       |                    | 3.41-05            |                    | 1.77-02            | 3.48-03            |                    | 2.13-02            |
| 2.00+04       |                    | 2.62-05            |                    | 1.78-02            | 3.50-03            |                    | 2.13-02            |
| 3.00+04       |                    | 1.81-05            |                    | 1.78-02            | 3.52-03            |                    | 2.13-02            |
| 4.00+04       |                    | 1.39-05            |                    | 1.78-02            | 3.52-03            |                    | 2.13-02            |
| 5.00+04       |                    | 1.13-05            |                    | 1.78-02            | 3.53-03            |                    | 2.13-02            |
| 6.00+04       |                    | 9.57-06            |                    | 1.78-02            | 3.53-03            |                    | 2.14-02            |
| 8.00+04       |                    | 7.33-06            |                    | 1.78-02            | 3.54-03            |                    | 2.14-02            |
| 1.00+05       |                    | 5.97-06            |                    | 1.78-02            | 3.54-03            |                    | 2.14-02            |

**Table 3.-25. SILICON DIOXIDE, SiO<sub>2</sub>**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 5.64-01            | 1.93-01            | 1.85+01            |                    |                    | 1.90+01            | 1.87+01            |
| 1.50-02       | 3.95-01            | 1.89-01            | 5.33+00            |                    |                    | 5.73+00            | 5.52+00            |
| 2.00-02       | 3.16-01            | 1.86-01            | 2.18+00            |                    |                    | 2.49+00            | 2.36+00            |
| 3.00-02       | 2.46-01            | 1.80-01            | 6.13-01            |                    |                    | 8.59-01            | 7.93-01            |
| 4.00-02       | 2.14-01            | 1.74-01            | 2.48-01            |                    |                    | 4.63-01            | 4.22-01            |
| 5.00-02       | 1.96-01            | 1.69-01            | 1.22-01            |                    |                    | 3.18-01            | 2.91-01            |
| 6.00-02       | 1.83-01            | 1.64-01            | 6.91-02            |                    |                    | 2.52-01            | 2.33-01            |
| 8.00-02       | 1.67-01            | 1.56-01            | 2.78-02            |                    |                    | 1.94-01            | 1.83-01            |
| 1.00-01       | 1.55-01            | 1.48-01            | 1.36-02            |                    |                    | 1.69-01            | 1.62-01            |
| 1.50-01       | 1.37-01            | 1.33-01            | 3.76-03            |                    |                    | 1.40-01            | 1.37-01            |
| 2.00-01       | 1.24-01            | 1.22-01            | 1.53-03            |                    |                    | 1.26-01            | 1.24-01            |
| 3.00-01       | 1.07-01            | 1.06-01            | 4.45-04            |                    |                    | 1.08-01            | 1.07-01            |
| 4.00-01       | 9.57-02            | 9.52-02            | 1.92-04            |                    |                    | 9.59-02            | 9.54-02            |
| 5.00-01       | 8.73-02            | 8.70-02            | 1.04-04            |                    |                    | 8.74-02            | 8.71-02            |
| 6.00-01       | 8.07-02            | 8.05-02            | 6.50-05            |                    |                    | 8.08-02            | 8.05-02            |
| 8.00-01       |                    | 7.07-02            | 3.28-05            |                    |                    |                    | 7.07-02            |
| 1.00+00       |                    | 6.36-02            | 2.03-05            |                    |                    |                    | 6.36-02            |
| 1.50+00       |                    | 5.16-02            | 9.49-06            | 1.47-04            |                    |                    | 5.18-02            |
| 2.00+00       |                    | 4.41-02            | 6.02-06            | 5.81-04            |                    |                    | 4.47-02            |
| 3.00+00       |                    | 3.47-02            | 3.33-06            | 1.66-03            | 1.21-05            |                    | 3.63-02            |
| 4.00+00       |                    | 2.89-02            | 2.26-06            | 2.69-03            | 4.97-05            |                    | 3.17-02            |
| 5.00+00       |                    | 2.50-02            | 1.63-06            | 3.60-03            | 9.76-05            |                    | 2.87-02            |
| 6.00+00       |                    | 2.21-02            | 1.38-06            | 4.42-03            | 1.50-04            |                    | 2.66-02            |
| 8.00+00       |                    | 1.81-02            | 9.81-07            | 5.76-03            | 2.57-04            |                    | 2.41-02            |
| 1.00+01       |                    | 1.54-02            | 7.68-07            | 6.86-03            | 3.51-04            |                    | 2.26-02            |
| 1.50+01       |                    | 1.14-02            |                    | 8.94-03            | 5.47-04            |                    | 2.09-02            |
| 2.00+01       |                    | 9.14-03            |                    | 1.05-02            | 7.02-04            |                    | 2.03-02            |
| 3.00+01       |                    | 6.65-03            |                    | 1.26-02            | 9.35-04            |                    | 2.02-02            |
| 4.00+01       |                    | 5.28-03            |                    | 1.40-02            | 1.11-03            |                    | 2.04-02            |
| 5.00+01       |                    | 4.41-03            |                    | 1.52-02            | 1.24-03            |                    | 2.08-02            |
| 6.00+01       |                    | 3.80-03            |                    | 1.60-02            | 1.35-03            |                    | 2.12-02            |
| 8.00+01       |                    | 3.00-03            |                    | 1.73-02            | 1.51-03            |                    | 2.18-02            |
| 1.00+02       |                    | 2.49-03            |                    | 1.83-02            | 1.64-03            |                    | 2.24-02            |
| 1.50+02       |                    | 1.77-03            |                    | 1.98-02            | 1.85-03            |                    | 2.34-02            |
| 2.00+02       |                    | 1.39-03            |                    | 2.07-02            | 1.99-03            |                    | 2.41-02            |
| 3.00+02       |                    | 9.85-04            |                    | 2.19-02            | 2.18-03            |                    | 2.50-02            |
| 4.00+02       |                    | 7.71-04            |                    | 2.25-02            | 2.30-03            |                    | 2.56-02            |
| 5.00+02       |                    | 6.39-04            |                    | 2.29-02            | 2.38-03            |                    | 2.60-02            |
| 6.00+02       |                    | 5.47-04            |                    | 2.33-02            | 2.45-03            |                    | 2.62-02            |
| 8.00+02       |                    | 4.27-04            |                    | 2.37-02            | 2.54-03            |                    | 2.66-02            |
| 1.00+03       |                    | 3.51-04            |                    | 2.39-02            | 2.61-03            |                    | 2.69-02            |
| 1.50+03       |                    | 2.45-04            |                    | 2.43-02            | 2.71-03            |                    | 2.73-02            |
| 2.00+03       |                    | 1.90-04            |                    | 2.45-02            | 2.78-03            |                    | 2.75-02            |
| 3.00+03       |                    | 1.32-04            |                    | 2.48-02            | 2.85-03            |                    | 2.78-02            |
| 4.00+03       |                    | 1.02-04            |                    | 2.49-02            | 2.89-03            |                    | 2.79-02            |
| 5.00+03       |                    | 8.33-05            |                    | 2.50-02            | 2.92-03            |                    | 2.80-02            |
| 6.00+03       |                    | 7.06-05            |                    | 2.50-02            | 2.94-03            |                    | 2.81-02            |
| 8.00+03       |                    | 5.44-05            |                    | 2.51-02            | 2.97-03            |                    | 2.81-02            |
| 1.00+04       |                    | 4.44-05            |                    | 2.52-02            | 2.98-03            |                    | 2.82-02            |
| 1.50+04       |                    | 3.07-05            |                    | 2.52-02            | 3.01-03            |                    | 2.83-02            |
| 2.00+04       |                    | 2.36-05            |                    | 2.53-02            | 3.02-03            |                    | 2.83-02            |
| 3.00+04       |                    | 1.63-05            |                    | 2.53-02            | 3.03-03            |                    | 2.83-02            |
| 4.00+04       |                    | 1.25-05            |                    | 2.53-02            | 3.04-03            |                    | 2.84-02            |
| 5.00+04       |                    | 1.02-05            |                    | 2.53-02            | 3.04-03            |                    | 2.84-02            |
| 6.00+04       |                    | 8.60-06            |                    | 2.53-02            | 3.05-03            |                    | 2.84-02            |
| 8.00+04       |                    | 6.60-06            |                    | 2.53-02            | 3.05-03            |                    | 2.84-02            |
| 1.00+05       |                    | 5.37-06            |                    | 2.54-02            | 3.05-03            |                    | 2.84-02            |

