

Recommended Atomic Electron Binding Energies, 1s to $6p_{3/2}$, for the Heavy Elements, $Z = 84$ to 103

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Recent experimental measurements of atomic electron binding energies, 1s to $6p_{3/2}$, for certain of the transuranic elements are incorporated into interpolation and extrapolation procedures yielding new recommendations for the electron binding energies from $Z = 84$ to 103.

Key words: Atomic electron binding energies; binding energies; core electron binding energies; heavy elements; transuranic elements.

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1. Introduction

Because of their physical characteristics, there are few or no direct experimental data concerning the atomic electron binding energies for several of the elements with atomic number (Z) greater than 84. Such binding energy values have been estimated [1-5]¹ by interpolation in Z between experimental values or by extrapolation in the case of transuranic elements. In recent years new data for several transuranic elements have become available from internal conversion electron, photoelectron and x-ray studies. The present table of recommended values for $Z = 84-103$ makes use of all experimental data available up to September 1977 for $Z \geq 73$. Significant revisions from values recommended in [1-5] do emerge.

Experimental data are now available for both outer and inner shells for some heavy elements with several eV accuracy.

The large differences, up to several keV, between inner shell binding energies for neighboring heavy elements makes direct interpolation to such accuracy quite difficult. The technique of subtracting most of the change with some regularly varying function of Z allows one to display the data for a single subshell over a range in Z , on a scale sufficiently expanded to exhibit the errors, to assess the errors of interpolation or extrapolation, and to obtain values for unmeasured or poorly measured cases.

One such technique which has been used before in limited regions of the periodic table is the modified Moseley plot [6] in which a parabolic ($aZ^2 + bZ + c$) function is subtracted from the experimental values and the differences exhibited in order to visualize any small (order of 1 eV) deviation from smooth behavior of the experimental values as a function of Z . This method has been shown to work well [6] over limited ranges in Z within which a single subshell is filled, such as the $4f$ shell in the rare earth sequence. However, the difference as a function of Z shows large sudden excursions in its slope as subshell edges are crossed. Any such smooth polynomial function would be an unsuitable reference [7] over the range $73 < Z < 103$ needed here, in which several subshells are

¹ Figures in brackets indicate literature references at the end of this paper.

traversed. A suitable reference function must incorporate at least the major deviations from the simple quadratic Z dependence of Moseley that are associated with subshell closures at $Z = 80, 82, 86,$ and 88 .

The recent improvements in the quality of the numerical self-consistent-field programs for calculating relativistic eigenvalues [8] or binding energies [9] do include, in the main "electrostatic energy" term (calculated by Dirac-Fock [8] or Dirac-Slater [9] prescription) the single electron wave function configuration that minimizes the energy at each Z . Thus they each do a much better job in following the actual Z dependence of the binding energies across shell edges than polynomials we have tested. We have tested and used them both as reference functions for interpolating and smoothing the experimental data. The differences between the calculated values and the experimental values (or their averages) are plotted for each subshell as a function of Z . A smooth curve drawn through the points can be read to 1 eV accuracy, and subtracting these smooth values from the calculated values yields the recommended values for the binding energies. Thus, as we demonstrate, it is principally the experimental values that in the end determine the recommendations in this empirical analysis, the local calculated reference value "cancelling out." Both calculations [8, 9] follow the course of true binding energies sufficiently well to enable smooth interpolation of the difference function across shell edges.

As will be seen, the plotted differences (calculated — experiment) still show local waves which differ somewhat for the different reference functions. These point to residual inaccuracies in the calculations in regions where the data are known to be accurate. Such waves in the differences make it very difficult to choose a suitable order for a polynomial (nor is there any theoretical guide thereto) to be used to calculate a least squares computer fit to the differences. In comparison to a numerical fit to an arbitrary polynomial, we adopt the policy of a smooth interpolating curve without local waves. We believe the smooth curve as fit by eye with a spline yields more credible predictions for the binding energies, without additionally attenuating the accuracy (error estimates) justified by the quality of the input experimental data. We offer supporting evidence in section 2.

The eigenvalues of Desclaux [8] from which we subtract the input data are the result of a Dirac-Fock frozen orbital procedure. They are only the Koopman's theorem approximation to binding energies. The differences which we plot are, in fact, approximately the sum of the excluded relaxation and field-theoretic contributions to a complete binding energy calculation. (These terms depend smoothly on Z , being independent of particular configurations.) Thus, the differences to experimental data and their Z dependence are much larger than those referred to the true binding energies calculated by Huang et al. [9], which include the extra terms. (See ordinates of figures 2 and 3A.) Nevertheless, we find that the Desclaux eigenvalues yield binding energy predictions by our method in excellent agreement with those derived using the Huang et al. calculations as reference in the most severe test cases, the K and L shells (see figure 4). Moreover, for the K shell the smooth interpolating curve using Desclaux's values demands

lower local curvature in the region of $Z=90-96$ than for the Huang et al. values. Note in figure 3A (K shell; Huang et al. [9] values) the failure of the smooth curve to fit the data averages at any Z in the range 90–96 compared to the corresponding fits in figure 2 and figure 3B, which use Desclaux's [8] values and similarly locally smooth curves.

These observations and other local differences lead us to use as reference only the Desclaux values for all shells beyond the K shell. In figure 5b we also show the difference function for the L_3 shell referred to the Huang et al. values.

2. Test of the Method

In order to test the use of the calculated eigenvalues [8] and binding energies [9] as described above, we display in figure 1 the two plots for the L_2 shell differences to the data for the Z range 41 to 83 where all values are accurately measured. Note this range spans the filling of the $4d$, the $5p$, and the $4f$ (lanthanides) shells. The experimental values are taken from

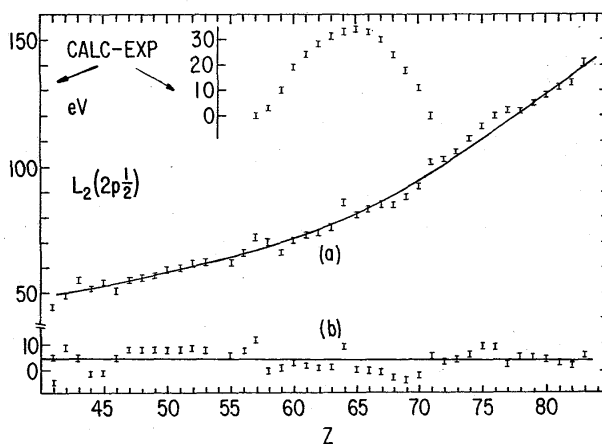


FIGURE 1. Plot of the differences between the calculated eigenvalues (a, Desclaux, ref. [8]), or binding energies (b, Huang et al. ref. [9]) and the experimental binding energies for the L_2 shell for a Z region where the values are well measured. This demonstrates the character and amplitude of the fluctuations about a smooth curve through the points which result both from experimental causes and from the calculation. The inset shows the difference between a smooth function ($aZ^2 + bZ + c$) and the same experimental values in the lanthanide region ($Z=57-71$).

the table of Siegbahn et al. [2]. Bearden and Burr [1] values may differ by 1 or 2 eV and are all quoted with standard deviation $\sigma > 1$ eV.

The fact that more than 5% of the points do not lie within 2σ of either smooth curve can be attributed mainly to two causes other than perhaps some optimistic assignment of a standard error by an experimenter. Most of these data rely on a photoelectron measurement on a solid sample for at least one and usually several shells for each Z , i.e., with the atom in question in a particular chemical state. No attempt is made to make any adjustment for the fact that the chemical state can affect the measured binding energy by several eV. The calculations of eigenvalues and binding energies, of course, are made for free atoms. Therefore, some of the deviations from the smooth curves can be attributed to differences in chemical shifts with Z .

The second reason for scatter around the smooth curves is due to the calculations. This assertion can be verified from a series of measurements on rare earths [6], all made with the same technique and instrumentation, in which some evidence is presented that each element was in a similar oxide state. When the results for the L_2 shell (as also for the K , L_1 and L_3 shells) from this series of measurements (all within the filling of the $4f$ shell) are subtracted from a parabolic function, it is clear that the values proceed smoothly, within the 1 eV errors, as a function of Z (the insert in figure 1 shows this plot; note the break at $Z=57$, the shell edge). Comparison to the same Z range on the other plots shows that the local deviation at Gd ($Z=64$) in our plots (of the differences between the calculated eigenvalues or binding energies and experimental values) is clearly due to the calculations and not to the experiment.

In the same region (lanthanides) but for the outer $6s$ shell, both a similar calculation [10] and the experiment show a similar local excessive increase of several eV in binding energy at $Z=64$ with the irregular $4f^7 5d 6s^2$ configuration (nearby lanthanides have no $5d$ electrons). The local increase persists even to the innermost shells in the calculation but not experimentally. The explanation for this is not clear, but it has been suggested [11] that if the calculations were done for atoms with a configuration more appropriate to the solid state that the increase in the calculated binding energy at $Z=64$ would not occur.

From the residual deviations of the accurate data from the smooth curves in the tests of the technique exhibited in figure 1, we are led to the conclusion that, using this method, an interpolated value can be assigned a "standard error" not less than about 5 eV. Errors assigned to extrapolations, of course, are increased as the distance from measured values increases (see figures 2, 3, and 4). Thus an "error band" is defined for each graph.

3. Results and Discussion

In figure 2 the differences between Desclaux's eigenvalues for the K shell and the weighted averages of the experimental data at each Z are plotted for the range $73 \leq Z \leq 100$. The 73000 eV span of the data is thus reduced to 700 eV, so the smoothing curve can be read to 1 eV on a 4-fold expanded plot. To show the differences on a still more expanded ordinate scale a parabolic function $F(Z)$ following the trend of the differences was subtracted and the remainder plotted in figure 3B. Here we can also show the individual data points and their errors; solid bars denote K x-ray measurements and dashed bars denote internal conversion electron spectroscopic results. The smooth curve was drawn independently of that in figure 2. Figure 3A gives the difference between the Huang et al. K shell binding energies, as revised (personal communication [9]), and the data. Again the smooth curve is independent of the others.

