Recommended Data on the Electron Impact Ionization of Light Atoms and Ions

K. L. Bell, H. B. Gilbody, J. G. Hughes, A. E. Kingston, and F. J. Smith

School of Physics and Mathematical Science, The Queen's University of Belfast, N. Ireland

Experimental and theoretical cross section data for electron impact ionization of light atoms and ions have been assessed. Based on this assessment and, in some cases, on the classical scaling laws, a recommended cross section has been produced for each species. This has been used to evaluate recommended Maxwellian rate coefficients over a wide range of temperatures. Convenient analytic expressions have been obtained for the recommended cross sections and rate coefficients. The data are presented in both graphical and tabular form and estimates of the reliability of the recommended data are given.

Key words: cross sections; electron impact ionization; isoelectronic sequences; rate coefficients.

Contents

1. Introduction

Cross sections and rates for electron impact ionization of positive ions are needed for the development of realistic models for high temperature plasmas and for the interpretation of diagnostic observations in such plasmas. Until recently, however, very little quantitative information concerning the electron impact ionization of positive ions has been available and relatively simple and approximate methods of calculating the rates have often been adopted (cf. Jordan[1,2]; Summers[3,4]; Jacobs *et al.*[5]).

In particular, the semiempirical formula of Seaton,[6] the exchange classical impact parameter (ECIP) method of Burgess,[7] and the empirical formula of Lotz[8,9] have all been widely used. Seaton's formula was designed to be applicable only in the near threshold energy range (the most important region for ionization balance calculations), and the accuracy of the ECIP method is also best in this range (Burgess *et al.*[10]). The Lotz formula, on the other hand, was designed to reproduce the available experimental data over a wide energy range and to predict cross sections for other atoms and ions using the classical scaling law. During the last five years, there have been considerable advances in calculating and measuring cross sections for ionization of positive ions. For example, it is only within the last five years that excitation autoionization has been recognized as an important ionization process. It is therefore timely to assess the state of the data and present a set of recommended cross sections and rate coefficients.

Most of the recent calculations have employed variations of the Coulomb–Born method (Moores[11,12]; Jakubowitz and Moores[13]), the scaled hydrogenic method (Golden and Sampson[14]) or the distorted wave Born exchange (DWBE) approximation (Younger[15–17]).

Experimental data on the ionization of positive ions by electron impact have been derived from intersecting beam studies, plasma measurements, and ion trap methods. There are considerable difficulties inherent in each of these three different approaches, but intersecting beam methods have produced the most reliable and extensive data to date.

The general principles underlying methods based on intersecting beams have been reviewed by Dolder and Peart.[18] A well defined monoenergetic beam of ions in the required charge state is arranged to intersect a beam of electrons. The interaction energy is specified according to the laboratory energies and angle of intersection of the beams. Ions arising as products of ionization must be carefully separated by the electrostatic or magnetic analyzers from the (typically at least 10^8 times) more intense primary ion beam. The product ion yield measured in conjunction with the intensity and spatial distribution of the intersecting beams then allows the ionization cross section to be determined on an absolute basis.

The main difficulties in the intersecting beams approach stem from the low signal to background ratios, the need for proper account of space charge effects in the interaction of the beams, and the possible presence of unknown fractions of long lived excited states in the primary ion beam. Most of the measurements to date have been carried out with singly and doubly charged ions and it is only in the past few years that suitable beams have been provided to permit studies of ions with charges up to 5. (See review by Crandall.[19])

Studies based on plasma measurements in magnetically confined high temperature plasmas (Kunze,[20] Kallne and Jones[21]) make use of a model which describes the time evolution of spectral lines in terms of ionization rates, electron densities, and electron temperatures. The model assumes a Maxwellian temperature distribution, thermodynamic equilibrium, and radiation produced through collisions with electrons. Ionization rates are determined by fitting the observed time evolution of spectral lines to the model. Large uncertainties in the derived ionization rates arise through the uncertainties in the measured electron temperatures and densities. While the method does not permit the energy dependence of the ionization process to be studied, it has provided some data in the ionization threshold region for ions in charge states greater than 5, which have so far been unattainable in intersecting beam experiments.

In the ion trap approach (see review by Dunn[22]), ions may be trapped in a suitable combination of electric and magnetic fields and then bombarded with a well defined electron beam. Alternatively, the ions may be contained in the space charge of an electron beam (Baker and Hasted[23]). The method provides only relative cross sections which require other techniques for normalization. Other difficulties arise from the dependence of trapping efficiency on electron energy, the presence of excited ions in the trap and the inability of the method to distinguish between products formed by single and multiple ionization. In the ion trap approach used by Donets,[24] observations have been carried out using an electron beam ion source (EBIS) in which plasma modeling is used to determine ionization rates. The method has provided data for ions of high charge state at energies well above the ionization threshold.

Although the theoretical and experimental data are now quite extensive, they sometimes exhibit significant differences. Indeed significant differences often occur for a specific atom or ion among the various theoretical treatments. Where such discrepancies have arisen, we have attempted to assess the results by consideration of (i) the sophistication of the target wave function employed, (ii) the sophistication of the scattering approximation employed, and (iii) where the results extend to sufficiently high energy, comparison of the Bethe coefficient A [Eq. (1)] with that obtained independently from photoionization cross sections. We believe that an assessment of the data is timely with a view to providing the potential user with an indication of the most reliable cross sections and rates for ionization by electron impact.

2. Method of Evaluation

At large impact energies, the Born or Coulomb–Born approximations should produce reliable results if accurate

TABLE 1. The recommended cross sections for carbon and its ions. The energy is given in terms of the ionization potential for each species, and the cross sections are in cm². The estimated errors are given Table 5.

E/I	C I $I=11.26$ eV	C II $I=24.38$ eV	C III $I=47.89$ eV	ᵃC III $I=41.38$ eV	C IV $I=64.49$ eV	C V $I=392.08$ eV	C VI $I=489.98$ eV
1.25	3.433E − 17	2.453E − 17	5.523E − 18	3.736E − 18	1.576E − 18	5.880E − 20	2.974E − 20
1.50	7.077E − 17	3.628E − 17	8.595E − 18	7.151E − 18	2.360E − 18	1.103E − 19	4.504E − 20
1.75	1.033E − 16	4.332E − 17	1.033E − 17	9.473E − 18	2.741E − 18	1.463E − 19	5.328E − 20
2.00	1.305E − 16	4.784E − 17	1.131E − 17	1.093E − 17	2.933E − 18	1.700E − 19	5.774E − 20
2.25	1.525E − 16	5.078E − 17	1.184E − 17	1.181E − 17	3.030E − 18	1.852E − 19	6.005E − 20
2.50	1.701E − 16	5.265E − 17	1.210E − 17	1.231E − 17	3.075E − 18	1.945E − 19	6.107E − 20
2.75	1.841E − 16	5.377E − 17	1.218E − 17	1.256E − 17	3.090E − 18	1.999E − 19	6.129E − 20
3.00	1.951E − 16	5.436E − 17	1.215E − 17	1.265E − 17	3.086E − 18	2.025E − 19	6.101E − 20
3.50	2.106E − 16	5.451E − 17	1.191E − 17	1.254E − 17	3.044E − 18	2.028E − 19	5.964E − 20
4.00	2.198E − 16	5.383E − 17	1.154E − 17	1.225E − 17	2.978E − 18	1.993E − 19	5.774E − 20
4.50	2.250E − 16	5.274E − 17	1.114E − 17	1.188E − 17	2.903E − 18	1.942E − 19	5.569E − 20
5.00	2.273E − 16	5.144E − 17	1.073E − 17	1.148E − 17	2.823E − 18	1.882E − 19	5.363E − 20
6.00	2.272E − 16	4.863E − 17	9.945E − 18	1.070E − 17	2.665E − 18	1.760E − 19	4.975E − 20
7.00	2.234E − 16	4.588E − 17	9.248E − 18	9.994E − 18	2.516E − 18	1.645E − 19	4.632E − 20
8.00	2.180E − 16	4.334E − 17	8.638E − 18	9.367E − 18	2.380E − 18	1.541E − 19	4.331E − 20
9.00	2.119E − 16	4.102E − 17	8.104E − 18	8.816E − 18	2.258E − 18	1.448E − 19	4.068E − 20
10.00	2.056E − 16	3.892E − 17	7.636E − 18	8.329E − 18	2.147E − 18	1.365E − 19	3.836E − 20
12.50	1.904E − 16	3.453E − 17	6.684E − 18	7.336E − 18	1.914E − 18	1.196E − 19	3.367E − 20
15.00	1.767E − 16	3.108E − 17	5.960E − 18	6.575E − 18	1.730E − 18	1.066E − 19	3.008E − 20
20.00	1.545E − 16	2.602E − 17	4.929E − 18	5.483E − 18	1.459E − 18	8.806E − 19	2.496E − 20
30.00	1.242E − 16	1.987E − 17	3.715E − 18	4.179E − 18	1.124E − 18	6.614E − 19	1.889E − 20
40.00	1.046E − 16	1.624E − 17	3.013E − 18	3.416E − 18	9.240E − 19	5.349E − 20	1.537E − 20
50.00	9.087E − 17	1.381E − 17	2.551E − 18	2.909E − 18	7.894E − 19	4.518E − 20	1.304E − 20
75.00	6.937E − 17	1.021E − 17	1.870E − 18	2.154E − 18	5.871E − 19	3.299E − 20	9.591E − 21
100.00	5.674E − 17	8.182E − 18	1.493E − 18	1.730E − 18	4.727E − 19	2.626E − 20	7.673E − 21

ᵃ Includes contributions from ions in metastable states (see text).

TABLE 2. Recommended cross sections for oxygen and its ions. The energy is given in terms of the ionization potential for each species and the cross sections are in cm^2. The estimated errors are given Table 5.

E/I	O I $I=13.62$ eV	O II $I=35.15$ eV	O III $I=54.93$ eV	O IV $I=77.41$ eV	[a]O IV $I=68.60$ eV	O V $I=113.90$ eV	[a]O V $I=103.68$ eV	O VI $I=138.68$ eV	O VII $I=739.32$ eV	O VIII $I=871.39$ eV
1.25	2.105E − 17	1.339E − 17	8.720E − 18	2.066E − 18	2.185E − 18	1.118E − 18	1.144E − 19	3.894E − 19	1.654E − 20	9.404E − 21
1.50	3.377E − 17	2.135E − 17	1.278E − 17	3.902E − 18	4.152E − 18	1.683E − 18	1.766E − 18	5.773E − 19	3.102E − 20	1.424E − 20
1.75	4.644E − 17	2.732E − 17	1.501E − 17	5.187E − 18	5.227E − 18	1.982E − 18	2.249E − 18	6.741E − 19	4.114E − 20	1.685E − 20
2.00	5.894E − 17	3.206E − 17	1.641E − 17	6.033E − 18	5.847E − 18	2.139E − 18	2.597E − 18	7.250E − 19	4.782E − 20	1.826E − 20
2.25	7.058E − 17	3.578E − 17	1.735E − 17	6.572E − 18	6.238E − 18	2.216E − 18	2.828E − 18	7.499E − 19	5.209E − 20	1.899E − 20
2.50	8.101E − 17	3.866E − 17	1.799E − 17	6.902E − 18	6.499E − 18	2.247E − 18	2.970E − 18	7.592E − 19	5.471E − 20	1.931E − 20
2.75	9.013E − 17	4.083E − 17	1.840E − 17	7.089E − 18	6.675E − 18	2.249E − 18	3.046E − 18	7.588E − 19	5.622E − 20	1.938E − 20
3.00	9.799E − 17	4.243E − 17	1.865E − 17	7.180E − 18	6.791E − 18	2.233E − 18	3.076E − 18	7.524E − 19	5.696E − 20	1.929E − 20
3.50	1.104E − 16	4.434E − 17	1.880E − 17	7.181E − 18	6.895E − 18	2.174E − 18	3.051E − 18	7.297E − 19	5.703E − 20	1.886E − 20
4.00	1.192E − 16	4.508E − 17	1.864E − 17	7.052E − 18	6.887E − 18	2.098E − 18	2.965E − 18	8.093E − 19	5.606E − 20	1.826E − 20
4.50	1.254E − 16	4.508E − 17	1.831E − 17	6.862E − 18	6.809E − 18	2.017E − 18	2.853E − 18	7.986E − 19	5.461E − 20	1.761E − 20
5.00	1.295E − 16	4.464E − 17	1.789E − 17	6.647E − 18	6.687E − 18	1.938E − 18	2.733E − 18	7.840E − 19	5.294E − 20	1.696E − 20
6.00	1.340E − 16	4.305E − 17	1.691E − 17	6.206E − 18	6.381E − 18	1.791E − 18	2.498E − 18	7.497E − 19	4.950E − 20	1.573E − 20
7.00	1.351E − 16	4.108E − 17	1.592E − 17	5.791E − 18	6.047E − 18	1.661E − 18	2.287E − 18	7.137E − 19	4.626E − 20	1.464E − 20
8.00	1.344E − 16	3.906E − 17	1.498E − 17	5.417E − 18	5.720E − 18	1.550E − 18	2.104E − 18	6.789E − 19	4.333E − 20	1.369E − 20
9.00	1.327E − 16	3.712E − 17	1.412E − 17	5.086E − 18	5.411E − 18	1.452E − 18	1.945E − 18	6.464E − 19	4.072E − 20	1.286E − 20
10.00	1.304E − 16	3.530E − 17	1.334E − 17	4.792E − 18	5.126E − 18	1.367E − 18	1.808E − 18	6.165E − 19	3.840E − 20	1.213E − 20
12.50	1.236E − 16	3.136E − 17	1.170E − 17	4.191E − 18	4.516E − 18	1.195E − 18	1.537E − 18	5.522E − 19	3.364E − 20	1.064E − 20
15.00	1.166E − 16	2.817E − 17	1.042E − 17	3.730E − 18	4.030E − 18	1.065E − 18	1.338E − 18	5.004E − 19	2.999E − 20	9.510E − 21
20.00	1.042E − 16	2.344E − 17	8.553E − 18	3.074E − 18	3.315E − 18	8.804E − 19	1.066E − 18	4.231E − 19	2.477E − 20	7.891E − 21
30.00	8.579E − 17	1.768E − 17	6.345E − 18	2.302E − 18	2.459E − 18	6.632E − 19	7.638E − 19	3.270E − 19	1.860E − 20	5.972E − 21
40.00	7.328E − 17	1.430E − 17	5.078E − 18	1.858E − 18	1.964E − 18	5.379E − 19	5.993E − 19	2.691E − 19	1.504E − 20	4.858E − 21
50.00	6.424E − 17	1.206E − 17	4.252E − 18	1.568E − 18	1.642E − 18	4.555E − 19	4.952E − 19	2.302E − 19	1.271E − 20	4.122E − 21
75.00	4.973E − 17	8.779E − 18	3.055E − 18	1.142E − 18	1.174E − 18	3.340E − 19	3.485E − 19	1.715E − 19	9.279E − 21	3.033E − 21
100.00	4.101E − 17	6.965E − 18	2.404E − 18	9.078E − 19	9.210E − 19	2.667E − 19	2.708E − 19	1.382E − 19	7.386E − 21	2.426E − 21

[a] Includes contributions from ions in metastable states (see text).

TABLE 3. The recommended rate coefficients for carbon and its ions. The electron temperature is given in eV and the rates are in $cm^3 s^{-1}$.

T(eV)	C I	C II	C III	[a]C III	C IV	C V	C VI
1.0	1.341E − 13	2.445E − 19	3.100E − 30	9.165E − 28	5.376E − 38	0.000E 00	0.000E 00
2.0	6.259E − 11	6.382E − 14	1.088E − 19	1.414E − 18	7.681E − 24	0.000E 00	0.000E 00
3.0	5.588E − 10	4.327E − 12	3.860E − 16	1.864E − 15	4.366E − 19	4.073E − 68	0.000E 00
4.0	1.778E − 09	3.661E − 11	2.386E − 14	7.202E − 14	1.081E − 16	7.388E − 54	1.399E − 64
5.0	3.685E − 09	1.339E − 10	2.893E − 13	6.680E − 13	3.015E − 15	2.735E − 45	6.812E − 54
7.0	8.893E − 09	6.045E − 10	5.170E − 12	8.966E − 12	1.395E − 13	1.784E − 35	1.160E − 41
10.0	1.815E − 08	1.929E − 09	4.661E − 11	6.656E − 11	2.562E − 12	4.383E − 28	1.816E − 32
15.0	3.325E − 08	4.916E − 09	2.679E − 10	3.347E − 10	2.552E − 11	2.677E − 22	2.730E − 25
20.0	4.618E − 08	7.994E − 09	6.558E − 10	7.720E − 10	8.211E − 11	2.221E − 19	1.100E − 21
30.0	6.571E − 08	1.325E − 08	1.641E − 09	1.830E − 09	2.699E − 10	2.001E − 16	4.657E − 18
40.0	7.930E − 08	1.722E − 08	2.623E − 09	2.852E − 09	4.957E − 10	6.370E − 15	3.137E − 16
50.0	8.909E − 08	2.021E − 08	3.491E − 09	3.738E − 09	7.185E − 10	5.251E − 14	3.998E − 15
70.0	1.020E − 07	2.428E − 08	4.851E − 09	5.104E − 09	1.108E − 09	6.150E − 13	7.543E − 14
100.0	1.126E − 07	2.776E − 08	6.201E − 09	6.434E − 09	1.545E − 09	4.120E − 12	7.057E − 13
150.0	1.205E − 07	3.044E − 08	7.446E − 09	7.637E − 09	2.012E − 09	1.916E − 11	4.158E − 12
200.0	1.234E − 07	3.153E − 08	8.089E − 09	8.247E − 09	2.297E − 09	4.256E − 11	1.028E − 11
300.0	1.244E − 07	3.201E − 08	8.642E − 09	8.769E − 09	2.612E − 09	9.743E − 11	2.593E − 11
400.0	1.230E − 07	3.174E − 08	8.805E − 09	8.922E − 09	2.768E − 09	1.495E − 10	4.160E − 11
500.0	1.210E − 07	3.123E − 08	8.819E − 09	8.936E − 09	2.850E − 09	1.943E − 10	5.544E − 11
700.0	1.167E − 07	3.010E − 08	8.683E − 09	8.809E − 09	2.912E − 09	2.630E − 10	7.718E − 11
1000.0	1.108E − 07	2.852E − 08	8.377E − 09	8.518E − 09	2.908E − 09	3.293E − 10	9.884E − 11
2000.0	9.694E − 08	2.481E − 08	7.478E − 09	7.650E − 09	2.742E − 09	4.172E − 10	1.295E − 10
4000.0	8.203E − 08	2.084E − 08	6.397E − 09	6.589E − 09	2.450E − 09	4.443E − 10	1.419E − 10
5000.0	7.729E − 08	1.959E − 08	6.041E − 09	6.238E − 09	2.341E − 09	4.422E − 10	1.424E − 10
10000.0	6.329E − 08	1.593E − 08	4.972E − 09	5.172E − 09	1.989E − 09	4.130E − 10	1.362E − 10

[a] Includes contributions from ions in metastable states (see text).

wave functions are used for both the initial and final states. The Born and Coulomb–Born approximations are not valid at low energies and hence in deciding on the recommended cross sections we have generally used experimental data where they are available and extrapolated to high energies if necessary, using the Born or Coulomb–Born approximations or theoretical estimates of the Bethe coefficients. When different experiments yield conflicting results, we have normally used the experimental results which agree best with the theoretical prediction at high energies. If no experimental data are available, we have used theoretical data. Where possible, we have tested the classical scaling law for ionization cross sections in each isoelectronic sequence and also used this scaling to predict recommended cross sections, particularly for highly charged hydrogenlike and heliumlike ions. For these ions, few experimental data are available and the simple scaling law should be reasonably accurate.

