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$K\alpha_2/K\alpha_1$ X-Ray Intensity Ratios for $Z>50$†

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The $K\alpha_2/K\alpha_1$ x-ray intensity ratios for 36 elements between $_{51}$Sb and $_{95}$Am have been measured with a Cauchois-type bent-crystal spectrometer and a Ge(Li) detector. The present experimental results are systematically 5–10% higher than the values reported by Beckman and by Wapstra *et al.*, but agree within experimental errors with the recent theoretical calculations of Scofield.

INTRODUCTION

Measurements of the $K\alpha_2/K\alpha_1$ x-ray ratios have been carried out by Williams ($24 \leq Z \leq 52$),[1] Meyers ($23 \leq Z \leq 49$),[2] and Beckman ($73 \leq Z \leq 92$).[3,4] In addition to these systematic studies, there have been measurements made on a few specific elements. Wapstra *et al.*[5] give a table of $K\alpha_2/K\alpha_1$ x-ray ratios as a function of Z for $16 \leq Z \leq 100$. Their values are derived from a graph drawn smoothly through the experimental values of Williams, Meyers, and Beckman.[1–4]

Relativistic calculations have been carried out by Massey and Burhop,[6] Laskar,[7] Payne and Levinger,[8] Asaad,[9] Taylor and Payne,[10] Babushkin,[11] and recently by Scofield.[12] Only Babushkin and Scofield properly include the effect of retardation. Babushkin uses a Coulomb potential with an effective nuclear charge to account for the screening of the nucleus by the electrons, while Scofield[12] uses the central potential given by the relativistic Hartree-Slater theory. Scofield's theoretical values are larger than those of Babushkin[11] which in turn are larger than the experimental values of Beckman[3,4] and the smooth curve of Wapstra *et al.*[5] Because of these discrepancies and the lack of experimental values between $_{53}$I and $_{72}$Hf, we have measured the $K\alpha_2/K\alpha_1$ x-ray ratios for elements with $Z>50$.

EXPERIMENTAL DETAILS

In the present experiments, two methods were used to determine the $K\alpha_2/K\alpha_1$ x-ray ratios. For elements up to and including $_{78}$Pt, a Cauchois-type bent-crystal spectrometer was used to determine the $K\alpha_2/K\alpha_1$ ratios. In this method, the bent-crystal spectrometer was set at the diffraction maximum for a given x-ray line. The number of counts per minute recorded in the Ge(Li) detector of the spectrometer is assumed to be proportional to the intensity of the line. It should be pointed out that in the case of x rays where the natural width is comparable to the instrumental width, this is a good assumption when comparing the intensity of x rays with nearly the same linewidths, as in the case with $K\alpha_1$ and $K\alpha_2$ x rays of the same element. In the general case, one must use the area under the diffraction curve to determine the intensity. However, the disadvantage in this case is that the area of the diffraction peak is difficult to determine because of the long tails characteristic of the Lorentzian shape of the x-ray line. For elements with $Z > 78$, the spectrometer was set at zero Bragg angle and the ratios were determined from pulse-height spectra obtained with the thin window Ge(Li) detector. In this region, the Ge(Li) detector had sufficient resolution to separate the $K\alpha_1$ and $K\alpha_2$ x-ray peaks without using diffraction. This eliminated one of the corrections necessary with the bent-crystal spectrometer method, namely, the correction for reflectivity of the bent crystal.

The 2-m Cauchois-type bent-crystal spectrometer used in the present measurements is described by Jewell *et al.*[13] Figure 1 is a schematic top view of this spectrometer. The K x rays which are being fluoresced by a 50-Ci Ta^{182} source are diffracted by the (310) planes of a 2-mm-thick quartz crystal. The diffracted rays converge at the 0.176-mm-wide detector slit and are recorded in the 2-cm^3 thin-window Ge(Li) detector.