Smoothed values for the K binding energies were obtained from all three curves. The differences among these, each referred to the value from the figure 2 curve, are shown in figure 4 as grouped triads of error bars at each Z , as a function of Z . Clearly the differences among the three sets of values are nowhere as large as the individual assigned errors. Thus we

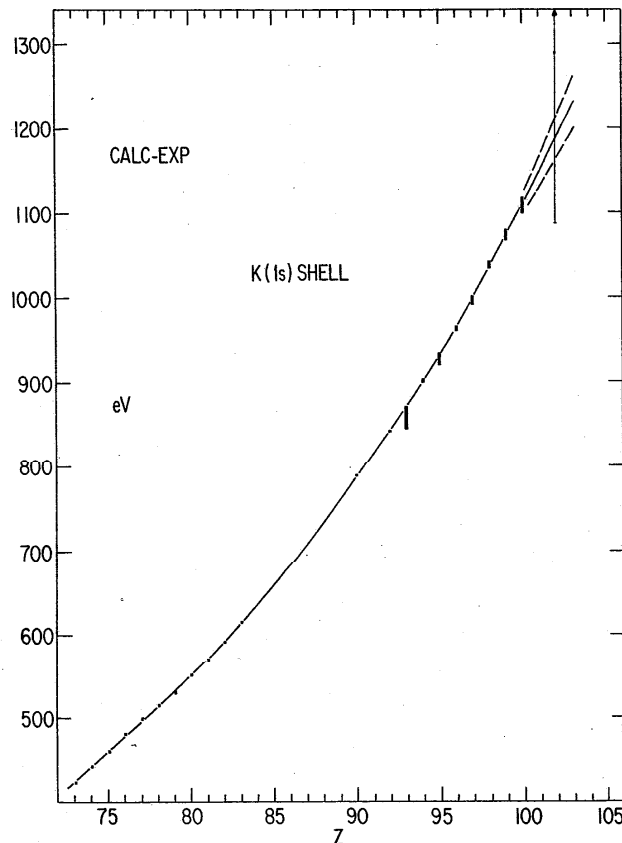


FIGURE 2. Plots of the differences between the calculated eigenvalues (Desclaux, ref. [8]), and the weighted averages of the experimental values for the K shells at each Z vs. Z from $Z=73-100$. These plots (figs. 2, 3, 5-9) are used for interpolation and extrapolation to obtain the recommended values of the binding energies for the unknown or poorly known cases.

give the average of the three values at each Z as our recommendation for the K binding energy, with an error assignment given by the envelope of figure 4.

We call attention to a thus far inexplicable trend in the K shell data. In both figures 3a and 3b one observes an increasing deviation above $Z=95$ between the smooth (solid) curve through the averages of all the data, determined mainly by the many accurate K x-ray measurements at $Z=95-100$ but including the data from the internal conversion electron spectroscopy at $Z=98$ and 100 , and the dashed curve which follows the trend of the latter measurements only. (The dashed curve leads to higher K binding energies.) The latter measurements are our own [12, 13] and are themselves averages of many measurements, e.g., ten at $Z=100$; in view of the deviation we have carefully reanalyzed them and find no reason to change them.

Thus the trend of the deviation, while not outside reasonable statistical expectations, is perhaps suggestive of the onset at very high Z , where K vacancy lifetimes $\approx 10^{-17}$ s, of a significant reduction of K x-ray energies below the difference of the adiabatic binding energies of the initial and final vacancy states. In earlier work [14] we have shown that, at $Z=95$, such possible non-adiabaticity equals 0 ± 12 eV. At $Z=100$ the deviation is about $+30$ eV, twice the assigned (external) error of our recommended binding energy, which is

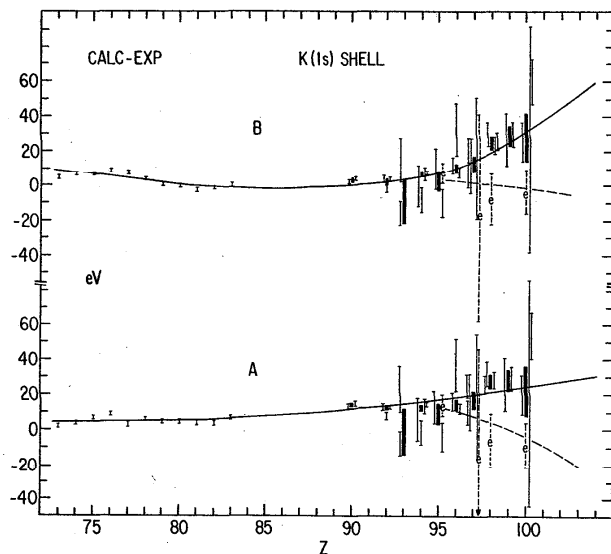


FIGURE 3. B) Plots of K shell differences (as in fig. 2) from which a function $F(Z) = aZ^2 + bZ + c$ (which follows the trend of the curve in fig. 2) has been subtracted. All individual data shown; solid error bars from K x-ray measurements, dashed error bars from internal conversion electron spectroscopy. Error bars spaced out slightly at each Z for visibility. Solid smooth curve follows data averages (heavy error bars); dashed curve follows dashed error bars. See text. A) Plot of the differences of calculated K shell binding energies (Huang et al. [9]) and experimental values. Remaining description same as above.

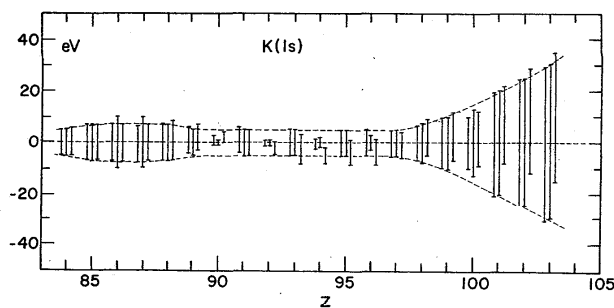


FIGURE 4. Plots of differences of smooth-curve values of K binding energies from figures 2, 3A and 3B, referred to those from curve of figure 2. Error bars grouped in triads at each Z ; right hand member from curve 3A (Huang et al.) and left hand member from curve 3B (Desclaux- $F(Z)$). Center member from figure 2 plotted at 0 eV ordinate. Errors assigned to recommended K -shell binding energies given by envelope of error bars at each Z .

based on the average of all the data. In addition, one can see from the comparisons of our recommended K binding energies at $Z = 100$ in table 2 to four theoretical calculations, columns 6, 7, 8 and 9, that the calculations are much closer to the binding energy derived from the internal conversion electron spectroscopic results than to our average value. This question

is challenging for future experiments, and may conceal fundamental physics.

In figures 5-9 are shown the plots for the other individual shells. These plots all refer to Desclaux's [8] eigenvalues except figure 5b for which the references are the L_3 binding energies of Huang et al. [9]. The L_3 binding energies obtained from this smooth curve agree with those from curve 5a within the range -1 to $+3$ eV from $84 < Z < 103$, with an average difference of 0.7 eV compared to our average assigned error of 4.5 eV in this range. (See table 1.) On the basis of this excellent agreement we refer all the other plots only to Desclaux's eigenvalues.

In a few cases where experiments report averages for unresolved spin-orbit splitting in the outer shells we have

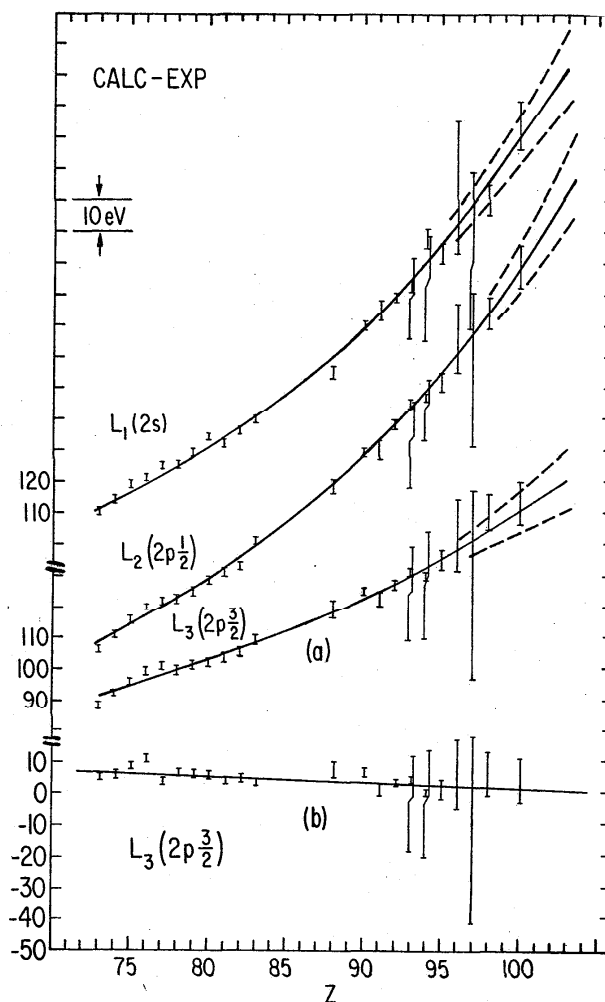


FIGURE 5. Plots of differences of calculated eigenvalues (Desclaux [8]) and experimental values for the L subshells. Figure 5b, L_3 differences from Huang et al. [9] binding energies.

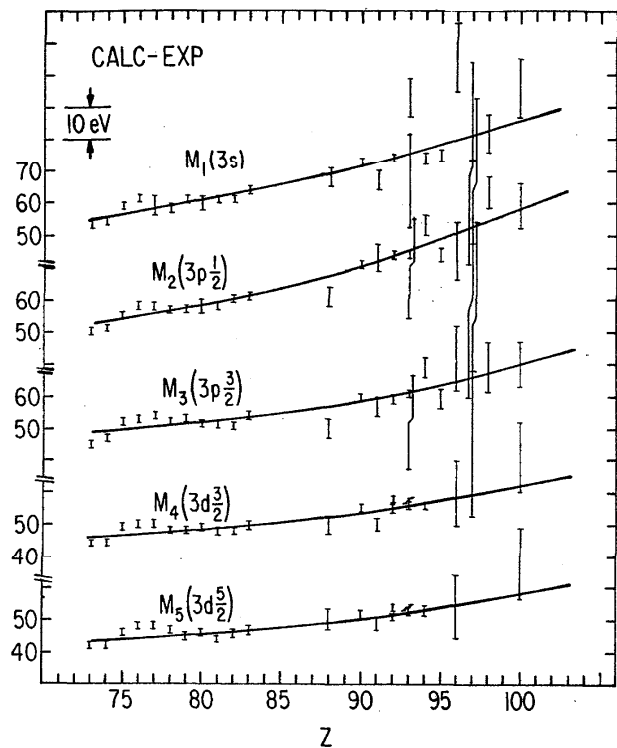


FIGURE 6. Plots of differences of calculated eigenvalues (Desclaux [8]) and experimental values for the *M* subshells.