**Table 3.-26. SODIUM IODIDE, NaI**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 2.53+00            | 1.65-01            | 1.36+02            |                    |                    | 1.39+02            | 1.36+02            |
| 1.50-02       | 1.69+00            | 1.62-01            | 4.57+01            |                    |                    | 4.74+01            | 4.59+01            |
| 2.00-02       | 1.23+00            | 1.59-01            | 2.11+01            |                    |                    | 2.23+01            | 2.12+01            |
| 3.00-02       | 7.48-01            | 1.54-01            | 6.70+00            |                    |                    | 7.45+00            | 6.86+00            |
| 3.32-02       | 6.60-01            | 1.52-01            | 5.03+00            |                    |                    | 5.69+00            | 5.19+00            |
| *3.32-02      | 6.60-01            | 1.52-01            | 3.03+01            |                    |                    | 3.09+01            | 3.04+01            |
| 4.00-02       | 5.28-01            | 1.49-01            | 1.88+01            |                    |                    | 1.93+01            | 1.89+01            |
| 5.00-02       | 4.10-01            | 1.44-01            | 1.03+01            |                    |                    | 1.07+01            | 1.05+01            |
| 6.00-02       | 3.36-01            | 1.40-01            | 6.28+00            |                    |                    | 6.62+00            | 6.42+00            |
| 8.00-02       | 2.49-01            | 1.33-01            | 2.87+00            |                    |                    | 3.12+00            | 3.00+00            |
| 1.00-01       | 2.02-01            | 1.27-01            | 1.52+00            |                    |                    | 1.72+00            | 1.64+00            |
| 1.50-01       | 1.49-01            | 1.14-01            | 4.76-01            |                    |                    | 6.25-01            | 5.90-01            |
| 2.00-01       | 1.24-01            | 1.05-01            | 2.09-01            |                    |                    | 3.34-01            | 3.14-01            |
| 3.00-01       | 9.99-02            | 9.09-02            | 6.68-02            |                    |                    | 1.67-01            | 1.58-01            |
| 4.00-01       | 8.64-02            | 8.15-02            | 3.10-02            |                    |                    | 1.17-01            | 1.12-01            |
| 5.00-01       | 7.78-02            | 7.44-02            | 1.77-02            |                    |                    | 9.55-02            | 9.21-02            |
| 6.00-01       | 7.12-02            | 6.88-02            | 1.14-02            |                    |                    | 8.26-02            | 8.02-02            |
| 8.00-01       | 6.17-02            | 6.05-02            | 5.88-03            |                    |                    | 6.76-02            | 6.63-02            |
| 1.00+00       | 5.49-02            | 5.43-02            | 3.66-03            |                    |                    | 5.86-02            | 5.80-02            |
| 1.50+00       | 4.45-02            | 4.42-02            | 1.66-03            | 7.36-04            |                    | 4.69-02            | 4.66-02            |
| 2.00+00       | 3.78-02            | 3.77-02            | 1.02-03            | 2.49-03            |                    | 4.13-02            | 4.12-02            |
| 3.00+00       | 2.97-02            | 2.97-02            | 5.46-04            | 6.40-03            | 1.03-05            | 3.66-02            | 3.66-02            |
| 4.00+00       | 2.48-02            | 2.47-02            | 3.61-04            | 9.89-03            | 4.25-05            | 3.51-02            | 3.50-02            |
| 5.00+00       |                    | 2.14-02            | 2.70-04            | 1.29-02            | 8.35-05            |                    | 3.46-02            |
| 6.00+00       |                    | 1.89-02            | 2.11-04            | 1.55-02            | 1.28-04            |                    | 3.47-02            |
| 8.00+00       |                    | 1.54-02            | 1.47-04            | 1.97-02            | 2.20-04            |                    | 3.55-02            |
| 1.00+01       |                    | 1.32-02            | 1.13-04            | 2.32-02            | 3.00-04            |                    | 3.68-02            |
| 1.50+01       |                    | 9.73-03            | 7.08-05            | 2.99-02            | 4.68-04            |                    | 4.02-02            |
| 2.00+01       |                    | 7.81-03            | 5.14-05            | 3.49-02            | 5.97-04            |                    | 4.33-02            |
| 3.00+01       |                    | 5.69-03            | 3.31-05            | 4.18-02            | 7.82-04            |                    | 4.84-02            |
| 4.00+01       |                    | 4.52-03            | 2.45-05            | 4.65-02            | 9.13-04            |                    | 5.20-02            |
| 5.00+01       |                    | 3.77-03            | 1.94-05            | 5.00-02            | 1.01-03            |                    | 5.48-02            |
| 6.00+01       |                    | 3.25-03            | 1.60-05            | 5.28-02            | 1.09-03            |                    | 5.71-02            |
| 8.00+01       |                    | 2.56-03            | 1.19-05            | 5.67-02            | 1.22-03            |                    | 6.05-02            |
| 1.00+02       |                    | 2.13-03            | 9.52-06            | 5.95-02            | 1.31-03            |                    | 6.29-02            |
| 1.50+02       |                    | 1.52-03            |                    | 6.40-02            | 1.46-03            |                    | 6.70-02            |
| 2.00+02       |                    | 1.19-03            |                    | 6.67-02            | 1.56-03            |                    | 6.95-02            |
| 3.00+02       |                    | 8.42-04            |                    | 6.99-02            | 1.69-03            |                    | 7.24-02            |
| 4.00+02       |                    | 6.59-04            |                    | 7.17-02            | 1.77-03            |                    | 7.41-02            |
| 5.00+02       |                    | 5.46-04            |                    | 7.28-02            | 1.82-03            |                    | 7.52-02            |
| 6.00+02       |                    | 4.68-04            |                    | 7.37-02            | 1.87-03            |                    | 7.60-02            |
| 8.00+02       |                    | 3.65-04            |                    | 7.49-02            | 1.92-03            |                    | 7.71-02            |
| 1.00+03       |                    | 3.00-04            |                    | 7.55-02            | 1.96-03            |                    | 7.78-02            |
| 1.50+03       |                    | 2.10-04            |                    | 7.66-02            | 2.02-03            |                    | 7.89-02            |
| 2.00+03       |                    | 1.62-04            |                    | 7.72-02            | 2.06-03            |                    | 7.94-02            |
| 3.00+03       |                    | 1.13-04            |                    | 7.78-02            | 2.09-03            |                    | 8.00-02            |
| 4.00+03       |                    | 8.71-05            |                    | 7.81-02            | 2.11-03            |                    | 8.03-02            |
| 5.00+03       |                    | 7.12-05            |                    | 7.83-02            | 2.13-03            |                    | 8.05-02            |
| 6.00+03       |                    | 6.04-05            |                    | 7.85-02            | 2.14-03            |                    | 8.07-02            |
| 8.00+03       |                    | 4.65-05            |                    | 7.86-02            | 2.15-03            |                    | 8.08-02            |
| 1.00+04       |                    | 3.80-05            |                    | 7.87-02            | 2.16-03            |                    | 8.09-02            |
| 1.50+04       |                    | 2.63-05            |                    | 7.89-02            | 2.17-03            |                    | 8.11-02            |
| 2.00+04       |                    | 2.02-05            |                    | 7.90-02            | 2.18-03            |                    | 8.12-02            |
| 3.00+04       |                    | 1.39-05            |                    | 7.91-02            | 2.18-03            |                    | 8.13-02            |
| 4.00+04       |                    | 1.07-05            |                    | 7.91-02            | 2.19-03            |                    | 8.13-02            |
| 5.00+04       |                    | 8.70-06            |                    | 7.92-02            | 2.19-03            |                    | 8.14-02            |
| 6.00+04       |                    | 7.36-06            |                    | 7.92-02            | 2.19-03            |                    | 8.14-02            |
| 8.00+04       |                    | 5.64-06            |                    | 7.93-02            | 2.19-03            |                    | 8.15-02            |
| 1.00+05       |                    | 4.59-06            |                    | 7.93-02            | 2.19-03            |                    | 8.15-02            |

\*Iodine K-edge

**Table 3.-27. AIR, NBS Handbook 85(1964) Composition**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.64-01            | 1.93-01            | 4.63+00            |                    |                    | 4.99+00            | 4.82+00            |
| 1.50-02       | 2.85-01            | 1.89-01            | 1.27+00            |                    |                    | 1.55+00            | 1.45+00            |
| 2.00-02       | 2.47-01            | 1.86-01            | 5.05-01            |                    |                    | 7.52-01            | 6.91-01            |
| 3.00-02       | 2.11-01            | 1.80-01            | 1.39-01            |                    |                    | 3.49-01            | 3.18-01            |
| 4.00-02       | 1.93-01            | 1.74-01            | 5.53-02            |                    |                    | 2.48-01            | 2.29-01            |
| 5.00-02       | 1.81-01            | 1.69-01            | 2.70-02            |                    |                    | 2.08-01            | 1.96-01            |
| 6.00-02       | 1.73-01            | 1.64-01            | 1.52-02            |                    |                    | 1.88-01            | 1.79-01            |
| 8.00-02       | 1.61-01            | 1.56-01            | 6.06-03            |                    |                    | 1.67-01            | 1.62-01            |
| 1.00-01       | 1.51-01            | 1.48-01            | 2.94-03            |                    |                    | 1.54-01            | 1.51-01            |
| 1.50-01       | 1.35-01            | 1.33-01            | 8.05-04            |                    |                    | 1.36-01            | 1.34-01            |
| 2.00-01       | 1.23-01            | 1.22-01            | 3.24-04            |                    |                    | 1.23-01            | 1.23-01            |
| 3.00-01       | 1.07-01            | 1.06-01            | 9.30-05            |                    |                    | 1.07-01            | 1.06-01            |
| 4.00-01       | 9.53-02            | 9.52-02            | 3.99-05            |                    |                    | 9.54-02            | 9.53-02            |
| 5.00-01       | 8.70-02            | 8.70-02            | 2.15-05            |                    |                    | 8.70-02            | 8.70-02            |
| 6.00-01       | 8.05-02            | 8.04-02            | 1.34-05            |                    |                    | 8.05-02            | 8.05-02            |
| 8.00-01       |                    | 7.07-02            | 6.79-06            |                    |                    |                    | 7.07-02            |
| 1.00+00       |                    | 6.36-02            | 4.20-06            |                    |                    |                    | 6.36-02            |
| 1.50+00       |                    | 5.17-02            | 1.96-06            | 9.89-05            |                    |                    | 5.18-02            |
| 2.00+00       |                    | 4.41-02            | 1.25-06            | 3.94-04            |                    |                    | 4.45-02            |
| 3.00+00       |                    | 3.47-02            | 6.97-07            | 1.13-03            | 1.21-05            |                    | 3.58-02            |
| 4.00+00       |                    | 2.89-02            | 4.73-07            | 1.83-03            | 4.97-05            |                    | 3.08-02            |
| 5.00+00       |                    | 2.50-02            | 3.61-07            | 2.46-03            | 9.76-05            |                    | 2.75-02            |
| 6.00+00       |                    | 2.21-02            | 2.88-07            | 3.01-03            | 1.50-04            |                    | 2.52-02            |
| 8.00+00       |                    | 1.81-02            | 2.06-07            | 3.94-03            | 2.57-04            |                    | 2.23-02            |
| 1.00+01       |                    | 1.54-02            | 1.61-07            | 4.70-03            | 3.51-04            |                    | 2.04-02            |
| 1.50+01       |                    | 1.14-02            |                    | 6.14-03            | 5.47-04            |                    | 1.81-02            |
| 2.00+01       |                    | 9.14-03            |                    | 7.18-03            | 7.02-04            |                    | 1.70-02            |
| 3.00+01       |                    | 6.65-03            |                    | 8.65-03            | 9.35-04            |                    | 1.62-02            |
| 4.00+01       |                    | 5.28-03            |                    | 9.67-03            | 1.11-03            |                    | 1.61-02            |
| 5.00+01       |                    | 4.41-03            |                    | 1.04-02            | 1.24-03            |                    | 1.61-02            |
| 6.00+01       |                    | 3.80-03            |                    | 1.11-02            | 1.36-03            |                    | 1.62-02            |
| 8.00+01       |                    | 3.00-03            |                    | 1.20-02            | 1.53-03            |                    | 1.65-02            |
| 1.00+02       |                    | 2.55-03            |                    | 1.26-02            | 1.65-03            |                    | 1.68-02            |
| 1.50+02       |                    | 1.77-03            |                    | 1.38-02            | 1.87-03            |                    | 1.74-02            |
| 2.00+02       |                    | 1.39-03            |                    | 1.45-02            | 2.02-03            |                    | 1.79-02            |
| 3.00+02       |                    | 9.85-04            |                    | 1.53-02            | 2.22-03            |                    | 1.85-02            |
| 4.00+02       |                    | 7.71-04            |                    | 1.58-02            | 2.34-03            |                    | 1.89-02            |
| 5.00+02       |                    | 6.38-04            |                    | 1.61-02            | 2.43-03            |                    | 1.92-02            |
| 6.00+02       |                    | 5.47-04            |                    | 1.63-02            | 2.50-03            |                    | 1.94-02            |
| 8.00+02       |                    | 4.27-04            |                    | 1.67-02            | 2.60-03            |                    | 1.97-02            |
| 1.00+03       |                    | 3.51-04            |                    | 1.69-02            | 2.67-03            |                    | 1.99-02            |
| 1.50+03       |                    | 2.45-04            |                    | 1.72-02            | 2.79-03            |                    | 2.02-02            |
| 2.00+03       |                    | 1.90-04            |                    | 1.73-02            | 2.86-03            |                    | 2.04-02            |
| 3.00+03       |                    | 1.32-04            |                    | 1.75-02            | 2.95-03            |                    | 2.06-02            |
| 4.00+03       |                    | 1.02-04            |                    | 1.76-02            | 2.99-03            |                    | 2.07-02            |
| 5.00+03       |                    | 8.33-05            |                    | 1.77-02            | 3.02-03            |                    | 2.08-02            |
| 6.00+03       |                    | 7.07-05            |                    | 1.77-02            | 3.05-03            |                    | 2.08-02            |
| 8.00+03       |                    | 5.44-05            |                    | 1.78-02            | 3.08-03            |                    | 2.09-02            |
| 1.00+04       |                    | 4.44-05            |                    | 1.78-02            | 3.10-03            |                    | 2.09-02            |
| 1.50+04       |                    | 3.07-05            |                    | 1.78-02            | 3.12-03            |                    | 2.10-02            |
| 2.00+04       |                    | 2.36-05            |                    | 1.79-02            | 3.14-03            |                    | 2.10-02            |
| 3.00+04       |                    | 1.63-05            |                    | 1.79-02            | 3.15-03            |                    | 2.11-02            |
| 4.00+04       |                    | 1.25-05            |                    | 1.79-02            | 3.16-03            |                    | 2.11-02            |
| 5.00+04       |                    | 1.02-05            |                    | 1.79-02            | 3.17-03            |                    | 2.11-02            |
| 6.00+04       |                    | 8.60-06            |                    | 1.79-02            | 3.17-03            |                    | 2.11-02            |
| 8.00+04       |                    | 6.60-06            |                    | 1.79-02            | 3.18-03            |                    | 2.11-02            |
| 1.00+05       |                    | 5.37-06            |                    | 1.79-02            | 3.18-03            |                    | 2.11-02            |