All the recommended cross sections and rates are presented in graphical form in Figs. 1–55, and in the form of analytic fits. Numerical data are also presented for carbon and oxygen and their ions in Tables 1–4. The cross section graphs for all atoms and ions include a representative selection of the available data. To ensure clarity it has not been possible to include all the data in every case but a full bibliography for each species is provided in a separate report (Smith, Gilliland, and Hughes[25]). Tabular values of cross sections for other atoms and ions apart from carbon and oxygen are given in a Culham report (Bell *et al.*[26]). The recommended rates for a few representative species are compared in Figs. 9–11 with recent measurements in plasma machines and with the calculated rates of other authors. It is clear that there is a considerable difference between the present rates and those obtained using semiempirical methods.

Estimates of the reliability of the recommended cross sections are given in the tables as percentages. The percentage error in the rates for each atom or ion should be the same as for the cross sections. These estimates are based on a review of the uncertainties or errors published with the original data. They normally adopt the error limits given by the author or authors of the "best" data measurement when these are available but are sometimes modified from an assessment of the scaled cross sections for each isoelectronic sequence. They have a confidence level of 67% except near threshold where the uncertainty is greater.

TABLE 4. Recommended rate coefficients for oxygen and its ions. The electron temperature is in eV and the rates are in $cm^3 s^{-1}$.

T(eV)	O I	O II	O III	O IV	ᵃO IV	O V	ᵃO V	O VI	O VII	O VIII
1.0	9.709E−15	2.739E−24	4.591E−33	1.148E−43	1.732E−40	1.429E−59	5.193E−55	1.507E−70	0.000E 00	0.000E 00
2.0	1.156E−11	1.593E−16	5.398E−21	1.119E−26	4.295E−25	1.084E−34	2.237E−32	2.083E−40	0.000E 00	0.000E 00
3.0	1.352E−10	6.655E−14	6.134E−17	5.803E−21	6.902E−20	2.309E−26	8.596E−25	2.522E−30	0.000E 00	0.000E 00
4.0	4.921E−10	1.411E−12	6.754E−15	4.441E−18	2.980E−17	3.503E−22	5.417E−21	2.886E−25	0.000E 00	0.000E 00
5.0	1.113E−09	9.018E−12	1.155E−13	2.475E−16	1.181E−15	1.155E−19	1.048E−18	3.201E−22	5.135E−76	0.000E 00
7.0	3.028E−09	7.803E−11	3.041E−12	2.595E−14	8.360E−14	9.020E−17	4.409E−16	1.001E−18	1.374E−57	8.007E−66
10.0	6.957E−09	4.142E−10	3.647E−11	9.125E−13	2.162E−12	1.389E−14	4.239E−14	4.362E−16	9.675E−44	1.579E−49
15.0	1.446E−08	1.616E−09	2.610E−10	1.574E−11	2.870E−11	7.311E−13	1.549E−12	5.162E−14	6.181E−33	7.918E−37
20.0	2.181E−08	3.320E−09	7.141E−10	6.844E−11	1.078E−10	5.451E−12	9.702E−12	5.773E−13	1.652E−27	1.845E−30
30.0	3.447E−08	7.151E−09	2.013E−09	3.134E−10	4.192E−10	4.199E−11	6.395E−11	6.673E−12	4.786E−22	4.538E−24
40.0	4.440E−08	1.078E−08	3.447E−09	6.906E−10	8.451E−10	1.188E−10	1.700E−10	2.315E−11	2.735E−19	7.388E−21
50.0	5.222E−08	1.395E−08	4.807E−09	1.124E−09	1.032E−09	2.238E−10	3.113E−10	4.934E−11	1.278E−17	6.380E−19
70.0	6.353E−08	1.895E−08	7.121E−09	1.993E−09	2.167E−09	4.669E−10	6.355E−10	1.188E−10	1.095E−15	1.077E−16
100.0	7.409E−08	2.401E−08	9.659E−09	3.098E−09	3.224E−09	8.185E−10	1.106E−09	2.338E−10	3.302E−14	5.243E−15
150.0	8.350E−08	2.879E−08	1.228E−08	4.384E−09	4.438E−09	1.273E−09	1.716E−09	4.063E−10	5.046E−13	1.125E−13
200.0	8.826E−08	3.127E−08	1.380E−08	5.201E−09	5.214E−09	1.587E−09	2.131E−09	5.529E−10	2.062E−12	5.342E−13
300.0	9.226E−08	3.337E−08	1.530E−08	6.105E−09	6.091E−09	1.965E−09	2.609E−09	7.341E−10	8.861E−12	2.614E−12
400.0	9.332E−08	3.392E−08	1.588E−08	6.540E−09	6.521E−09	2.170E−09	2.841E−09	8.859E−10	1.890E−11	5.881E−12
500.0	9.324E−08	3.387E−08	1.607E−08	6.759E−09	6.735E−09	2.288E−09	2.955E−09	9.689E−10	3.016E−11	9.645E−12
700.0	9.180E−08	3.317E−08	1.598E−08	6.912E−09	6.867E−09	2.403E−09	3.024E−09	1.064E−09	5.223E−11	1.714E−11
1000.0	8.884E−08	3.179E−08	1.548E−08	6.875E−09	6.787E−09	2.448E−09	2.986E−09	1.169E−09	7.972E−11	2.657E−11
2000.0	8.016E−08	2.796E−08	1.378E−08	6.387E−09	6.186E−09	2.362E−09	2.703E−09	1.220E−09	1.309E−10	4.438E−11
4000.0	6.942E−08	2.350E−08	1.163E−08	5.591E−09	5.295E−09	2.132E−09	2.286E−09	1.161E−09	1.629E−10	5.603E−11
5000.0	6.581E−08	2.205E−08	1.092E−08	5.306E−09	4.986E−09	2.042E−09	2.144E−09	1.138E−09	1.680E−10	5.810E−11
10000.0	5.478E−08	1.780E−08	8.806E−09	4.414E−09	4.039E−09	1.741E−09	1.713E−09	1.012E−09	1.703E−10	5.992E−11

ᵃ Includes contributions from ions in metastable states (see text).

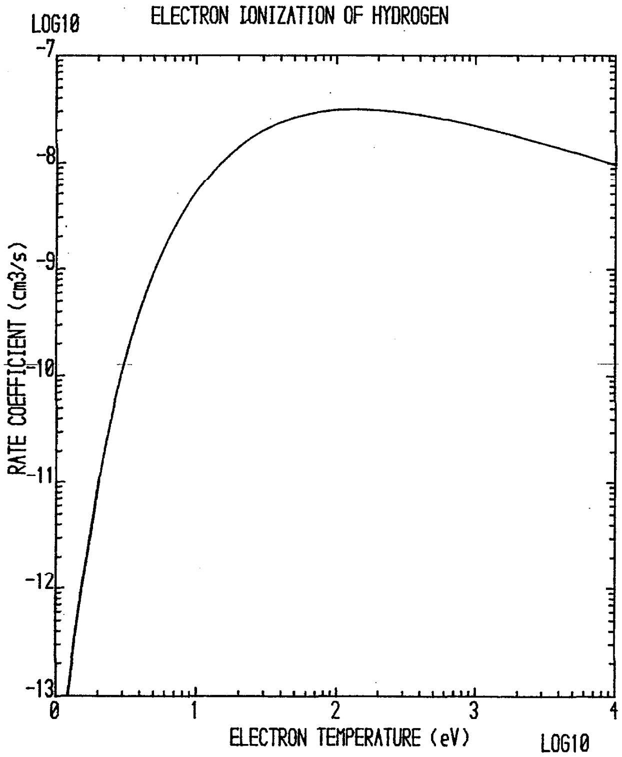

FIGURE 1. Recommended rate for hydrogen.

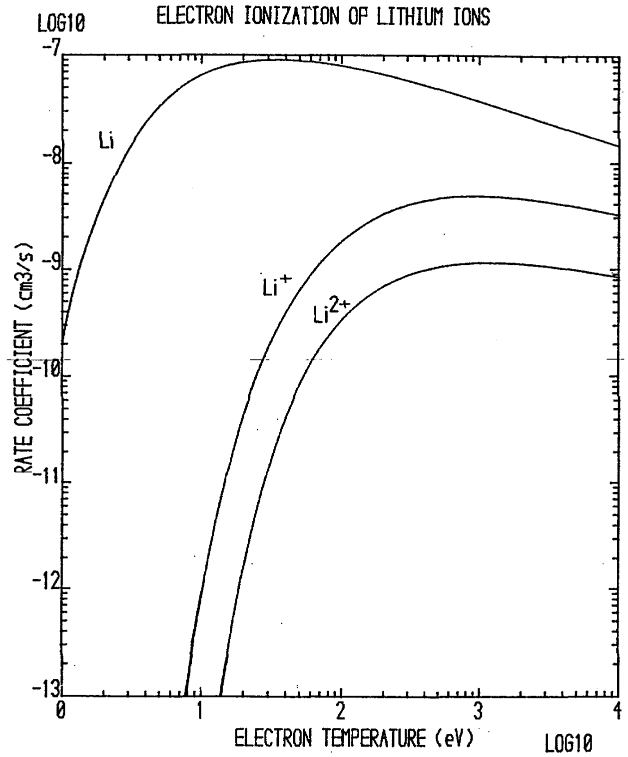

FIGURE 3. Recommended rates for lithium and its ions.

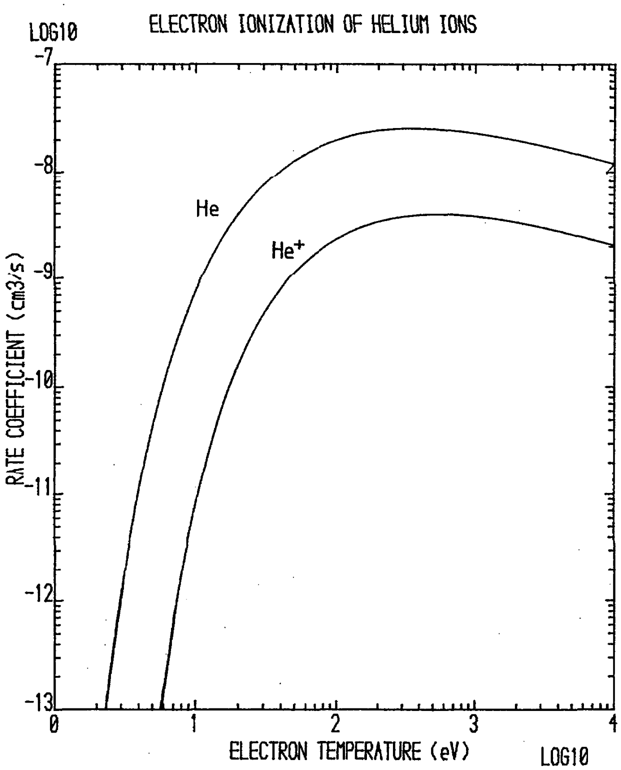

FIGURE 2. Recommended rates for helium and its ion.

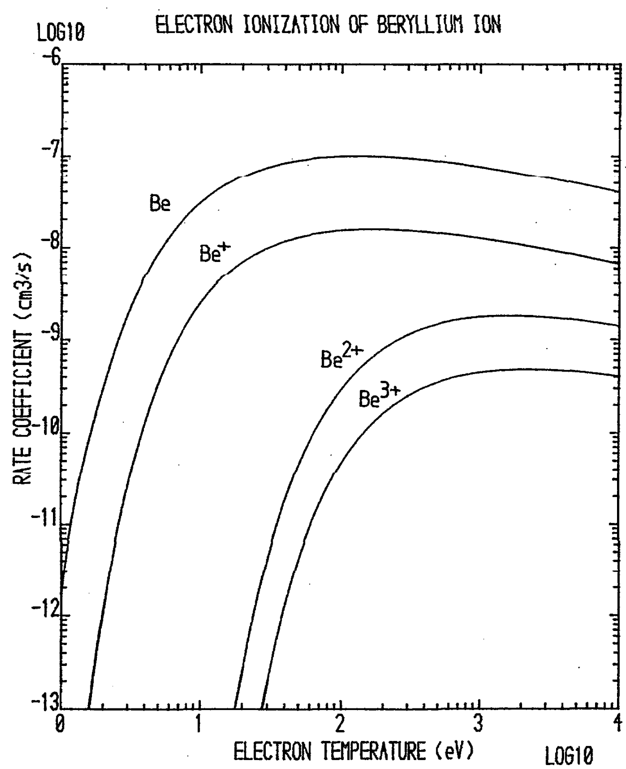

FIGURE 4. Recommended rates for beryllium and its ions.

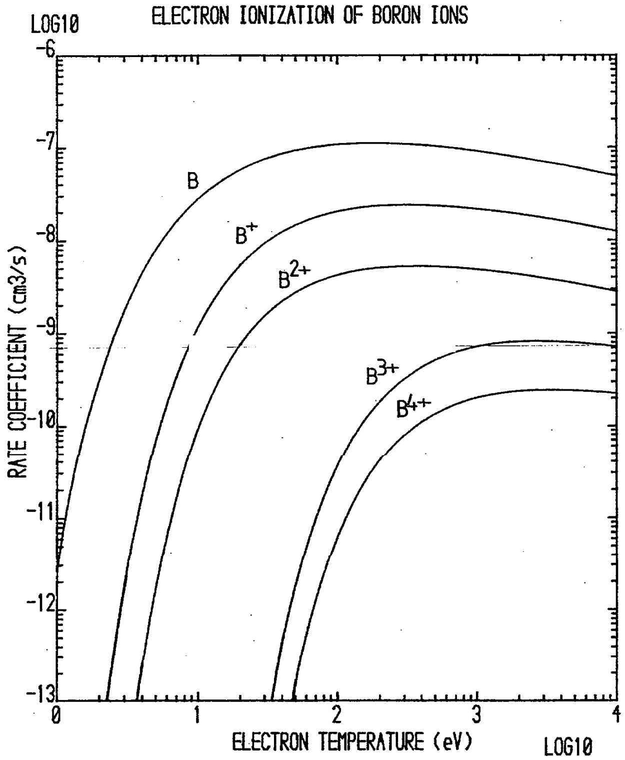

FIGURE 5. Recommended rates for boron and its ions.

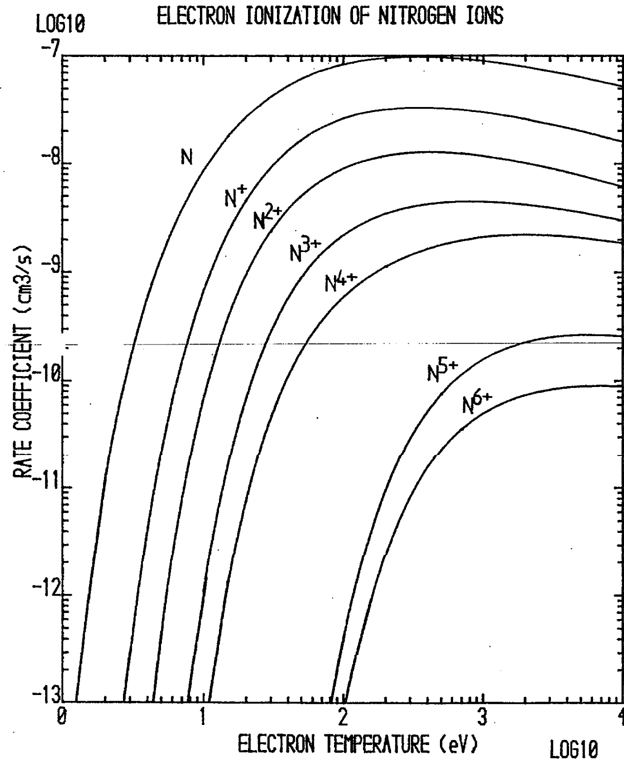

FIGURE 7. Recommended rates for nitrogen and its ions.

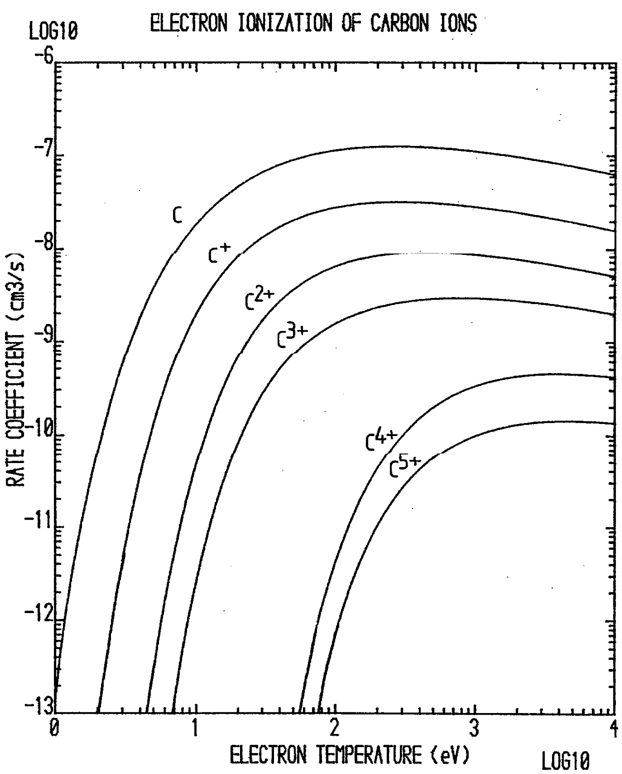

FIGURE 6. Recommended rates for carbon and its ions.