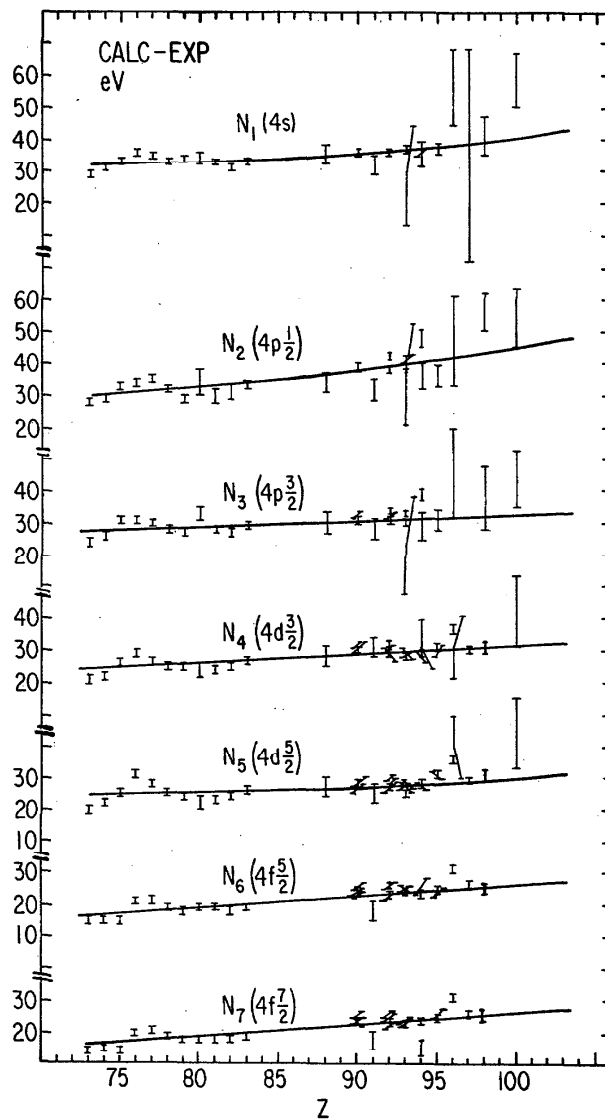


FIGURE 7. Plots of differences of calculated eigenvalues (Desclaux [8]) and experimental values for the *N* subshells.

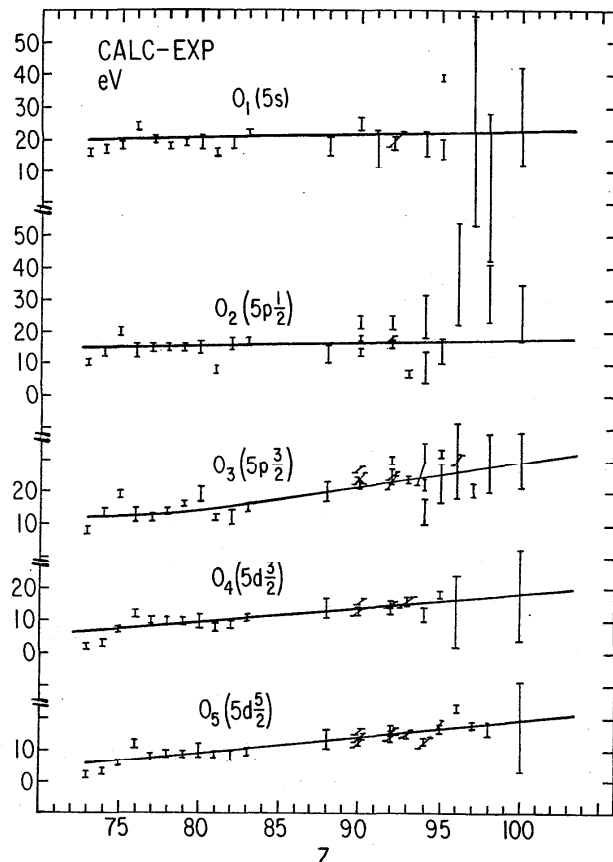


FIGURE 8. Plots of differences of calculated eigenvalues (Desclaux [8]) and experimental values for the *O* subshells.

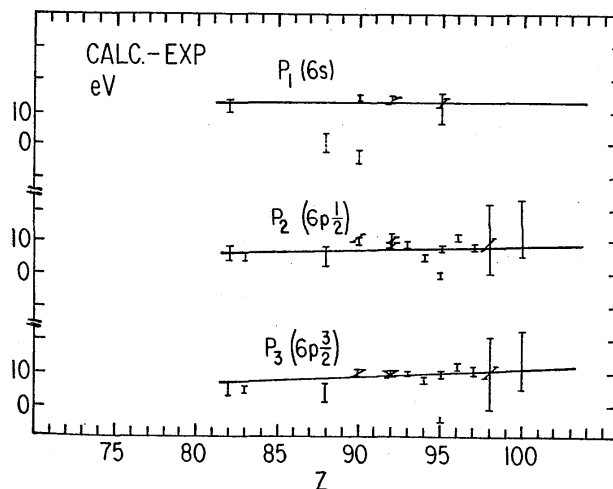


FIGURE 9. Plots of differences of calculated eigenvalues (Desclaux [8]) and experimental values for the *P* subshells.

made use of plots of experimental spin-orbit splitting as a function of Z to assign experimental values to the individual components. There is evidence that $5d_{3/2}$ peaks in photoelectron experiments [15] are smeared in energy (~ 10 eV) for those cases in which the $5f$ shell is partially filled. No values for this subshell are given in [15].

In the region from $Z = 73$ – 94 no attempt has been made to adjust any experimental value for the chemical nature of the source. For $Z \geq 94$ we have plotted the experimental values

adjusted, if necessary, to the “metal” or “condensed elemental” state. If, for example, the original experimental work indicates source deposition in an isotope-separator with low ion energy or thin vacuum-evaporated films, both exposed to air in the source handling process, the quoted experimental values have been reduced by 3 eV for inner shells and 2 eV for the *P* shells to account for the shift from the oxide environment to a “metal” environment.

One other adjustment we have made occurs at $Z = 96$ at the irregular $5f^7 6d7s^2$ configuration analogous to the half-filled $4f$ shell at $Z = 64$. Fortunately we have some photoelectron data [15] for the outer shells which confirms a smooth experimental behavior compared to a jump in both the calculated eigenvalue [8] and calculated binding energy [9] at $Z = 96$. Consequently, we have recommended values at $Z = 96$ which are smooth interpolations between neighboring recommended values. The adjustment is 5 to 6 eV for the inner shells and becomes smaller for the outer shells.

The binding energies given in table 1 are the energies required to move an electron from the particular orbit to the Fermi level in a solid source. The electronic work function of the material, typically 3–5 eV, is not included; see discussions in [1–3]. In comparing these energies to those from calculations for free atoms, the neglect of the electron work function, as well as the neglect of the energy needed to extract the resulting inner-vacancy ion from the solid, this latter energy being very difficult to measure or to estimate, must be taken into account. These corrections may total + (5–10) eV. However, since these corrections should depend very little on the particular inner shell ionized, they would not affect comparison to calculated x-ray energies.

In table 2 is exhibited a comparison of some of the present recommended values with others which have appeared as well as some calculations where they exist. For $Z=87$, which falls roughly in the middle of the interpolation region between $Z=83$ to 90 , we see that the present recommended values are generally 2 to 14 eV lower than the Bearden and Burr interpolation (up to N_5) and the ESCA interpolation (from N_5 to the outer shells) except at N_2 and N_3 where our values are ~ 20 eV larger, significant compared to our estimated errors of ~ 5 eV. At $Z=100$ we see an example of the very poor *K* shell values which were the result of early calculations [16] quoted in Bearden and Burr ($98 < Z < 103$) and in subsequent tabulations [2,5] but corrected by the semi-empirical calculations of Carlson et al. [4]. Note also the high *P* shell extrapolation of Lotz [3] at $Z=100$ and 103 made without benefit of recent experimental values for $Z \geq 92$.

In table 3 we compare the energies of $K_{\alpha 1}$ x-ray transitions ($2p_{3/2}-1s$) from the recommended binding energies of table 1 with those from the least-squares fit of an even Z^8 polynomial to the data from $Z=90$ – 100 by Krause and Nestor [17], and with the recent calculations by Carlson and Nestor [17], and from the (revised) binding energies of Huang et al. [9]. One sees the tendency of the polynomial fit, column 3, to deviate sharply above its fitting range. In early attempts we have made similar observations. The agreement with the semi-empirically fitted calculations of Carlson and Nestor [17] is much more uniform and the values from Huang et al. [9] tend to diverge significantly at higher Z .

Prefatory Comments on Table I

Recommended values for each subshell are underlined. Recommended values marked * are actual experimental values (or averages) instead of value from graphical smoothing procedure. This choice is made only if error bar of experimental average lies entirely inside estimated error band of graph.

Standard errors given as less than 1 eV in input data are given here as 1 eV. Errors assigned to averages of input data are larger of internal and external errors. For the *K* shell the error assignments are given by the envelope of the error bars in figure 4. The error band width for the *L* and higher shells is ± 5 eV from $Z=83-96$; at higher Z it flares out as shown in figure 5 and in this table.

Under each recommended value are listed all input data

with references. Each reference is coded with the measuring technique:

p=photoelectron spectroscopy;

e=internal conversion electron spectroscopy;

a=x-ray absorption edge;

x=x-ray transition $R_i S_j$ plus S_j -shell binding energy (S_j -shell binding energy from this table for Z above 83, or from refs. [1 and 2] for $73 \leq Z \leq 83$).

For the range $73 \leq Z \leq 83$ used in the interpolating graphs the references to input data are: p—19, 20, 21, 22; x—18.

All those experimental input values for $Z \geq 94$ derived from internal conversion or photoelectron spectroscopy on oxide-coated sources have been reduced by 3 eV for shells *K* to *O*₅ and by 2 eV for the *P* shell, in the smoothing graphs and in this table, to account for the shift from the oxide environment to a "metal" environment.

TABLE I. Recommended values for atomic electron binding energies to the Fermi level in solids for the heavy elements ($Z=84-103$). Values in eV with estimate of standard errors.