**Table 3.—28. CONCRETE, Grodstein—McGinnies Composition**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 6.00-01            | 1.93-01            | 2.63+01            |                    |                    | 2.69+01            | 2.65+01            |
| 1.50-02       | 4.21-01            | 1.89-01            | 7.82+00            |                    |                    | 8.24+00            | 8.01+00            |
| 2.00-02       | 3.34-01            | 1.86-01            | 3.26+00            |                    |                    | 3.59+00            | 3.45+00            |
| 3.00-02       | 2.56-01            | 1.80-01            | 9.38-01            |                    |                    | 1.19+00            | 1.12+00            |
| 4.00-02       | 2.20-01            | 1.74-01            | 3.84-01            |                    |                    | 6.05-01            | 5.59-01            |
| 5.00-02       | 2.00-01            | 1.69-01            | 1.92-01            |                    |                    | 3.92-01            | 3.61-01            |
| 6.00-02       | 1.86-01            | 1.64-01            | 1.09-01            |                    |                    | 2.95-01            | 2.73-01            |
| 8.00-02       | 1.69-01            | 1.56-01            | 4.45-02            |                    |                    | 2.13-01            | 2.00-01            |
| 1.00-01       | 1.57-01            | 1.48-01            | 2.19-02            |                    |                    | 1.79-01            | 1.70-01            |
| 1.50-01       | 1.37-01            | 1.34-01            | 6.20-03            |                    |                    | 1.44-01            | 1.40-01            |
| 2.00-01       | 1.25-01            | 1.22-01            | 2.56-03            |                    |                    | 1.27-01            | 1.25-01            |
| 3.00-01       | 1.07-01            | 1.07-01            | 7.52-04            |                    |                    | 1.08-01            | 1.07-01            |
| 4.00-01       | 9.60-02            | 9.54-02            | 3.27-04            |                    |                    | 9.63-02            | 9.58-02            |
| 5.00-01       | 8.75-02            | 8.72-02            | 1.77-04            |                    |                    | 8.77-02            | 8.73-02            |
| 6.00-01       | 8.09-02            | 8.06-02            | 1.11-04            |                    |                    | 8.10-02            | 8.07-02            |
| 8.00-01       | 7.09-02            | 7.08-02            | 5.64-05            |                    |                    | 7.09-02            | 7.09-02            |
| 1.00+00       |                    | 6.37-02            | 3.50-05            |                    |                    |                    | 6.37-02            |
| 1.50+00       |                    | 5.18-02            | 1.63-05            | 1.58-04            |                    |                    | 5.19-02            |
| 2.00+00       |                    | 4.42-02            | 1.03-05            | 6.22-04            |                    |                    | 4.48-02            |
| 3.00+00       |                    | 3.47-02            | 5.67-06            | 1.77-03            | 1.21-05            |                    | 3.65-02            |
| 4.00+00       |                    | 2.90-02            | 3.84-06            | 2.87-03            | 4.98-05            |                    | 3.19-02            |
| 5.00+00       |                    | 2.50-02            | 2.86-06            | 3.84-03            | 9.78-05            |                    | 2.90-02            |
| 6.00+00       |                    | 2.21-02            | 2.32-06            | 4.70-03            | 1.50-04            |                    | 2.70-02            |
| 8.00+00       |                    | 1.81-02            | 1.65-06            | 6.13-03            | 2.57-04            |                    | 2.45-02            |
| 1.00+01       |                    | 1.54-02            | 1.29-06            | 7.31-03            | 3.52-04            |                    | 2.31-02            |
| 1.50+01       |                    | 1.14-02            | 9.21-08            | 9.52-03            | 5.48-04            |                    | 2.15-02            |
| 2.00+01       |                    | 9.15-03            | 6.58-08            | 1.11-02            | 7.03-04            |                    | 2.10-02            |
| 3.00+01       |                    | 6.67-03            |                    | 1.34-02            | 9.37-04            |                    | 2.10-02            |
| 4.00+01       |                    | 5.30-03            |                    | 1.49-02            | 1.11-03            |                    | 2.13-02            |
| 5.00+01       |                    | 4.42-03            |                    | 1.61-02            | 1.24-03            |                    | 2.18-02            |
| 6.00+01       |                    | 3.81-03            |                    | 1.70-02            | 1.35-03            |                    | 2.22-02            |
| 8.00+01       |                    | 3.00-03            |                    | 1.84-02            | 1.51-03            |                    | 2.29-02            |
| 1.00+02       |                    | 2.49-03            |                    | 1.94-02            | 1.64-03            |                    | 2.35-02            |
| 1.50+02       |                    | 1.78-03            |                    | 2.11-02            | 1.85-03            |                    | 2.47-02            |
| 2.00+02       |                    | 1.39-03            |                    | 2.20-02            | 1.99-03            |                    | 2.54-02            |
| 3.00+02       |                    | 9.87-04            |                    | 2.32-02            | 2.18-03            |                    | 2.64-02            |
| 4.00+02       |                    | 7.73-04            |                    | 2.39-02            | 2.30-03            |                    | 2.69-02            |
| 5.00+02       |                    | 6.40-04            |                    | 2.43-02            | 2.38-03            |                    | 2.73-02            |
| 6.00+02       |                    | 5.48-04            |                    | 2.47-02            | 2.44-03            |                    | 2.76-02            |
| 8.00+02       |                    | 4.28-04            |                    | 2.51-02            | 2.54-03            |                    | 2.81-02            |
| 1.00+03       |                    | 3.52-04            |                    | 2.54-02            | 2.60-03            |                    | 2.83-02            |
| 1.50+03       |                    | 2.46-04            |                    | 2.58-02            | 2.71-03            |                    | 2.87-02            |
| 2.00+03       |                    | 1.90-04            |                    | 2.60-02            | 2.77-03            |                    | 2.90-02            |
| 3.00+03       |                    | 1.32-04            |                    | 2.63-02            | 2.85-03            |                    | 2.92-02            |
| 4.00+03       |                    | 1.02-04            |                    | 2.64-02            | 2.89-03            |                    | 2.94-02            |
| 5.00+03       |                    | 8.35-05            |                    | 2.65-02            | 2.92-03            |                    | 2.95-02            |
| 6.00+03       |                    | 7.08-05            |                    | 2.65-02            | 2.93-03            |                    | 2.95-02            |
| 8.00+03       |                    | 5.45-05            |                    | 2.66-02            | 2.96-03            |                    | 2.96-02            |
| 1.00+04       |                    | 4.45-05            |                    | 2.67-02            | 2.97-03            |                    | 2.97-02            |
| 1.50+04       |                    | 3.08-05            |                    | 2.67-02            | 3.00-03            |                    | 2.98-02            |
| 2.00+04       |                    | 2.37-05            |                    | 2.68-02            | 3.01-03            |                    | 2.98-02            |
| 3.00+04       |                    | 1.63-05            |                    | 2.68-02            | 3.02-03            |                    | 2.98-02            |
| 4.00+04       |                    | 1.25-05            |                    | 2.68-02            | 3.03-03            |                    | 2.99-02            |
| 5.00+04       |                    | 1.02-05            |                    | 2.68-02            | 3.03-03            |                    | 2.99-02            |
| 6.00+04       |                    | 8.62-06            |                    | 2.68-02            | 3.04-03            |                    | 2.99-02            |
| 8.00+04       |                    | 6.61-06            |                    | 2.68-02            | 3.04-03            |                    | 2.99-02            |
| 1.00+05       |                    | 5.38-06            |                    | 2.69-02            | 3.04-03            |                    | 2.99-02            |