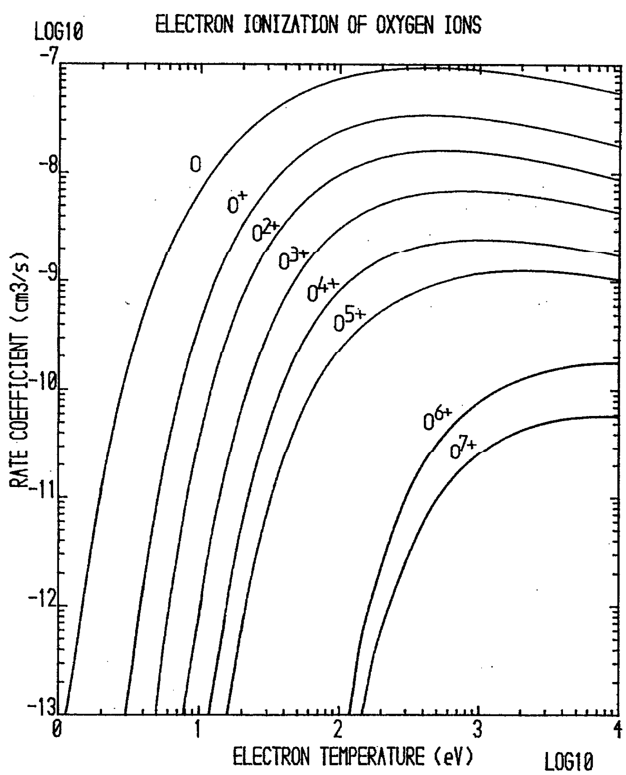

FIGURE 8. Recommended rates for oxygen and its ions.

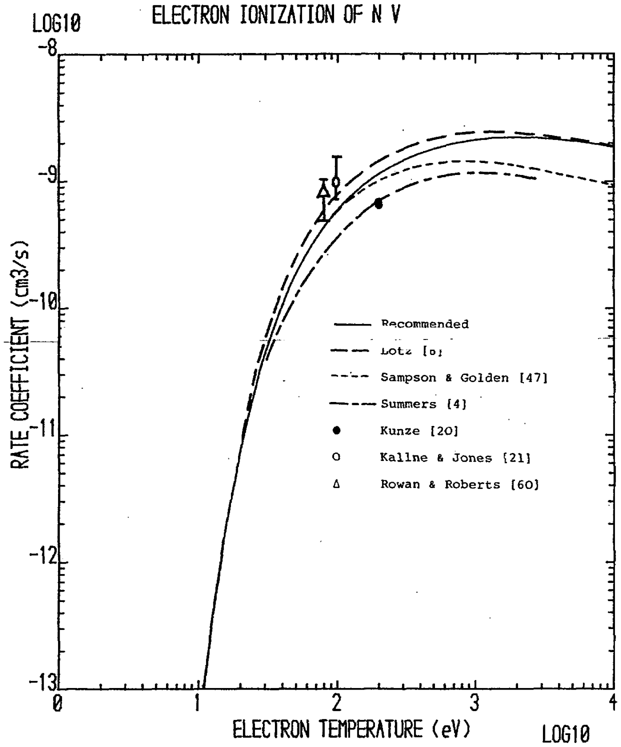

FIGURE 9. Comparison of recommended rates for N V with other calculations and measurements.

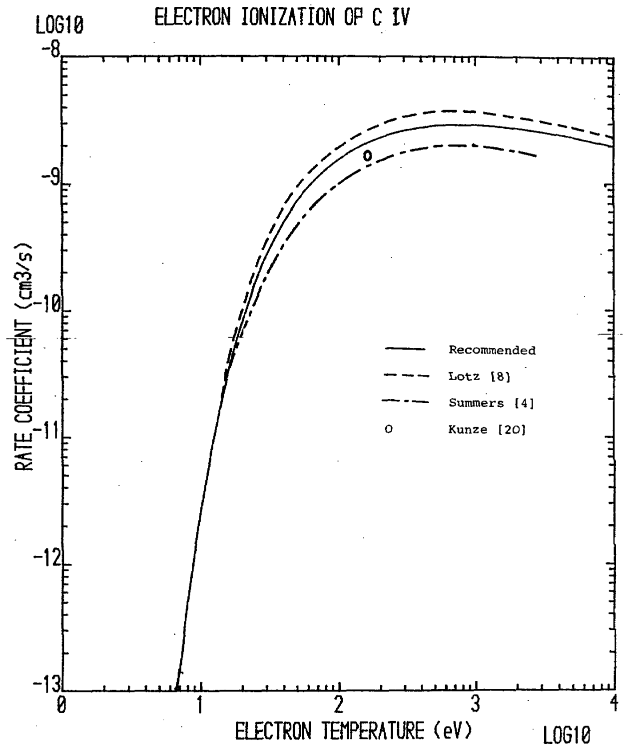

FIGURE 11. Comparison of recommended rate for C IV with other calculations and measurements.

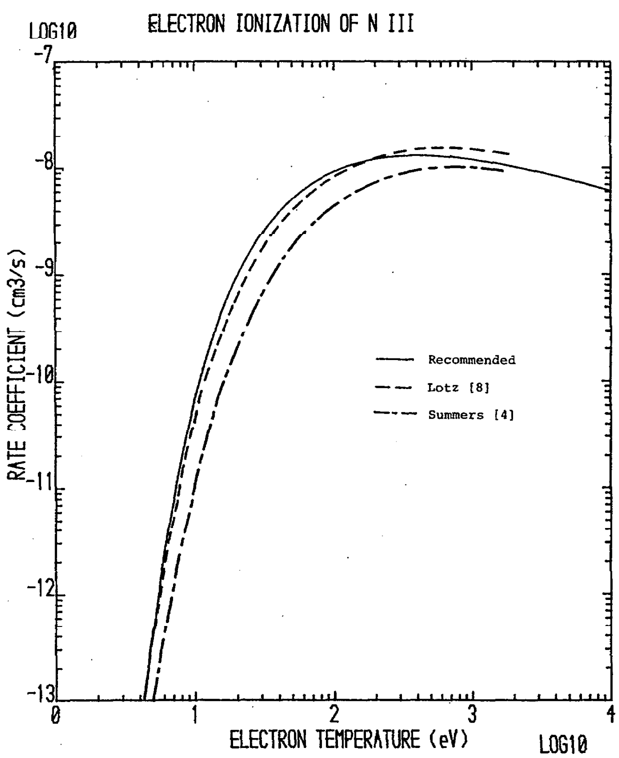

FIGURE 10. Comparison of recommended rate for N III with other calculations and measurements.

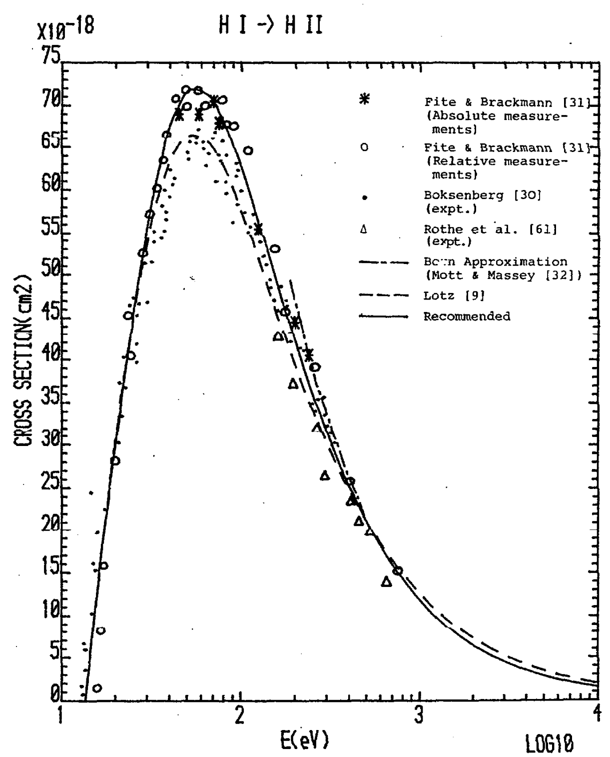

FIGURE 12. Electron impact ionization cross sections for H I.

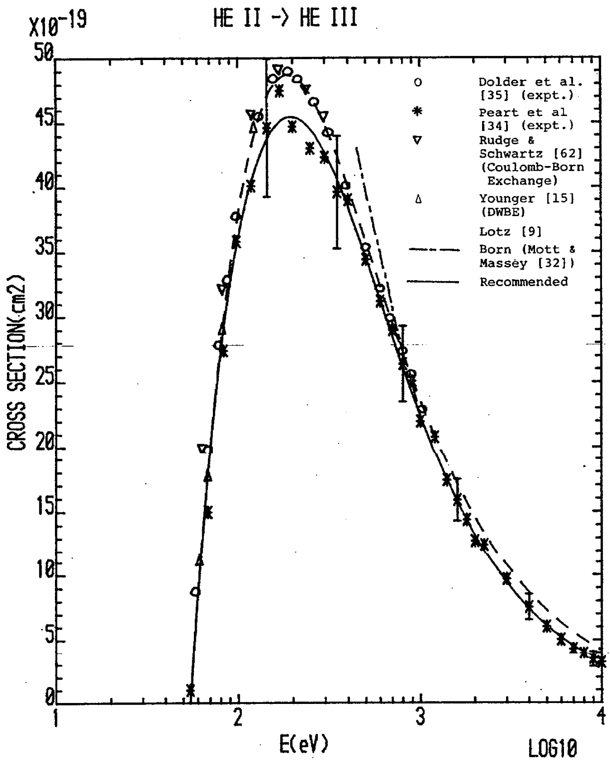

FIGURE 13. Electron impact ionization cross sections for He II.

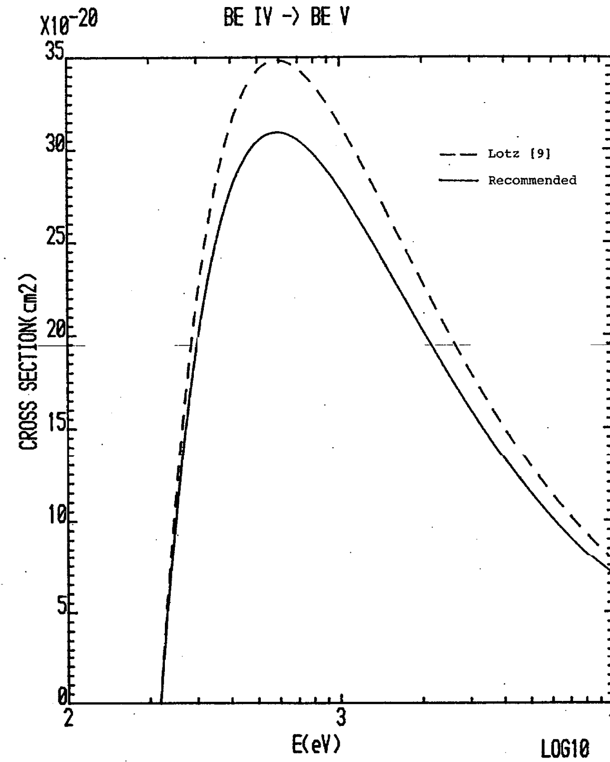

FIGURE 15. Electron impact ionization cross sections for Be IV.

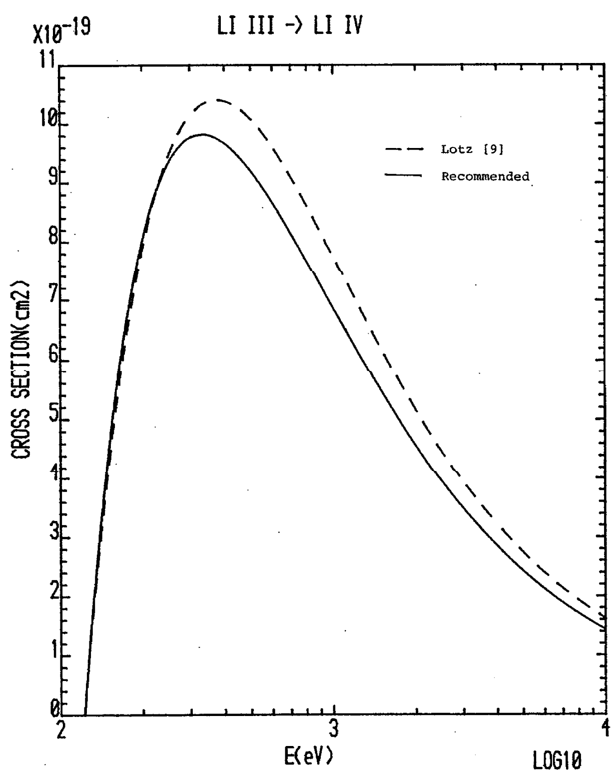

FIGURE 14. Electron impact ionization cross sections for Li III.

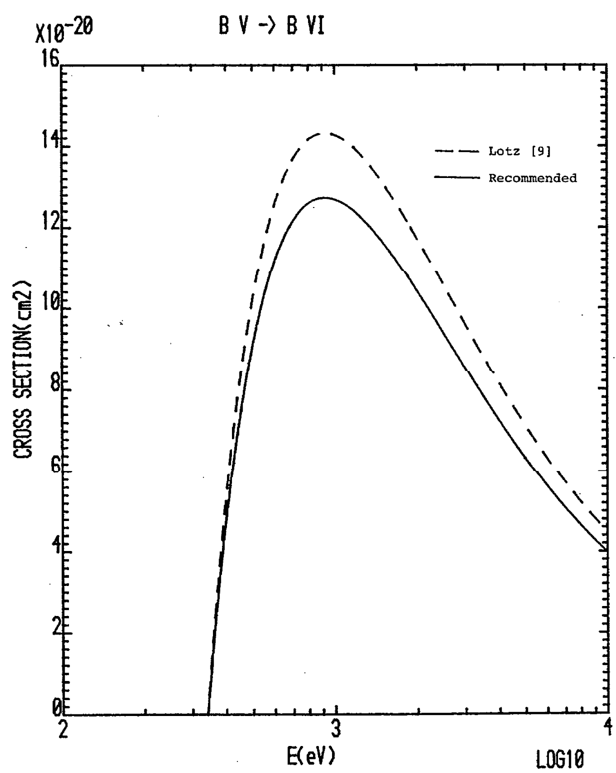

FIGURE 16. Electron impact ionization cross sections for B V.

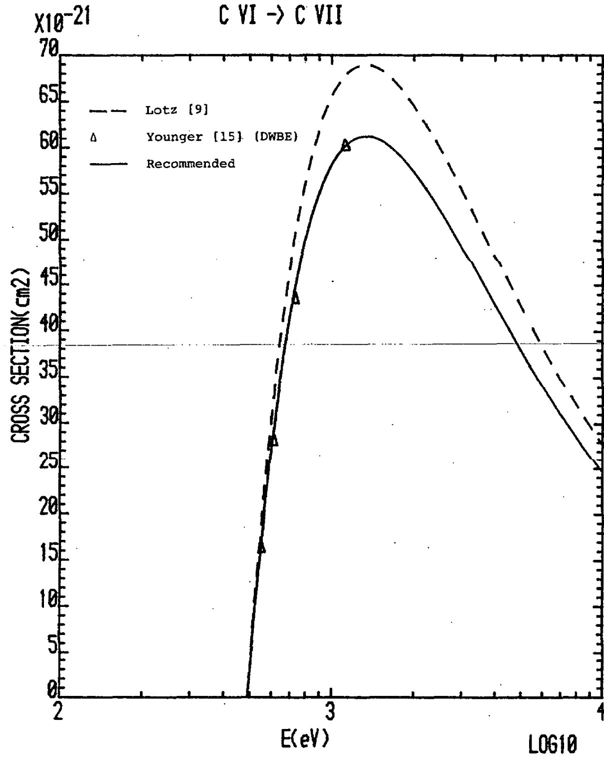

FIGURE 17. Electron impact ionization cross sections for C VI.

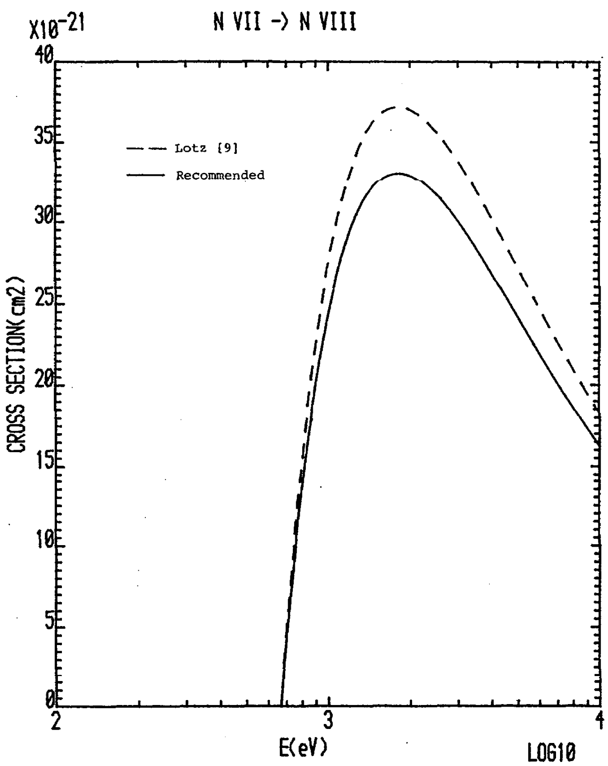

FIGURE 18. Electron impact ionization cross sections for N VII.

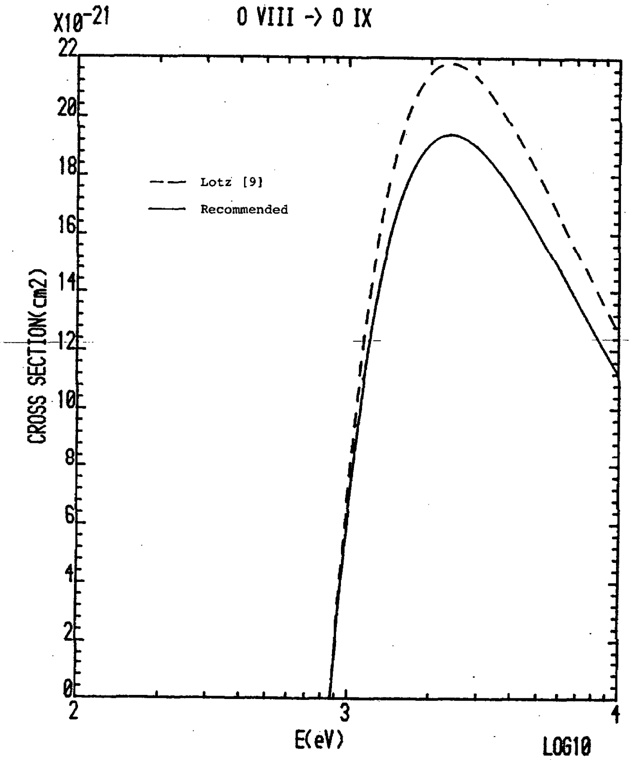

FIGURE 19. Electron impact ionization cross sections for O VIII

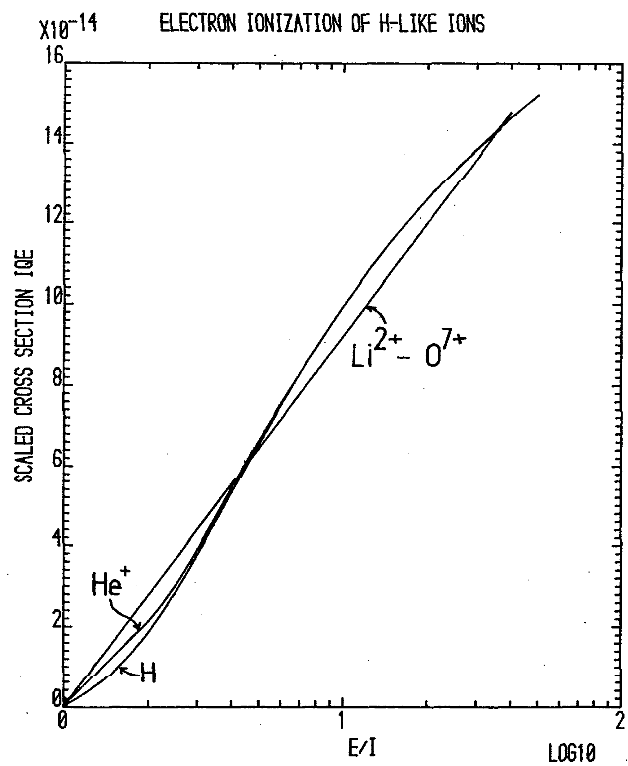

FIGURE 20. Scaled cross sections for H-like ions.