| Shell | 84 Po | ref. | 85 At | ref. | 86 Rn | ref. | 87 Fr | ref. | 88 Ra | ref. |
|-------------------------------------|----------|------|----------|------|----------|------|-----------|------|--------------------------------|------------|
| K(1s) | 93100 ±5 | | 95724 ±7 | | 98397 ±7 | | 101130 ±7 | | 103915 ±7 | |
| L ₁ (2s) | 16928 ±5 | | 17482 ±5 | | 18048 ±5 | | 18634 ±5 | | 19232 ±5 19237 ±2 19236 | x18 a18 |
| L ₂ (2p _{1/2}) | 16237 ±5 | | 16776 ±5 | | 17328 ±5 | | 17899 ±5 | | 18484 ±2* 18484 ±2 18486 | x18 a18 |
| L ₃ (2p _{3/2}) | 13810 ±5 | | 14207 ±5 | | 14610 ±5 | | 15025 ±5 | | 15444 ±2* 15444 ±2 15444 | x18 a18 |
| M ₁ (3s) | 4152 ±5 | | 4310 ±5 | | 4473 ±5 | | 4644 ±5 | | 4822 ±2* 4822 ±2 | x18 |
| M ₂ (3p _{1/2}) | 3844 ±5 | | 3994 ±5 | | 4150 ±5 | | 4315 ±5 | | 4483 ±5 4489 ±3 | x18 |
| M ₃ (3p _{3/2}) | 3293 ±5 | | 3409 ±5 | | 3529 ±5 | | 3656 ±5 | | 3785 ±5 3792 ±3 | x18 |
| M ₄ (3d _{3/2}) | 2794 ±5 | | 2901 ±5 | | 3012 ±5 | | 3129 ±5 | | 3248 ±2* 3248 ±2 | x18 |
| M ₅ (3d _{5/2}) | 2680 ±5 | | 2781 ±5 | | 2884 ±5 | | 2994 ±5 | | 3105 ±2* 3105 ±2 | x18 |
| N ₁ (4s) | 987 ±5 | | 1038 ±5 | | 1090 ±5 | | 1148 ±5 | | 1208 ±2* 1208 ±2 | x18 |
| N ₂ (4p _{1/2}) | 851 ±5 | | 897 ±5 | | 944 ±5 | | 999 ±5 | | 1055 ±5 1058 ±3 | x18 |
| N ₃ (4p _{3/2}) | 715 ±5 | | 751 ±5 | | 790 ±5 | | 834 ±5 | | 879 ±3* 879 ±3 | x18 |
| N ₄ (4d _{3/2}) | 495 ±5 | | 527 ±5 | | 558 ±5 | | 597 ±5 | | 636 ±2* 636 ±2 | x18 |
| N ₅ (4d _{5/2}) | 469 ±5 | | 499 ±5 | | 530 ±5 | | 567 ±5 | | 603 ±3* 603 ±3 | x18 |
| N ₆ (4f _{5/2}) | 184 ±5 | | 206 ±5 | | 229 ±5 | | 258 ±5 | | 287 ±5 | |
| N ₇ (4f _{7/2}) | 178 ±5 | | 199 ±5 | | 222 ±5 | | 249 ±5 | | 279 ±5 | |
| O ₁ (5s) | 176 ±5 | | 192 ±5 | | 208 ±5 | | 229 ±5 | | 251 ±5 254 ±3 | x18 |
| O ₂ (5p _{1/2}) | 132 ±5 | | 144 ±5 | | 158 ±5 | | 178 ±5 | | 197 ±5 200 ±3 | x18 |
| O ₃ (5p _{3/2}) | 102 ±5 | | 113 ±5 | | 123 ±5 | | 138 ±5 | | 153 ±3* 153 ±3 | x18 |
| O ₄ (5d _{3/2}) | 34 ±5 | | 41 ±5 | | 48 ±5 | | 60 ±5 | | 72 ±5 ^a | |
| O ₅ (5d _{5/2}) | 30 ±5 | | 37 ±5 | | 43 ±5 | | 55 ±5 | | 66 ±5 ^a | |
| P ₁ (6s) | 9 ±5 | | 13 ±5 | | 16 ±5 | | 24 ±5 | | 31 ±5 44 ±3 | x18 |
| P ₂ (6p _{1/2}) | 4 ±5 | | 6 ±5 | | 8 ±5 | | 14 ±5 | | 20 ±5 ^a | |
| P ₃ (6p _{3/2}) | 1 ±5 | | 1 ±5 | | 2 ±5 | | 7 ±5 | | 12 ±5 ^a | |

TABLE 1. Recommended values for atomic electron binding energies to the Fermi level in solids for the heavy elements (Z = 84-103). Values in eV with estimate of standard errors..continued

| Shell | 89 Ac | ref. | 90 Th | ref. | 91 Pa | ref. | 92 U | ref. | 93 Np | ref. |
|-------------------------------------|------------------|------|------------|------|-----------|----------|------------|----------|------------|------|
| K (1s) | <u>106756 ±5</u> | | 109650 ±1* | | 112596 ±5 | | 115602 ±1* | | 118669 ±5 | |
| | | | 109651 ±1 | x18 | | | 115606 ±2 | x18 | 118690 ±7 | x33 |
| | | | 109649 ±1 | x24 | | | 115601 ±1 | x24 | 118659 ±13 | x30 |
| | | | | | | | 115601 ±2 | x30 | 118663 ±31 | e51 |
| L ₁ (2s) | <u>19846 ±5</u> | | 20472 ±1* | | 21105 ±3* | | 21758 ±1* | | 22427 ±2* | |
| | | | 20472 ±1 | x18 | 21105 ±3 | x18 | 21758 ±1 | x18 | 22427 ±2 | x18 |
| | | | | | 21128 | a18 | | | 22431 ±13 | e51 |
| | | | | | | | | | 22445 ±14 | e52 |
| L ₂ (2p _{1/2}) | <u>19081 ±5</u> | | 19693 ±1* | | 20314 ±3* | | 20948 ±1* | | 21600 ±1* | |
| | | | 19693 ±1 | x18 | 20314 ±3 | x18 | 20948 ±1 | x18 | 21600 ±1 | x18 |
| | | | | | 20319 | a18 | | | 21612 ±14 | e51 |
| | | | | | | | | | 21618 ±14 | e52 |
| L ₃ (2p _{3/2}) | <u>15870 ±5</u> | | 16300 ±1* | | 16733 ±2* | | 17168 ±1* | | 17610 ±1* | |
| | | | 16300 ±1 | x18 | 16733 ±2 | x18 | 17166 ±1 | x18 | 17610 ±1 | x18 |
| | | | 16300 ±1 | p23 | 16733 | a18 | 17168 ±1 | p26 | 17617 ±15 | e51 |
| | | | | | | | | | 17627 ±14 | e52 |
| M ₁ (3s) | <u>4999 ±5</u> | | 5182 ±1* | | 5361 ±5 | | 5548 ±1* | | 5739 ±5 | |
| | | | 5182 ±1 | x18 | 5367 ±3 | x18 | 5548 ±1 | x18 | 5723 ±5 | x18 |
| | | | 5182 ±1 | p23 | | | | | 5748 ±15 | e51 |
| | | | | | | | | | 5750 ±15 | e52 |
| M ₂ (3p _{1/2}) | <u>4655 ±5</u> | | 4831 ±1* | | 5001 ±4* | | 5181 ±1* | | 5366 ±1* | |
| | | | 4830 ±1 | x18 | 5001 ±4 | x18 | 5182 ±1 | x18 | 5366 ±1 | x18 |
| | | | 4831 ±1 | p23 | | | 5181 ±1 | p26 | 5366 ±1 | p32 |
| | | | | | | | | | 5370 ±16 | e51 |
| | | | | | | 5377 ±19 | e52 | | | |
| M ₃ (3p _{3/2}) | <u>3915 ±5</u> | | 4046 ±1* | | 4174 ±3* | | 4304 ±1* | | 4435 ±1* | |
| | | | 4046 ±1 | x18 | 4174 ±3 | x18 | 4303 ±1 | x18 | 4435 ±1 | x18 |
| | | | 4046 ±1 | p23 | | | 4304 ±1 | p26 | 4435 ±1 | p32 |
| | | | | | | | | | 4444 ±15 | e51 |
| | | | | | | 4446 ±19 | e52 | | | |
| M ₄ (3d _{3/2}) | <u>3370 ±5</u> | | 3491 ±1* | | 3606 ±5 | | 3726 ±1* | | 3849 ±1* | |
| | | | 3491 ±1 | x18 | 3608 | a18 | 3728 ±1 | x18 | 3850 ±1 | x18 |
| | | | 3491 ±1 | p23 | 3611 ±2 | x18 | 3728 ±1 | p26 | 3850 ±1 | p32 |
| | | | | | | | 3725 ±1 | x31 | 3848 ±1 | x34 |
| | | | | | | | | 3858 ±19 | e52 | |
| M ₅ (3d _{5/2}) | <u>3219 ±5</u> | | 3332 ±1* | | 3442 ±2* | | 3550 ±1* | | 3664 ±1* | |
| | | | 3332 ±1 | x18 | 3436 | a18 | 3552 ±1 | x18 | 3666 ±1 | x18 |
| | | | 3332 ±1 | p23 | 3442 ±2 | x18 | 3552 ±1 | p26 | 3664 ±1 | p32 |
| | | | | | | | 3549 ±1 | x31 | 3663 ±1 | x34 |
| | | | | | | | | 3674 ±24 | e51 | |
| | | | | | | | | 3670 ±19 | e52 | |
| N ₁ (4s) | <u>1269 ±5</u> | | 1330 ±1* | | 1383 ±5 | | 1441 ±1* | | 1501 ±1* | |
| | | | 1330 ±1 | x18 | 1387 ±3 | x18 | 1441 ±1 | x18 | 1501 ±1 | x18 |
| | | | 1330 ±1 | p23 | | | 1441 ±1 | p26 | 1501 ±1 | p32 |
| | | | | | | | | | 1509 ±16 | e51 |
| | | | | | | | | 1506 ±23 | e52 | |
| N ₂ (4p _{1/2}) | <u>1112 ±5</u> | | 1168 ±1* | | 1217 ±5 | | 1271 ±2* | | 1328 ±2* | |
| | | | 1168 ±1 | x18 | 1224 ±2 | x18 | 1273 ±1 | x18 | 1328 ±1 | x18 |
| | | | 1168 ±1 | p23 | | | 1273 ±1 | p26 | 1328 ±1 | p32 |
| | | | | | | | 1269 ±1 | x31 | 1327 ±1 | x34 |
| | | | | | | | | 1331 ±16 | e51 | |
| | | | | | | | | 1334 ±23 | e52 | |
| N ₃ (4p _{3/2}) | <u>924 ±5</u> | | 967 ±1* | | 1004 ±5 | | 1043 ±1* | | 1085 ±2* | |
| | | | 967 ±1 | x18 | 1007 ±3 | x18 | 1045 ±1 | x18 | 1087 ±1 | x18 |
| | | | 968 ±1 | p23 | | | 1045 ±1 | p26 | 1087 ±1 | p32 |
| | | | 966 ±1 | p28 | | | 1042 ±1 | x31 | 1084 ±1 | x34 |
| | | | | | | 1043 ±1 | p28 | 1094 ±16 | e51 | |
| | | | | | | | | 1093 ±25 | e52 | |

TABLE I. Recommended values for atomic electron binding energies to the Fermi level in solids
for the heavy elements ($Z = 84-103$). Values in eV with estimate of standard errors.--continued.