**Table 3.-29. 0.8N H<sub>2</sub>SO<sub>4</sub> SOLUTION**

| Photon energy | Scattering              |                         | Photo-electric          | Pair production         |                         | Total                   |                         |
|---------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
|               | With coherent           | Without coherent        |                         | Nuclear field           | Electron field          | With coherent           | Without coherent        |
| <i>MeV</i>    | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> |
| 1.00-02       | 4.03-01                 | 2.13-01                 | 5.36+00                 |                         |                         | 5.76+00                 | 5.57+00                 |
| 1.50-02       | 3.13-01                 | 2.10-01                 | 1.45+00                 |                         |                         | 1.76+00                 | 1.66+00                 |
| 2.00-02       | 2.72-01                 | 2.06-01                 | 5.78-01                 |                         |                         | 8.49-01                 | 7.84-01                 |
| 3.00-02       | 2.32-01                 | 1.99-01                 | 1.59-01                 |                         |                         | 3.91-01                 | 3.58-01                 |
| 4.00-02       | 2.13-01                 | 1.93-01                 | 6.32-02                 |                         |                         | 2.76-01                 | 2.56-01                 |
| 5.00-02       | 2.00-01                 | 1.87-01                 | 3.10-02                 |                         |                         | 2.31-01                 | 2.18-01                 |
| 6.00-02       | 1.91-01                 | 1.82-01                 | 1.74-02                 |                         |                         | 2.08-01                 | 1.99-01                 |
| 8.00-02       | 1.78-01                 | 1.72-01                 | 6.92-03                 |                         |                         | 1.85-01                 | 1.79-01                 |
| 1.00-01       | 1.68-01                 | 1.64-01                 | 3.33-03                 |                         |                         | 1.71-01                 | 1.68-01                 |
| 1.50-01       | 1.49-01                 | 1.48-01                 | 9.11-04                 |                         |                         | 1.50-01                 | 1.49-01                 |
| 2.00-01       | 1.36-01                 | 1.35-01                 | 3.67-04                 |                         |                         | 1.37-01                 | 1.36-01                 |
| 3.00-01       | 1.18-01                 | 1.18-01                 | 1.05-04                 |                         |                         | 1.18-01                 | 1.18-01                 |
| 4.00-01       | 1.06-01                 | 1.06-01                 | 4.49-05                 |                         |                         | 1.06-01                 | 1.06-01                 |
| 5.00-01       | 9.65-02                 | 9.64-02                 | 2.43-05                 |                         |                         | 9.65-02                 | 9.64-02                 |
| 6.00-01       | 8.93-02                 | 8.92-02                 | 1.52-05                 |                         |                         | 8.93-02                 | 8.92-02                 |
| 8.00-01       |                         | 7.83-02                 | 7.64-06                 |                         |                         |                         | 7.83-02                 |
| 1.00+00       |                         | 7.04-02                 | 4.73-06                 |                         |                         |                         | 7.04-02                 |
| 1.50+00       |                         | 5.72-02                 | 2.22-06                 | 1.00-04                 |                         |                         | 5.73-02                 |
| 2.00+00       |                         | 4.88-02                 | 1.41-06                 | 3.99-04                 |                         |                         | 4.92-02                 |
| 3.00+00       |                         | 3.84-02                 | 7.85-07                 | 1.15-03                 | 1.34-05                 |                         | 3.96-02                 |
| 4.00+00       |                         | 3.21-02                 | 5.35-07                 | 1.86-03                 | 5.51-05                 |                         | 3.40-02                 |
| 5.00+00       |                         | 2.77-02                 | 4.08-07                 | 2.49-03                 | 1.08-04                 |                         | 3.03-02                 |
| 6.00+00       |                         | 2.45-02                 | 3.25-07                 | 3.05-03                 | 1.66-04                 |                         | 2.77-02                 |
| 8.00+00       |                         | 2.00-02                 | 2.33-07                 | 3.99-03                 | 2.85-04                 |                         | 2.43-02                 |
| 1.00+01       |                         | 1.70-02                 | 1.82-07                 | 4.76-03                 | 3.89-04                 |                         | 2.22-02                 |
| 1.50+01       |                         | 1.26-02                 |                         | 6.21-03                 | 6.06-04                 |                         | 1.94-02                 |
| 2.00+01       |                         | 1.01-02                 |                         | 7.27-03                 | 7.78-04                 |                         | 1.82-02                 |
| 3.00+01       |                         | 7.37-03                 |                         | 8.77-03                 | 1.04-03                 |                         | 1.72-02                 |
| 4.00+01       |                         | 5.86-03                 |                         | 9.78-03                 | 1.23-03                 |                         | 1.69-02                 |
| 5.00+01       |                         | 4.89-03                 |                         | 1.06-02                 | 1.38-03                 |                         | 1.68-02                 |
| 6.00+01       |                         | 4.21-03                 |                         | 1.12-02                 | 1.50-03                 |                         | 1.69-02                 |
| 8.00+01       |                         | 3.32-03                 |                         | 1.21-02                 | 1.69-03                 |                         | 1.71-02                 |
| 1.00+02       |                         | 2.76-03                 |                         | 1.28-02                 | 1.83-03                 |                         | 1.74-02                 |
| 1.50+02       |                         | 1.96-03                 |                         | 1.39-02                 | 2.08-03                 |                         | 1.80-02                 |
| 2.00+02       |                         | 1.54-03                 |                         | 1.46-02                 | 2.25-03                 |                         | 1.84-02                 |
| 3.00+02       |                         | 1.09-03                 |                         | 1.55-02                 | 2.47-03                 |                         | 1.90-02                 |
| 4.00+02       |                         | 8.55-04                 |                         | 1.60-02                 | 2.61-03                 |                         | 1.94-02                 |
| 5.00+02       |                         | 7.08-04                 |                         | 1.63-02                 | 2.72-03                 |                         | 1.97-02                 |
| 6.00+02       |                         | 6.06-04                 |                         | 1.65-02                 | 2.79-03                 |                         | 1.99-02                 |
| 8.00+02       |                         | 4.73-04                 |                         | 1.68-02                 | 2.91-03                 |                         | 2.02-02                 |
| 1.00+03       |                         | 3.89-04                 |                         | 1.70-02                 | 2.98-03                 |                         | 2.04-02                 |
| 1.50+03       |                         | 2.72-04                 |                         | 1.73-02                 | 3.11-03                 |                         | 2.07-02                 |
| 2.00+03       |                         | 2.10-04                 |                         | 1.75-02                 | 3.19-03                 |                         | 2.09-02                 |
| 3.00+03       |                         | 1.46-04                 |                         | 1.77-02                 | 3.28-03                 |                         | 2.11-02                 |
| 4.00+03       |                         | 1.13-04                 |                         | 1.78-02                 | 3.33-03                 |                         | 2.12-02                 |
| 5.00+03       |                         | 9.23-05                 |                         | 1.78-02                 | 3.37-03                 |                         | 2.13-02                 |
| 6.00+03       |                         | 7.83-05                 |                         | 1.79-02                 | 3.39-03                 |                         | 2.13-02                 |
| 8.00+03       |                         | 6.03-05                 |                         | 1.79-02                 | 3.42-03                 |                         | 2.14-02                 |
| 1.00+04       |                         | 4.92-05                 |                         | 1.79-02                 | 3.44-03                 |                         | 2.14-02                 |
| 1.50+04       |                         | 3.40-05                 |                         | 1.80-02                 | 3.47-03                 |                         | 2.15-02                 |
| 2.00+04       |                         | 2.62-05                 |                         | 1.80-02                 | 3.49-03                 |                         | 2.15-02                 |
| 3.00+04       |                         | 1.80-05                 |                         | 1.81-02                 | 3.50-03                 |                         | 2.16-02                 |
| 4.00+04       |                         | 1.39-05                 |                         | 1.81-02                 | 3.51-03                 |                         | 2.16-02                 |
| 5.00+04       |                         | 1.13-05                 |                         | 1.81-02                 | 3.52-03                 |                         | 2.16-02                 |
| 6.00+04       |                         | 9.54-06                 |                         | 1.81-02                 | 3.52-03                 |                         | 2.16-02                 |
| 8.00+04       |                         | 7.31-06                 |                         | 1.81-02                 | 3.52-03                 |                         | 2.16-02                 |
| 1.00+05       |                         | 5.95-06                 |                         | 1.81-02                 | 3.53-03                 |                         | 2.16-02                 |

**Table 3.-30. COMPACT BONE, NBS Handbook 85(1964) Composition**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 4.90-01            | 2.05-01            | 1.98+01            |                    |                    | 2.03+01            | 2.00+01            |
| 1.50-02       | 3.67-01            | 2.01-01            | 5.95+00            |                    |                    | 6.32+00            | 6.15+00            |
| 2.00-02       | 3.05-01            | 1.97-01            | 2.49+00            |                    |                    | 2.79+00            | 2.68+00            |
| 3.00-02       | 2.46-01            | 1.91-01            | 7.16-01            |                    |                    | 9.62-01            | 9.07-01            |
| 4.00-02       | 2.18-01            | 1.85-01            | 2.93-01            |                    |                    | 5.12-01            | 4.78-01            |
| 5.00-02       | 2.02-01            | 1.79-01            | 1.47-01            |                    |                    | 3.49-01            | 3.27-01            |
| 6.00-02       | 1.90-01            | 1.74-01            | 8.39-02            |                    |                    | 2.74-01            | 2.58-01            |
| 8.00-02       | 1.75-01            | 1.65-01            | 3.45-02            |                    |                    | 2.09-01            | 2.00-01            |
| 1.00-01       | 1.63-01            | 1.57-01            | 1.70-02            |                    |                    | 1.80-01            | 1.74-01            |
| 1.50-01       | 1.45-01            | 1.42-01            | 4.86-03            |                    |                    | 1.49-01            | 1.47-01            |
| 2.00-01       | 1.31-01            | 1.30-01            | 2.01-03            |                    |                    | 1.33-01            | 1.32-01            |
| 3.00-01       | 1.14-01            | 1.13-01            | 5.93-04            |                    |                    | 1.14-01            | 1.14-01            |
| 4.00-01       | 1.02-01            | 1.01-01            | 2.59-04            |                    |                    | 1.02-01            | 1.01-01            |
| 5.00-01       | 9.26-02            | 9.24-02            | 1.40-04            |                    |                    | 9.27-02            | 9.25-02            |
| 6.00-01       | 8.56-02            | 8.55-02            | 8.79-05            |                    |                    | 8.57-02            | 8.56-02            |
| 8.00-01       | 7.52-02            | 7.51-02            | 4.46-05            |                    |                    | 7.52-02            | 7.51-02            |
| 1.00+00       | 6.75-02            | 6.75-02            | 2.77-05            |                    |                    | 6.76-02            | 6.75-02            |
| 1.50+00       |                    | 5.49-02            | 1.29-05            | 1.27-04            |                    |                    | 5.50-02            |
| 2.00+00       |                    | 4.68-02            | 8.15-06            | 5.01-04            |                    |                    | 4.73-02            |
| 3.00+00       |                    | 3.68-02            | 4.48-06            | 1.43-03            | 1.29-05            |                    | 3.83-02            |
| 4.00+00       |                    | 3.07-02            | 3.02-06            | 2.31-03            | 5.28-05            |                    | 3.31-02            |
| 5.00+00       |                    | 2.65-02            | 2.30-06            | 3.10-03            | 1.04-04            |                    | 2.97-02            |
| 6.00+00       |                    | 2.35-02            | 1.83-06            | 3.79-03            | 1.59-04            |                    | 2.74-02            |
| 8.00+00       |                    | 1.92-02            | 1.30-06            | 4.95-03            | 2.73-04            |                    | 2.44-02            |
| 1.00+01       |                    | 1.63-02            | 1.02-06            | 5.90-03            | 3.73-04            |                    | 2.26-02            |
| 1.50+01       |                    | 1.21-02            |                    | 7.69-03            | 5.81-04            |                    | 2.04-02            |
| 2.00+01       |                    | 9.71-03            |                    | 8.99-03            | 7.45-04            |                    | 1.94-02            |
| 3.00+01       |                    | 7.07-03            |                    | 1.08-02            | 9.93-04            |                    | 1.89-02            |
| 4.00+01       |                    | 5.62-03            |                    | 1.21-02            | 1.18-03            |                    | 1.89-02            |
| 5.00+01       |                    | 4.69-03            |                    | 1.30-02            | 1.32-03            |                    | 1.90-02            |
| 6.00+01       |                    | 4.04-03            |                    | 1.38-02            | 1.44-03            |                    | 1.93-02            |
| 8.00+01       |                    | 3.18-03            |                    | 1.49-02            | 1.61-03            |                    | 1.97-02            |
| 1.00+02       |                    | 2.65-03            |                    | 1.57-02            | 1.75-03            |                    | 2.01-02            |
| 1.50+02       |                    | 1.88-03            |                    | 1.71-02            | 1.98-03            |                    | 2.10-02            |
| 2.00+02       |                    | 1.48-03            |                    | 1.79-02            | 2.14-03            |                    | 2.15-02            |
| 3.00+02       |                    | 1.05-03            |                    | 1.89-02            | 2.35-03            |                    | 2.23-02            |
| 4.00+02       |                    | 8.19-04            |                    | 1.95-02            | 2.48-03            |                    | 2.28-02            |
| 5.00+02       |                    | 6.78-04            |                    | 1.98-02            | 2.57-03            |                    | 2.31-02            |
| 6.00+02       |                    | 5.81-04            |                    | 2.01-02            | 2.65-03            |                    | 2.33-02            |
| 8.00+02       |                    | 4.54-04            |                    | 2.05-02            | 2.75-03            |                    | 2.37-02            |
| 1.00+03       |                    | 3.73-04            |                    | 2.07-02            | 2.83-03            |                    | 2.39-02            |
| 1.50+03       |                    | 2.61-04            |                    | 2.11-02            | 2.95-03            |                    | 2.43-02            |
| 2.00+03       |                    | 2.02-04            |                    | 2.13-02            | 3.02-03            |                    | 2.45-02            |
| 3.00+03       |                    | 1.40-04            |                    | 2.15-02            | 3.10-03            |                    | 2.47-02            |
| 4.00+03       |                    | 1.08-04            |                    | 2.16-02            | 3.15-03            |                    | 2.49-02            |
| 5.00+03       |                    | 8.85-05            |                    | 2.17-02            | 3.18-03            |                    | 2.49-02            |
| 6.00+03       |                    | 7.51-05            |                    | 2.17-02            | 3.20-03            |                    | 2.50-02            |
| 8.00+03       |                    | 5.78-05            |                    | 2.18-02            | 3.23-03            |                    | 2.51-02            |
| 1.00+04       |                    | 4.72-05            |                    | 2.18-02            | 3.25-03            |                    | 2.51-02            |
| 1.50+04       |                    | 3.26-05            |                    | 2.19-02            | 3.28-03            |                    | 2.52-02            |
| 2.00+04       |                    | 2.51-05            |                    | 2.19-02            | 3.29-03            |                    | 2.52-02            |
| 3.00+04       |                    | 1.73-05            |                    | 2.19-02            | 3.31-03            |                    | 2.53-02            |
| 4.00+04       |                    | 1.33-05            |                    | 2.20-02            | 3.32-03            |                    | 2.53-02            |
| 5.00+04       |                    | 1.08-05            |                    | 2.20-02            | 3.32-03            |                    | 2.53-02            |
| 6.00+04       |                    | 9.14-06            |                    | 2.20-02            | 3.33-03            |                    | 2.53-02            |
| 8.00+04       |                    | 7.01-06            |                    | 2.20-02            | 3.33-03            |                    | 2.53-02            |
| 1.00+05       |                    | 5.70-06            |                    | 2.20-02            | 3.33-03            |                    | 2.53-02            |

