Measurements of $K\alpha_2$ to $K\alpha_1$ intensity ratios for $62 \leq Z \leq 82$ by 3.5-MeV proton bombardment

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Systematic measurements of $K\alpha_2$ to $K\alpha_1$ intensity ratios have been carried out for a wide range of targets with $62 \leq Z \leq 82$ using 3.5-MeV protons. The total uncertainty in the measured values is mostly less than 0.5%. All the results agree with Scofield's calculations within the uncertainty.

The ratios of K-shell emission rates $I(K\alpha_2/K\alpha_1)$ have been extensively measured for a whole region of the atomic table.[1,2] According to the compilation of Salem *et al.*,[2] the values of $I(K\alpha_2/K\alpha_1)$ are well reproduced by Scofield's calculations.[3] However, the experimental uncertainty in the high-Z region is not small enough to test the calculations rigorously. Campbell and Schulte[4] have recently performed measurements of $I(K\alpha_2/K\alpha_1)$ values for $Z=70$, 73, 78, and 80 with careful convolution analyses for the $K\alpha$ peaks in x-ray spectra observed with a Ge(Li) detector. They have concluded that Scofield's calculations are confirmed within the uncertainty of about 1%. However, their values tend to fall slightly above the calculations and are not in agreement with them for $Z=70$ and 73 within the experimental uncertainty of three standard deviations.

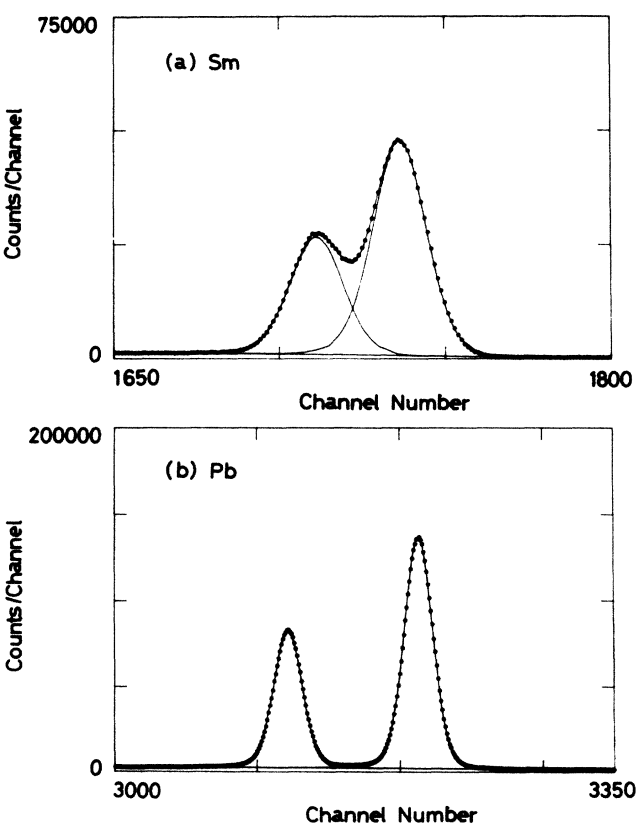

FIG. 1. $K\alpha$ x-ray spectra of (a) Sm and (b) Pb. Determined background and the results of the fit are drawn by solid lines.

We have measured the $I(K\alpha_2/K\alpha_1)$ ratios for eight elements with $62 \leq Z \leq 82$, especially around $Z=72$. We have measured x-rays from proton bombardments instead of those from radioactive sources. The measurement of relative intensities of x-rays from proton bombardment is very useful to test Scofield's calculations because the $I(K\beta/K\alpha)$ ratios are known to be constant for a given element over the proton energy range between 0.2 and 10 MeV,[5] and to be the same as those observed as a result of radioactive decay. Large yields of x-rays from the proton bombardment, together with the use of a Ge(Li) detector, have made possible systematic measurements with good statistics for a wide range of elements. In addition, the observed spectra have shown much less background since γ-ray transitions cannot occur in bombardment with such a low incident energy as 3.5 MeV. Consequently, $I(K\alpha_2/K\alpha_1)$ ratios with an experimental uncertainty less than 0.5% have been obtained.

The experiment was performed with a 3.5-MeV proton beam from the Van de Graaff accelerator at Tokyo Institute of Technology. The targets were metallic foils of 0.4-mg/cm^2 Sm, 2.2-mg/cm^2 Ho, 3.1-mg/cm^2 Tm, 3.1-mg/cm^2 Lu, 0.05-mm Ta, 0.1-mm W, 0.1-mm Au, and 0.1-mm Pb. The Ge(Li) detector used was an ORTEC LEPS and its energy resolution was 600 eV at 122 keV. The detector was placed at 90° to the beam direction and at 6 cm from the target. In order to avoid resolution

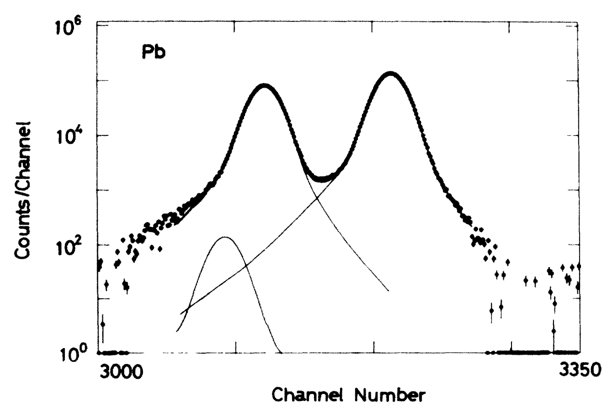

FIG. 2. $K\alpha$ x-ray spectrum of Pb after subtracting background. Lines are the results of three-peak fit.