| Shell | 89 Ac | ref. | 90 Th | ref. | 91 Pa | ref. | 92 U | ref. | 93 Np | ref. |
|-----------------|---------------|------|----------------|------|----------------|-------|----------------|------|----------------|------|
| $N_4(4d_{3/2})$ | <u>676 ±5</u> | | <u>713 ±1*</u> | | <u>743 ±3*</u> | | <u>779 ±1*</u> | | <u>816 ±1*</u> | |
| | | | 714 ±1 | x18 | 743 ±3 | x18 | 780 ±1 | x18 | 816 ±1 | x18 |
| | | | 714 ±1 | p23 | | | 780 ±1 | p26 | 817 ±1 | p32 |
| | | | 713 ±2 | p15 | | | 780 ±2 | p15 | 816 ±2 | p15 |
| | | | 712 ±1 | p28 | | | 777 ±1 | p29 | 816 ±1 | p34 |
| | | | | | | | 778 ±1 | p28 | 831 ±30 | e52 |
| $N_5(4d_{5/2})$ | <u>640 ±5</u> | | <u>677 ±1*</u> | | <u>708 ±3*</u> | | <u>737 ±1*</u> | | <u>771 ±1*</u> | |
| | | | 676 ±1 | x18 | 708 ±3 | x18 | 738 ±1 | x18 | 770 ±1 | x18 |
| | | | 676 ±1 | p23 | | | 738 ±1 | p26 | 773 ±1 | p32 |
| | | | 676 ±2 | p15 | | | 735 ±1 | p29 | 771 ±1 | p15 |
| | | | 678 ±1 | p25 | | | 738 ±2 | p15 | 771 ±1 | p34 |
| | | | | | | | 736 ±1 | p28 | 786 ±30 | e52 |
| $N_6(4f_{5/2})$ | <u>316 ±5</u> | | <u>344 ±1*</u> | | <u>366 ±5</u> | | <u>389 ±1*</u> | | <u>414 ±1*</u> | |
| | | | 344 ±1 | x18 | 371 ±2 | x18 | 391 ±1 | x18 | 415 ±1 | p32 |
| | | | 344 ±1 | p23 | | | 391 ±2 | p15 | 414 ±1 | p15 |
| | | | 344 ±1 | p15 | | | 388 ±1 | p28 | 414 ±1 | p34 |
| | | | 345 ±1 | p25 | | | 388 ±1 | p29 | | |
| | | | 342 ±1 | p28 | | | | | | |
| $N_7(4f_{7/2})$ | <u>307 ±5</u> | | <u>335 ±1*</u> | | <u>355 ±5</u> | | <u>379 ±1*</u> | | <u>403 ±1*</u> | |
| | | | 335 ±1 | x18 | 360 ±3 | x18 | 381 ±2 | x18 | 403 ±1 | p34 |
| | | | 335 ±1 | p23 | | | 378 ±1 | p29 | 403 ±1 | p15 |
| | | | 335 ±2 | p15 | | | 380 ±1 | p15 | 404 ±1 | p32 |
| | | | 333 ±1 | p28 | | | 377 ±1 | p28 | | |
| | | | 335 ±1 | p25 | | | | | | |
| $O_1(5s)$ | <u>272 ±5</u> | | <u>290 ±1*</u> | | <u>305 ±5</u> | | <u>324 ±2*</u> | | <u>338 ±5</u> | |
| | | | 290 ±1 | x18 | 310 ±7 | x18 | 324 ±2 | x18 | | |
| | | | | | | | 323 ±2 | p29 | | |
| $O_2(5p_{1/2})$ | <u>217 ±5</u> | | <u>236 ±1*</u> | | <u>245 ±5</u> | | <u>257 ±1*</u> | | <u>274 ±5</u> | |
| | | | 229 ±2 | x18 | | | 259 ±1 | x18 | 283 ±1 | p32 |
| | | | 238 ±1 | p25 | | | 253 ±2 | p29 | | |
| | | | 234 ±1 | p28 | | | 258 ±1 | p28 | | |
| $O_3(5p_{3/2})$ | <u>168 ±5</u> | | <u>180 ±1*</u> | | <u>188 ±5</u> | | <u>194 ±2*</u> | | <u>206 ±1*</u> | |
| | | | 182 ±1 | x18 | | | 195 ±2 | x18 | 206 ±1 | p32 |
| | | | 182 ±1 | p23 | | | 190 ±1 | p29 | 206 ±2 | p15 |
| | | | 179 ±2 | p15 | | | 197 ±2 | p15 | | |
| | | | 180 ±1 | p25 | | | 195 ±1 | p28 | | |
| | | | 177 ±1 | p28 | | | | | | |
| $O_4(5d_{3/2})$ | <u>84 ±5</u> | | <u>94 ±1*</u> | | <u>97 ±5</u> | | <u>104 ±1*</u> | | <u>109 ±1*</u> | |
| | | | 94 ±1 | x18 | | | 105 ±1 | x18 | 109 ±1 | x18 |
| | | | 94 ±1 | p23 | | | 103 ±1 | p28 | 109 ±1 | p32 |
| | | | 95 ±1 | p25 | | | 103 ±1 | p29 | | |
| | | | 92 ±1 | p28 | | | | | | |
| $O_5(5d_{5/2})$ | <u>76 ±5</u> | | <u>87 ±1*</u> | | <u>90 ±5</u> | | <u>95 ±2*</u> | | <u>101 ±1*</u> | |
| | | | 88 ±1 | x18 | | | 96 ±2 | x18 | 101 ±1 | x18 |
| | | | 88 ±1 | p23 | | | 96 ±1 | p15 | 101 ±1 | p32 |
| | | | 87 ±2 | p15 | | | 93 ±1 | p29 | 101 ±2 | p15 |
| | | | 88 ±1 | p25 | | | 94 ±1 | p28 | | |
| | | | 85 ±1 | p28 | | | | | | |
| $P_1(6s)$ | <u>37 ±5</u> | | <u>41 ±1*</u> | | <u>43 ±5</u> | | <u>44 ±1*</u> | | <u>47 ±5</u> | |
| | | | 60 ±2 | x18 | | | 71 ±2 | x18 | | |
| | | | 41 ±1 | p28 | | | 44 ±1 | p28 | | |
| | | | | | | | 74 ±3 | p29 | | |
| | | | | | | 44 ±1 | p27 | | | |
| $P_2(6p_{1/2})$ | <u>24 ±5</u> | | <u>24 ±1*</u> | | <u>27 ±5</u> | | <u>27 ±1*</u> | | <u>29 ±1*</u> | |
| | | | 49 ±4 | x18 | | | 42 ±13 | x18 | 29 ±1 | p15 |
| | | | 25 ±2 | p15 | | | 27 ±1 | p28 | | |
| | | | 24 ±1 | p28 | | | 26 ±1 | p27 | | |
| | | | | | | 28 ±2 | p15 | | | |
| | | | | | | 58 ±3 | p29 | | | |
| $P_3(6p_{3/2})$ | <u>15 ±5</u> | | <u>17 ±1*</u> | | <u>17 ±5</u> | | <u>17 ±1*</u> | | <u>18 ±1*</u> | |
| | | | 43 ±4 | x18 | | | 32 ±13 | x18 | 18 ±1 | p15 |
| | | | 17 ±1 | p28 | | | 17 ±1 | p15 | | |
| | | | 17 ±1 | p15 | | | 17 ±1 | p28 | | |
| | | | | | | 32 ±4 | p29 | | | |
| | | | | | | 17 ±1 | p27 | | | |

TABLE 1. Recommended values for atomic electron binding energies to the Fermi level in solids for the heavy elements (Z = 84-103). Values in eV with estimate of standard errors.--continued.

| Shell | 94 Pu | ref. | 95 Am | ref. | 96 Cm | ref. | 97 Bk | ref. | 98 Cf | ref. |
|-------------------------------------|------------|------|------------|------|------------|-----------|------------|------|------------|------|
| K (1s) | 121791 ±2* | | 124982 ±5 | | 128241 ±3* | | 131556 ±5* | | 134939 ±7 | |
| | 121805 ±7 | x33 | 124982 ±6 | e39 | 128239 ±5 | x41 | 131587 ±60 | e42 | 134968 ±15 | e13 |
| | 121790 ±1 | x24 | 124997 ±8 | x33 | 128218 ±15 | x37 | 131553 ±35 | x44 | 134930 ±7 | x37 |
| | 121788 ±4 | x30 | 124978 ±12 | x39 | 128243 ±3 | x30 | 131557 ±16 | x41 | 134936 ±5 | x43 |
| | 121794 ±12 | x37 | | | | | 131548 ±7 | x43 | 134934 ±5 | x41 |
| 121798 ±23 | e36 | | | | | 131563 ±7 | x30 | | | |
| L ₁ (2s) | 23104 ±5 | | 23808 ±3* | | 24526 ±5 | | 25256 ±5 | | 26010 ±7 | |
| | 23097 ±2 | x18 | 23808 ±3 | e39 | 24515 ±21 | e40 | 25272 ±25 | e42 | 26016 ±5 | e13 |
| | 23113 ±17 | e36 | | | | | | | | |
| L ₂ (2p _{1/2}) | 22266 ±1* | | 22952 ±3* | | 23651 ±5 | | 24371 ±5 | | 25108 ±5* | |
| | 22266 ±1 | x18 | 22952 ±3 | e39 | 23651 ±11 | e40 | 24832 ±25 | e42 | 25108 ±5 | e13 |
| | 22270 ±10 | e36 | | | | | | | | |
| L ₃ (2p _{3/2}) | 18057 ±1* | | 18510 ±3* | | 18970 ±5 | | 19435 ±5 | | 19907 ±5 | |
| | 18057 ±1 | x18 | 18510 ±3 | e39 | 18970 ±11 | e40 | 19449 ±30 | e42 | 19901 ±6 | e13 |
| | 18060 ±17 | e36 | | | | | | | | |
| M ₁ (3s) | 5933 ±2* | | 6133 ±2* | | 6337 ±5 | | 6545 ±7 | | 6761 ±6* | |
| | 5933 ±2 | x18 | 6133 ±2 | e39 | 6314 ±11 | e40 | 6553 ±31 | e42 | 6761 ±6 | e13 |
| M ₂ (3p _{1/2}) | 5547 ±5 | | 5739 ±5 | | 5937 ±5 | | 6138 ±5 | | 6345 ±6 | |
| | 5541 ±3 | x18 | 5744 ±2 | e39 | 5947 ±9 | e40 | 6144 ±46 | e42 | 6337 ±5 | e13 |
| M ₃ (3p _{3/2}) | 4563 ±5 | | 4698 ±5 | | 4838 ±5 | | 4976 ±5 | | 5116 ±5 | |
| | 4557 ±2 | x18 | 4703 ±3 | e39 | 4835 ±10 | e40 | 4974 ±46 | e42 | 5115 ±8 | e13 |
| M ₄ (3d _{3/2}) | 3970 ±1* | | 4096 ±5 | | 4224 ±5 | | 4353 ±5 | | 4484 ±6 | |
| | 3970 ±1 | p35 | | | 4227 ±10 | e40 | | | | |
| M ₅ (3d _{5/2}) | 3775 ±1* | | 3890 ±5 | | 4009 ±5 | | 4127 ±5 | | 4247 ±6 | |
| | 3775 ±1 | p35 | | | 4014 ±10 | e40 | | | | |
| N ₁ (4s) | 1559 ±1* | | 1620 ±2* | | 1684 ±5 | | 1748 ±6 | | 1813 ±6* | |
| | 1559 ±1 | x18 | 1620 ±2 | e39 | 1671 ±12 | e40 | 1752 ±33 | e42 | 1813 ±6 | e13 |
| | 1560 ±4 | e36 | | | | | | | | |
| N ₂ (4p _{1/2}) | 1380 ±5 | | 1438 ±5 | | 1498 ±5 | | 1558 ±8 | | 1620 ±10 | |
| | 1372 ±3 | x18 | 1443 ±3 | e39 | 1497 ±14 | e40 | | | 1607 ±6 | e13 |
| | 1384 ±4 | e36 | | | | | | | | |
| N ₃ (4p _{3/2}) | 1123 ±5 | | 1165 ±3* | | 1207 ±5 | | 1249 ±5 | | 1292 ±6 | |
| | 1115 ±2 | x18 | 1165 ±3 | e39 | 1197 ±14 | e40 | | | 1286 ±10 | e13 |
| | 1125 ±4 | e36 | | | | | | | | |
| N ₄ (4d _{3/2}) | 846 ±1* | | 880 ±1* | | 916 ±2* | | 955 ±2* | | 991 ±2* | |
| | 846 ±1 | p35 | 880 ±2 | p15 | 916 ±2 | p15 | 955 ±2 | p15 | 991 ±2 | p15 |
| | 847 ±2 | p15 | 880 ±1 | p38 | 922 ±10 | e40 | | | | |
| | 843 ±8 | e36 | | | | | | | | |
| N ₅ (4d _{5/2}) | 798 ±1* | | 829 ±1* | | 862 ±2* | | 898 ±2* | | 930 ±2* | |
| | 798 ±1 | p35 | 829 ±1 | p15 | 862 ±2 | p15 | 898 ±2 | p15 | 930 ±2 | p15 |
| | 799 ±1 | p15 | 829 ±1 | p38 | 858 ±10 | e40 | | | | |
| N ₆ (4f _{5/2}) | 436 ±2* | | 461 ±1* | | 484 ±2* | | 511 ±2* | | 538 ±2* | |
| | 436 ±2 | p15 | 460 ±2 | p15 | 484 ±2 | p15 | 511 ±2 | p15 | 538 ±2 | p15 |
| | 443 ±3 | x18 | 461 ±1 | p38 | | | | | | |
| N ₇ (4f _{7/2}) | 424 ±2* | | 446 ±1* | | 470 ±2* | | 495 ±2* | | 520 ±2* | |
| | 424 ±2 | p15 | 445 ±2 | p15 | 470 ±2 | p15 | 495 ±2 | p15 | 520 ±2 | p15 |
| | 432 ±3 | x18 | 446 ±1 | p38 | | | | | | |