**Table 3.-31. MUSCLE, Striated, NBS Handbook 85(1964) Composition**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.89-01            | 2.12-01            | 4.88+00            |                    |                    | 5.27+00            | 5.09+00            |
| 1.50-02       | 3.05-01            | 2.08-01            | 1.32+00            |                    |                    | 1.63+00            | 1.53+00            |
| 2.00-02       | 2.66-01            | 2.05-01            | 5.26-01            |                    |                    | 7.93-01            | 7.31-01            |
| 3.00-02       | 2.29-01            | 1.98-01            | 1.44-01            |                    |                    | 3.73-01            | 3.42-01            |
| 4.00-02       | 2.10-01            | 1.92-01            | 5.73-02            |                    |                    | 2.68-01            | 2.49-01            |
| 5.00-02       | 1.98-01            | 1.86-01            | 2.81-02            |                    |                    | 2.27-01            | 2.14-01            |
| 6.00-02       | 1.90-01            | 1.81-01            | 1.58-02            |                    |                    | 2.05-01            | 1.97-01            |
| 8.00-02       | 1.76-01            | 1.71-01            | 6.31-03            |                    |                    | 1.83-01            | 1.78-01            |
| 1.00-01       | 1.67-01            | 1.63-01            | 3.04-03            |                    |                    | 1.70-01            | 1.66-01            |
| 1.50-01       | 1.49-01            | 1.47-01            | 8.32-04            |                    |                    | 1.49-01            | 1.48-01            |
| 2.00-01       | 1.35-01            | 1.35-01            | 3.35-04            |                    |                    | 1.36-01            | 1.35-01            |
| 3.00-01       | 1.18-01            | 1.17-01            | 9.59-05            |                    |                    | 1.18-01            | 1.17-01            |
| 4.00-01       | 1.05-01            | 1.05-01            | 4.11-05            |                    |                    | 1.05-01            | 1.05-01            |
| 5.00-01       | 9.59-02            | 9.58-02            | 2.22-05            |                    |                    | 9.60-02            | 9.59-02            |
| 6.00-01       | 8.88-02            | 8.87-02            | 1.39-05            |                    |                    | 8.88-02            | 8.87-02            |
| 8.00-01       |                    | 7.79-02            | 6.99-06            |                    |                    |                    | 7.79-02            |
| 1.00+00       |                    | 7.00-02            | 4.33-06            |                    |                    |                    | 7.00-02            |
| 1.50+00       |                    | 5.69-02            | 2.03-06            | 9.69-05            |                    |                    | 5.70-02            |
| 2.00+00       |                    | 4.86-02            | 1.29-06            | 3.86-04            |                    |                    | 4.89-02            |
| 3.00+00       |                    | 3.82-02            | 7.18-07            | 1.11-03            | 1.33-05            |                    | 3.93-02            |
| 4.00+00       |                    | 3.19-02            | 4.89-07            | 1.80-03            | 5.47-05            |                    | 3.37-02            |
| 5.00+00       |                    | 2.75-02            | 3.73-07            | 2.41-03            | 1.08-04            |                    | 3.00-02            |
| 6.00+00       |                    | 2.43-02            | 2.97-07            | 2.95-03            | 1.65-04            |                    | 2.74-02            |
| 8.00+00       |                    | 1.99-02            | 2.13-07            | 3.86-03            | 2.83-04            |                    | 2.40-02            |
| 1.00+01       |                    | 1.69-02            | 1.66-07            | 4.60-03            | 3.87-04            |                    | 2.19-02            |
| 1.50+01       |                    | 1.25-02            |                    | 6.00-03            | 6.03-04            |                    | 1.92-02            |
| 2.00+01       |                    | 1.01-02            |                    | 7.03-03            | 7.73-04            |                    | 1.79-02            |
| 3.00+01       |                    | 7.33-03            |                    | 8.47-03            | 1.03-03            |                    | 1.68-02            |
| 4.00+01       |                    | 5.82-03            |                    | 9.46-03            | 1.22-03            |                    | 1.65-02            |
| 5.00+01       |                    | 4.86-03            |                    | 1.02-02            | 1.37-03            |                    | 1.64-02            |
| 6.00+01       |                    | 4.19-03            |                    | 1.08-02            | 1.49-03            |                    | 1.65-02            |
| 8.00+01       |                    | 3.30-03            |                    | 1.17-02            | 1.68-03            |                    | 1.67-02            |
| 1.00+02       |                    | 2.75-03            |                    | 1.24-02            | 1.82-03            |                    | 1.70-02            |
| 1.50+02       |                    | 1.95-03            |                    | 1.35-02            | 2.07-03            |                    | 1.75-02            |
| 2.00+02       |                    | 1.53-03            |                    | 1.42-02            | 2.24-03            |                    | 1.79-02            |
| 3.00+02       |                    | 1.09-03            |                    | 1.50-02            | 2.46-03            |                    | 1.85-02            |
| 4.00+02       |                    | 8.50-04            |                    | 1.54-02            | 2.60-03            |                    | 1.89-02            |
| 5.00+02       |                    | 7.04-04            |                    | 1.58-02            | 2.70-03            |                    | 1.92-02            |
| 6.00+02       |                    | 6.02-04            |                    | 1.60-02            | 2.78-03            |                    | 1.94-02            |
| 8.00+02       |                    | 4.70-04            |                    | 1.63-02            | 2.89-03            |                    | 1.97-02            |
| 1.00+03       |                    | 3.87-04            |                    | 1.65-02            | 2.97-03            |                    | 1.99-02            |
| 1.50+03       |                    | 2.70-04            |                    | 1.68-02            | 3.10-03            |                    | 2.02-02            |
| 2.00+03       |                    | 2.09-04            |                    | 1.69-02            | 3.18-03            |                    | 2.03-02            |
| 3.00+03       |                    | 1.46-04            |                    | 1.71-02            | 3.27-03            |                    | 2.05-02            |
| 4.00+03       |                    | 1.12-04            |                    | 1.72-02            | 3.32-03            |                    | 2.06-02            |
| 5.00+03       |                    | 9.18-05            |                    | 1.73-02            | 3.36-03            |                    | 2.07-02            |
| 6.00+03       |                    | 7.79-05            |                    | 1.73-02            | 3.38-03            |                    | 2.08-02            |
| 8.00+03       |                    | 6.00-05            |                    | 1.74-02            | 3.41-03            |                    | 2.08-02            |
| 1.00+04       |                    | 4.90-05            |                    | 1.74-02            | 3.43-03            |                    | 2.09-02            |
| 1.50+04       |                    | 3.38-05            |                    | 1.74-02            | 3.46-03            |                    | 2.09-02            |
| 2.00+04       |                    | 2.60-05            |                    | 1.75-02            | 3.48-03            |                    | 2.10-02            |
| 3.00+04       |                    | 1.79-05            |                    | 1.75-02            | 3.49-03            |                    | 2.10-02            |
| 4.00+04       |                    | 1.38-05            |                    | 1.75-02            | 3.50-03            |                    | 2.10-02            |
| 5.00+04       |                    | 1.12-05            |                    | 1.75-02            | 3.51-03            |                    | 2.10-02            |
| 6.00+04       |                    | 9.48-06            |                    | 1.75-02            | 3.51-03            |                    | 2.10-02            |
| 8.00+04       |                    | 7.27-06            |                    | 1.75-02            | 3.52-03            |                    | 2.10-02            |
| 1.00+05       |                    | 5.91-06            |                    | 1.75-02            | 3.52-03            |                    | 2.11-02            |

