MASTER

UCRL- 85683
PREPRINT

CNF-810651--2

Uranium Soft-X-Ray Total-Attenuation Coefficients

N. Kerr Del Grande
A. J. Oliver

Topical Conference on
Low Energy X-Ray Diagnostics
June 8-10, 1981
Monterey, California

June 5, 1981

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
REPRODUCTION IS UNLIMITED

Uranium Soft-X-Ray Total-Absorption Coefficients

N. Kerr Del Grande and A. J. Oliver*

Lawrence Livermore National Laboratory, P. O. Box 808, Livermore, California 94550

ABSTRACT

Uranium total attenuation coefficients were measured continuously from 0.84 to 6.0 keV and at selected higher energies using a vacuum single crystal diffractometer and flow-proportional counter. Statistical fluctuations ranged from 0.5% to 2%. The overall accuracy was 3%. Prominent structure was measured within 20 eV of the M_5 (3.552 keV) and M_4 (3.728 keV) edges. Jump ratios were determined from log-log polynomial fits to data at energies apart from the near-edge regions. These data were compared with calculations based on a relativistic HFS central potential model and with previously tabulated data.

INTRODUCTION

Experimental data is needed to understand theoretical predictions for photoexcitation and photoionization of uranium. The theory of photoeffect above 10 keV has been reviewed by Pratt et al. (1) and at lower energies by Fano and Cooper. (2) The major tabulations of theoretical cross sections are due to Scofield, (3) to Storm and Israel (4) and to Veigele. (5)

Verification of theory by experiment for uranium has not been possible below 10 keV. There are no measurements from .8 to 3.1 keV as shown in Figure 1. (6) Measurement differences are nearly 80% at 3.8 keV (7,8) and more than 40% at 9.0 keV. (9,10) These discrepancies have forced authors of compilations which synthesize theory and experiment to contend with large uncertainties for uranium. (5,11-13)

Figure 1. The status of uranium attenuation coefficients in 1971. The conversion factor, 395.3, reduces the ordinate scale to cm^2/g . (From reference 6.)

It is particularly important to understand deviations from the generally used single-electron central-potential approximation. The deviations are due to exchange and correlation effects; the influence of the atomic environment; solid-state structure and bonding. Actinides have special properties that are due to the partially filled 5f shell. Their 6d and 7s electrons form the conduction band in the metal whose energy is close to the 5f binding energy. In order to understand the behavior of the 5f electrons, their degree of localization must be determined. (14) Band structures have been developed to explain the electronic properties of the actinide metals. (15) Relativistic Hartree-Fock-Slater (HFS) models have been used to calculate oscillator strengths for the $3d_{5/2} - 5f$ and $3d_{3/2} - 5f$ transitions. (3,16-19)

Measurements of emission and absorption spectra show prominent resonance lines (14,20) at energies close to the M_5 and M_4 edge energies. (21) These energies are given in Table 1. They are compared with measurements discussed in this summary paper.

Table 1. Resonance absorption line energies and related M edge energies (keV) for photoexcitation of uranium.

Edge	Transition	Edge Energy	Line Energy
M_5	$3d_{5/2} - 5f_{7/2}$	3.551 (17), 3.5512 (14,20)	3.5554*
			3.547 (16)
			3.605 (19)
M_4	$3d_{3/2} - 5f_{5/2}$	3.7276 (22), 3.7254 (14,20)	3.7287*
			3.728 (16)
			3.780 (19)

*Based on 3: total attenuation measurements by Del Grande and Oliver.

The Lawrence Livermore National Laboratory developed a technique to obtain absolute-value total attenuation coefficients. (22) This technique was applied to uranium. (11,23) This paper reports new data which extend the existing measurement region to include 0.844 to 3.000 keV. It gives details of the areas under the M_5 and M_4 x-ray absorption peaks. These areas relate to oscillator strengths for the $3d-5f$ bound-bound transitions. They are compared with recent calculations (16,19). Details of these data and their implications are discussed here-in.