Most of the targets used in this experiment consisted of 2.5×7.6-cm metal foils with thicknesses of 0.02–0.05 cm. The U, Bi, and Sb targets ranged from 0.2 to 0.4 cm in thickness. The Tl, Hg, Os, Ba, Cs, I, and Te targets consisted of the material in powder form sealed in a 2.5×7.6 ×0.43-cm Lucite holder. The Am, Pu, and Np sources were sealed in Al cans to prevent radioactive contamination.

In the low Z region, where the bent-crystal spectrometer was used, the relative intensity of the $K\alpha_2$ x ray was obtained by first locating the $K\alpha_2$ diffracted peak position. This was determined from a plot of counts versus position, obtained by automatically stepping the detector slit 200 steps of 0.01 mm each across the diffraction peak. A single-channel analyzer was used to select the energy region of interest. The spectrometer and slit were then set at the peak position and the x-ray pulse-height spectrum was recorded. The relative intensity represented by the area under the pulse-height spectrum was obtained from a nonlinear least-squares fit of the sum of a Gaussian and a quadratic background to the data points. Figure 2 shows a computer fit to the $K\alpha_2$ pulse-height peak of Eu. The total number of counts falling within the single-channel analyzer window with the spectrometer and slit set at the $K\alpha_2$ peak position was also recorded. Background for the single-channel analyzer data were determined by replacing the foil under investigation with a Mo foil, maintaining the spectrometer and slit at the same position and recording the counts within the single-channel analyzer window. The $K\alpha_1$ intensity was measured by similar procedures. The uncorrected $K\alpha_2/K\alpha_1$ x-ray ratios were then determined by averaging the intensities measured from the pulse-height spectra with the single-channel analyzer data.

In the case of elements with $Z > 78$, where the Ge(Li) detector had sufficient resolution to separate the $K\alpha_1$ and $K\alpha_2$ peaks, the bent-crystal spectrometer was set at zero Bragg angle and the

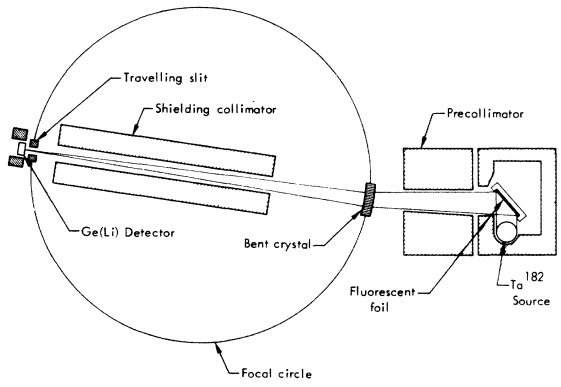

FIG. 1. Schematic top view of the bent-crystal spectrometer. Shaded areas are lead.

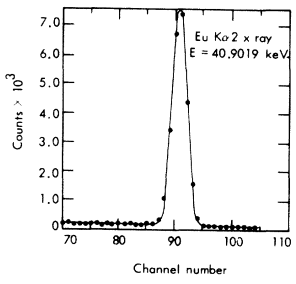

FIG. 2. Computer fit to the Eu $K\alpha_2$ pulse-height spectrum recorded in the diffracted position.

pulse-height spectra were recorded. Except for the absorption due to the quartz crystal, these pulse-height spectra are the same as those recorded with a conventional Ge(Li) detector system. In this case, the spectra were fitted by a function which consisted of a sum of two Gaussians plus a quadratic background. Figure 3 is a computer fit to the $K\alpha_1$ and $K\alpha_2$ x-ray pulse-height spectrum of Am.

The $K\alpha_2/K\alpha_1$ x-ray ratios for elements $_{51}$Sb to $_{95}$Am were then determined by correcting the relative ratios for the efficiency of the Ge(Li) detector, the self-absorption in the source, the absorption in the quartz crystal, the absorption in the air path between the source and detector, and, in the case of the data obtained from the diffracted peak height, the reflectivity of the quartz crystal. Calibrated Co^{57}, Am^{251}, and Cd^{109} sources were used to determine the detector efficiency as a function of energy in the range of 14–135 keV. Figure 4 is a plot of the corrections applied to the $K\alpha_2/K\alpha_1$ x-ray ratios due to the efficiency of the detector and the absorption due to the quartz crystal and the air path. This correction is predominantly due to the energy-dependent efficiency of the Ge(Li) detector. The self-absorption corrections to the $K\alpha_2/K\alpha_1$ x-ray ratios were determined from