**Table 3.-32. POLYSTYRENE, (C<sub>8</sub>H<sub>8</sub>O<sub>2</sub>)<sub>n</sub>**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.13-01            | 2.08-01            | 1.82+00            |                    |                    | 2.13+00            | 2.03+00            |
| 1.50-02       | 2.64-01            | 2.04-01            | 4.91-01            |                    |                    | 7.55-01            | 6.95-01            |
| 2.00-02       | 2.39-01            | 2.00-01            | 1.86-01            |                    |                    | 4.24-01            | 3.86-01            |
| 3.00-02       | 2.13-01            | 1.94-01            | 4.63-02            |                    |                    | 2.59-01            | 2.40-01            |
| 4.00-02       | 1.99-01            | 1.88-01            | 1.76-02            |                    |                    | 2.17-01            | 2.05-01            |
| 5.00-02       | 1.90-01            | 1.82-01            | 8.95-03            |                    |                    | 1.99-01            | 1.91-01            |
| 6.00-02       | 1.83-01            | 1.77-01            | 5.33-03            |                    |                    | 1.88-01            | 1.82-01            |
| 8.00-02       | 1.71-01            | 1.68-01            | 2.09-03            |                    |                    | 1.73-01            | 1.70-01            |
| 1.00-01       | 1.62-01            | 1.60-01            | 1.00-03            |                    |                    | 1.63-01            | 1.61-01            |
| 1.50-01       | 1.45-01            | 1.44-01            | 2.67-04            |                    |                    | 1.45-01            | 1.44-01            |
| 2.00-01       |                    | 1.32-01            | 1.06-04            |                    |                    |                    | 1.32-01            |
| 3.00-01       |                    | 1.15-01            | 2.99-05            |                    |                    |                    | 1.15-01            |
| 4.00-01       |                    | 1.03-01            | 1.28-05            |                    |                    |                    | 1.03-01            |
| 5.00-01       |                    | 9.38-02            | 6.91-06            |                    |                    |                    | 9.38-02            |
| 6.00-01       |                    | 8.68-02            | 4.30-06            |                    |                    |                    | 8.68-02            |
| 8.00-01       |                    | 7.63-02            | 2.17-06            |                    |                    |                    | 7.63-02            |
| 1.00+00       |                    | 6.85-02            | 1.34-06            |                    |                    |                    | 6.85-02            |
| 1.50+00       |                    | 5.57-02            | 6.26-07            | 7.64-05            |                    |                    | 5.58-02            |
| 2.00+00       |                    | 4.75-02            | 3.99-07            | 3.05-04            |                    |                    | 4.78-02            |
| 3.00+00       |                    | 3.74-02            | 2.23-07            | 8.76-04            | 1.30-05            |                    | 3.83-02            |
| 4.00+00       |                    | 3.12-02            | 1.53-07            | 1.42-03            | 5.36-05            |                    | 3.27-02            |
| 5.00+00       |                    | 2.69-02            | 1.17-07            | 1.91-03            | 1.05-04            |                    | 2.90-02            |
| 6.00+00       |                    | 2.38-02            | 9.32-08            | 2.34-03            | 1.62-04            |                    | 2.63-02            |
| 8.00+00       |                    | 1.95-02            | 6.68-08            | 3.06-03            | 2.77-04            |                    | 2.28-02            |
| 1.00+01       |                    | 1.66-02            | 5.19-08            | 3.65-03            | 3.79-04            |                    | 2.06-02            |
| 1.50+01       |                    | 1.23-02            |                    | 4.77-03            | 5.90-04            |                    | 1.76-02            |
| 2.00+01       |                    | 9.86-03            |                    | 5.59-03            | 7.57-04            |                    | 1.62-02            |
| 3.00+01       |                    | 7.17-03            |                    | 6.74-03            | 1.01-03            |                    | 1.49-02            |
| 4.00+01       |                    | 5.70-03            |                    | 7.54-03            | 1.19-03            |                    | 1.44-02            |
| 5.00+01       |                    | 4.76-03            |                    | 8.14-03            | 1.34-03            |                    | 1.42-02            |
| 6.00+01       |                    | 4.10-03            |                    | 8.62-03            | 1.46-03            |                    | 1.42-02            |
| 8.00+01       |                    | 3.23-03            |                    | 9.34-03            | 1.65-03            |                    | 1.42-02            |
| 1.00+02       |                    | 2.69-03            |                    | 9.87-03            | 1.79-03            |                    | 1.44-02            |
| 1.50+02       |                    | 1.91-03            |                    | 1.08-02            | 2.04-03            |                    | 1.47-02            |
| 2.00+02       |                    | 1.50-03            |                    | 1.13-02            | 2.20-03            |                    | 1.50-02            |
| 3.00+02       |                    | 1.06-03            |                    | 1.20-02            | 2.42-03            |                    | 1.55-02            |
| 4.00+02       |                    | 8.32-04            |                    | 1.24-02            | 2.57-03            |                    | 1.58-02            |
| 5.00+02       |                    | 6.89-04            |                    | 1.27-02            | 2.67-03            |                    | 1.60-02            |
| 6.00+02       |                    | 5.90-04            |                    | 1.29-02            | 2.75-03            |                    | 1.62-02            |
| 8.00+02       |                    | 4.61-04            |                    | 1.31-02            | 2.86-03            |                    | 1.65-02            |
| 1.00+03       |                    | 3.79-04            |                    | 1.33-02            | 2.94-03            |                    | 1.66-02            |
| 1.50+03       |                    | 2.65-04            |                    | 1.36-02            | 3.07-03            |                    | 1.69-02            |
| 2.00+03       |                    | 2.05-04            |                    | 1.37-02            | 3.15-03            |                    | 1.71-02            |
| 3.00+03       |                    | 1.43-04            |                    | 1.39-02            | 3.25-03            |                    | 1.73-02            |
| 4.00+03       |                    | 1.10-04            |                    | 1.39-02            | 3.31-03            |                    | 1.74-02            |
| 5.00+03       |                    | 8.99-05            |                    | 1.40-02            | 3.34-03            |                    | 1.74-02            |
| 6.00+03       |                    | 7.62-05            |                    | 1.40-02            | 3.37-03            |                    | 1.75-02            |
| 8.00+03       |                    | 5.87-05            |                    | 1.41-02            | 3.40-03            |                    | 1.75-02            |
| 1.00+04       |                    | 4.79-05            |                    | 1.41-02            | 3.42-03            |                    | 1.76-02            |
| 1.50+04       |                    | 3.31-05            |                    | 1.42-02            | 3.45-03            |                    | 1.76-02            |
| 2.00+04       |                    | 2.55-05            |                    | 1.42-02            | 3.47-03            |                    | 1.77-02            |
| 3.00+04       |                    | 1.76-05            |                    | 1.42-02            | 3.49-03            |                    | 1.77-02            |
| 4.00+04       |                    | 1.35-05            |                    | 1.42-02            | 3.50-03            |                    | 1.77-02            |
| 5.00+04       |                    | 1.10-05            |                    | 1.42-02            | 3.51-03            |                    | 1.77-02            |
| 6.00+04       |                    | 9.28-06            |                    | 1.42-02            | 3.51-03            |                    | 1.77-02            |
| 8.00+04       |                    | 7.12-06            |                    | 1.42-02            | 3.52-03            |                    | 1.78-02            |
| 1.00+05       |                    | 5.79-06            |                    | 1.42-02            | 3.52-03            |                    | 1.78-02            |

**Table 3.-33. POLYMETHYL METHACRYLATE (Lucite), (C<sub>5</sub>H<sub>8</sub>O<sub>2</sub>)<sub>n</sub>**

| Photon energy | Scattering              |                         | Photo-electric          | Pair production         |                         | Total                   |                         |
|---------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
|               | With coherent           | Without coherent        |                         | Nuclear field           | Electron field          | With coherent           | Without coherent        |
| <i>MeV</i>    | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> | <i>cm<sup>2</sup>/g</i> |
| 1.00-02       | 3.42-01                 | 2.08-01                 | 2.90+00                 |                         |                         | 3.25+00                 | 3.11+00                 |
| 1.50-02       | 2.79-01                 | 2.04-01                 | 7.78-01                 |                         |                         | 1.06+00                 | 9.82-01                 |
| 2.00-02       | 2.48-01                 | 2.01-01                 | 3.03-01                 |                         |                         | 5.51-01                 | 5.03-01                 |
| 3.00-02       | 2.18-01                 | 1.94-01                 | 7.98-02                 |                         |                         | 2.98-01                 | 2.74-01                 |
| 4.00-02       | 2.03-01                 | 1.88-01                 | 3.12-02                 |                         |                         | 2.34-01                 | 2.19-01                 |
| 5.00-02       | 1.92-01                 | 1.83-01                 | 1.54-02                 |                         |                         | 2.08-01                 | 1.98-01                 |
| 6.00-02       | 1.84-01                 | 1.77-01                 | 8.86-03                 |                         |                         | 1.93-01                 | 1.86-01                 |
| 8.00-02       | 1.72-01                 | 1.68-01                 | 3.50-03                 |                         |                         | 1.76-01                 | 1.72-01                 |
| 1.00-01       | 1.63-01                 | 1.60-01                 | 1.68-03                 |                         |                         | 1.64-01                 | 1.62-01                 |
| 1.50-01       | 1.46-01                 | 1.44-01                 | 4.52-04                 |                         |                         | 1.46-01                 | 1.45-01                 |
| 2.00-01       | 1.33-01                 | 1.32-01                 | 1.81-04                 |                         |                         | 1.33-01                 | 1.32-01                 |
| 3.00-01       | 1.15-01                 | 1.15-01                 | 5.14-05                 |                         |                         | 1.15-01                 | 1.15-01                 |
| 4.00-01       | 1.03-01                 | 1.03-01                 | 2.19-05                 |                         |                         | 1.03-01                 | 1.03-01                 |
| 5.00-01       | 9.41-02                 | 9.41-02                 | 1.18-05                 |                         |                         | 9.41-02                 | 9.41-02                 |
| 6.00-01       | 8.71-02                 | 8.70-02                 | 7.39-06                 |                         |                         | 8.71-02                 | 8.70-02                 |
| 8.00-01       |                         | 7.65-02                 | 3.72-06                 |                         |                         |                         | 7.65-02                 |
| 1.00+00       |                         | 6.87-02                 | 2.30-06                 |                         |                         |                         | 6.87-02                 |
| 1.50+00       |                         | 5.59-02                 | 1.08-06                 | 8.49-05                 |                         |                         | 5.59-02                 |
| 2.00+00       |                         | 4.77-02                 | 6.85-07                 | 3.38-04                 |                         |                         | 4.80-02                 |
| 3.00+00       |                         | 3.75-02                 | 3.83-07                 | 9.72-04                 | 1.31-05                 |                         | 3.85-02                 |
| 4.00+00       |                         | 3.13-02                 | 2.62-07                 | 1.58-03                 | 5.37-05                 |                         | 3.29-02                 |
| 5.00+00       |                         | 2.70-02                 | 2.00-07                 | 2.12-03                 | 1.06-04                 |                         | 2.92-02                 |
| 6.00+00       |                         | 2.39-02                 | 1.59-07                 | 2.59-03                 | 1.62-04                 |                         | 2.66-02                 |
| 8.00+00       |                         | 1.95-02                 | 1.14-07                 | 3.39-03                 | 2.78-04                 |                         | 2.32-02                 |
| 1.00+01       |                         | 1.66-02                 | 8.92-08                 | 4.05-03                 | 3.80-04                 |                         | 2.11-02                 |
| 1.50+01       |                         | 1.23-02                 |                         | 5.29-03                 | 5.91-04                 |                         | 1.82-02                 |
| 2.00+01       |                         | 9.88-03                 |                         | 6.19-03                 | 7.59-04                 |                         | 1.68-02                 |
| 3.00+01       |                         | 7.19-03                 |                         | 7.46-03                 | 1.01-03                 |                         | 1.57-02                 |
| 4.00+01       |                         | 5.72-03                 |                         | 8.34-03                 | 1.20-03                 |                         | 1.53-02                 |
| 5.00+01       |                         | 4.77-03                 |                         | 9.00-03                 | 1.35-03                 |                         | 1.51-02                 |
| 6.00+01       |                         | 4.11-03                 |                         | 9.54-03                 | 1.47-03                 |                         | 1.51-02                 |
| 8.00+01       |                         | 3.24-03                 |                         | 1.03-02                 | 1.65-03                 |                         | 1.52-02                 |
| 1.00+02       |                         | 2.69-03                 |                         | 1.09-02                 | 1.79-03                 |                         | 1.54-02                 |
| 1.50+02       |                         | 1.92-03                 |                         | 1.19-02                 | 2.04-03                 |                         | 1.59-02                 |
| 2.00+02       |                         | 1.50-03                 |                         | 1.25-02                 | 2.20-03                 |                         | 1.62-02                 |
| 3.00+02       |                         | 1.06-03                 |                         | 1.32-02                 | 2.42-03                 |                         | 1.67-02                 |
| 4.00+02       |                         | 8.34-04                 |                         | 1.37-02                 | 2.56-03                 |                         | 1.71-02                 |
| 5.00+02       |                         | 6.90-04                 |                         | 1.40-02                 | 2.67-03                 |                         | 1.73-02                 |
| 6.00+02       |                         | 5.91-04                 |                         | 1.42-02                 | 2.74-03                 |                         | 1.75-02                 |
| 8.00+02       |                         | 4.62-04                 |                         | 1.45-02                 | 2.86-03                 |                         | 1.78-02                 |
| 1.00+03       |                         | 3.80-04                 |                         | 1.46-02                 | 2.94-03                 |                         | 1.80-02                 |
| 1.50+03       |                         | 2.65-04                 |                         | 1.49-02                 | 3.06-03                 |                         | 1.82-02                 |
| 2.00+03       |                         | 2.05-04                 |                         | 1.51-02                 | 3.14-03                 |                         | 1.84-02                 |
| 3.00+03       |                         | 1.43-04                 |                         | 1.52-02                 | 3.24-03                 |                         | 1.86-02                 |
| 4.00+03       |                         | 1.10-04                 |                         | 1.53-02                 | 3.29-03                 |                         | 1.87-02                 |
| 5.00+03       |                         | 9.01-05                 |                         | 1.54-02                 | 3.33-03                 |                         | 1.88-02                 |
| 6.00+03       |                         | 7.64-05                 |                         | 1.54-02                 | 3.35-03                 |                         | 1.88-02                 |
| 8.00+03       |                         | 5.89-05                 |                         | 1.55-02                 | 3.38-03                 |                         | 1.89-02                 |
| 1.00+04       |                         | 4.81-05                 |                         | 1.55-02                 | 3.40-03                 |                         | 1.89-02                 |
| 1.50+04       |                         | 3.32-05                 |                         | 1.55-02                 | 3.43-03                 |                         | 1.90-02                 |
| 2.00+04       |                         | 2.55-05                 |                         | 1.56-02                 | 3.45-03                 |                         | 1.90-02                 |
| 3.00+04       |                         | 1.76-05                 |                         | 1.56-02                 | 3.47-03                 |                         | 1.91-02                 |
| 4.00+04       |                         | 1.35-05                 |                         | 1.56-02                 | 3.48-03                 |                         | 1.91-02                 |
| 5.00+04       |                         | 1.10-05                 |                         | 1.56-02                 | 3.48-03                 |                         | 1.91-02                 |
| 6.00+04       |                         | 9.31-06                 |                         | 1.56-02                 | 3.49-03                 |                         | 1.91-02                 |
| 8.00+04       |                         | 7.14-06                 |                         | 1.56-02                 | 3.49-03                 |                         | 1.91-02                 |
| 1.00+05       |                         | 5.80-06                 |                         | 1.56-02                 | 3.50-03                 |                         | 1.91-02                 |