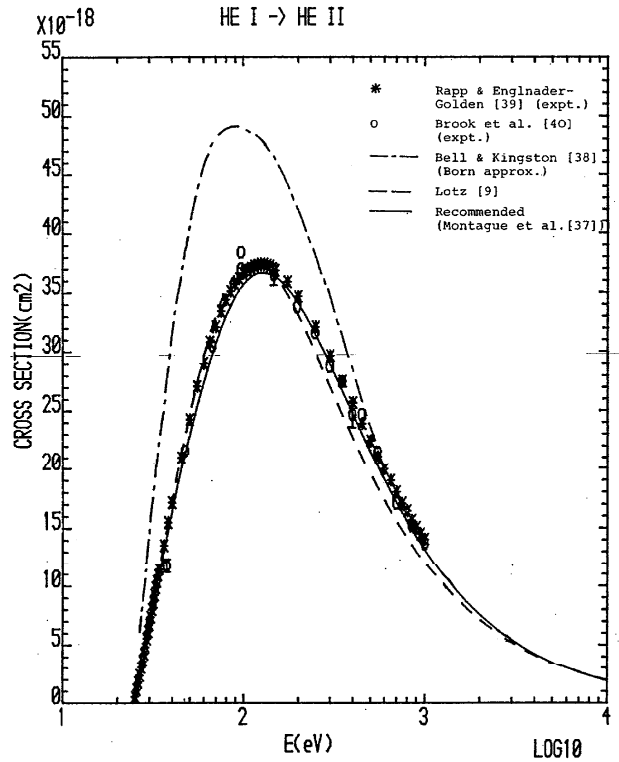

FIGURE 21. Electron impact ionization cross sections for He I.

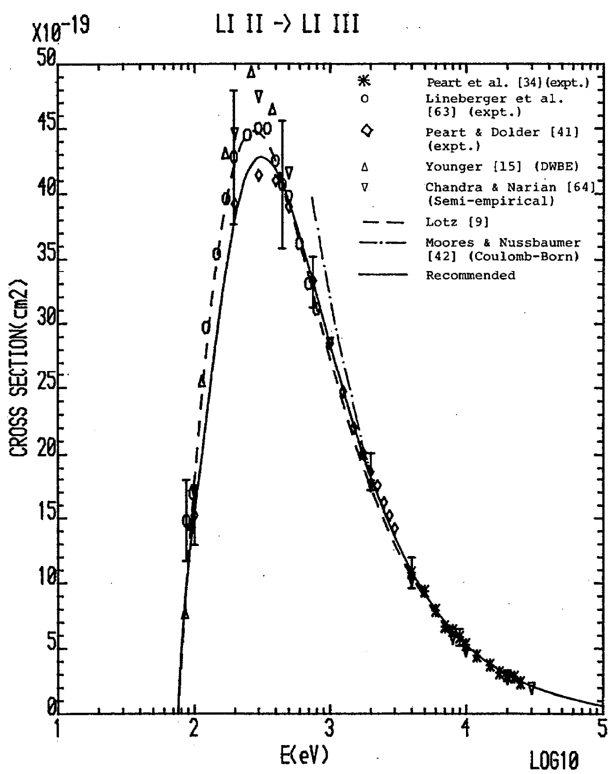

FIGURE 22. Electron impact ionization cross sections for Li II.

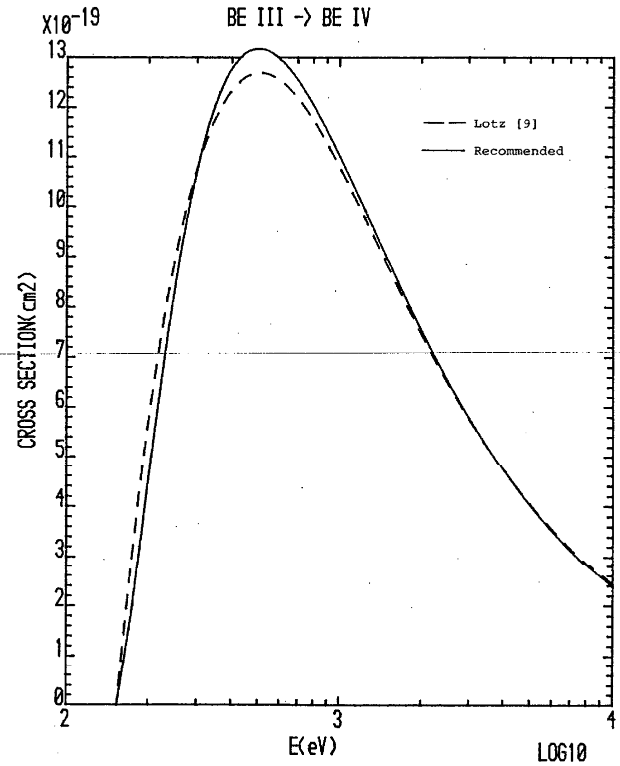

FIGURE 23. Electron impact ionization cross sections for Be III.

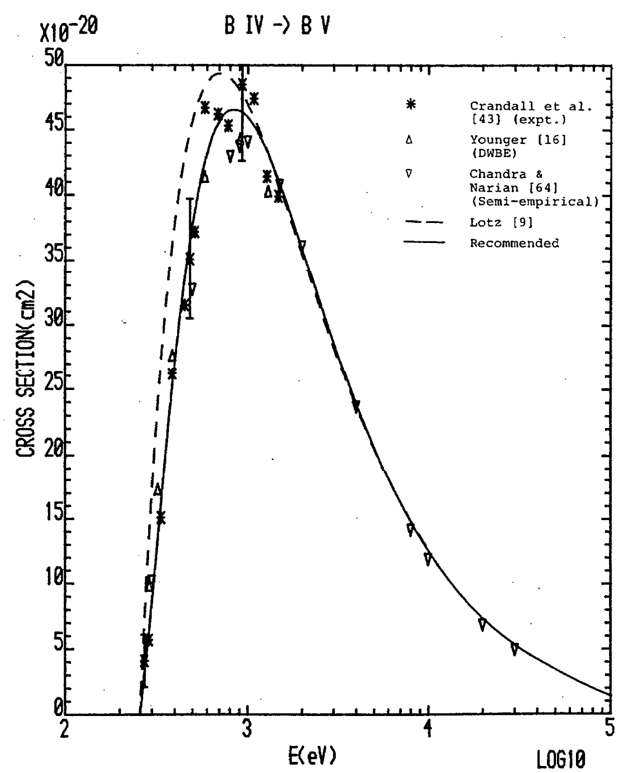

FIGURE 24. Electron impact ionization cross sections for B IV.

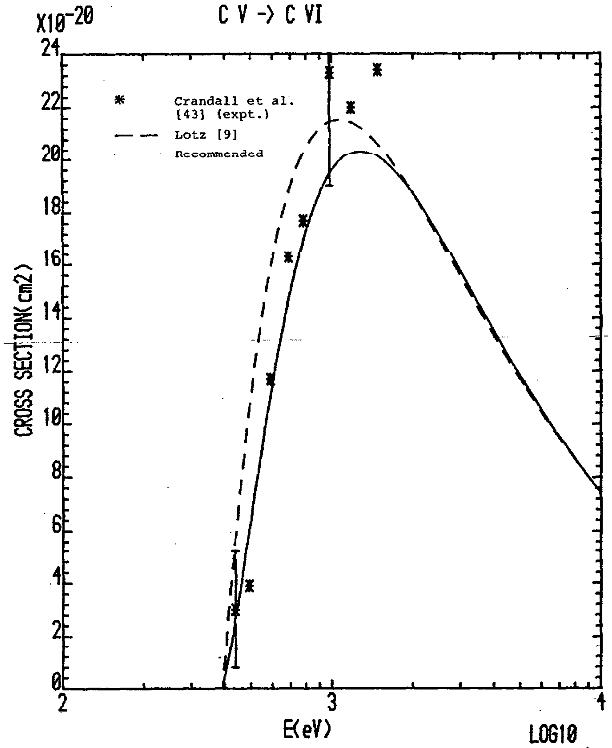

FIGURE 25. Electron impact ionization cross sections for C V.

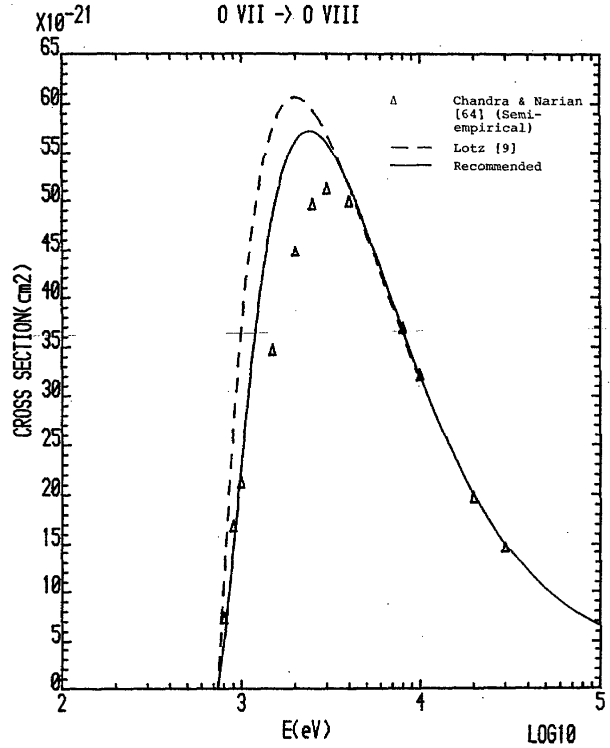

FIGURE 27. Electron impact ionization cross sections for O VII.

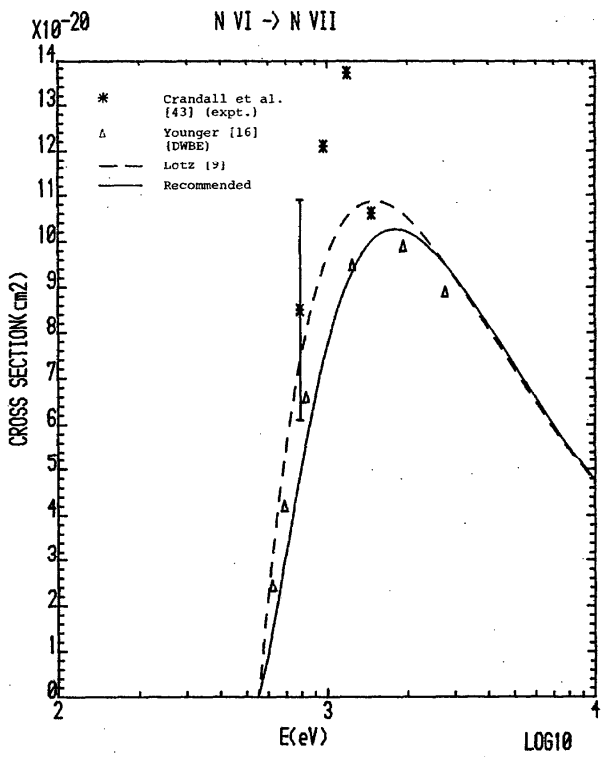

FIGURE 26. Electron impact ionization cross sections for N VI.

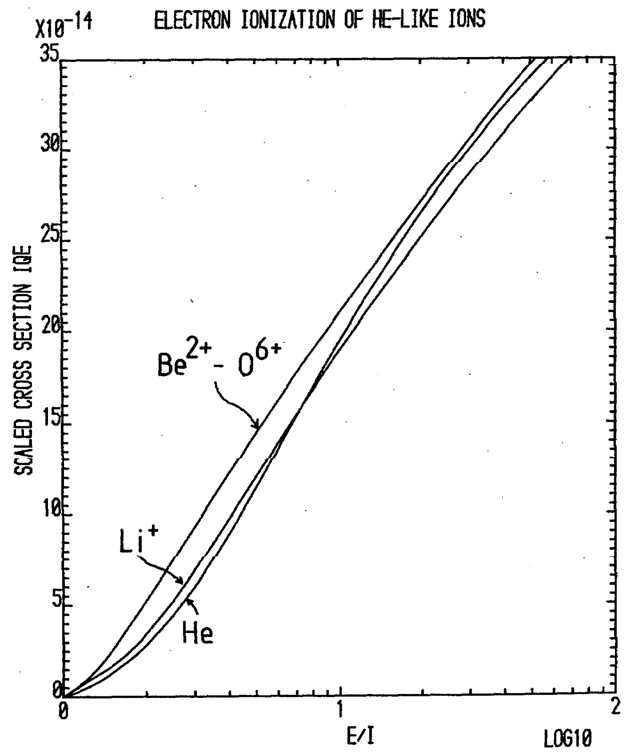

FIGURE 28. Scaled cross sections for He-like ions.

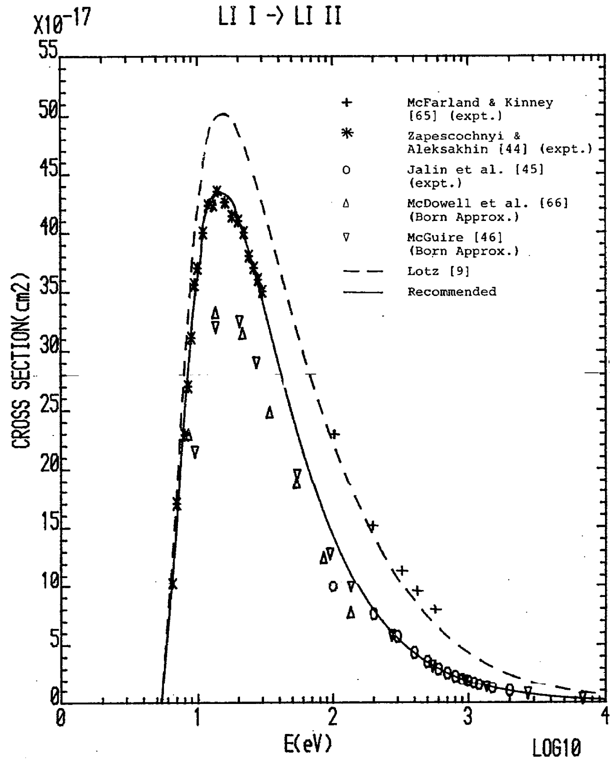

FIGURE 29. Electron impact ionization cross sections for Li I.

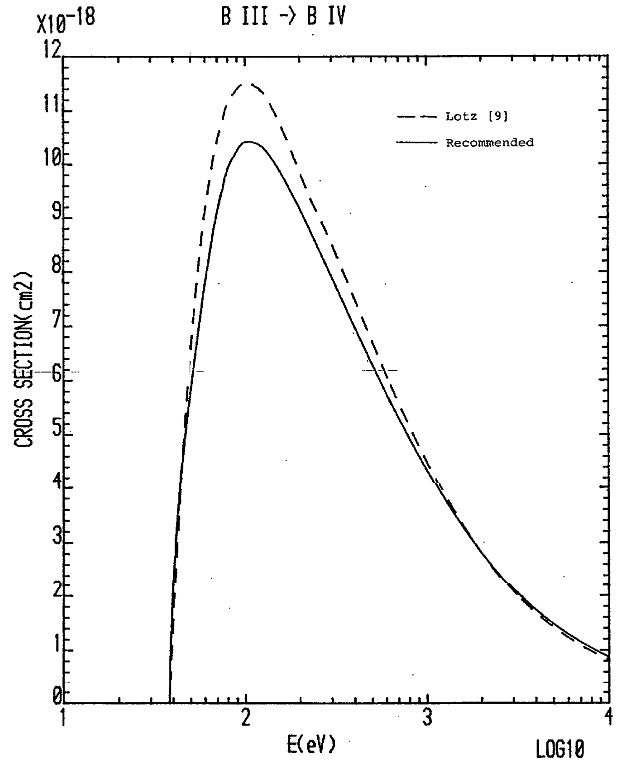

FIGURE 31. Electron impact ionization cross sections for B III.

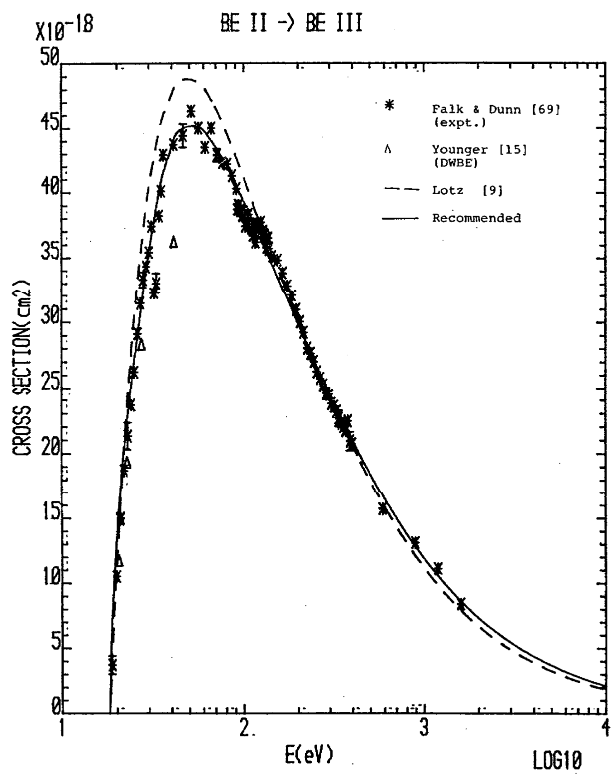

FIGURE 30. Electron impact ionization cross sections for Be II.