EXPERIMENTAL PROCEDURE AND RESULTS

Del Grande and Oliver measured the magnitude and extended range of x-ray K-absorption fine structure for transition elements Ti-Zn. (22) The procedure for obtaining 1% total attenuation coefficients at selected energies from 5 to 45 keV was discussed in detail. A double-Be-window demountable-tube x-ray generator by

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore Laboratory under contract No. W-7405-Eng-88.

Hilger and Watts was used in conjunction with two crystal spectrometers. Figure 2 shows the configuration for one of the spectrometers. Figure 3 is a block diagram of the electronic system.

Figure 2. The single crystal spectrometer. The 4 mm line focus beam had a narrow (0.15 mm) spread at the crystal not shown on the schematic.

Figure 3. A block diagram of the electronic system.

A Ag target was used for measurements at energies above 5 keV. The impurities in the target provided a convenient way to align the spectrometer. These impurities (e.g., Fe, Ni, Cu and W) were assumed to have emission line energies tabulated by Dr. J.A. Bearden. (24) A LiF crystal was used in the spectrometer. The gas used in the flow proportional counter was H_2 .

Both a Mo target and a multielement target were used for measurements at energies below 5 keV. The multielement target had 10^4 Å of Al vapor-deposited on a Cr target with additional impurities of Nd and W. These measurements required a Siemens vacuum spectrometer which was used with either a pyrolytic graphite crystal, a lead stearate crystal (provided by Dr. Burton Henke) or a KAP crystal. The soft x-ray measurements required using a 9 µm Be window (coated with formvar) to separate the x-ray tube from the spectrometer chamber. The flow proportional counter gas was methane at 10 cm H_2O above atmospheric pressure.

Thin free-standing Be-U-Be sandwich foils were vacuum evaporated by the Battelle Columbus Laboratory. Sixteen foils were prepared at a given time, using a precision mask. Some foils were Be-only foils. They had the same amount of Be as the two protective layers of Be, each about $42 \mu\text{g}/\text{cm}^2$. The Be-coatings prevented the U sandwich foils from oxidizing. The foils were

deposited on smooth glass substrates and floated off the substrates. They were weighed. Some foils were analyzed for impurities (from the releasing agent) using an ion probe. Other foils were mounted on filter-wheels in shock-proof containers. The uranium samples contained about $125 \mu\text{g}/\text{cm}^2$ and $340 \mu\text{g}/\text{cm}^2$ of uranium. Many of the thin foils did not survive both the aircraft vibrations and transporting the filter wheel to the vacuum spectrometer.

Several methods were used to estimate the uranium content of the sandwiches (e.g., weights, ion exchange calorimetry, ultraviolet fluorimetry and controlled potential coulometry). We believe the accuracy of these results to be between 10% and 15%, although original estimates were 5%. (23)

We needed to reduce the measurement uncertainties associated with determining the thin sandwich foil uniformity, purity and thickness. Hence, we took more x-ray measurements using thicker rolled foils. These foils had average weight per unit area of about $34 \text{ mg}/\text{cm}^2$. Their uranium contents and uniformities were known to within 1%. Their x-ray transmissions were recorded at 8.000, 9.9615 and 15.000 keV. The sturdiest and most uniform Be-U-Be sandwich foil had no evidence of damage from releasing or mounting. Hence, this foil was used for measurements from 0.844 to 6.000 keV. It was calibrated at 8.000 and 9.9615 keV, using the same procedure as was used to calibrate the rolled U foils, but with one difference. The Be-U-Be sandwich was measured relative to the Be-only foil which had been deposited at the same deposition time. The uranium content of the sandwich foil was thus determined by comparison with the rolled foils of known weight per unit area. It was $384 \mu\text{g}/\text{cm}^2$ with an uncertainty of 2%.