Table 3.-34. POLYETHYLENE, (CH<sub>2</sub>)<sub>n</sub>

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.18-01            | 2.20-01            | 1.69+00            |                    |                    | 2.01+00            | 1.91+00            |
| 1.50-02       | 2.72-01            | 2.16-01            | 4.56-01            |                    |                    | 7.28-01            | 6.72-01            |
| 2.00-02       | 2.48-01            | 2.13-01            | 1.73-01            |                    |                    | 4.20-01            | 3.85-01            |
| 3.00-02       | 2.23-01            | 2.06-01            | 4.30-02            |                    |                    | 2.66-01            | 2.49-01            |
| 4.00-02       | 2.10-01            | 1.99-01            | 1.63-02            |                    |                    | 2.26-01            | 2.15-01            |
| 5.00-02       | 2.00-01            | 1.93-01            | 8.30-03            |                    |                    | 2.09-01            | 2.01-01            |
| 6.00-02       | 1.93-01            | 1.88-01            | 4.95-03            |                    |                    | 1.98-01            | 1.93-01            |
| 8.00-02       | 1.81-01            | 1.78-01            | 1.94-03            |                    |                    | 1.83-01            | 1.80-01            |
| 1.00-01       | 1.71-01            | 1.69-01            | 9.29-04            |                    |                    | 1.72-01            | 1.70-01            |
| 1.50-01       | 1.54-01            | 1.53-01            | 2.47-04            |                    |                    | 1.54-01            | 1.53-01            |
| 2.00-01       |                    | 1.40-01            | 9.85-05            |                    |                    |                    | 1.40-01            |
| 3.00-01       |                    | 1.22-01            | 2.78-05            |                    |                    |                    | 1.22-01            |
| 4.00-01       |                    | 1.09-01            | 1.19-05            |                    |                    |                    | 1.09-01            |
| 5.00-01       |                    | 9.95-02            | 6.41-06            |                    |                    |                    | 9.95-02            |
| 6.00-01       |                    | 9.21-02            | 3.99-06            |                    |                    |                    | 9.21-02            |
| 8.00-01       |                    | 8.09-02            | 2.01-06            |                    |                    |                    | 8.09-02            |
| 1.00+00       |                    | 7.27-02            | 1.24-06            |                    |                    |                    | 7.27-02            |
| 1.50+00       |                    | 5.91-02            | 5.81-07            | 7.28-05            |                    |                    | 5.92-02            |
| 2.00+00       |                    | 5.04-02            | 3.70-07            | 2.91-04            |                    |                    | 5.07-02            |
| 3.00+00       |                    | 3.96-02            | 2.07-07            | 8.35-04            | 1.38-05            |                    | 4.05-02            |
| 4.00+00       |                    | 3.31-02            | 1.42-07            | 1.35-03            | 5.68-05            |                    | 3.45-02            |
| 5.00+00       |                    | 2.86-02            | 1.08-07            | 1.82-03            | 1.12-04            |                    | 3.05-02            |
| 6.00+00       |                    | 2.53-02            | 8.65-08            | 2.23-03            | 1.72-04            |                    | 2.77-02            |
| 8.00+00       |                    | 2.07-02            | 6.20-08            | 2.92-03            | 2.94-04            |                    | 2.39-02            |
| 1.00+01       |                    | 1.76-02            | 4.82-08            | 3.48-03            | 4.02-04            |                    | 2.15-02            |
| 1.50+01       |                    | 1.30-02            |                    | 4.55-03            | 6.26-04            |                    | 1.82-02            |
| 2.00+01       |                    | 1.05-02            |                    | 5.33-03            | 8.03-04            |                    | 1.66-02            |
| 3.00+01       |                    | 7.61-03            |                    | 6.42-03            | 1.07-03            |                    | 1.51-02            |
| 4.00+01       |                    | 6.05-03            |                    | 7.19-03            | 1.27-03            |                    | 1.45-02            |
| 5.00+01       |                    | 5.05-03            |                    | 7.76-03            | 1.42-03            |                    | 1.42-02            |
| 6.00+01       |                    | 4.35-03            |                    | 8.22-03            | 1.55-03            |                    | 1.41-02            |
| 8.00+01       |                    | 3.43-03            |                    | 8.91-03            | 1.75-03            |                    | 1.41-02            |
| 1.00+02       |                    | 2.85-03            |                    | 9.42-03            | 1.90-03            |                    | 1.42-02            |
| 1.50+02       |                    | 2.03-03            |                    | 1.03-02            | 2.17-03            |                    | 1.45-02            |
| 2.00+02       |                    | 1.59-03            |                    | 1.08-02            | 2.34-03            |                    | 1.47-02            |
| 3.00+02       |                    | 1.13-03            |                    | 1.15-02            | 2.58-03            |                    | 1.52-02            |
| 4.00+02       |                    | 8.82-04            |                    | 1.19-02            | 2.73-03            |                    | 1.55-02            |
| 5.00+02       |                    | 7.30-04            |                    | 1.21-02            | 2.85-03            |                    | 1.57-02            |
| 6.00+02       |                    | 6.25-04            |                    | 1.23-02            | 2.93-03            |                    | 1.59-02            |
| 8.00+02       |                    | 4.88-04            |                    | 1.26-02            | 3.05-03            |                    | 1.61-02            |
| 1.00+03       |                    | 4.02-04            |                    | 1.27-02            | 3.14-03            |                    | 1.63-02            |
| 1.50+03       |                    | 2.81-04            |                    | 1.30-02            | 3.28-03            |                    | 1.65-02            |
| 2.00+03       |                    | 2.17-04            |                    | 1.31-02            | 3.36-03            |                    | 1.67-02            |
| 3.00+03       |                    | 1.51-04            |                    | 1.33-02            | 3.46-03            |                    | 1.69-02            |
| 4.00+03       |                    | 1.17-04            |                    | 1.33-02            | 3.52-03            |                    | 1.70-02            |
| 5.00+03       |                    | 9.53-05            |                    | 1.34-02            | 3.56-03            |                    | 1.70-02            |
| 6.00+03       |                    | 8.08-05            |                    | 1.34-02            | 3.59-03            |                    | 1.71-02            |
| 8.00+03       |                    | 6.23-05            |                    | 1.35-02            | 3.62-03            |                    | 1.72-02            |
| 1.00+04       |                    | 5.08-05            |                    | 1.35-02            | 3.64-03            |                    | 1.72-02            |
| 1.50+04       |                    | 3.51-05            |                    | 1.35-02            | 3.68-03            |                    | 1.73-02            |
| 2.00+04       |                    | 2.70-05            |                    | 1.36-02            | 3.70-03            |                    | 1.73-02            |
| 3.00+04       |                    | 1.86-05            |                    | 1.36-02            | 3.72-03            |                    | 1.73-02            |
| 4.00+04       |                    | 1.43-05            |                    | 1.36-02            | 3.73-03            |                    | 1.73-02            |
| 5.00+04       |                    | 1.16-05            |                    | 1.36-02            | 3.73-03            |                    | 1.73-02            |
| 6.00+04       |                    | 9.84-06            |                    | 1.36-02            | 3.74-03            |                    | 1.74-02            |
| 8.00+04       |                    | 7.55-06            |                    | 1.36-02            | 3.74-03            |                    | 1.74-02            |
| 1.00+05       |                    | 6.14-06            |                    | 1.36-02            | 3.75-03            |                    | 1.74-02            |