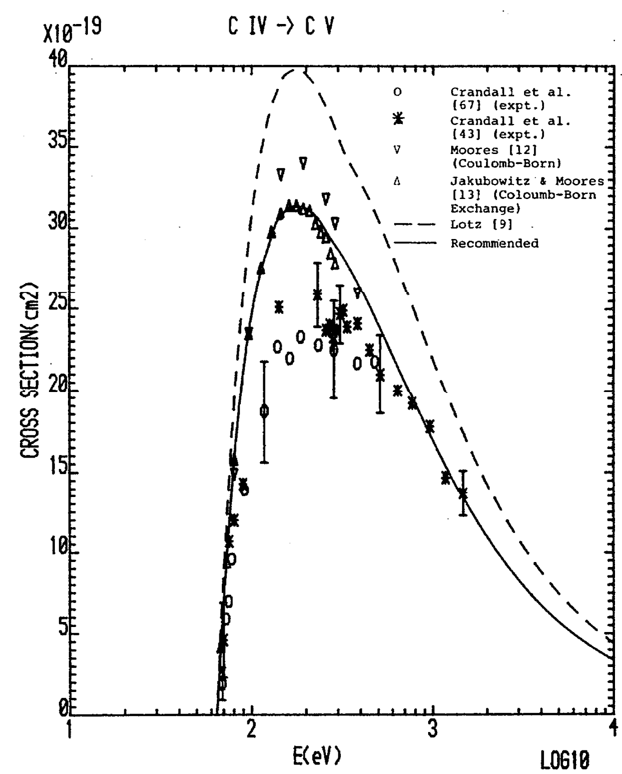

FIGURE 32. Electron impact ionization cross sections for C IV.

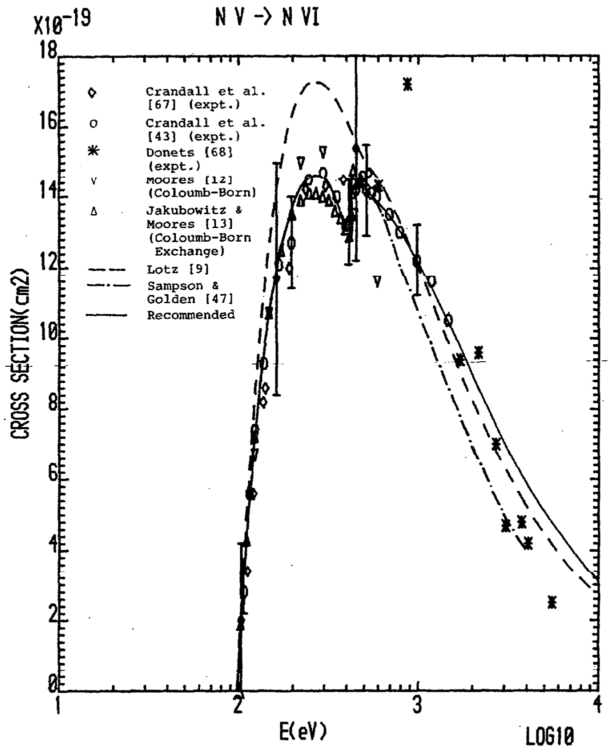

FIGURE 33. Electron impact ionization cross sections for N v.

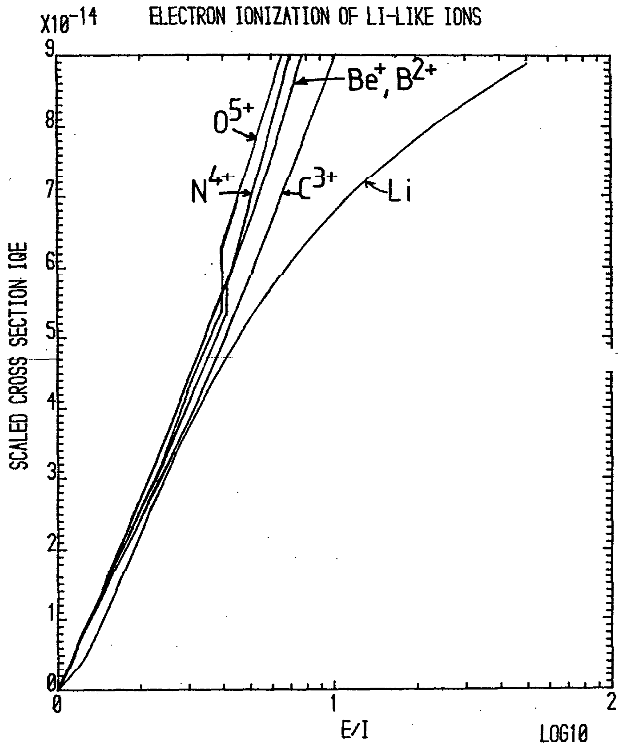

FIGURE 35. Scaled cross sections for Li-like ions.

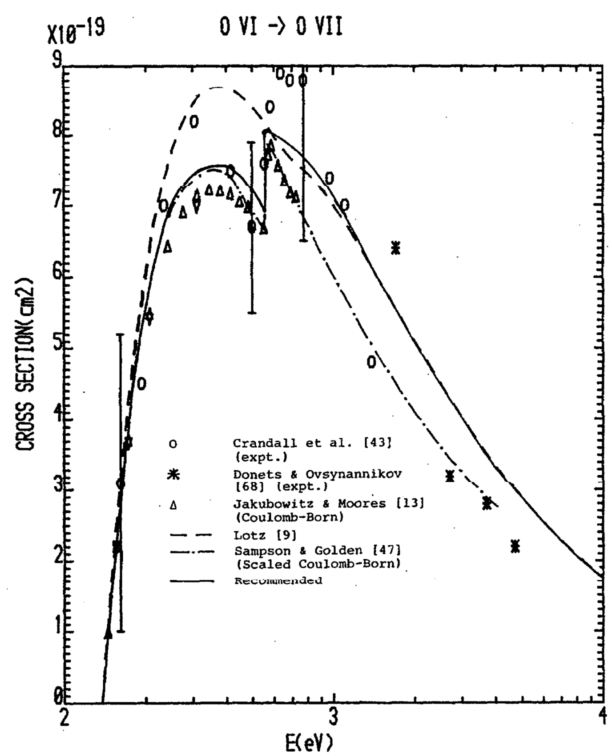

FIGURE 34. Electron impact ionization cross sections for O vi.

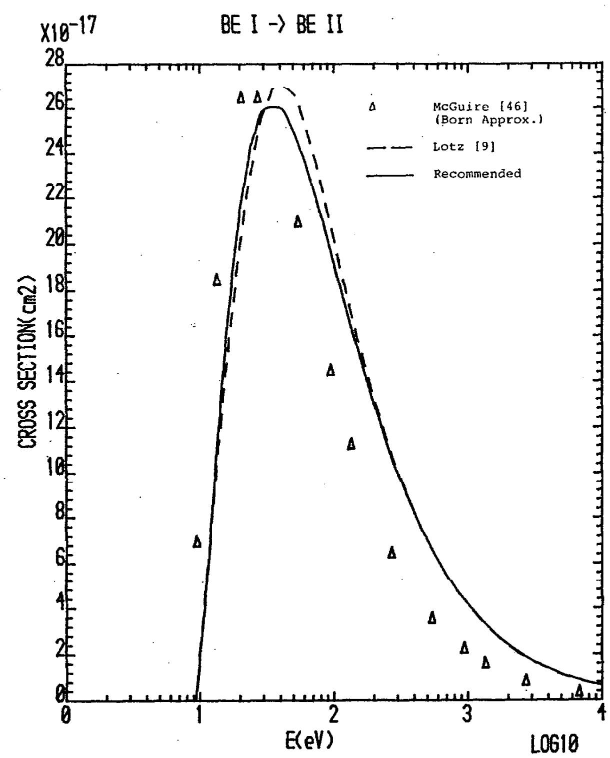

FIGURE 36. Electron impact ionization cross sections for Be i.

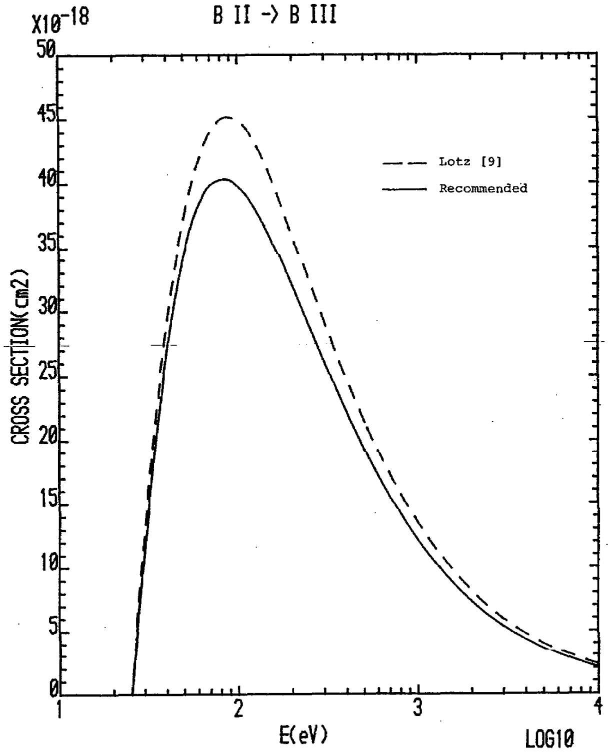

FIGURE 37. Electron impact ionization cross sections for B II.

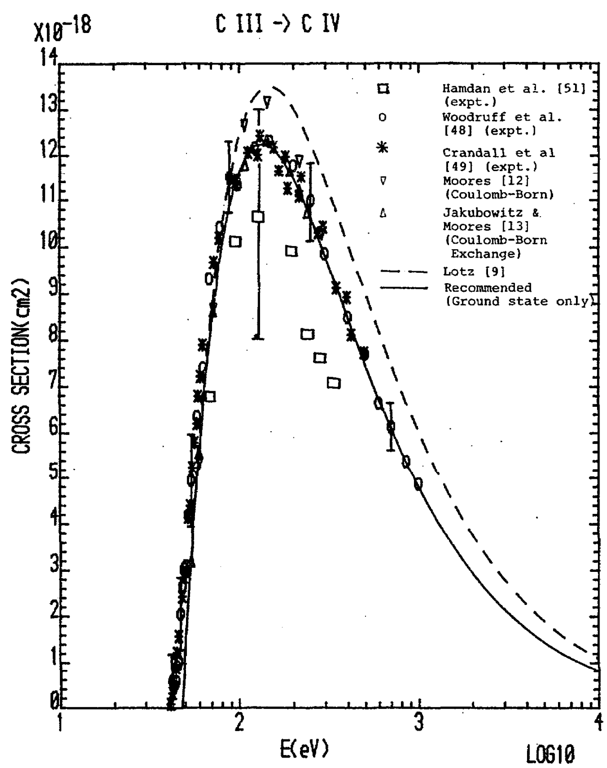

FIGURE 38. Electron impact ionization cross sections for C III.

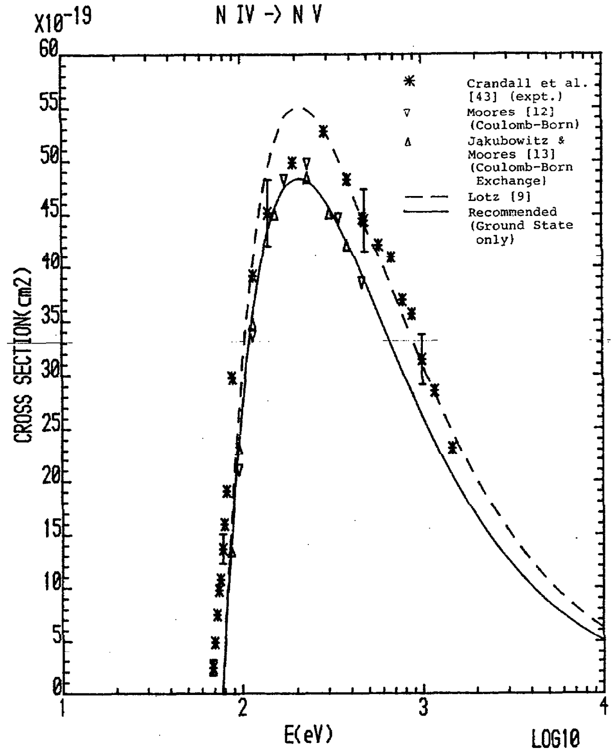

FIGURE 39. Electron impact ionization cross sections for N IV.

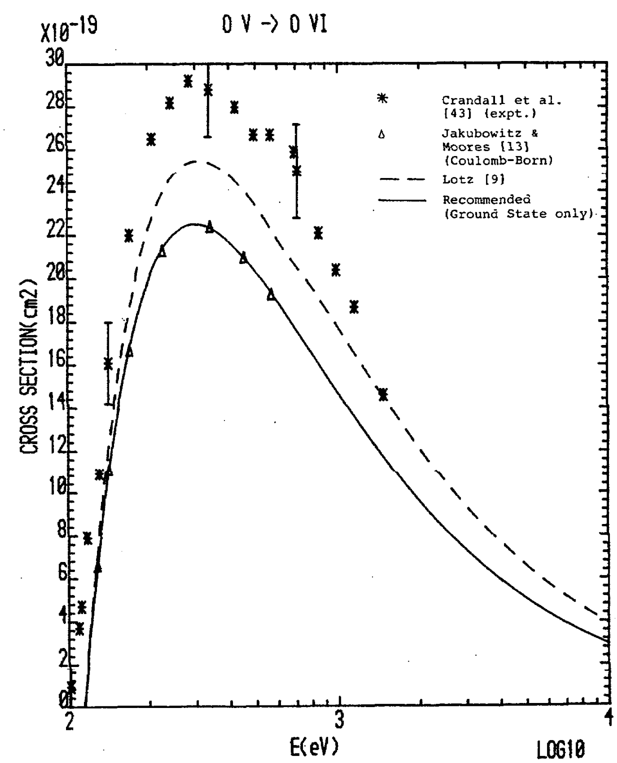

FIGURE 40. Electron impact ionization cross sections for O V.

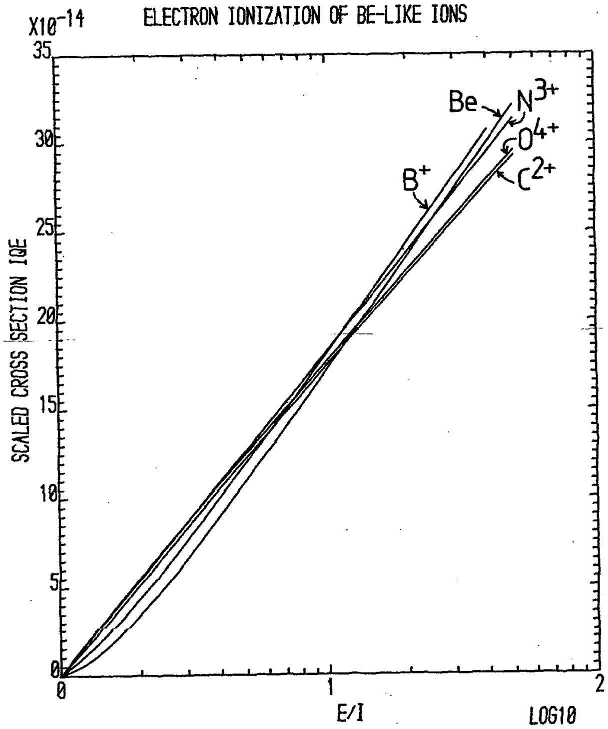

FIGURE 41. Scaled cross sections for Be-like ions.

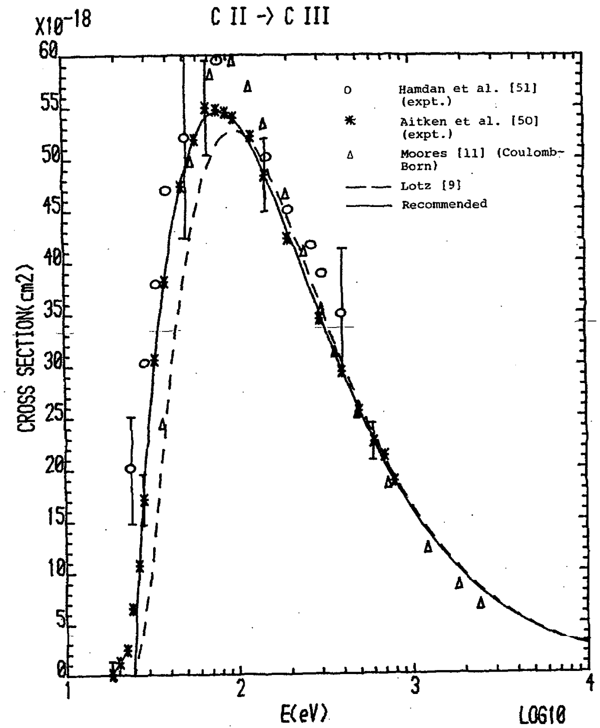

FIGURE 43. Electron impact ionization cross sections for C II.

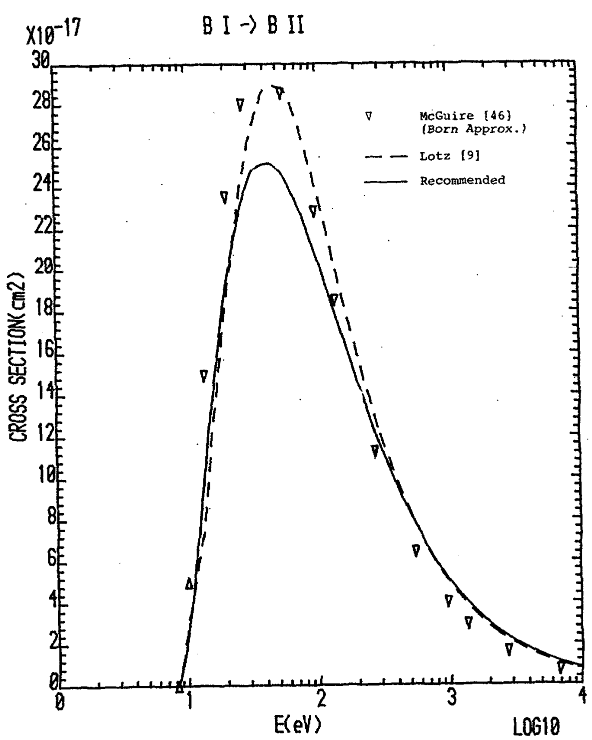

FIGURE 42. Electron impact ionization cross sections for B I.