TABLE 1. Recommended values for atomic electron binding energies to the Fermi level in solids
for the heavy elements ($Z = 84-103$). Values in eV with estimate of standard errors.--continued.

| Shell | 94 Pu | ref. | 95 Am | ref. | 96 Cm | ref. | 97 Bk | ref. | 98 Cf | ref. |
|-----------------|--|-------------------|---|------------|--|------------|------------------------------|------|--------------------------------|------|
| $0_1(5s)$ | 350 ± 5 352 ± 4 | x18 | 365 ± 5 370 ± 3 348 ± 1 | e39 p38 | 383 ± 5 | | 399 ± 5 395 ± 33 | e42 | 416 ± 5 433 ± 23 | e13 |
| $0_2(5p_{1/2})$ | 283 ± 5 274 ± 7 290 ± 5 | x18 e36 | 298 ± 5 300 ± 4 | e39 | 313 ± 5 296 ± 16 | e40 | 326 ± 7 | | 341 ± 9 326 ± 9 | e13 |
| $0_3(5p_{3/2})$ | $213 \pm 2^*$ 206 ± 7 218 ± 4 213 ± 2 | x18 e36 p15 | 219 ± 5 222 ± 6 213 ± 1 | e39 p38 | $229 \pm 2^*$ 229 ± 12 229 ± 2 | e40 p15 | 237 ± 5 243 ± 2 | p15 | 245 ± 6 244 ± 9 | e13 |
| $0_4(5d_{3/2})$ | 113 ± 5 116 ± 2 | x18 | $116 \pm 1^*$ 116 ± 1 | p38 | 124 ± 5 132 ± 11 | e40 | 130 ± 5 | | 137 ± 6 | |
| $0_5(5d_{5/2})$ | $102 \pm 2^*$ 105 ± 2 102 ± 2 | x18 p15 | $106 \pm 1^*$ 105 ± 2 106 ± 1 | p15 p38 | $110 \pm 2^*$ 110 ± 2 | p15 | $117 \pm 2^*$ 117 ± 2 | p15 | $122 \pm 2^*$ 122 ± 2 | p15 |
| $P_1(6s)$ | 46 ± 5 | | $48 \pm 1^*$ 50 ± 5 48 ± 1 | e39 p38 | 50 ± 5 | | 52 ± 5 | | 54 ± 8 | |
| $P_2(6p_{1/2})$ | $29 \pm 2^*$ 29 ± 2 | p15 | $29 \pm 2^*$ 29 ± 2 38 ± 1 | p15 p38 | $30 \pm 2^*$ 30 ± 2 | p15 | $32 \pm 2^*$ 32 ± 2 | p15 | $33 \pm 2^*{}^b$ 33 ± 2 | p15 |
| $P_3(6p_{3/2})$ | $16 \pm 2^*$ 16 ± 2 | p15 | $16 \pm 2^*$ 16 ± 2 30 ± 1 | p15 p38 | $16 \pm 2^*$ 16 ± 2 31 ± 27 | p15 e40 | $16 \pm 2^*$ 16 ± 2 | p15 | $17 \pm 2^*{}^b$ 17 ± 2 | p15 |

TABLE 1. Recommended values for atomic electron binding energies to the Fermi level in solids for the heavy elements (Z = 84-103). Values in eV with estimate of standard errors.--continued.

| Shell | 99 Es | ref. | 100 Fm | ref. | 101 Md | ref. | 102 No | ref. | 103 Lw | ref. |
|-------------------------------------|------------|------|---------------------|------|------------|------|-------------|------|------------|------|
| K (1s) | 138396 ±10 | | 141926 ±15 | | 145526 ±20 | | 149208 ±25 | | 152970 ±30 | |
| | 138394 ±15 | x41 | 141960 ±13 | e12 | | | 149103 ±200 | x48 | | |
| | 138391 ±7 | x37 | 141931 ±11 | x46 | | | | | | |
| | | | 141930 ±65 | x45 | | | | | | |
| | | | 141897 ±13 | x47 | | | | | | |
| L ₁ (2s) | 26182 ±1 | | 27514 ±8 | | 28387 ±8 | | 29221 ±10 | | 30083 ±12 | |
| | | | 27570 ±8 | e12 | | | | | | |
| L ₂ (2p _{1/2}) | 25865 ±6 | | 26641 ±7* | | 27438 ±10 | | 28255 ±11 | | 29103 ±12 | |
| | | | 26641 ±7 | e12 | | | | | | |
| L ₃ (2p _{3/2}) | 20384 ±6 | | 20868 ±7 | | 21356 ±7 | | 21851 ±8 | | 22359 ±10 | |
| | | | 20865 ±7 | e12 | | | | | | |
| M ₁ (3s) | 6981 ±7 | | 7208 ±9 | | 7440 ±10 | | 7678 ±11 | | 7930 ±12 | |
| | | | 7197 ±9 | e12 | | | | | | |
| M ₂ (3p _{1/2}) | 6558 ±7 | | 6776 ±7* | | 7001 ±8 | | 7231 ±9 | | 7474 ±10 | |
| | | | 6776 ±7 | e12 | | | | | | |
| M ₃ (3p _{3/2}) | 5259 ±6 | | 5405 ±7* | | 5552 ±8 | | 5702 ±9 | | 5860 ±10 | |
| | | | 5405 ±7 | e12 | | | | | | |
| M ₄ (3d _{3/2}) | 4617 ±6 | | 4752 ±7 | | 4889 ±9 | | 5028 ±11 | | 5176 ±13 | |
| | | | 4743 ±11 | e12 | | | | | | |
| M ₅ (3d _{5/2}) | 4368 ±8 | | 4491 ±10 | | 4615 ±11 | | 4741 ±13 | | 4876 ±15 | |
| | | | 4481 ±11 | e12 | | | | | | |
| N ₁ (4s) | 1883 ±11 | | 1952 ±14 | | 2024 ±18 | | 2097 ±21 | | 2180 ±25 | |
| | | | 1937 ±11 | e12 | | | | | | |
| N ₂ (4p _{1/2}) | 1683 ±11 | | 1749 ±13 | | 1816 ±15 | | 1885 ±17 | | 1963 ±20 | |
| | | | 1740 ±9 | e12 | | | | | | |
| N ₃ (4p _{3/2}) | 1336 ±8 | | 1379 ±10 | | 1424 ±11 | | 1469 ±13 | | 1523 ±17 | |
| | | | 1368 ±9 | e12 | | | | | | |
| N ₄ (4d _{3/2}) | 1029 ±9 | | 1067 ±11 | | 1105 ±13 | | 1145 ±16 | | 1192 ±18 | |
| | | | 1056 ±11 | e12 | | | | | | |
| N ₅ (4d _{5/2}) | 965 ±9 | | 1000 ±15 | | 1034 ±18 | | 1070 ±20 | | 1112 ±24 | |
| | | | 986 ±11 | e12 | | | | | | |
| N ₆ (4f _{5/2}) | 564 ±6 | | 591 ±8 | | 618 ±10 | | 645 ±13 | | 680 ±15 | |
| N ₇ (4f _{7/2}) | 546 ±6 | | 572 ±8 | | 597 ±10 | | 624 ±13 | | 658 ±15 | |
| O ₁ (5s) | 434 ±7 | | 452 ±9 | | 471 ±11 | | 490 ±13 | | 516 ±15 | |
| | | | 447 ±15 | e12 | | | | | | |
| O ₂ (5p _{1/2}) | 357 ±11 | | 373 ±9 | | 389 ±16 | | 406 ±18 | | 429 ±20 | |
| | | | 364 ±9 | e12 | | | | | | |
| O ₃ (5p _{3/2}) | 255 ±7 | | 262 ±9* | | 272 ±9 | | 280 ±10 | | 296 ±12 | |
| | | | 262 ±9 | e12 | | | | | | |
| O ₄ (5d _{3/2}) | 142 ±7 | | 149 ±9 ^C | | 154 ±10 | | 161 ±11 | | 174 ±12 | |
| O ₅ (5d _{5/2}) | 127 ±7 | | 133 ±9 ^C | | 137 ±10 | | 142 ±11 | | 154 ±12 | |
| P ₁ (6s) | 57 ±9 | | 59 ±10 | | 61 ±11 | | 63 ±12 | | 71 ±13 | |
| P ₂ (6p _{1/2}) | 35 ±6 | | 36 ±7 ^C | | 37 ±8 | | 38 ±10 | | 44 ±11 | |
| P ₃ (6p _{3/2}) | 17 ±6 | | 17 ±7 ^C | | 17 ±8 | | 18 ±10 | | 21 ±11 | |

^aExperimental points (x 18) on figures 8 and 9 from unresolved O_{4,5} and P_{2,3} peaks, using extrapolated spin-orbit splitting.