Usually two or more measurements consisting of ten pairs (but occasionally up to twenty) of Be-U-Be followed by Be-only measurement periods, provided standard deviations of the mean error, ranging from 0.2 to 2%. These measurements were followed by background measurements. The backgrounds were determined using exit slits $2^\circ \times 2^\circ$ on both sides of the diffracted beam. Corrections for backgrounds were typically 1 or 2%. Dead time corrections were less than 1%. Overall errors were 3% for uranium total attenuation coefficients at energies from 0.844 to 6.000 keV in Table 2. The additional data from 8.000 to 40.000 keV in Table 2 had overall errors of 2%. Most of these data were reported previously in Vol. 3 of McMaster et al. (11) and as reference 69DE1 in Figure 1 (6).

The absolute measurement energies of continuum radiation were known to 3 or 4 eV. Uncertainties were 2 eV relative to tabulated emission line energies for W(M), Mo(L), Mo(L), Cr(K) and Al(K). The alignment was done in first or second order. Multiple orders were separated with discriminators on the multichannel analyzer. Higher order radiations did not affect measurements because they were eliminated by reducing the target voltage sufficiently.

Previous measurements for the uranium resonance absorption lines in Figure 4 were 3 or 4 eV lower in excitation voltage energies (14,20) as shown in Table 1. Also, the clean-surface uranium M and O shell binding energies (25) average 3 or 4 eV lower than the tabulated x-ray values (21). Measurements apparently specify the resonance line and M-edge energies better than present theoretical calculations (16,19).

Figure 4 shows the transitions of $3d_{5/2}$ electrons to $5f_{7/2}$ vacancies and $3d_{3/2}$ electrons to $5f_{5/2}$ vacancies. The M₅ and M₄ edges (dashed) were assumed to be symmetric about their tabulated energies (21) with the resolution measured at the M₃ edge which did not have structure. These photoionization data were subtracted from the total photoexcitation plus photoionization peak values to determine the areas under the photoexcitation resonance lines. These areas were measured to within $\pm 5\%$. They were each fit to a Gaussian with a full width at half maximum of 17.5 eV.

Table 2. Uranium attenuation coefficients, $\mu(\text{cm}^2/\text{g})$ at energies $E(\text{keV})$ from 0.844 to 47.309 keV.