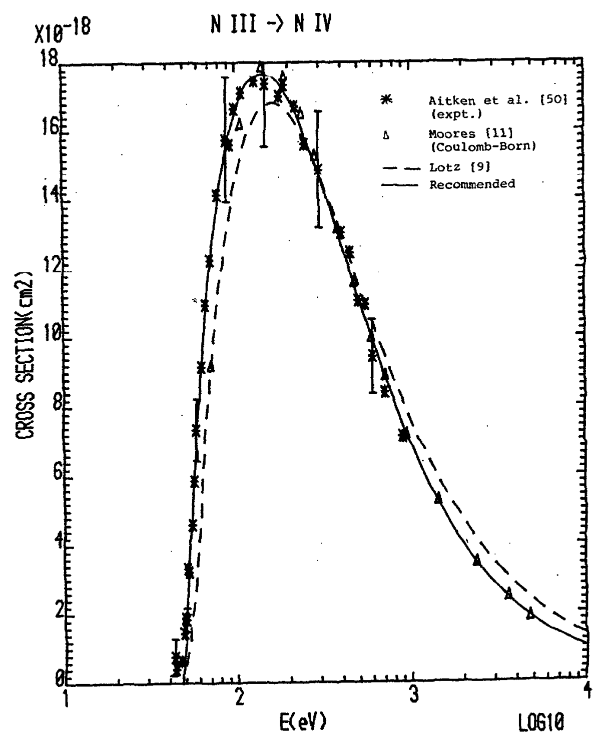

FIGURE 44. Electron impact ionization cross sections for N III.

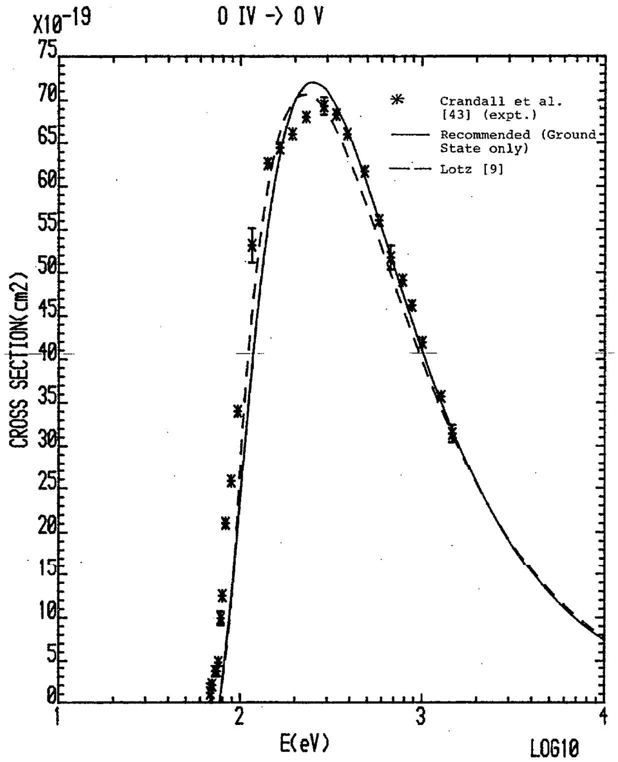

FIGURE 45. Electron impact ionization cross sections for O IV.

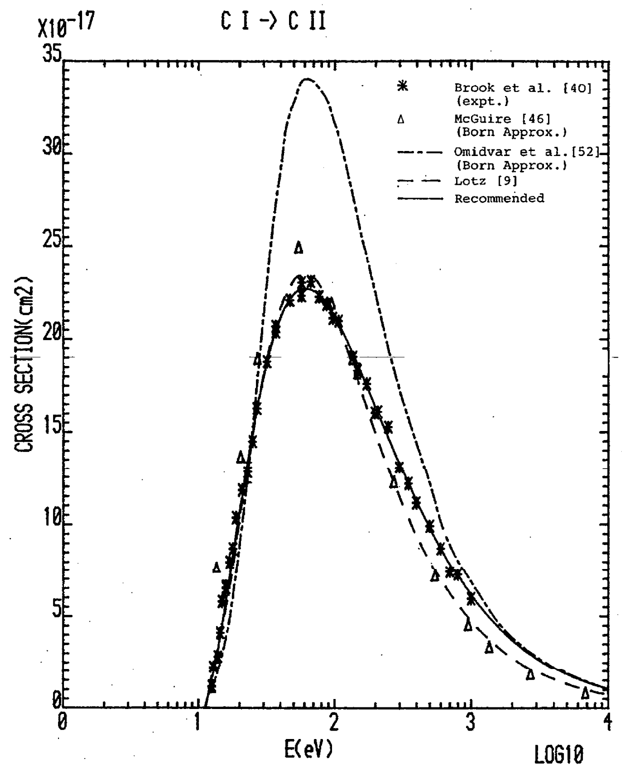

FIGURE 47. Electron impact ionization cross sections for C I.

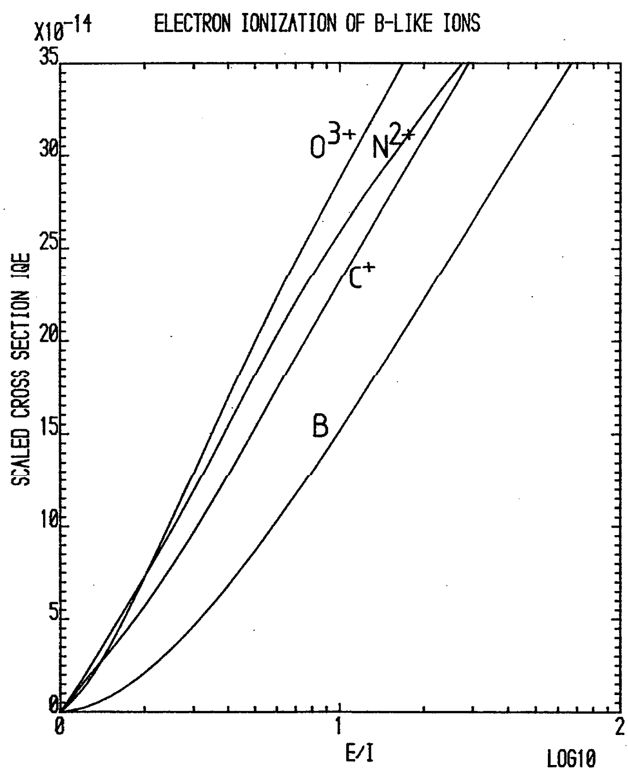

FIGURE 46. Scaled cross sections for B-like ions.

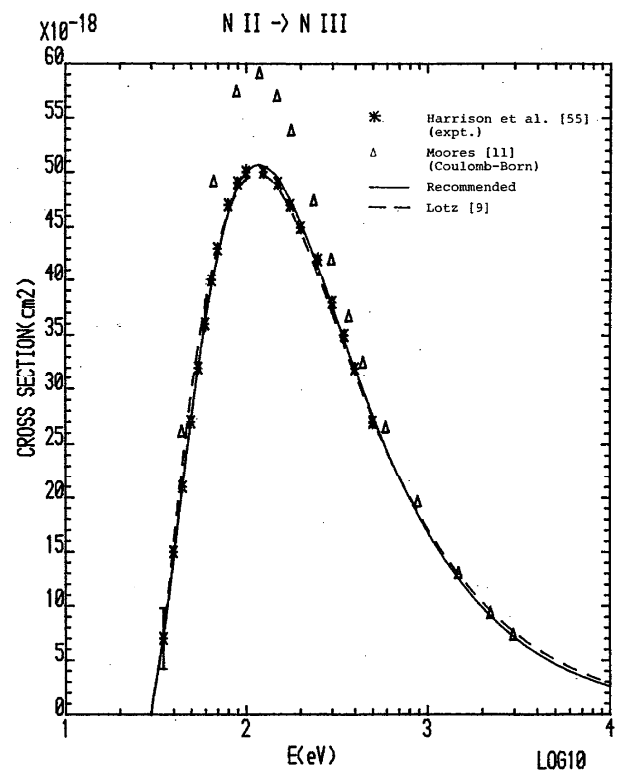

FIGURE 48. Electron impact ionization cross sections for N II.

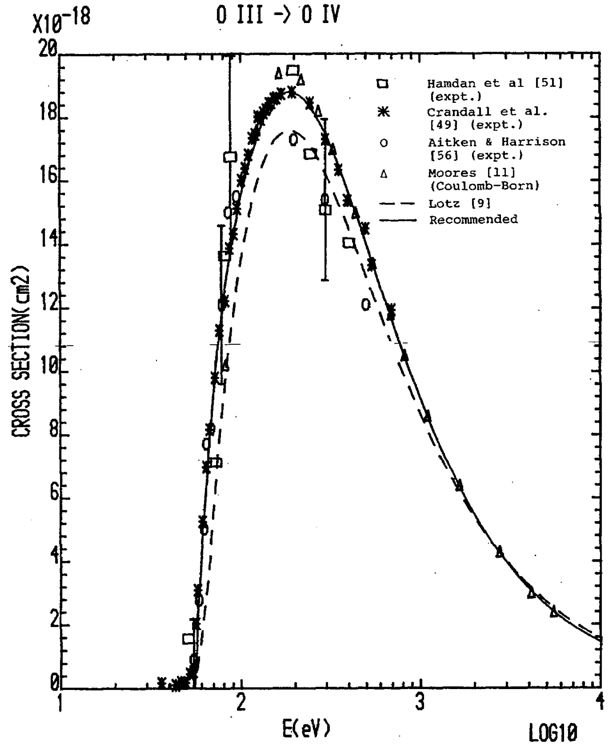

FIGURE 49. Electron impact ionization cross sections for O III.

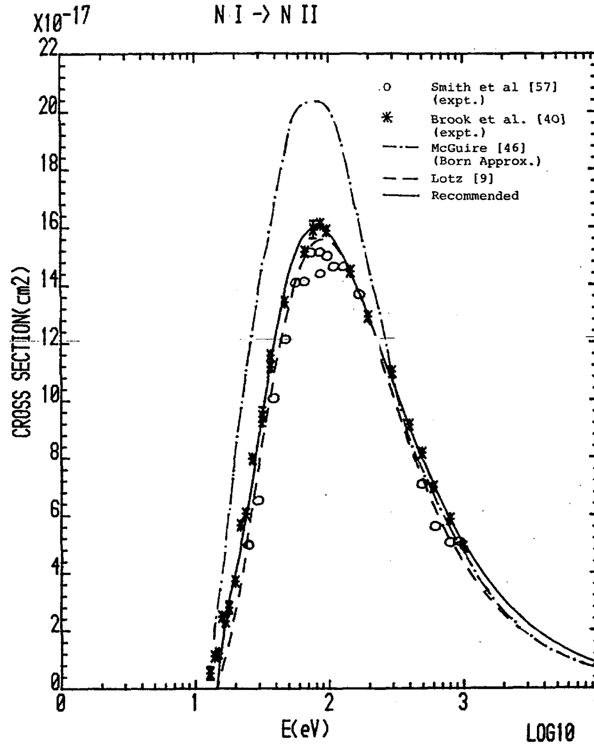

FIGURE 51. Electron impact ionization cross sections for N.'

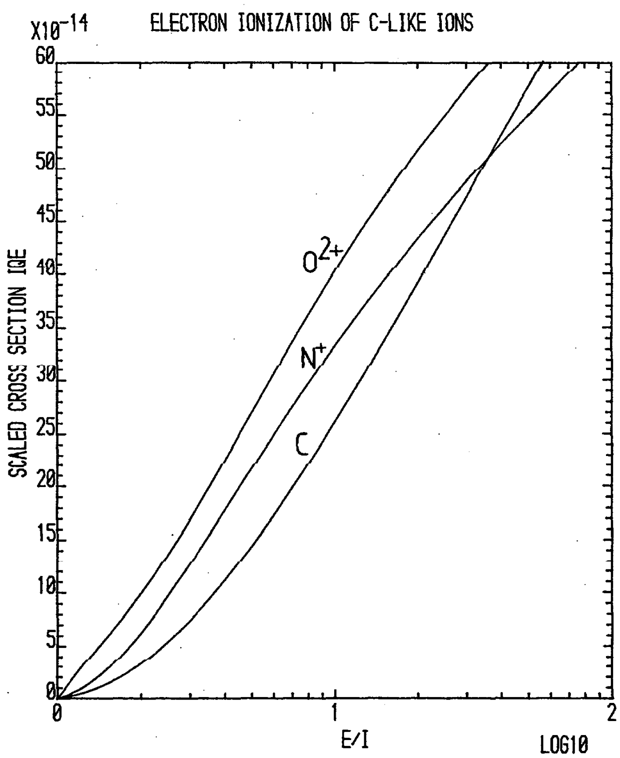

FIGURE 50. Scaled cross sections for C-like ions.

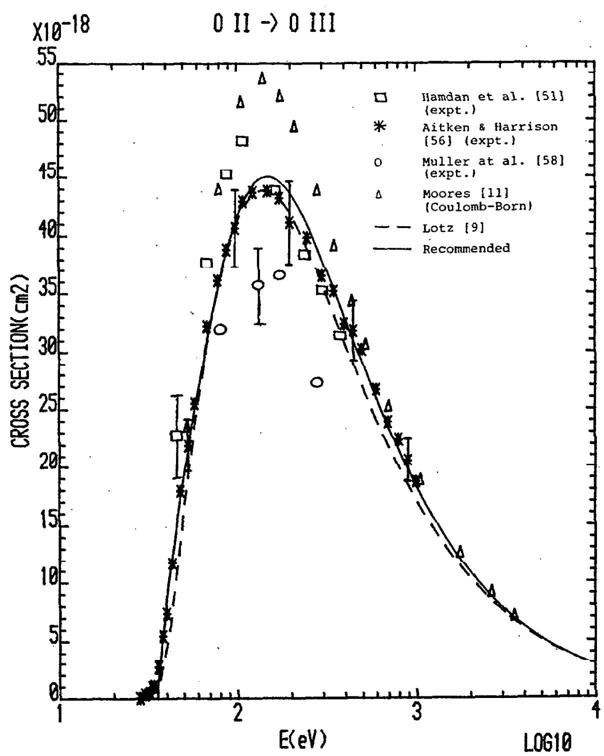

FIGURE 52. Electron impact ionization cross sections for O II.

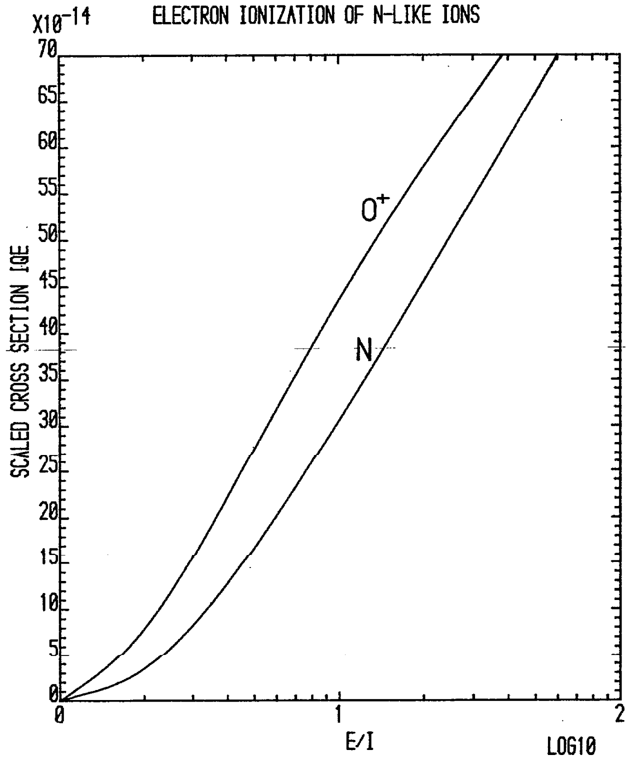

FIGURE 53. Scaled cross sections for N-like ions.

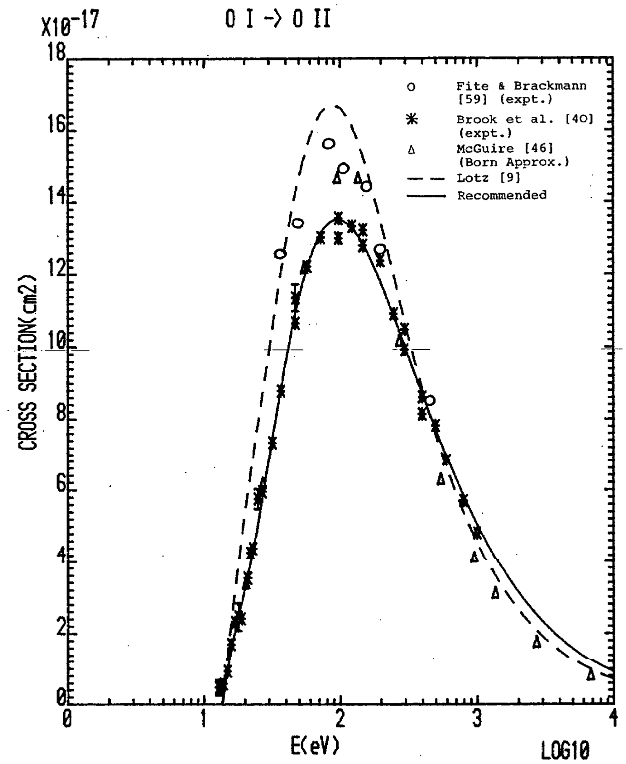

FIGURE 54. Electron impact ionization cross sections for O I.

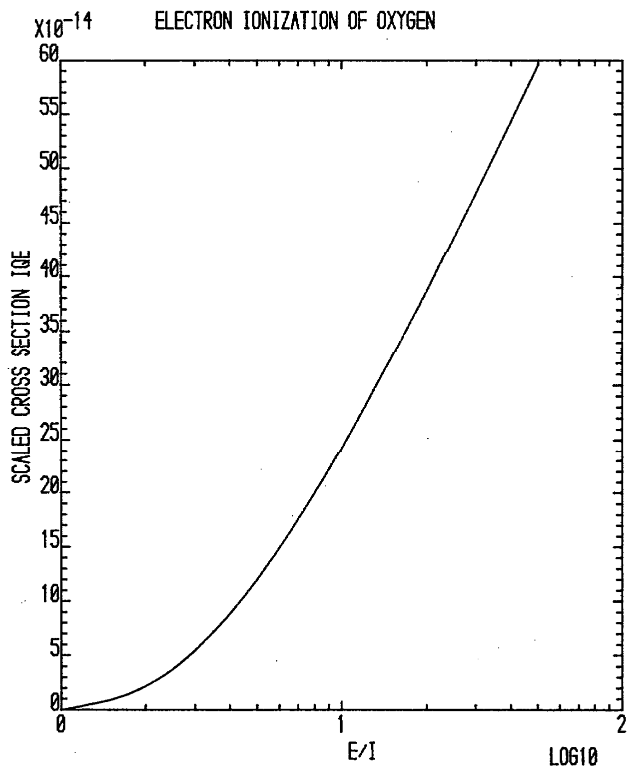

FIGURE 55. Scaled cross section for oxygen.