^bExperimental points with larger error bars [e13] on figure 9 from unresolved P_{2,3} peak using extrapolated spin-orbit splitting.

^cExperimental points [e12] on figure 8 from unresolved O_{4,5} and P_{2,3} peaks using extrapolated spin-orbit splitting.

TABLE 2. Comparison of atomic electron binding energies at three values of the atomic number (Z). Column two in eV. Other columns give excess over values in column two in eV. Standard errors given in eV.

| Shell | Recommended values (TABLE 1) ^a | ...Adjusted compilations... | | |Calculations..... | | | |
|-------------------------------------|---|-----------------------------|-------------------------------|-------------------|--------------------------|----------------------------|-------------------------|---------------------------|
| | | ESCA ^b | Bearden and Burr ^c | Lotz ^d | Huang et al ^e | Carlson et al ^f | Mann et al ^g | Fricke et al ^l |
| <u>Z = 87</u> | | | | | | | | |
| K(1s) | 101130 ± 7 | +7 | +7 ± 20 | +4 | +9 | | | |
| L ₁ (2s) | 18634 ± 5 | +5 | +5 ± 60 | +3 | +14 | | | |
| L ₂ (2p _{1/2}) | 17899 ± 5 | +7 | +7 ± 5 | +4 | +5 | | | |
| L ₃ (2p _{3/2}) | 15025 ± 5 | +6 | +6 ± 5 | +3 | +6 | | | |
| M ₁ (3s) | 4644 ± 5 | +8 | +8 | +8 | +27 | | | |
| M ₂ (3p _{1/2}) | 4315 ± 5 | +12 | +12 ± 60 | +9 | +15 | | | |
| M ₃ (3p _{3/2}) | 3656 ± 5 | +7 | +7 ± 60 | +10 | +14 | | | |
| M ₄ (3d _{3/2}) | 3129 ± 5 | +7 | +7 ± 5 | +5 | +9 | | | |
| M ₅ (3d _{5/2}) | 2994 ± 5 | +6 | +6 ± 5 | +4 | +9 | | | |
| N ₁ (4s) | 1148 ± 5 | +5 | +5 | +5 | +18 | | | |
| N ₂ (4p _{1/2}) | 999 ± 5 | -19 | -19 ± 60 | +4 | +17 | | | |
| N ₃ (4p _{3/2}) | 834 ± 5 | -24 | -24 ± 60 | +5 | +14 | | | |
| N ₄ (4d _{3/2}) | 597 ± 5 | +6 | +6 ± 6 | +6 | +10 | | | |
| N ₅ (4d _{5/2}) | 567 ± 5 | +10 | +10 ± 50 | +5 | +11 | | | |
| N ₆ (4f _{5/2}) | 258 ± 5 | +14 | | +10 | +7 | | | |
| N ₇ (4f _{7/2}) | 249 ± 5 | | | +11 | +9 | | | |
| O ₁ (5s) | 229 ± 5 | +5 | | +2 | +15 | | | |
| O ₂ (5p _{1/2}) | 178 ± 5 | +4 | | +5 | +9 | | | |
| O ₃ (5p _{3/2}) | 138 ± 5 | +2 | | +9 | +14 | | | |
| O ₄ (5d _{3/2}) | 60 ± 5 | 0 | | +5 | +8 | | | |
| O ₅ (5d _{5/2}) | 55 ± 5 | | | +6 | +8 | | | |
| P ₁ (6s) | 24 ± 5 | +10 | | +19 | +11 | | | |
| P ₂ (6p _{1/2}) | 14 ± 5 | +4 | | +3 | +5 | | | |
| P ₃ (6p _{3/2}) | 7 ± 5 | | | +6 | +7 | | | |

TABLE 2. Comparison of atomic electron binding energies at three values of the atomic number (Z).
 Column two in eV. Other columns give excess over values in column two in eV. Standard
 errors given in eV. --continued..

| Shell | Recommended values (TABLE 1) ^a | ...Adjusted Compilations... | | |Calculations..... | | | |
|-------------------------------------|--|-----------------------------|----------------------------------|-------------------|------------------------------|--------------------------------|-----------------------------|-------------------------------|
| | | ESCA ^b | Bearden and Burr ^c | Lotz ^d | Huang et al. ^e | Carlson et al. ^f | Mann et al. ^g | Fricke et al. ^h |
| <u>Z = 100</u> | | | | | | | | |
| K(1s) | 141926 ±15 | +1164 | +1164 | +913 | +25 | +17 ±34 | +30 ±25 | +27 ±26 |
| L ₁ (2s) | 27574 ±8 | +126 | +126 | -15 | +19 | +10 ±25 | | +7 ±20 |
| L ₂ (2p _{1/2}) | 26641 ±7 | +169 | +169 | -27 | 0 | +2 ±16 | | +5 ±10 |
| L ₃ (2p _{3/2}) | 20868 ±7 | +32 | +32 | -8 | +1 | +4 ±14 | | +1 ±10 |
| M ₁ (3s) | 7208 ±9 | -3 | -3 | 0 | +30 | -2 ±12 | | +5 ±15 |
| M ₂ (3p _{1/2}) | 6776 ±7 | +17 | +17 | +3 | +17 | +7 ±11 | | +7 ±4 |
| M ₃ (3p _{3/2}) | 5405 ±7 | -8 | -8 | +21 | +14 | +9 ±11 | | |
| M ₄ (3d _{3/2}) | 4752 ±7 | +14 | +14 | +14 | +5 | +5 ±11 | | |
| M ₅ (3d _{5/2}) | 4491 ±10 | +7 | +7 | +17 | +6 | +6 ±11 | | |
| N ₁ (4s) | 1952 ±14 | -15 | -15 | -13 | +15 | +2 ±20 | | |
| N ₂ (4p _{1/2}) | 1749 ±13 | -2 | -2 | -10 | +15 | +4 ±20 | | |
| N ₃ (4p _{3/2}) | 1379 ±10 | -13 | -13 | -6 | +9 | +4 ±20 | | |
| N ₄ (4d _{3/2}) | 1067 ±11 | | | +2 | +8 | +4 ±10 | | |
| N ₅ (4d _{5/2}) | 1000 ±15 | | | +2 | +8 | +5 ±10 | | |
| N ₆ (4f _{5/2}) | 591 ±8 | | | +24 | +4 | | | |
| N ₇ (4f _{7/2}) | 572 ±8 | | | +27 | +4 | | | |
| O ₁ (5s) | 452 ±9 | +2 | +2 | +13 | +10 | | | |
| O ₂ (5p _{1/2}) | 373 ±9 | | | +4 | +5 | +2 ±15 | | |
| O ₃ (5p _{3/2}) | 262 ±9 | | | +8 | +19 | | | |
| O ₄ (5d _{3/2}) | 149 ±9 | | | +17 | +10 | +4 ±15 | | |
| O ₅ (5d _{5/2}) | 133 ±9 | | | +10 | +9 | +5 ±15 | | |
| P ₁ (6s) | 59 ±10 | | | +55 | +9 | | | |
| P ₂ (6p _{1/2}) | 36 ±7 | | | +57 | +5 | | | |
| P ₃ (6p _{3/2}) | 17 ±7 | | | +58 | +8 | | | |

TABLE 2. Comparison of atomic electron binding energies at three values of the atomic number (Z).
Column two in eV. Other columns give excess over values in column two in eV. Standard
errors given in eV. --continued.

| Shell | Recommended values (TABLE 1) ^a | ...Adjusted Compilations... | | | | | | |
|-------------------------------------|--|-----------------------------|----------------------------------|-------------------|-----------------------------|-------------------------------|----------------------------|------------------------------|
| | | ESCA ^b | Bearden and Burr ^c | Lotz ^d | Huang et al ^e | Carlson et al ^f | Mann et al ^g | Fricke et al ^h |
| <u>Z = 103</u> | | | | | | | | |
| K(1s) | 152970 ±30 | +1410 | +1410 | +766 | +36 | +11 ±62 | | |
| L ₁ (2s) | 30083 ±12 | +157 | +157 | -60 | +20 | +7 ±44 | | |
| L ₂ (2p _{1/2}) | 29103 ±12 | +177 | +177 | -76 | 0 | -4 ±25 | | |
| L ₃ (2p _{3/2}) | 22359 ±10 | +1 | +1 | -27 | +2 | +1 ±22 | | |
| M ₁ (3s) | 7930 ±12 | -30 | -30 | -5 | +32 | -9 ±20 | | |
| M ₂ (3p _{1/2}) | 7474 ±10 | -14 | -14 | -5 | +17 | 0 ±17 | | |
| M ₃ (3p _{3/2}) | 5860 ±10 | -50 | -150 | +31 | +14 | +3 ±17 | | |
| M ₄ (3d _{3/2}) | 5176 ±13 | -26 | -26 | +20 | +5 | -3 ±17 | | |
| M ₅ (3d _{5/2}) | 4876 ±15 | -16 | -16 | +25 | +6 | +2 ±17 | | |
| N ₁ (4s) | 2180 ±25 | -40 | -40 | -33 | +15 | -6 ±20 | | |
| N ₂ (4p _{1/2}) | 1963 ±20 | -33 | -33 | -17 | +15 | -4 ±20 | | |
| N ₃ (4p _{3/2}) | 1523 ±17 | -43 | -43 | -17 | +7 | -4 ±20 | | |
| N ₄ (4d _{3/2}) | 1192 ±18 | | | -4 | +7 | -3 ±15 | | |
| N ₅ (4d _{5/2}) | 1112 ±24 | | | -3 | +9 | 0 ±15 | | |
| N ₆ (4f _{5/2}) | 680 ±15 | | | +36 | +4 | | | |
| N ₇ (4f _{7/2}) | 658 ±15 | | | +39 | +4 | | | |
| O ₁ (5s) | 516 ±15 | -26 | -26 | +3 | +9 | | | |
| O ₂ (5p _{1/2}) | 429 ±20 | | | +1 | +4 | -5 ±15 | | |
| O ₃ (5p _{3/2}) | 296 ±12 | | | +4 | +21 | | | |
| O ₄ (5d _{3/2}) | 174 ±12 | | | +24 | +9 | -3 ±15 | | |
| O ₅ (5d _{5/2}) | 154 ±12 | | | +9 | +12 | -1 ±15 | | |
| P ₁ (6s) | 71 ±13 | | | +63 | +8 | | | |
| P ₂ (6p _{1/2}) | 44 ±11 | | | +69 | +6 | | | |
| P ₃ (6p _{3/2}) | 21 ±11 | | | +72 | +9 | | | |

^aBinding energies to Fermi level in condensed source.

^bRef. 2; binding energies to Fermi level in condensed source. Ref. 5; same values for Z=87, 100, 103.

^cRef. 1; binding energies to Fermi level in condensed source.

^dRef. 3; binding energies for free atoms, i.e., includes work function of 5 eV. Standard error estimates are stated for Z=87 as < 3 eV; for Z=100 and 103 error estimates are stated to be > 15 but < 90 eV.