$$R = \sum_i w_i \frac{\mu_1 + \mu_{0i}}{\mu_2 + \mu_{0i}} \left(\frac{1 - e^{-(\mu_{0i} + \mu_2)D}}{1 - e^{-(\mu_{0i} + \mu_1)D}} \right),$$

where R is the ratio of self-absorption corrections, w_i is the fraction of the total γ-ray intensity due to the ith Ta^{182} γ ray, μ_1 and μ_2 are the total absorption coefficients for the $K\alpha_1$ and $K\alpha_2$ x rays of the fluorescent foil, μ_{0i} is the total absorption coefficient for the ith Ta^{182} γ ray, and D is $\sqrt{2}$ times the thickness of the foil. The appropriate absorption coefficients were obtained from the table of Storm *et al.*[14] The Ta^{182} γ-ray relative intensities were taken from the Lederer *et al.*[15] The self-absorption corrections varied from 1 to 5%. Lind, West, and DuMond[16] have investigated the quartz crystal reflectivity in the region of 25–1332 keV and have found that it varies as E^{-2}. In the present experiment, a E^{-2} reflectivity was assumed for all x-ray energies. Because of the small $K\alpha_1$-$K\alpha_2$ energy difference, any deviation of the exponent from exactly 2 would introduce only a small error in the $K\alpha_2/K\alpha_1$ x-ray ratio. For example, at $Z = 51$ only a 1% error would result from using an exponent of 1.

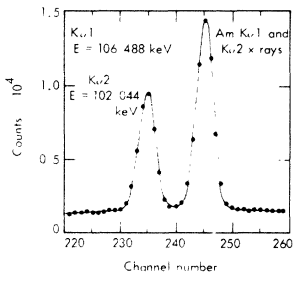

FIG. 3. Computer fit to the Am $K\alpha_1 + K\alpha_2$ pulse-height spectrum recorded with the spectrometer set at zero Bragg angle.

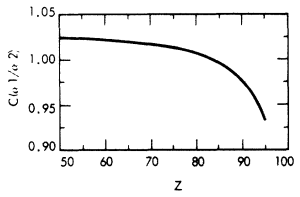

FIG. 4. Efficiency and quartz and air-absorption corrections applied to the $K\alpha_2/K\alpha_1$ ratios as a function of Z.

RESULTS AND DISCUSSION

Table I lists the present results for the $K\alpha_2/K\alpha_1$ x-ray ratios along with the values obtained from Scofield's K x-ray emission rates. The statistical plus systematic errors in the present values are estimated to be 4% for elements where the direct pulse-height spectra were used to determine the intensity ratios (above Pt) and 5% for elements where the diffracted pulse-height spectra were used. A more clear comparison of the measured values and the theoretical calculations are made in Fig. 5. As can be seen from the graph, the present results are in good agreement with the theoretical calculations of Scofield, but do not agree with the calculations of Babushkin or with the measured values of Beckman and the smooth curve of Wapstra *et al.* Since the diffracted peak-height method used in this work was similar to that used by Beckman, the difference in the experimental values probably lies in the applied corrections. Of the corrections that were applied to the relative areas to determine the $K\alpha_2/K\alpha_1$ x-ray ratios, the most difficult to determine was the self-absorption correction. In Beckman's case, where high-energy electrons were used to excite the x rays, it was necessary for him to make the difficult correction for excitation of the x rays as the electrons slowed down in the target. When γ rays are used to excite the x rays, as was the case in the present experiments, the correction is much simpler to calculate.

During the preparation of this manuscript, unpublished data of Ebert and Slivinsky[17] were made available to us. They have measured the $K\alpha_2/K\alpha_1$ x-ray ratios for eleven elements from $_{62}$Sm to $_{92}$U with a high resolution Ge(Li) detector. Their ex-

TABLE I. A comparison of the experimentally determined $K\alpha_2/K\alpha_1$ x-ray ratios with the calculated values of Scofield.