3. Approximate Analytic Formulas

For each species investigated, the recommended cross section has been fitted by the following equation

$$\sigma(E)=\frac{1}{IE}\left\{A\ln(E/I)+\sum_{i=1}^{N}B_i\left(1-\frac{I}{E}\right)^i\right\}, \quad (1)$$

where E is the incident electron energy, I is the ionization potential, and the coefficients B_i are determined by a least squares fitting procedure. These coefficients are given in Table 5. This formula ensures the correct behavior of the cross section at both high and low impact energies. In many cases, two or three coefficients are sufficient. If ionization by excitation autoionization is important (N V and O VI), it is not possible to fit the cross section using Eq. (1). For these ions, we use two fits of the form of Eq. (1), one fit from the ionization threshold to the autoionization threshold and a second fit for energies above the autoionization threshold. The parameter A is a Bethe coefficient and determines the high energy behavior of the cross section. It may be calculated by fitting the equation

$$\sigma(E)=\frac{1}{IE}\{A\ln(E)+B\}, \quad (2)$$

to the high energy form of the Born approximation, or from the equation

$$A=\frac{I}{\pi\alpha}\int_I^\infty\frac{\sigma_{\rm ph}}{\epsilon}\,d\epsilon, \quad (3)$$

where $\sigma_{\rm ph}$ is the photoionization cross section and α is the fine structure constant. We have evaluated the A coefficient for a number of the atoms and ions under investigation and this value has been incorporated in Eq. (1) to enable high energy extrapolation.

TABLE 5. The parameters I, A, and B_i of Eq. (1) of the text for the recommended cross sections. The ionization potential I is given in eV and the parameters A and B are in units of 10^{-13} eV^2·cm^2. The reliability has a confidence level of 67%.

Species	I(eV)	A	B_1	B_2	B_3	B_4	B_5	Reliability (%)
H I	13.60	0.1845	−0.0186	0.1231	−0.1901	0.9527		±7
He I	24.60	0.5720	−0.3440	−0.5230	3.4450	−6.8210	5.5780	±5
He II	54.42	0.1845	0.0887	0.1315	0.3877	−1.0910	1.3541	±10
Li I	5.39	0.0854	−0.0040	0.7573	−0.1779			±10
Li II	75.64	0.7220	−0.1492	−1.3007	1.9443			±12
Li III	122.45	0.4000						±10
Be I	9.32	0.9239	−0.7697	0.3619				±20
Be II	18.21	0.7542	−0.0189	−2.9618	7.5182	−8.5431	3.1108	±20
Be III	153.89	0.7960	−0.5004	0.8836				±20
Be IV	217.71	0.4000						±10
B I	8.30	1.1063	−1.0694	−0.0879				±20
B II	25.15	0.9070	−0.4770	0.1970				±20
B III	37.93	0.7542	−0.0189	−2.9618	7.5182	−8.5431	3.1108	±20
B IV	259.37	0.7960	−0.5004	0.8836				±20
B V	340.22	0.4000						±10
C I	11.26	2.1143	−1.9647	−0.6084				±5
C II	24.38	1.0824	−0.1611	−0.8563	0.9062			±10
C III	47.89	0.7150	−0.0410	0.1754				±10
[a]C III	41.38	0.6910	−0.5081	0.6993	0.0142	−0.4325		±10
C IV	64.49	0.4667	−0.1298	0.2577	−0.9561	0.6441		±20
C V	392.08	0.7960	−0.5004	0.8836				±20
C VI	489.98	0.4000						±10
N I	14.53	2.2648	−1.7100	−2.3220	1.7324			±5
N II	29.60	1.0755	−0.8287	0.8724	−0.1618	1.5331		±10
N III	47.45	0.5004	0.2234	2.2074	−4.1555	3.7686		±10
N IV	77.47	0.8125	−0.0066	−0.0459				±10
[a]N IV	69.13	0.3270	0.3570	−0.0420	−0.8740	2.1670		±10
N V	97.89	0.2182	0.2376	−0.2201	−0.4463	2.5227	−1.9021	±10 for $E\leqslant 4.2I$
	97.89	0.8368	−0.2135	−2.5377	7.4882	−11.0056	5.5226	±10 for $E>4.2I$
N VI	552.06	0.7960	−0.5004	0.8836				+20
N VII	667.03	0.4000						±10
O I	13.62	2.4554	−2.1811	−1.5701				±5
O II	35.12	1.5257	−0.5935	−0.3994	−0.5833	3.2355		±10
O III	54.93	1.0657	0.4420	0.4751	−2.9613	4.4700		±7
O IV	77.41	1.0446	−0.6519	1.2988				±10
[a]O IV	68.60	0.5605	−0.6091	4.6523	−8.9404	6.7354		±5
O V	113.90	0.7268	0.0911	0.0220				±10
[a]O V	103.68	0.3287	0.6097	−2.1048	5.9130	−3.0004		±10
O VI	138.12	0.3362	0.0803	0.1432	−0.7309	1.3363	−0.7846	±20 for $E<4.0I$
	138.12	0.6362	−0.3127	1.3187	−5.2457	6.3866	−2.4415	±20 for $E\geqslant 4.0I$
O VII	739.32	0.7960	−0.5004	0.8836				±20
O VIII	871.39	0.4000						±10

[a] Includes contributions from ions in metastable states (see text).

The form of Eq. (1) was also dictated by the classical scaling law by which the electron ionization cross section $\sigma(E)$ for an ion of ionization potential I at energy E is given by

$$I^2\sigma(E) = \sigma_c(X), \tag{4}$$

where $X = E/I$ and where $\sigma_c(X)$ is a scaled cross section which is the same for all ions in a given isoelectronic sequence.

In this work, we found that for hydrogen- and helium-like ions the experimental and theoretical data closely satisfied the scaling law except for low values of the nuclear charge. However, for more complex systems, the available data does not satisfy the classical scaling law and in this work classical scaling is used only if no other data is available.

The rate coefficients $\langle\sigma{\cdot}v\rangle$ (cross sections at a given energy multiplied by electron velocity v at the same energy, evaluated over a Maxwellian velocity distribution) are given by

$$\langle\sigma{\cdot}v\rangle = \left(\frac{8kT}{\pi m}\right)^{1/2}\int_{I/kT}^{\infty}\sigma(E)(E/kT)e^{-E/kT}\,d(E/kT), \tag{5}$$

where m is the electron mass.

For the temperature range $I/10 \leqslant kT \leqslant 10I$, we fit the rate coefficient with the following functional form

$$\langle\sigma{\cdot}v\rangle = e^{-I/kT}(kT/I)^{1/2}\sum_{n=0}^{5}a_n\{\log_{10}(kT/I)\}^n, \tag{6}$$

and for $kT > 10I$ we use the formula

$$\langle\sigma{\cdot}v\rangle = (kT/I)^{-1/2}\left\{\gamma\ln(kT/I) + \sum_{n=0}^{2}\beta_n\left(\frac{I}{kT}\right)^n\right\} \tag{7}$$

The coefficients $a_0, ..., a_5$ are given in Table 6 and the parameters γ, β_0, β_1, and β_2 are given in Table 7. For T in K, I in eV, and $k = 0.8617 \times 10^{-4}$ eV/K, these coefficients give the rate

TABLE 6. The coefficients $a_0, ..., a_5$ in $cm^3\,s^{-1}$ of Eq. (6) of the text for the recommended rate coefficients.

Species	a_0	a_1	a_2	a_3	a_4	a_5
H I	2.3742E − 08	− 3.6866E − 09	− 1.0366E − 08	− 3.8010E − 09	3.4159E − 09	1.6834E − 09
He I	1.4999E − 08	5.6656E − 10	− 6.0821E − 09	− 3.5894E − 09	1.5529E − 09	1.3207E − 09
He II	3.4356E − 09	− 1.6865E − 09	− 6.9236E − 10	9.7863E − 11	1.5591E − 10	6.2236E − 11
Li I	9.9655E − 08	− 5.5941E − 08	− 5.5228E − 08	4.0589E − 08	1.4800E − 08	− 1.3120E − 08
Li II	3.4023E − 09	− 7.6588E − 10	− 8.6078E − 10	− 8.9748E − 10	4.1661E − 10	3.3188E − 10
Li III	1.1786E − 09	− 8.7637E − 10	− 9.3373E − 11	2.1173E − 10	1.9017E − 11	− 4.0679E − 11
Be I	7.4206E − 08	− 1.5520E − 08	− 3.9403E − 08	7.2155E − 09	1.1098E − 08	− 2.5501E − 09
Be II	2.0072E − 08	− 1.2724E − 08	− 2.6991E − 09	3.7890E − 09	5.1141E − 10	− 9.7697E − 10
Be III	1.6039E − 09	− 6.4336E − 10	− 7.7804E − 10	3.3527E − 10	2.1889E − 10	− 1.0600E − 10
Be IV	4.9587E − 10	− 3.6870E − 10	− 3.9284E − 11	8.8928E − 11	8.0007E − 12	− 1.7114E − 11
B I	5.8365E − 08	1.0047E − 08	− 3.6230E − 08	− 7.3448E − 09	1.0220E − 08	1.6951E − 09
B II	2.0590E − 08	− 9.8899E − 09	− 6.0949E − 09	2.7762E − 09	1.6499E − 09	− 6.7692E − 10
B III	6.6770E − 09	− 4.2326E − 09	− 8.9787E − 10	1.2604E − 09	1.7012E − 10	− 3.2499E − 10
B IV	7.3539E − 10	− 2.9498E − 10	− 3.5672E − 10	1.5372E − 10	1.0036E − 10	− 4.8602E − 11
B V	2.5458E − 10	− 1.8930E − 10	− 2.0169E − 11	4.5657E − 11	4.1076E − 12	− 8.7867E − 12
C I	5.9848E − 08	1.1903E − 08	− 3.0140E − 08	− 1.3693E − 08	8.3748E − 09	4.0150E − 09
C II	2.8395E − 08	− 1.6698E − 08	− 2.3557E − 09	3.2161E − 10	9.6016E − 10	5.2713E − 10
C III	9.0555E − 09	− 6.3206E − 09	− 1.3256E − 09	1.7441E − 09	3.2680E − 10	− 3.8303E − 10
[a]C III	8.0945E − 09	− 3.6568E − 09	− 3.9572E − 09	2.3802E − 09	1.0515E − 09	− 7.9301E − 10
C IV	2.7464E − 09	− 2.0070E − 09	− 2.3595E − 11	4.2011E − 10	− 8.1600E − 11	− 3.9729E − 11
C V	3.9495E − 10	− 1.5842E − 10	− 1.9158E − 10	8.2555E − 11	5.3899E − 11	− 2.6102E − 11
C VI	1.4715E − 10	− 1.0941E − 10	− 1.1657E − 11	2.6389E − 11	2.3742E − 12	− 5.0786E − 12
N I	4.6209E − 08	9.2264E − 09	− 1.2092E − 08	− 2.4852E − 08	5.1361E − 09	8.3068E − 09
N II	2.4369E − 08	− 2.2155E − 09	− 1.4805E − 08	− 4.4218E − 10	4.5211E − 09	1.7874E − 10
N III	1.2964E − 08	− 8.3408E − 09	− 2.3684E − 09	2.2485E − 09	2.6234E − 10	− 2.6333E − 10
N IV	4.6322E − 09	− 3.4645E − 09	− 3.1014E − 10	8.0576E − 10	5.7791E − 11	− 1.4907E − 10
[a]N IV	4.5344E − 09	− 2.3692E − 09	− 3.5513E − 10	− 4.9395E − 10	1.2611E − 10	3.3892E − 10
N V	1.5862E − 09	− 9.8633E − 10	7.5130E − 11	3.1005E − 11	− 8.1970E − 12	2.6759E − 11
N VI	2.3635E − 10	− 9.4805E − 11	− 1.1465E − 10	4.9404E − 11	3.2255E − 11	− 1.5620E − 11
N VII	9.2653E − 11	− 6.8892E − 11	− 7.3402E − 12	1.6616E − 11	1.4949E − 12	− 3.1978E − 12
O I	3.3559E − 08	1.3449E − 08	− 6.7112E − 09	− 1.9976E − 08	1.6214E − 09	6.5852E − 09
O II	2.4476E − 08	− 5.3141E − 09	− 7.3316E − 09	− 4.4515E − 09	2.4257E − 09	1.9791E − 09
O III	1.4741E − 08	− 8.7905E − 09	− 8.6099E − 10	− 2.4143E − 10	1.2598E − 10	6.4901E − 10
O IV	6.2130E − 09	− 2.5047E − 09	− 3.0813E − 09	1.3559E − 09	8.6816E − 10	− 4.3189E − 10
[a]O IV	5.7525E − 09	− 2.3510E − 09	− 2.3387E − 09	1.4063E − 09	1.2451E − 10	− 1.9423E − 10
O V	2.6145E − 09	− 2.0276E − 09	− 1.6569E − 10	5.0245E − 10	3.0067E − 11	− 9.8231E − 11
[a]O V	3.1263E − 09	− 1.6820E − 09	− 9.4803E − 10	8.4311E − 11	5.0188E − 10	− 4.1921E − 11
O VI	1.0099E − 09	− 6.5165E − 10	2.8863E − 12	3.0336E − 11	− 1.4065E − 11	4.5106E − 11
O VII	1.5258E − 10	− 6.1203E − 11	− 7.4014E − 11	3.1894E − 11	2.0823E − 11	− 1.0084E − 11
O VIII	6.2090E − 11	− 4.6167E − 11	− 4.9189E − 12	1.1135E − 11	1.0018E − 12	− 2.1430E − 12

[a] Includes contributions from ions in metastable states (see text).

TABLE 7. The parameters γ, β_0, β_1, and β_2 in $cm^3 s^{-1}$ of Eq. (7) of the text for the recommended rate coefficients.

Species	γ	β_0	β_1	β_2
H I	2.4617E−08	9.5986E−08	−9.2463E−07	3.9973E−06
He I	3.1373E−08	4.7893E−08	−7.7359E−07	3.7366E−06
He II	3.0772E−09	1.1902E−08	−1.1514E−07	5.0489E−07
Li I	4.5456E−08	2.7800E−07	−1.5830E−06	5.4650E−06
Li II	7.3504E−09	5.3459E−10	−5.6387E−08	2.9577E−07
Li III	1.9767E−09	−1.0926E−09	8.8700E−10	6.0764E−09
Be I	2.1743E−07	−2.1649E−07	2.8120E−07	5.3031E−07
Be II	6.4950E−08	−1.1093E−07	4.8139E−07	−1.4844E−06
Be III	2.7873E−09	−2.4333E−10	−9.7973E−09	5.2094E−08
Be IV	8.3163E−10	−4.5966E−10	3.7317E−10	2.5564E−09
B I	3.0952E−07	−4.9240E−07	1.3750E−06	−2.5387E−06
B II	4.7980E−08	−4.1361E−08	5.5259E−08	9.9841E−08
B III	2.1606E−08	−3.6902E−08	1.6014E−07	−4.9379E−07
B IV	1.2780E−09	−1.1156E−10	−1.4902E−09	2.3885E−08
B V	4.2697E−10	−2.3600E−10	1.9159E−10	1.3125E−09
C I	3.7442E−07	−6.5826E−07	2.0521E−06	−4.4694E−06
C II	6.0150E−08	−4.0217E−08	−2.7908E−08	5.5499E−07
C III	1.4501E−08	−5.3596E−09	−1.0473E−08	1.0629E−07
[a]C III	1.7372E−08	−1.5019E−08	4.1275E−08	−8.8581E−08
C IV	6.0330E−09	−5.7710E−09	9.9302E−09	7.4462E−09
C V	6.8634E−10	−5.9916E−11	−2.4124E−09	1.2828E−08
C VI	2.4679E−10	−1.3640E−10	1.1074E−10	7.5862E−10
N I	2.7367E−07	−4.2976E−07	9.8352E−07	−9.5745E−07
N II	4.4690E−08	3.0430E−08	−5.2696E−07	2.4863E−06
N III	1.0243E−08	3.4218E−08	−2.9155E−07	1.2324E−06
N IV	7.9743E−09	−4.9184E−09	6.3763E−09	1.4917E−08
[a]N IV	3.8072E−09	1.5619E−08	−1.4346E−07	6.1960E−07
~~N V~~	~~5.7812E−09~~	~~−8.5163E−09~~	~~1.8527E−08~~	~~−7.8181E−09~~
N VI	4.1073E−10	−3.5856E−11	−1.4437E−09	7.6765E−09
N VII	1.5539E−10	−8.5888E−11	6.9728E−11	4.7767E−10
O I	3.2721E−07	−6.7484E−07	2.3938E−06	−6.0438E−06
O II	4.9003E−08	2.1747E−08	−5.4612E−07	2.7213E−06
O III	1.7523E−08	2.8129E−08	−3.1692E−07	1.4381E−06
O IV	1.0270E−08	4.8134E−10	−4.3936E−08	2.1924E−07
[a]O IV	6.6074E−09	1.6481E−08	−1.7855E−07	8.0359E−07
O V	4.0023E−09	−1.5957E−09	−7.2485E−10	1.9724E−08
[a]O V	2.0855E−09	7.7559E−09	−4.8816E−08	1.7611E−07
O VI	2.6228E−09	−2.6662E−09	2.8968E−09	1.7246E−08
O VII	2.6516E−10	−2.3148E−11	−9.3201E−10	4.9557E−09
O VIII	1.0413E−10	−5.7557E−11	4.6727E−11	3.2010E−10

[a] Includes contributions from ions in metastable states (see text).

in $cm^3 s^{-1}$. It should be noted that many of the figures and tables in this paper refer to an "electron temperature" which is actually the equivalent electron energy (kT) expressed in eV.

Alternatively, the rates may be accurately computed from the cross sections using the following equation:

$$\langle \sigma \cdot v \rangle = 6.692 \times 10^7 \, e^{-I/kT} \sqrt{kT} \sum_{i=1}^{n} w_i x_i \sigma(y_i), \quad (8)$$

where $y_i = kTx_i + I$ and w_i and x_i are, respectively, the weights and abscissas of the Gauss–Laguerre quadrature formula of degree n. We find that $n = 8$ gives the rate to within 1% accuracy.

4. Review of Data Sources

In this section, we describe the experimental and theoretical cross section data available for each species and outline the decisions made in determining a recommended curve.