^eRef. 9; calculations for free atoms. Expected to be ~5 eV higher than experimental values for binding energies to Fermi level of a condensed source.

^fT. A. Carlson and C. W. Nestor, Jr., ref. 17. Errors from this ref. only; no contribution from error in column 2. Calculations for free atoms.

^gRef. 29. Error from this ref. only; no contribution from error in column 2. Calculations for free atoms.

^hRef. 50. Error from this ref. only; no contribution from error in column 2. Calculations for free atoms.

TABLE 3. Comparison of $K\alpha_1$ ($1s-2p_{3/2}$) x-ray transition energies.

| Other columns give excess (eV) over column 2 values. | | | | |
|--|------------|----------------------------|--------------------------|--------------------------|
| Z | This paper | Empirical Fit ^a | Calculation ^b | Calculation ^c |
| 89 | 90886 ±7 | -6 ±11 | | +5 |
| 90 | 93350 ±2 | -2 ±3 | | +6 |
| 91 | 95863 ±5 | +2 ±3 | | +12 |
| 92 | 98434 ±3 | -1 ±3 | +9 | +9 |
| 93 | 101059 ±5 | -3 ±3 | | +9 |
| 94 | 103734 ±2 | +1 ±3 | | +13 |
| 95 | 106472 ±3 | 0 ±3 | +11 ±29 | +13 |
| 96 | 109271 ±6 | -3 ±3 | +8 ±49 | +8 |
| 97 | 112121 ±7 | +5 ±5 | +10 ±49 | +15 |
| 98 | 115032 ±9 | +13 ±6 | +15 ±49 | +22 |
| 99 | 118012 ±12 | +14 ±8 | +13 ±49 | +23 |
| 100 | 121058 ±17 | +12 ±13 | +13 ±37 | +24 |
| 101 | 124170 ±21 | +6 ±29 | +15 ±65 | +29 |
| 102 | 127357 ±27 | -12 ±59 | +11 ±65 | +31 |
| 103 | 130611 ±31 | -38 ±111 | +10 ±65 | +34 |

^aM. O. Krause and C. W. Nestor, Jr., ref. 17. Error from this ref. only.

^bT. C. Carlson and C. W. Nestor, Jr., ref. 17. Error from this ref. only.

^cHuang et al., ref. 9.

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References

- [1] Bearden, J. A., and Burr, A. F., *Rev. Mod. Phys.* **39**, 125 (1967).
- [2] Siegbahn, K., Nordling, C., Fahlman, A., Nordberg, R., Hamrin, K., Hedman, J., Johansson, C., Bergmark, T., Karlsson, S.-E., Lindgren, I., and Lindberg, B., *ESCA—Atomic, Molecular and Solid State Structure Studied by Means of Electron Spectroscopy*, (Almqvist and Wiksells Boktryckeri AB, Uppsala, Sweden, 1967) Appendix I.
- [3] Lotz, W., *J. Opt. Soc. Am.* **60**, 206 (1970).
- [4] Carlson, T. A., Nestor, C. W., Jr., Malik, F. B., and Tucker, T. C., *Nucl. Phys.* **A135**, 57 (1969).
- [5] Sevier, K. D., *Low Energy Electron Spectrometry* (Wiley—Interscience, New York, 1972) Appendix F.
- [6] Bergvall, P., and Hagström, S., *Arkiv. Fysik.* **17**, 61 (1960).
- [7] We have also tried including a Z^4 term as suggested by S. Hagström [*Z. Physik* **178**, 82 (1964)] to reduce the total span of the data. While such a function does indeed reduce the total range of the differences and is good for interpolation, we find it poor for extrapolation.
- [8] Desclaux, J. P., *Atomic Data Nucl. Data Tables*, **12**, 312 (1973). We have compared the calculations of Desclaux with those of J. B. Mann and J. T. Waber (ref. 10 and private communication) and find them to be the same (within ~ 1 eV) for the cases we have checked.
- [9] Huang, K.-N., Aoyagi, M., Chen, M. H., Crasemann, B. and Mark, H., *Atomic Data and Nuclear Data Tables*, **18**, 243 (1976). This calculation of binding energies includes relaxation and field-theoretic contributions. Approximations to the form of the Breit interaction and to the form of the nuclear charge distribution used in the program for the published table lead to rapidly increasing deviations from K shell experimental values above $Z = 90$. The Huang et al. values we use for the K shell were revisions based on corrections of these factors (Dr. Chen private communication) above $Z = 80$, extrapolated by us down to $Z = 73$.
- [10] Mann, J. B., and Waber, J. T., *Atomic Data* **5**, 201 (1973).
- [11] Mann, J. B., private communication.
- [12] Porter, F. T., and Freedman, M. S., *Phys. Rev. Letters* **27**, 293 (1971).
- [13] Porter, F. T., and Freedman, M. S., unpublished work, based on: Freedman, M. S., Ahmad, I., Porter, F. T., Sjoblom, R. K., Barnes, R. P., Lerner, J., and Fields, P. R., *Phys. Rev. C* **15**, 760 (1977).
- [14] Freedman, M. S., and Porter, F. T., *Phys. Rev. A* **6**, 659 (1972).
- [15] Veal, B. W., Lam, D. J., Diamond, H., and Hoekstra, H. R., *Phys. Rev. B* **15**, 2929 (1977); Veal, B., Lam, D. J., Carnall, W. T., and Hoekstra, H. R., *Phys. Rev. B* **12**, 5651 (1975).
- [16] Liberman, D., Waber, J. T., and Cromer, D. T., *Phys. Rev.* **137**, A 27 (1965).
- [17] Krause, M. O., and Nestor, C. W., Jr., *Proc. Symposium on Electron Spectroscopy, Uppsala, 1977. Physica Scripta.—Suppl. issue; Carlson, T. A. and Nestor, C. W. Jr., At. Data Nucl. Data Tables*, **19**, 153 (1977).
- [18] Bearden, J. A., *Rev. Mod. Phys.* **39**, 78 (1967) and ref. 1.
- [19] Fahlman, A. and Hagström, S., *Arkiv Fysik* **27**, 69 (1964).
- [20] Nordling, R., Hedman, J., Nordling, C., and Siegbahn, K., unpublished, quoted in ref. 2.
- [21] Sokolowski, E., *Arkiv Fysik* **15**, 1 (1959).
- [22] Karlsson, S.-E., Norbert, C.-H., Nilsson, Ö., Högborg, S., el-Farrash, A. H., Nordling, C., and Siegbahn, K., unpublished, quoted in ref. 2.

- [23] Nordling, C., and Hagström, S., *Z. Phys.* **178**, 418 (1964).
- [24] Borchert, G. L., and Fricke, B., Abstr., 5th Int. Conf. Atomic Physics, Marrus, R., Prior, M. H., Shugart, H. A., eds., Berkeley 1976, p. 321; Borchert, G. L., *Z. Naturf.* **31a**, 102 (1976).
- [25] Bancroft, G. Michael and Sham, Tsun, K., *Chem. Phys. Lett.* **46**, 551 (1977).
- [26] Nordling, C., and Hagström, S., *Arkiv Fysik* **15**, 431 (1959).
- [27] Verbist, J., Riga, J., Pireaux, J. J. and Caudano, R., *J. Elec. Spec. Rel. Phenom.* **5**, 193 (1974).
- [28] Fuggle, J. C., Burr, A. F., Watson, L. M., Fabian, D. J., and Lang, W., *J. Phys. F.* **4**, 335 (1974).
- [29] Park, R. L., and Houston, J. E., *Phys. Rev. A* **7**, 1447 (1973).
- [30] Börner, H., (personal communication).
- [31] Keski-Rahkonen, O. and Krause, M. O., *Phys. Rev. A* **15**, 959 (1977).
- [32] Hagström, S., *Bull. Am. Phys. Soc.*, **11**, 389 (1966).
- [33] Nelson, G. C., Saunders, B. G., and Salem, S. I., *Z. Physik* **235**, 308 (1970).
- [34] Krause, M. O., Nestor, C. W., Jr., and Oliver, J. H., *Phys. Rev. A* **15**, 2335 (1977).
- [35] Fahlman, A., Hamrin, K., Nordling, R., Nordling, C., Siegbahn, K., and Holm, L. W., *Phys. Letters* **19**, 643 (1966).
- [36] Porter, F. T., Ahmad, I., Freedman, M. S., Barnes, R. F., Sjoblom, R. K., Wagner, F., Jr., and Fields, P. R., *Phys. Rev. C* **5**, 1738 (1972).
- [37] Ahmad, I., unpublished work (personal communication).
- [38] Krause, M. O., and Wuilleumier, F., *Electron Spectroscopy* (Ed. Shirley, D. A., North Holland Publishing Co., Netherlands, 1972) p. 759.
- [39] Porter, F. T., Ahmad, I., Freedman, M. S., Milsted, J., and Friedman, A. M., *Phys. Rev. C* **10**, 803 (1974) gives experimental data only. Binding energy calculation unpublished.
- [40] Chu, Y. Y., Perlman, M. L., Dittner, P. F., and Bemis, C. E., Jr., *Phys. Rev. A* **5**, 67 (1972).
- [41] Dittner, P. F., and Bemis, C. E., Jr., *Phys. Rev. A* **5**, 481 (1972).
- [42] Hollander, J. M., Holtz, M. D., Novakov, T., and Graham, R. L., *Arkiv Fysik*, **28**, 375 (1965).
- [43] Helmer, R. G., unpublished work (personal communication).
- [44] Fields, P. R., Ahmad, I., Barnes, R. F., Sjoblom, R. K., and McHarris, W. C., *Nuc. Phys.* **A208**, 269 (1973).
- [45] Dittner, P. F., Bemis, C. E., Hensley, D. C., Silva, R. J., and Goodman, C. D., *Phys. Rev. Letters* **17**, 1037 (1971).
- [46] Ahmad, I., Diamond, H., Milsted, J., Lerner, J., and Sjoblom, R. K., *Nucl. Phys.* **A208**, 287 (1973); Ahmad, I., private communication.
- [47] Clark, R. G., and Glendenin, L. E., unpublished work (personal communication).
- [48] Bemis, C. E., Jr., Silva, R. J., Hensley, D. C., Keller, O. L., Jr., Tarrant, J. R., Hunt, L. D., Dittner, P. F., Hahn, R. L., and Goodman, C. D., *Phys. Rev. Lett.* **31**, 647 (1973).
- [49] Freedman, M. S., Porter, F. T., and Mann, J. B., *Phys. Rev. Lett.* **28**, 711 (1972).
- [50] Fricke, B., Desclaux, J. P., and Waber, J. T., *Phys. Rev. Lett.* **28**, 714 (1972).
- [51] Yamazaki, T., and Hollander, J. M., *Nucl. Phys.* **84**, 505 (1966).
- [52] Wolfson, J. L., and Park, J. J. H., *Can. J. Phys.* **42**, 1387 (1964).