Z	Element	$K\alpha_2/K\alpha_1$ ratio Present results	Scofield
51	Sb	0.517	0.534
52	Te	0.527	0.537
53	I	0.536	0.539
55	Cs	0.540	0.542
56	Ba	0.562	0.543
57	La	0.564	0.545
58	Ce	0.508	0.546
59	Pr	0.530	0.548
60	Nd	0.532	0.549
62	Sm	0.540	0.553
63	Eu	0.549	0.554
64	Gd	0.569	0.556
65	Tb	0.562	0.558
66	Dy	0.551	0.560
67	Ho	0.560	0.562
68	Er	0.522	0.564
69	Im	0.576	0.566
70	Yb	0.587	0.568
71	Lu	0.585	0.570
72	Hf	0.571	0.572
73	Ta	0.554	0.574
74	W	0.578	0.576
75	Re	0.587	0.578
76	Os	0.602	0.581
77	Ir	0.577	0.583
78	Pt	0.563	0.585
79	Au	0.585	0.588
80	Hg	0.595	0.590
81	Tl	0.574	0.593
82	Pb	0.596	0.596
83	Bi	0.599	0.598
90	Th	0.610	0.619
92	U	0.610	0.626
93	Np	0.635	0.629
94	Pu	0.630	0.633
95	Am	0.619	0.636

perimental results are in good agreement with the present measurements.

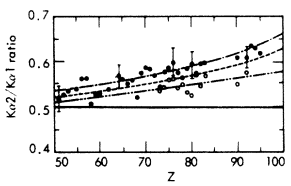

FIG. 5. Comparison of the experimental and theoretical $K\alpha_2/K\alpha_1$ x-ray ratios. Solid circle, this work; open circle, Beckman; solid line, nonrelativistic value; dot-dash-line, Scofield; dashed line, Babushkin; dot-dot-dashed line, Wapstra *et al.*

SUMMARY

A 2-m Cauchois-type bent-crystal spectrometer and a Ge(Li) detector have been used to determine the $K\alpha_2/K\alpha_1$ x-ray ratios for 36 elements from $_{51}$Sb to $_{95}$Am. Experimental values in the region of $52 < Z < 73$ have been determined for the first time. A comparison of the experimental results with those of Beckman ($Z \geq 73$) shows the present results to be systematically 5 to 10% higher. The present results are in good agreement with the calculations of Scofield, which are based on the central potential given by the relativistic Hartree-Slater theory.

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Measurement of the Radiation Emitted f Values and Stark Half-Widths for the Strong Vacuum Ultraviolet Lines of O I and N I†

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Vacuum ultraviolet atomic nitrogen and oxygen lines can contribute significantly to the transfer of energy in a high-density plasma for temperatures in the order of 1 eV. To calculate the amount of energy transferred via these lines for optically thick conditions, the f value and Stark half-widths are needed. This paper presents experimental measurements of these parameters which were obtained from a graphical solution to the curve of growth. The results are compared with theory and other experimental data. A comparison is also made between experiment and theory for the radiation emitted normally from an infinite homogeneous slab by the strongest ultraviolet multiplets of these gases.

INTRODUCTION

Atomic nitrogen lines in the vacuum ultraviolet contribute significantly to the energy transfer in a nitrogen plasma. At temperatures in the order of 1 eV and greater they have been found to transport as much energy in an arc column as by thermal conduction.[1] Presently, there is little experimental data available for the parameters needed to calculate this mode of radiation transfer. For high-density plasmas where a Voigt profile may be assumed as a first approximation for the line shape, the parameters needed for a calculation of the line radiation transfer are the Stark linewidth at half-intensity and the f value. Electron broadened line half-widths in the vacuum ultraviolet are very difficult to determine by direct measurement because they are extremely small. Fortunately, for most conditions where lines are important, the radiation transfer is very nearly proportional to the square root of the product of f value and half-width. This quantity may be readily determined from low-dis-