**Table 3.-35. BAKELITE (Typical), (C<sub>45</sub>H<sub>38</sub>O<sub>7</sub>)<sub>n</sub>**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 3.27-01            | 2.04-01            | 2.43+00            |                    |                    | 2.76+00            | 2.64+00            |
| 1.50-02       | 2.69-01            | 2.00-01            | 6.53-01            |                    |                    | 9.23-01            | 8.54-01            |
| 2.00-02       | 2.41-01            | 1.97-01            | 2.52-01            |                    |                    | 4.92-01            | 4.48-01            |
| 3.00-02       | 2.12-01            | 1.90-01            | 6.50-02            |                    |                    | 2.77-01            | 2.55-01            |
| 4.00-02       | 1.98-01            | 1.84-01            | 2.51-02            |                    |                    | 2.23-01            | 2.09-01            |
| 5.00-02       | 1.88-01            | 1.79-01            | 1.26-02            |                    |                    | 2.00-01            | 1.91-01            |
| 6.00-02       | 1.80-01            | 1.74-01            | 7.31-03            |                    |                    | 1.87-01            | 1.81-01            |
| 8.00-02       | 1.68-01            | 1.65-01            | 2.88-03            |                    |                    | 1.71-01            | 1.68-01            |
| 1.00-01       | 1.59-01            | 1.57-01            | 1.38-03            |                    |                    | 1.61-01            | 1.58-01            |
| 1.50-01       | 1.42-01            | 1.41-01            | 3.70-04            |                    |                    | 1.43-01            | 1.42-01            |
| 2.00-01       | 1.30-01            | 1.29-01            | 1.48-04            |                    |                    | 1.30-01            | 1.30-01            |
| 3.00-01       |                    | 1.13-01            | 4.19-05            |                    |                    |                    | 1.13-01            |
| 4.00-01       |                    | 1.01-01            | 1.79-05            |                    |                    |                    | 1.01-01            |
| 5.00-01       |                    | 9.21-02            | 9.66-06            |                    |                    |                    | 9.21-02            |
| 6.00-01       |                    | 8.52-02            | 6.02-06            |                    |                    |                    | 8.52-02            |
| 8.00-01       |                    | 7.49-02            | 3.04-06            |                    |                    |                    | 7.49-02            |
| 1.00+00       |                    | 6.73-02            | 1.88-06            |                    |                    |                    | 6.73-02            |
| 1.50+00       |                    | 5.47-02            | 8.78-07            | 8.20-05            |                    |                    | 5.48-02            |
| 2.00+00       |                    | 4.67-02            | 5.59-07            | 3.27-04            |                    |                    | 4.70-02            |
| 3.00+00       |                    | 3.67-02            | 3.13-07            | 9.40-04            | 1.28-05            |                    | 3.77-02            |
| 4.00+00       |                    | 3.06-02            | 2.13-07            | 1.53-03            | 5.26-05            |                    | 3.22-02            |
| 5.00+00       |                    | 2.64-02            | 1.63-07            | 2.05-03            | 1.03-04            |                    | 2.86-02            |
| 6.00+00       |                    | 2.34-02            | 1.30-07            | 2.50-03            | 1.59-04            |                    | 2.60-02            |
| 8.00+00       |                    | 1.91-02            | 9.32-08            | 3.28-03            | 2.72-04            |                    | 2.27-02            |
| 1.00+01       |                    | 1.63-02            | 7.27-08            | 3.91-03            | 3.72-04            |                    | 2.06-02            |
| 1.50+01       |                    | 1.21-02            |                    | 5.12-03            | 5.79-04            |                    | 1.78-02            |
| 2.00+01       |                    | 9.67-03            |                    | 5.99-03            | 7.43-04            |                    | 1.64-02            |
| 3.00+01       |                    | 7.04-03            |                    | 7.22-03            | 9.90-04            |                    | 1.53-02            |
| 4.00+01       |                    | 5.60-03            |                    | 8.07-03            | 1.17-03            |                    | 1.48-02            |
| 5.00+01       |                    | 4.67-03            |                    | 8.72-03            | 1.32-03            |                    | 1.47-02            |
| 6.00+01       |                    | 4.02-03            |                    | 9.23-03            | 1.44-03            |                    | 1.47-02            |
| 8.00+01       |                    | 3.17-03            |                    | 1.00-02            | 1.62-03            |                    | 1.48-02            |
| 1.00+02       |                    | 2.64-03            |                    | 1.06-02            | 1.76-03            |                    | 1.50-02            |
| 1.50+02       |                    | 1.88-03            |                    | 1.15-02            | 2.00-03            |                    | 1.54-02            |
| 2.00+02       |                    | 1.47-03            |                    | 1.21-02            | 2.16-03            |                    | 1.57-02            |
| 3.00+02       |                    | 1.04-03            |                    | 1.28-02            | 2.37-03            |                    | 1.62-02            |
| 4.00+02       |                    | 8.17-04            |                    | 1.33-02            | 2.51-03            |                    | 1.66-02            |
| 5.00+02       |                    | 6.76-04            |                    | 1.35-02            | 2.61-03            |                    | 1.68-02            |
| 6.00+02       |                    | 5.79-04            |                    | 1.37-02            | 2.69-03            |                    | 1.70-02            |
| 8.00+02       |                    | 4.52-04            |                    | 1.40-02            | 2.80-03            |                    | 1.73-02            |
| 1.00+03       |                    | 3.72-04            |                    | 1.42-02            | 2.88-03            |                    | 1.74-02            |
| 1.50+03       |                    | 2.60-04            |                    | 1.45-02            | 3.00-03            |                    | 1.77-02            |
| 2.00+03       |                    | 2.01-04            |                    | 1.46-02            | 3.08-03            |                    | 1.79-02            |
| 3.00+03       |                    | 1.40-04            |                    | 1.48-02            | 3.17-03            |                    | 1.81-02            |
| 4.00+03       |                    | 1.08-04            |                    | 1.49-02            | 3.23-03            |                    | 1.82-02            |
| 5.00+03       |                    | 8.82-05            |                    | 1.49-02            | 3.26-03            |                    | 1.83-02            |
| 6.00+03       |                    | 7.48-05            |                    | 1.50-02            | 3.29-03            |                    | 1.83-02            |
| 8.00+03       |                    | 5.76-05            |                    | 1.50-02            | 3.32-03            |                    | 1.84-02            |
| 1.00+04       |                    | 4.71-05            |                    | 1.50-02            | 3.34-03            |                    | 1.84-02            |
| 1.50+04       |                    | 3.25-05            |                    | 1.51-02            | 3.37-03            |                    | 1.85-02            |
| 2.00+04       |                    | 2.50-05            |                    | 1.51-02            | 3.39-03            |                    | 1.85-02            |
| 3.00+04       |                    | 1.72-05            |                    | 1.51-02            | 3.41-03            |                    | 1.85-02            |
| 4.00+04       |                    | 1.32-05            |                    | 1.51-02            | 3.42-03            |                    | 1.86-02            |
| 5.00+04       |                    | 1.08-05            |                    | 1.51-02            | 3.42-03            |                    | 1.86-02            |
| 6.00+04       |                    | 9.11-06            |                    | 1.52-02            | 3.43-03            |                    | 1.86-02            |
| 8.00+04       |                    | 6.99-06            |                    | 1.52-02            | 3.43-03            |                    | 1.86-02            |
| 1.00+05       |                    | 5.68-06            |                    | 1.52-02            | 3.44-03            |                    | 1.86-02            |

**Table 3.-36. PYREX GLASS, (Corning 7740)**

| Photon energy | Scattering         |                    | Photo-electric     | Pair production    |                    | Total              |                    |
|---------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
|               | With coherent      | Without coherent   |                    | Nuclear field      | Electron field     | With coherent      | Without coherent   |
| MeV           | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g | cm <sup>2</sup> /g |
| 1.00-02       | 5.36-01            | 1.92-01            | 1.65+01            |                    |                    | 1.71+01            | 1.67+01            |
| 1.50-02       | 3.79-01            | 1.88-01            | 4.76+00            |                    |                    | 5.14+00            | 4.95+00            |
| 2.00-02       | 3.06-01            | 1.85-01            | 1.94+00            |                    |                    | 2.25+00            | 2.13+00            |
| 3.00-02       | 2.40-01            | 1.79-01            | 5.46-01            |                    |                    | 7.86-01            | 7.24-01            |
| 4.00-02       | 2.10-01            | 1.73-01            | 2.21-01            |                    |                    | 4.31-01            | 3.94-01            |
| 5.00-02       | 1.93-01            | 1.68-01            | 1.09-01            |                    |                    | 3.02-01            | 2.77-01            |
| 6.00-02       | 1.81-01            | 1.63-01            | 6.15-02            |                    |                    | 2.42-01            | 2.25-01            |
| 8.00-02       | 1.65-01            | 1.55-01            | 2.47-02            |                    |                    | 1.90-01            | 1.80-01            |
| 1.00-01       | 1.54-01            | 1.47-01            | 1.21-02            |                    |                    | 1.66-01            | 1.60-01            |
| 1.50-01       | 1.36-01            | 1.33-01            | 3.34-03            |                    |                    | 1.39-01            | 1.36-01            |
| 2.00-01       | 1.23-01            | 1.22-01            | 1.36-03            |                    |                    | 1.25-01            | 1.23-01            |
| 3.00-01       | 1.07-01            | 1.06-01            | 3.95-04            |                    |                    | 1.07-01            | 1.06-01            |
| 4.00-01       | 9.53-02            | 9.48-02            | 1.71-04            |                    |                    | 9.54-02            | 9.50-02            |
| 5.00-01       | 8.69-02            | 8.66-02            | 9.23-05            |                    |                    | 8.70-02            | 8.67-02            |
| 6.00-01       | 8.03-02            | 8.01-02            | 5.77-05            |                    |                    | 8.04-02            | 8.02-02            |
| 8.00-01       |                    | 7.04-02            | 2.91-05            |                    |                    |                    | 7.04-02            |
| 1.00+00       |                    | 6.33-02            | 1.80-05            |                    |                    |                    | 6.33-02            |
| 1.50+00       |                    | 5.14-02            | 8.43-06            | 1.40-04            |                    |                    | 5.16-02            |
| 2.00+00       |                    | 4.39-02            | 5.35-06            | 5.53-04            |                    |                    | 4.44-02            |
| 3.00+00       |                    | 3.45-02            | 2.96-06            | 1.58-03            | 1.20-05            |                    | 3.61-02            |
| 4.00+00       |                    | 2.88-02            | 2.01-06            | 2.56-03            | 4.95-05            |                    | 3.14-02            |
| 5.00+00       |                    | 2.49-02            | 1.46-06            | 3.43-03            | 9.72-05            |                    | 2.84-02            |
| 6.00+00       |                    | 2.20-02            | 1.22-06            | 4.20-03            | 1.49-04            |                    | 2.63-02            |
| 8.00+00       |                    | 1.80-02            | 8.71-07            | 5.49-03            | 2.56-04            |                    | 2.37-02            |
| 1.00+01       |                    | 1.53-02            | 6.82-07            | 6.54-03            | 3.50-04            |                    | 2.22-02            |
| 1.50+01       |                    | 1.13-02            |                    | 8.52-03            | 5.44-04            |                    | 2.04-02            |
| 2.00+01       |                    | 9.10-03            |                    | 9.96-03            | 6.99-04            |                    | 1.98-02            |
| 3.00+01       |                    | 6.62-03            |                    | 1.20-02            | 9.31-04            |                    | 1.95-02            |
| 4.00+01       |                    | 5.26-03            |                    | 1.34-02            | 1.10-03            |                    | 1.98-02            |
| 5.00+01       |                    | 4.39-03            |                    | 1.45-02            | 1.24-03            |                    | 2.01-02            |
| 6.00+01       |                    | 3.78-03            |                    | 1.53-02            | 1.34-03            |                    | 2.04-02            |
| 8.00+01       |                    | 2.98-03            |                    | 1.65-02            | 1.51-03            |                    | 2.10-02            |
| 1.00+02       |                    | 2.48-03            |                    | 1.74-02            | 1.63-03            |                    | 2.15-02            |
| 1.50+02       |                    | 1.76-03            |                    | 1.89-02            | 1.84-03            |                    | 2.25-02            |
| 2.00+02       |                    | 1.38-03            |                    | 1.98-02            | 1.99-03            |                    | 2.32-02            |
| 3.00+02       |                    | 9.80-04            |                    | 2.09-02            | 2.17-03            |                    | 2.40-02            |
| 4.00+02       |                    | 7.68-04            |                    | 2.15-02            | 2.29-03            |                    | 2.45-02            |
| 5.00+02       |                    | 6.36-04            |                    | 2.19-02            | 2.38-03            |                    | 2.49-02            |
| 6.00+02       |                    | 5.44-04            |                    | 2.22-02            | 2.44-03            |                    | 2.52-02            |
| 8.00+02       |                    | 4.25-04            |                    | 2.26-02            | 2.54-03            |                    | 2.56-02            |
| 1.00+03       |                    | 3.50-04            |                    | 2.29-02            | 2.60-03            |                    | 2.58-02            |
| 1.50+03       |                    | 2.44-04            |                    | 2.32-02            | 2.71-03            |                    | 2.62-02            |
| 2.00+03       |                    | 1.89-04            |                    | 2.34-02            | 2.78-03            |                    | 2.64-02            |
| 3.00+03       |                    | 1.31-04            |                    | 2.37-02            | 2.85-03            |                    | 2.67-02            |
| 4.00+03       |                    | 1.01-04            |                    | 2.38-02            | 2.90-03            |                    | 2.68-02            |
| 5.00+03       |                    | 8.29-05            |                    | 2.39-02            | 2.92-03            |                    | 2.69-02            |
| 6.00+03       |                    | 7.03-05            |                    | 2.39-02            | 2.94-03            |                    | 2.69-02            |
| 8.00+03       |                    | 5.42-05            |                    | 2.40-02            | 2.97-03            |                    | 2.70-02            |
| 1.00+04       |                    | 4.42-05            |                    | 2.40-02            | 2.98-03            |                    | 2.71-02            |
| 1.50+04       |                    | 3.06-05            |                    | 2.41-02            | 3.01-03            |                    | 2.71-02            |
| 2.00+04       |                    | 2.35-05            |                    | 2.41-02            | 3.02-03            |                    | 2.72-02            |
| 3.00+04       |                    | 1.62-05            |                    | 2.42-02            | 3.04-03            |                    | 2.72-02            |
| 4.00+04       |                    | 1.24-05            |                    | 2.42-02            | 3.04-03            |                    | 2.72-02            |
| 5.00+04       |                    | 1.01-05            |                    | 2.42-02            | 3.05-03            |                    | 2.72-02            |
| 6.00+04       |                    | 8.57-06            |                    | 2.42-02            | 3.05-03            |                    | 2.73-02            |
| 8.00+04       |                    | 6.57-06            |                    | 2.42-02            | 3.06-03            |                    | 2.73-02            |
| 1.00+05       |                    | 5.34-06            |                    | 2.42-02            | 3.06-03            |                    | 2.73-02            |



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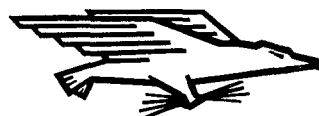
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