4.1. The Hydrogen Sequence

H I

Despite its apparent simplicity, the electron impact ionization of hydrogen atoms presents a difficult problem for both theorists and experimentalists. There have been no recent measurements of this cross section but some recent calculations by Klar[27] confirm that at low impact energies the ionization cross section rises as $(E-I)^{1.127}$ (Wannier[28]). Experimental measurements by McGowan and Clarke[29] show an $(E-I)^{1.13}$ dependence at 0.4 eV above threshold and a linear relationship for 1 eV $<(E-I)<$ 3 eV. However, for most practical applications the form of the cross sections given in Eq. (1) should be adequate.

In fitting his empirical formula to the experimental data, Lotz[8] chose to follow the unpublished data of Boksenberg,[30] but we believe the measurements of Fite and Brackmann[31] are more accurate and our recommended curve follows their data. At high energies, it merges smoothly into the curve based on the Born approximation (Mott and Massey[32]). General support for the validity of the Born approximation at impact energies above about 300 eV is provided by the close accord between measured ionization cross sections for electron and equivelocity protons in a number of gas targets (Hooper *et al.*[33]).

He II

The measurements of Peart *et al.*[34] and Dolder *et al.*[35] are in good agreement except near the peak in the cross sections where the older measurements are about 10% higher. Our recommended curve favors the measurements of Peart *et al.* which agree well with the Coulomb–Born and Bethe approximations at high energies (Mott and Massey[32]). The calculations of Younger[15] are in good agreement with experiment.

Li III–O VIII

The only available data for the six ions between Li III and O VIII are the calculations of Younger[15] for C VI. We find that these data are accurately simulated by formula (1) with $A = 4.0\times 10^{-14}$ eV^2 cm^2 and $B_i = 0$ for all i. Although this A coefficient differs significantly from the value, $A = 1.8\times 10^{-14}$, of the Bethe approximation it provides a good fit to Younger's calculations, and should be a good approximation to the cross section for the range of energies covered in the tables.

Noting that Younger's calculations are, in general, in good agreement with experiment for He II and for highly charged ions in other isoelectronic sequences, we have scaled the C VI curve to give recommended curves for the other members of the sequence with charge state ≥ 3. This scaled curve agrees well with Younger's calculations for Ne X (Younger[15]).

4.2. The Helium Sequence

He I

The recommended cross section for Helium is that due to Montague *et al.*[36,37] which is a smooth curve fit to a large number of experimental measurements. At 750 eV this curve merges smoothly with the Born values (Bell and Kingston[38]). The recommended curve is in good agreement with the earlier measurements of Rapp and Englander-Golden[39] and Brook *et al.*[40]

Li II

The recommended curve is based on the data of Peart and Dolder[41] up to 3 keV and the data of Peart *et al.*[34] from 4 to 25 keV. These high energy data of Peart *et al.* are in good agreement with the Coulomb–Born calculations of Moores and Nussbaumer.[42]

Be III–O VII

Crandall *et al.*[43] have measured the cross sections for B IV, C V, and N VI, but crossed beam experiments with such highly charged ions are very difficult and their data are sparse with large associated uncertainties. For the case of B IV however, we have been able to generate a reasonable fit to the experimental data, which also agrees well with the DWBE calculations of Younger.[16] Cross sections for the other ions have then been obtained by scaling the B IV curve according to classical scaling laws.

4.3. The Lithium Sequence

Li I

Our recommended curve for Li I follows the measurements of Zapesochyni and Aleksakhin[44] out to about 30 eV, and the data of Jalin *et al.*[45] at high energies which are in good accord with the theoretical calculations of McGuire.[46]

Be II

Our recommended curve follows the experimental data of Falk and Dunn.[69]

B III

The recommended curve has been derived from that of Be II using the classical scaling law, there being no experimental or theoretical data available.

C IV

The data of Crandall *et al.*[43] include a significant contribution from autoionization at energies above the inner shell excitation threshold. However, there is a large difference between the experimental data and the theoretical calculations of Jakubowitz[13] and Sampson and Golden.[47] Comparison of the scaled cross sections also shows that the scaled experimental curve for C IV lies well below those of the other members in the sequence. Our recommended curve therefore follows the theoretical calculations for this ion. There is however, good agreement with experiment at high energies.

N V

Our recommended curve follows the data of Crandall *et al.*[43] In this case (unlike C IV), there is good agreement with theory.

O VI

The recommended curve is based mainly on the data of Crandall *et al.*[43] Account is also taken of the theoretical calculations of Jakubowitz and Moores,[13] Younger,[15] and

Sampson and Golden[47], all of which are in good accord with each other. In particular, the magnitude of the second peak (due to autoionization) is surprisingly large in the experimental data and cannot be accounted for by either the measured or calculated inner shell excitation cross sections.

4.4. The Beryllium Sequence

Be I, B II

There are no reliable experimental or theoretical data for ionization of the ground state of Be I or B II and our recommended curves are empirical estimates based on an analysis of the scaled cross sections.

C III

The experimental measurements by Woodruff *et al.*[48] and by Crandall *et al.*[49] include contributions from the ionization of both $(1s^2 2s^2)^1S$ ground state and $(1s^2 2s2p)^3P$ metastable ions; Crandall *et al.* have estimated roughly a 40% contribution from metastables but no estimate of the contribution from metastables is given by Woodruff *et al.* For ground state ionization, we have therefore followed the Coulomb–Born calculations of Jakubowitz and Moores,[13] adding to these a small contribution from inner shell ionization. The recent distorted wave calculations by Younger[17] for the ground state are close to these calculations, adding some confidence to our recommendation.

Also in the tables, we present a fit to the experimental data of Crandall *et al.*[49] and to the rate derived from these data.

N IV

The experimental measurements of Crandall *et al.*[49] include estimated contributions of 50% from ions in metastable states. Because of this uncertainty, as for C III, our recommended cross section for ionization of the ground state was obtained by fitting to the Coulomb–Born calculation of Jakubowitz and Moores[13] which are close to the distorted wave calculations of Younger. However, we also present fits based on the data of Crandall *et al.*

O V

As for C III and N IV, the experimental values of Crandall *et al.*[43] for O V include contributions from ions in both the ground state and metastable state, estimated to be about 50% metastable. Because of the uncertainty, we have again used the theoretical calculations of Jakubowitz and Moores for the ground state which are close to Younger's ground state calculations. The experimental values lie well above these values indicating that the ionization cross section for ions in the metastable state is considerably larger than for ions in the ground state. This is supported by Younger's calculations. There is also evidence in Crandall's data of a contribution from autoionization for energies greater than about 600 eV. As for C III and N IV the tables also include fits based on Crandall's data.

4.5. The Boron Sequence

B I

In the absence of any reliable experimental data for B I we adopt an empirical estimate based on an analysis of the scaled cross sections. The recommended curve is in reasonable accord with the Born calculations of McGuire.[46]

C II

The recommended curve follows the crossed-beam measurements of Aitken *et al.*[50] and, at the higher energies, the Coulomb–Born calculations of Moores.[11] The recommended curve lies within the error bars of the relative, trapped-ion measurements of Hamdan *et al.*[51] which are about 10% above the crossed-beam results.

N III

For N III, as for C II, our recommended curve follows the experimental data of Aitken *et al.*[50] up to about 800 eV and the Coulomb–Born calculations of Moores[11] at higher energies.

O IV

In their measurements, Crandall *et al.*[43] estimate a 16% contribution from ionization of ions in the $(1s^2 2s2p)^4P$ metastable state. Our recommended curve is an estimate of the ionization cross section of ions in the ground state only.

However, we also present a fit to Crandall's data and provide a table of the rate coefficient based on these data.

4.6. The Carbon Sequence

C I

For C I, the recommended curve follows the experimental data of Brook *et al.*[40] and is extrapolated beyond 1 keV using Eq. (2). At high energies, it is in good agreement with the Born calculations of Omidvar *et al.*[52] The experimental data of Wang and Crawford[53] lie more than a factor of two above those of Brook *et al.* (above even the Born results), and have not been included.

Our extrapolation procedure in this case yields a value for the Bethe A coefficient of Eq. (1) of 2.114×10^{-13} $eV^2\ cm^2$. It has been possible to check this value by evaluating the A coefficient from the formula given by Bethe [cf. Eqs. (2) and (3)]. Using the calculations of Taylor and Burke[54] for the photoionization cross section, an approximate evaluation of the integral in Eq. (3) yields a value for A of 2.1×10^{-13} $eV^2\ cm^2$.

This result suggests that our extrapolation procedure is valid in this case.

N II

For N II, the experimental data of Harrison *et al.*[55] is taken and extrapolated beyond 500 eV using Eq. (1). At high energies, the recommended curve is in good agreement with the calculations of Moores.[11]

O III

There have been three different measurements of the ionization cross section of O III—two crossed-beam experiments, one by Crandall *et al.*[49] and the second by Aitken and Harrison,[56] and relative, trapped-ion measurements by Hamden *et al.*[51] Of the three, the data of Crandall *et al.* is the most extensive and subject to the smallest estimated uncertainties. Our recommended curve therefore follows Crandall's data but still lies within the error bars of the other two experiments. Once again, the recommended curve is in good agreement with Moore's Coulomb–Born calculations at high energies.

4.7. The Nitrogen Sequence

N I

For N I, the two sets of experimental data, due to Smith *et al.*[57] and Brook *et al.*,[40] differ only by about 7% at the peak but by considerably more at low energies. However, the data of Brook *et al.* exhibit less scatter and are subject to very small uncertainties. Our recommended curve therefore follows the data of Brook *et al.*, which are extrapolated beyond 1 keV using Eq. (1).

O II

There have been three experimental measurements of the ionization cross section of O II. The two crossed-beam experiments, due to Aitken and Harrison[56] and Muller *et al.*,[58] differ by about 20%. The relative, trapped-ion measurements of Hamdan *et al.*[51] were normalized to the data of Aitken and Harrison, but lie about 10% higher near the peak. The most accurate results are judged to be those of Aitken and Harrison, performed on a well characterized cross-beams apparatus and with sufficient care to establish the presence of $^2P^0$ and $^2D^0$ metastable ions in the O^+ beam. At high energies, our recommended cross section is in good agreement with the Coulomb–Born results of Moores.[11]

4.8. The Oxygen Sequence

O I

The recommended curve for atomic oxygen follows the data of Brook *et al.*[40] The older measurements of Fite and Brackmann[59] lie above the Born calculations near the peak and are therefore probably too high.

5. Belfast Database

The ionization data described in this report is part of the Belfast Database on Atomic and Molecular Physics. The database will be kept up-to-date on the computers at Queen's University, Belfast and at the Daresbury Laboratory. Requests for data or for on-line access to the database may be made in writing to Dr. J. G. Hughes, Department of Computer Science, Queen's University, Belfast.

6. Acknowledgments

This work was supported by the United Kingdom Atomic Energy Authority, Culham Laboratory under Contract No. AGMT/CUL/231.

Our thanks are due to Mr. M. F. A. Harrison for his expert advice and critical comment on the work described in this report. We would also like to thank Dr. D. H. Crandall, Dr. H. Jakubowitz, and Dr. S. M. Younger for communicating their results prior to publication.

In addition, we wish to gratefully acknowledge the receipt of some very useful data from Dr. Y. Itikawa of the Institute of Plasma Physics, Nagoya University and Dr. E. C. Beaty of the Information Center, Joint Institute for Laboratory Astrophysics, University of Colorado.

7. References

[1]C. Jordan, Mon. Not. R. Ast. Soc. **142**, 501 (1969).
[2]C. Jordan, Mon. Not. R. Ast. Soc. **148**, 17 (1970).
[3]H. P. Summers, Mon. Not. R. Ast. Soc. **158**, 255 (1972).
[4]H. P. Summers, Mon. Not. R. Ast. Soc. **169**, 663 (1974).
[5]J. Jacobs, J. Davis, P. C. Kepple, and M. Blaha, Astrophys. J. **211**, 605 (1977).
[6]M. J. Seaton, Planet, Sp. Sci. **12**, 55 (1964).
[7]A. Burgess, Proc. Symp. Atomic Collision Processes in Plasmas, Culham, UKAEA (1964).
[8]W. Lotz, Astrophys. J. Suppl. **14**, 207 (1967).
[9]W. Lotz, Z. Phys. **216**, 241 (1968).
[10]A. Burgess, H. P. Summers, D. M. Cochrane, and R. W. P. McWhirter, Mon. Not. R. Ast. Soc. **179**, 275 (1977).
[11]D. L. Moores, J. Phys. B **5**, 286 (1972).
[12]D. L. Moores, J. Phys. B **11**, L403 (1978).
[13]H. Jakubowitz and D. L. Moores, J. Phys. B **14**, 3733–3760 (1981).
[14]L. B. Golden and D. H. Sampson, J. Phys. B **10**, 2229 (1977).
[15]S. M. Younger, Phys. Rev. A **22**, 111 (1980).
[16]S. M. Younger, Phys. Rev. A **22**, 1425 (1980).
[17]S. M. Younger, Phys. Rev. A **24**, 1272 and 1278 (1981).
[18]K. T. Dolder and B. Peart, Rep. Prog. Phys. **39**, 693 (1976).
[19]D. H. Crandall, Phys. Scripta **23**, 153 (1981).
[20]H. J. Kunze, Phys. Rev. A **3**, 937 (1971).
[21]E. Kallne and L. A. Jones, J. Phys. B **10**, 3637 (1977).
[22]G. H. Dunn, IEEE Trans. Nucl. Sci. **23**, 926 (1976).
[23]F. A. Baker and J. B. Hasted, Phil Trans. Roy. Soc. A **261**, 33 (1966).
[24]E. D. Donets, IEEE Trans. Nucl. Sci. **23**, 897 (1976).
[25]F. J. Smith, S. J. Gilliland, and J. G. Hughes, "Bibliography on Electron Impact Ionization of Light Atoms and Ions." Report, Department of Computer Science, Queen's University, Belfast (1981).
[26]K. L. Bell, H. B. Gilbody, J. G. Hughes, A. E. Kingston, and F. J. Smith, Culham Report, CLM-R216 (H.M.S.O) (1982).
[27]H. Klar, J. Phys. B. **14**, 3255 (1981).
[28]G. H. Wannier, Phys. Rev. **90**, 817 (1953).
[29]J. W. McGowan and E. M. Clarke, Phys. Rev. **167**, 43 (1968).
[30]A. Boksenberg, Ph.D. thesis (University College London, 1961).
[31]W. L. Fite and R. T. Brackmann, Phys. Rev. **112**, 1141 (1958).
[32]N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions*, 3rd ed. (Clarendon, Oxford, 1965).
[33]J. W. Hooper, D. S. Harner, D. W. Martin, and E. W. McDaniel, Phys. Rev. **125**, 2000 (1962).
[34]B. Peart, D. S. Walton, and K. T. Dolder, J. Phys. B **2**, 1347 (1969).
[35]K. T. Dolder, M. F. A. Harrison, and P. C. Thonemann, Proc. Roy. Soc. A **264**, 367 (1961).
[36]M. F. A. Harrison (private communication, 1981).
[37]R. Montague, M. F. A. Harrison, and A. C. H. Smith (to be published).
[38]K. L. Bell and A. E. Kingston, J. Phys. B **2**, 1125 (1969).
[39]D. Rapp and P. Englander-Golden, J. Chem. Phys. **43**, 1464 (1965).

[40]E. Brook, M. F. A. Harrison, and A. C. H. Smith, J. Phys. B **11**, 3115 (1978).
[41]B. Peart and K. T. Dolder, J. Phys. B **1**, 872 (1968).
[42]D. L. Moores and H. Nussbaumer, J. Phys. B **3**, 161 (1970).
[43]D. H. Crandall, R. A. Phaneuf, and D. A. Gregory, Report No. ORNL/TM-7020, Oak Ridge National Laboratory, Tennessee, USA. (1979).
[44]I. P. Zapesochyni and I. S. Aleksakhin, Sov. Phys. J.E.T.P. **28**, 41 (1969).
[45]R. Jalin, R. Hagenmann, and R. Botter, J. Chem. Phys. **59**, 952 (1973).
[46]E. J. McGuire, Phys. Rev. A **3**, 267 (1971).
[47]D. H. Sampson and L. B. Golden, J. Phys. B **12**, L785 (1979).
[48]P. R. Woodruff, M. C. Hublet, M. F. A. Harrison, and E. Brook, J. Phys. B **11**, L679 (1978).
[49]D. H. Crandall, R. A. Phaneuf, R. A. Falk, D. S. Belic, and G. H. Dunn (private communication, 1980).
[50]K. L. Aitken, M. F. A. Harrison, and R. D. Rundel, J. Phys. B **4**, 1189 (1971).
[51]M. Hamdan, K. Burkinshaw, and J. B. Hasted, J. Phys. B **11**, 331 (1978).
[52]K. Omidvar, H. L. Kyle, and E. C. Sullivan, Phys. Rev. A **5**, 1174 (1972).
[53]K. I. Wang and C. K. Crawford, Particle Optics Lab., MIT, Technical Report No. 6, AFML-TR-70-289 (1971).
[54]K. T. Taylor and P. G. Burke, J. Phys. B **9**, L353 (1976).
[55]M. F. A. Harrison, J. T. Dolder, and P. C. Thonemann, Proc. Phys. Soc. **82**, 368 (1963).
[56]K. L. Aitken and M. F. A. Harrison, J. Phys. B **4**, 1176 (1971).
[57]A. C. H. Smith, E. Caplinger, R. H. Neynaber, E. W. Rothe, and S. M. Trujillo, Phys. Rev. **127**, 1647 (1962).
[58]A. Muller, E. Salzborn, R. Frodl, R. Becker, H. Klein, and H. Winter, J. Phys. B **13**, 1877 (1980).
[59]W. L. Fite and R. T. Brackmann, Phys. Rev. **113**, 815 (1959).
[60]W. L. Rowan and J. R. Roberts, Phys. Rev. A **19**, 90 (1979).
[61]E. W. Rothe, L. L. Marino, R. H. Neynaber, and S. M. Trujillo, Phys. Rev. **125**, 582 (1962).
[62]M. R. H. Rudge and S. B. Schwartz, Proc. Phys. Soc. **86**, 773 (1965).
[63]W. C. Lineberger, J. W. Hooper, and E. W. McDaniel, Phys. Rev. **141**, 151 (1966).
[64]S. Chandra and U. Narian, J. Phys. B **8**, 770 (1975).
[65]R. H. McFarland and J. D. Kinney, Phys. Rev. A **137**, 1058 (1965).
[66]M. R. C. McDowell, V. P. Mysescough, and G. Peach, Proc. Phys. Soc. **85**, 703 (1965).
[67]D. H. Crandall, R. A. Phaneuf, and P. O. Taylor, Phys. Rev. A **18**, 1911 (1978).
[68]E. D. Donets and V. P. Ovsynannikov, J.I.N.R. Report No. P7-10780 (1977).
[69]R. A. Falk and G. H. Dunn, Phys. Rev. A **27**, 754 (1983).