E	μ	E	μ	E	μ
1 6.400E-01	7.970E+03	71 1.5974E+00	3 2950E+03	141 3.960E+00	1.230E+03
2 6.400E-01	7.950E+03	72 1.5700E+00	3 1400E+03	142 3.970E+00	1.210E+03
3 6.400E-01	7.930E+03	73 1.5400E+00	3 0530E+03	143 3.9870E+00	1.200E+03
4 6.400E-01	7.910E+03	74 1.5100E+00	3 0150E+03	144 4.000E+00	1.190E+03
5 6.400E-01	7.890E+03	75 1.6000E+00	3 0270E+03	145 4.0250E+00	1.170E+03
6 6.400E-01	7.870E+03	76 1.6200E+00	3 0390E+03	146 4.0440E+00	1.160E+03
7 6.400E-01	7.850E+03	77 1.6400E+00	3 0510E+03	147 4.060E+00	1.150E+03
8 6.400E-01	7.830E+03	78 1.6600E+00	2 8810E+03	148 4.070E+00	1.130E+03
9 6.400E-01	7.810E+03	79 1.6800E+00	2 8230E+03	149 4.080E+00	1.130E+03
10 6.400E-01	7.790E+03	80 1.7000E+00	2 7170E+03	150 4.1220E+00	1.120E+03
11 6.400E-01	7.770E+03	81 1.7200E+00	2 6360E+03	151 4.140E+00	1.140E+03
12 6.400E-01	7.750E+03	82 1.7400E+00	2 5820E+03	152 4.1610E+00	1.170E+03
13 6.400E-01	7.730E+03	83 1.7600E+00	2 5500E+03	153 4.1800E+00	1.080E+03
14 6.400E-01	7.710E+03	84 1.7800E+00	2 4710E+03	154 4.2000E+00	1.080E+03
15 6.400E-01	7.690E+03	85 1.8349E+00	2 2890E+03	155 4.200E+00	1.0790E+03
16 6.400E-01	7.670E+03	86 2.0000E+00	1.9020E+03	156 4.2200E+00	1.0750E+03
17 6.400E-01	7.650E+03	87 2.0400E+00	1.6030E+03	157 4.2400E+00	1.0870E+03
18 6.400E-01	7.630E+03	88 2.2532E+00	1.3810E+03	158 4.2600E+00	1.0550E+03
19 6.400E-01	7.610E+03	89 2.5000E+00	1.1560E+03	159 4.2700E+00	1.070E+03
20 6.400E-01	7.590E+03	90 2.8000E+00	8.6720E+02	160 4.2800E+00	1.0920E+03
21 6.400E-01	7.570E+03	91 3.0000E+00	7.3290E+02	161 4.2900E+00	1.0610E+03
22 6.400E-01	7.550E+03	92 3.2000E+00	6.3590E+02	162 4.3000E+00	1.0710E+03
23 6.400E-01	7.530E+03	93 3.5000E+00	5.6030E+02	163 4.3100E+00	1.1520E+03
24 6.400E-01	7.510E+03	94 3.8190E+00	4.8960E+02	164 4.3200E+00	1.1930E+03
25 6.400E-01	7.490E+03	95 4.1680E+00	4.3000E+02	165 4.3300E+00	1.1990E+03
26 6.400E-01	7.470E+03	96 4.5480E+00	3.8530E+02	166 4.3400E+00	1.160E+03
27 6.400E-01	7.450E+03	97 4.9570E+00	3.4300E+02	167 4.3500E+00	1.1660E+03
28 6.400E-01	7.430E+03	98 5.3970E+00	3.0510E+02	168 4.3600E+00	1.1600E+03
29 6.400E-01	7.410E+03	99 5.8680E+00	2.7070E+02	169 4.3700E+00	1.170E+03
30 6.400E-01	7.390E+03	100 6.3700E+00	2.3960E+02	170 4.3800E+00	1.140E+03
31 6.400E-01	7.370E+03	101 6.8950E+00	2.1000E+02	171 4.3900E+00	1.130E+03
32 6.400E-01	7.350E+03	102 7.4400E+00	1.810E+02	172 4.400E+00	1.140E+03
33 6.400E-01	7.330E+03	103 7.990E+00	1.530E+02	173 4.410E+00	1.140E+03
34 6.400E-01	7.310E+03	104 8.560E+00	1.260E+02	174 4.420E+00	1.140E+03
35 6.400E-01	7.290E+03	105 9.140E+00	1.000E+02	175 4.430E+00	1.140E+03
36 6.400E-01	7.270E+03	106 9.730E+00	7.500E+01	176 4.440E+00	1.140E+03
37 6.400E-01	7.250E+03	107 1.0340E+00	5.000E+01	177 4.450E+00	1.140E+03
38 6.400E-01	7.230E+03	108 1.0960E+00	3.500E+01	178 4.460E+00	1.140E+03
39 6.400E-01	7.210E+03	109 1.1600E+00	2.000E+01	179 4.470E+00	1.140E+03
40 6.400E-01	7.190E+03	110 1.2260E+00	1.500E+01	180 4.480E+00	1.140E+03
41 6.400E-01	7.170E+03	111 1.2940E+00	1.000E+01	181 4.490E+00	1.140E+03
42 6.400E-01	7.150E+03	112 1.3640E+00	7.000E+00	182 4.500E+00	1.140E+03
43 6.400E-01	7.130E+03	113 1.4360E+00	5.000E+00	183 4.510E+00	1.140E+03
44 6.400E-01	7.110E+03	114 1.5100E+00	3.500E+00	184 4.520E+00	1.140E+03
45 6.400E-01	7.090E+03	115 1.5860E+00	2.500E+00	185 4.530E+00	1.140E+03
46 6.400E-01	7.070E+03	116 1.6640E+00	1.800E+00	186 4.540E+00	1.140E+03
47 6.400E-01	7.050E+03	117 1.7440E+00	1.300E+00	187 4.550E+00	1.140E+03
48 6.400E-01	7.030E+03	118 1.8260E+00	1.000E+00	188 4.560E+00	1.140E+03
49 6.400E-01	7.010E+03	119 1.9100E+00	7.000E+00	189 4.570E+00	1.140E+03
50 6.400E-01	6.990E+03	120 1.9960E+00	5.000E+00	190 4.580E+00	1.140E+03
51 6.400E-01	6.970E+03	121 2.0840E+00	3.500E+00	191 4.590E+00	1.140E+03
52 6.400E-01	6.950E+03	122 2.1740E+00	2.500E+00	192 4.600E+00	1.140E+03
53 6.400E-01	6.930E+03	123 2.2660E+00	1.800E+00	193 4.610E+00	1.140E+03
54 6.400E-01	6.910E+03	124 2.3600E+00	1.300E+00	194 4.620E+00	1.140E+03
55 6.400E-01	6.890E+03	125 2.4560E+00	1.000E+00	195 4.630E+00	1.140E+03
56 6.400E-01	6.870E+03	126 2.5540E+00	7.000E+00	196 4.640E+00	1.140E+03
57 6.400E-01	6.850E+03	127 2.6540E+00	5.000E+00	197 4.650E+00	1.140E+03
58 6.400E-01	6.830E+03	128 2.7560E+00	3.500E+00	198 4.660E+00	1.140E+03
59 6.400E-01	6.810E+03	129 2.8600E+00	2.500E+00	199 4.670E+00	1.140E+03
60 6.400E-01	6.790E+03	130 2.9660E+00	1.800E+00	200 4.680E+00	1.140E+03
61 6.400E-01	6.770E+03	131 3.0740E+00	1.300E+00	201 4.690E+00	1.140E+03
62 6.400E-01	6.750E+03	132 3.1840E+00	1.000E+00	202 4.700E+00	1.140E+03
63 6.400E-01	6.730E+03	133 3.2960E+00	7.000E+00	203 4.710E+00	1.140E+03
64 6.400E-01	6.710E+03	134 3.4100E+00	5.000E+00	204 4.720E+00	1.140E+03
65 6.400E-01	6.690E+03	135 3.5260E+00	3.500E+00	205 4.730E+00	1.140E+03
66 6.400E-01	6.670E+03	136 3.6440E+00	2.500E+00	206 4.740E+00	1.140E+03
67 6.400E-01	6.650E+03	137 3.7640E+00	1.800E+00	207 4.750E+00	1.140E+03
68 6.400E-01	6.630E+03	138 3.8860E+00	1.300E+00	208 4.760E+00	1.140E+03
69 6.400E-01	6.610E+03	139 4.0100E+00	1.000E+00	209 4.770E+00	1.140E+03
70 6.400E-01	6.590E+03	140 4.1360E+00	7.000E+00	210 4.780E+00	1.140E+03

The relationship of $\mu(\text{cm}^2/\text{g})$ to the oscillator strength per keV, f/dE , is a constant equal to 277.81 $\text{cm}^2 \text{g}^{-1} \text{keV}$. The measured oscillator strengths were 0.084 ± 0.013 for M_2 and 0.050 ± 0.008 for M_4 bound-bound transitions.

Figure 4. Measured photoexcitation of 3d electrons to vacancies in the partially filled 5f states.

Two relativistic M_4 calculations were made to determine the M_2 and M_4 photoexcitation oscillator strengths (16, 19). One used the Dirac equation to calculate wave functions (16). The other used the Schrodinger equation with the Pauli approximation to account for relativistic effects (19). The differences shown in Figure 4 were about 8%. The theoretical values were about twice the measurement values. This suggests that the 5f states are non-localized. Part of the bound-bound transitions may go to the continuum states (i.e., photoionization, in contrast to photoexcitation). This would explain the unusually high logarithmic slope for the photoeffect versus energy relationship above the M_2 edge as shown in Table 3.

Figure 5 indicates that there is good qualitative agreement between theory and experiment for the photoexcitation peaks. Since the theoretical calculation did not determine the resonance line energies precisely, they were shifted to line up with the measurements. Also, the calculations were folded with a Gaussian which had a full width at half maximum of 15 eV.

Table 3. $\log_e \mu$ versus $\log_e E$ linear and quadratic regression fits to 3% measurements of uranium attenuation coefficients, μ_F (cm²/g) compared with theory (3) and compilations (11,12).

Edge	Energy keV ^a	λ	μ	Log _e Fit Coefficients ^b			$\mu_F(E^*)$ cm ² /g	$\mu_F(E^*)$ cm ² /g	Percent μ_F is above other μ values					
				a_0	a_1	a_2			Scofield, ³ 1973	near E [*]	near E [*]	near E [*]	near E [*]	near E [*]
N ₃	1.0449	1.048	8.788	-1.231			6208	6509	1.3	-0.1	-10.8	-6.5	2.4	
N ₂	1.2726	1.009	8.856	-1.700			4655	4695	2.8	2.3	5.5	6.4	-3.8	
N ₁	1.4408	1.001	8.884	-1.783			3763	3765	4.5	2.6	10.8	8.4		-7.1
M ₅	3.5517	2.299	8.903	-1.707	-0.3466		484.3	1111	-7.9	-12.2	-7.0	1.9		
M ₄	3.7276	1.478	11.566	-3.593			933.7	1380	-16.2	-12.8	-3.2	5.5		
M ₃	4.303	1.167	9.830	-1.976			1039	1213	-6.6	-6.0	14.5	-0.6		
M ₂	5.182	1.058	10.572	-2.378			779.6	824.6	-4.1	-4.2	2.4	-4.7		
M ₁	5.548	1.024	10.554	-2.333			703.3	720.1	-3.4	-5.1	-3.2	-8.1		
L ₃	17.1663	2.329	9.842	-1.566	-0.1972		44.49	103.6	-4.7	-3.2	-3.1	3.1		
L ₂	20.9476	1.372	11.752	-2.501			62.94	86.33	-0.1	-2.3	1.9	0.3		
L ₁	21.7574	1.158	11.170	-2.706			79.40	91.98	-1.1	-0.4	1.4	1.7		

^aFrom J.A. Bearden and A.F. Burr, Rev. Mod. Phys. 39, 125 (1967)

^bFit parameters for 174 data values with 2% or better precision and 0.4% or better standard errors of the mean (avoiding structure regions). Fit parameters apply to energy region above edge energy

$\log_e$ of attenuation coefficients versus $\log_e$ of energy fits are given in Table 3.

Figure 5. Comparison of 3% experimental data, adjusted theoretical data (19) and compiled uranium attenuation coefficients which ignore structure (13) near the M₅ and M₄ edges of uranium.

NEW DATA COMPARED WITH OTHER RESULTS

The 3% uranium attenuation coefficients near the M₅ and M₄ edges are significantly different from theory (19) and compilation values (13). The percentage differences of the measurements from other results are shown in Figure 6. Apart from the M-edge region, differences are shown in Figure 7, Figure 8 and Figure 9. Percent differences relative to smooth

Figure 6. Comparison of uranium experimental data with adjusted theoretical data (19) and compiled data (13) for photoionization near photoexcitation peak energies.

Figure 7. Uranium attenuation coefficients.

Figure 8. Uranium attenuation coefficients.

Jumps were measured at three N edges, five M edges and three L edges based on log-log, linear and quadratic regression fits to the structureless data between edges. The data minus fit differences averaged about 0.0%. The standard deviations of the mean error were 0.4% or less. The standard deviation of individual data values from the smooth fit values, outside of regions with structure, were 2% or less. In one instance, the M_5 and M_4 edge jumps were based on smooth fit parameters above the M_5 edge, and below the M_4 edge, extended to the Cr K α emission line energy at 5.4147 keV. These jumps produced simulated data values at the M_1 and M_2 edges, although there was only one measured value between these edges. Data elsewhere were numerous between edges as shown in Table 2.

CONCLUSION

New 3% uranium total attenuation coefficient data extends the measurement region to include 0.844 to 3.000 keV. Agreement with relativistic HFS calculations (3) is typically 1-4% apart from the M edge region. The

Figure 9. Comparison of uranium experimental data with compiled data (13) for the attenuation coefficient from 0.84 to 8.0 keV.

photoionization data are 3-16% lower than theory, from 3.5 to 5.5 keV (between the M edges) when photoexcitation is ignored.

Measured oscillator strengths were about half the predicted values based on two calculations (16,19). This suggests that the 5f unoccupied states are in part non-localized.

REFERENCES

1. R. W. Pratt, A. Ron, H. K. Tseng, *Rev. Mod. Phys.*, **45**, 273, 1973.
2. U. Fano and J. W. Cooper, *Rev. Mod. Phys.*, **40**, 441, 1968.
3. J. Scofield, Lawrence Livermore Laboratory Report UCLRL-51326, p. 313-318, Univ. of Ca., Livermore, 1973.
4. E. Storm and H. I. Israel, *Nucl. Data Tables*, **A7**, 565, 1970.
5. W. J. Veigele, *Atomic Data Tables*, **5**, 51, 1973.
6. J. H. Hubbell, *Atomic Data*, **3**, 241, 1971.
7. G. V. Bezdrozhnykh, A. I. Zapysov, I. M. Israilev, V. N. Ganyrkin, *Opt. i Spektroskopiya* **23**, 980, 1967.
8. S. J. M. Allen, *Phys. Rev.*, **26**, 901, 1926 (Also: *Phys. Rev.*, **24**, 1, 1924, *ibid* **27**, 366, 1926.)
9. J. L. Perkins, A. C. Douglas, *Proc. Phys. Soc. (London)*, **92**, 618, 1967.
10. R. B. Roof Jr., *Phys. Rev.*, **113**, 120, 1959.
11. W. H. McMaster, N. Kerr Del Grande, J. H. Mallett and J. H. Hubbell, Lawrence Livermore Laboratory Report UCLRL-50174, Sec. 2, *Rev. 1*, p. 343-346, Sec. 3, p. 191-192, Univ. of Ca., Livermore, 1969.
12. C. L. Henke and E. S. Ebisu in *Advances in X-Ray Analysis*, Vol. 17, Ed. by C. L. Grant, C. S. Barnett, J. B. Newkirk and C. O. Rudd (Plenum Press, New York and London, 1974), p. 150-213.
13. E. F. Plechaty, D. E. Cullen and R. J. Howerton, Lawrence Livermore Laboratory Report UCLRL-50400, Vol. 6, *Rev. 2*, Univ. of Ca., Livermore, 1978, p. 470-475.
14. C. Bonelle in *Structure And Bonding*, Vol. 31, Ed. by J. D. Dunitz, P. Hemmerich, J. A. Ibers, C. K. Jorgensen, J. B. Neiland, R. Reinert, R. J. P. Williams, (Springer-Verlag, Berlin, Heidelberg, New York, 1976) p. 24-48.

15. A. J. Freeman and D. D. Koelling in The Actinides, Vol. 2, (Academic Press, New York, 1974), Ch. 6.
16. J. Scofield, private communication, 1981.
17. B. F. Rozsnyai, Phys. Rev. A, 5, 1137, 1972.
18. B. F. Rozsnyai, J. Quant. Spectrosc. Radiat. Transfer, 13, 1285, 1973.
19. B. F. Rozsnyai, private communication, 1981.
20. C. Bonnelle and G. Lachere, J. de Phys. 35, 295, 1974.
21. J. A. Bearden and A. F. Burr, Rev. Mod. Phys., 39, 125, 1967.
22. N. Kerr Del Grande and A. J. Oliver, in X-Ray Spectra And Electronic Structure of Matter, Vol. 1, Proc. International Symp. Ed. by A. Faessler and G. Ziegler, Munich, 1973 p. 183-204.
23. N. Kerr Del Grande and A. J. Oliver, Bull. Amer. Phys. Soc. Ser. II, Vol. 18, 635, 1973.
24. J. A. Bearden, Rev. Mod. Phys. 39, 78, 1967.
25. R. L. Park and J. E. Houston, Phys. Rev. A, 7, 1447, 1973.