TABLE I. Relative uncertainty from various sources.

		Uncertainty (%)					
Measurement	Target	(a) Line shape	(b) Background	(c) Efficiency	(d) Absorption	(e) Statistics	Total
$I(K\alpha_2/K\alpha_1)$	Sm	0.6	0.2	0.1	0.005	1.2	1.4
	Lu	0.3	0.2	0.05	0.003	0.3	0.47
	Pb	0.2	0.2	0.003	0.15	0.3	0.44
$I(K\beta/K\alpha)$	Sm		0.3	0.2	0.01	0.6	0.70
	Lu		0.3	0.1	0.2	0.24	0.44
	Pb		0.3	0.5	0.6	0.1	0.90

deterioration, counting rates were kept below 2 kcps and a pileup rejector was used.

A window of the target chamber was made of a 50-μm Mylar foil and a beryllium window of the detector was 0.13 mm in thickness. Therefore, measurements for large-Z targets suffered from huge numbers of L x-rays. In such cases, thin Al foils were placed in front of the detector to absorb the low-energy photons. The relative detection efficiency was calculated for the experimental arrangement and was checked with the γ rays from ^{57}Co, ^{133}Ba, and ^{241}Am sources set at the target position.

Figure 1 shows $K\alpha$ spectra of Sm and Pb. For the Pb case, two peaks are well separated, although there are small contributions under each peak from the other. On the other hand, two peaks are partially overlapped for the Sm case. We have consistently analyzed the spectrum for each element as follows. The background under the peaks was assumed to be a smooth interpolation of the yields at the right and left of the portion of the spectrum shown in the figure. The interpolation was made by using a cubic equation. After subtracting the background, two peaks were separated by a peak-fit program. The γ-ray peak from the radioactive source had a low-energy tail and its line shape was not reproduced perfectly by analytical functions. Therefore a program which can use any line shape as the reference was developed. The reference line shape $F(x)$ is given as

$$F(x)=Cf[(x-x_0)/\beta] ,$$

where $f(x)$ is an arbitrary function defined numerically. Starting with an initial line shape, the program varies the width β, the peak location x_0 and the normalization factor C so as to give the best fit to the data. The same line shape was assumed for both $K\alpha_1$ and $K\alpha_2$ peaks. The initial line shape at a given energy was extrapolated with the γ-ray peaks at 59 keV (^{241}Am) and 81 keV (^{133}Ba). Changing the slope of the low-energy tail of the peak slightly affected the relative intensity of the two peaks. Therefore we tried to fit the data with several different tails and estimated the systematic error of the fitting. The results of the fit are drawn with solid lines in Fig. 1. Reduced χ^2 values of about 3–5 were obtained.

For the Pb and Au spectra, a three-peak fit was also performed since there is a non-negligible contribution from K-L_I transitions for large-Z elements.[4,6] In this analysis, the energy of the $K\alpha_3$ line was fixed at the predicted one,[3] and the same line shape was used for each peak. The result of the fit for Pb is shown in Fig. 2.

We have also extracted the $I(K\beta/K\alpha)$ values. The relative yields of the $K\alpha$ and $K\beta$ peaks were obtained by simply adding the counts of the peak area.

Possible sources of uncertainty include (a) difference of the line shape of the peak, (b) background determination, (c) detection efficiency, (d) absorption in the target, and (e) statistics. Relative values of the uncertainty for Sm, Lu, and Pb are listed in Table I. The uncertainty due to (a) was extracted by taking the value corresponding to three standard deviations from the χ^2 minimum. The uncertainty due to (e) listed in the table corresponds to three standard deviations. For the $I(K\alpha_2/K\alpha_1)$ ratios, the uncertainty due to (a) is largest, especially for the small-Z targets. For the $I(K\beta/K\alpha)$ ratios, the uncertainty due to (c) and (d) was not small, since the difference of transition energies is rather large. The total combined error was typically about 0.5% for the $I(K\alpha_2/K\alpha_1)$ ratios and about 0.8% for the $I(K\beta/K\alpha)$ ratios as shown in Table I.

Results of the present work are shown in Table II to-

TABLE II. $K\beta/K\alpha$ and $K\alpha_2/K\alpha_1$ intensity ratios.

	$I(K\beta/K\alpha)$		$I(K\alpha_2/K\alpha_1)$		
Element	Calc.[a]	Expt.	Calc.[a]	Expt.	$I(K\alpha_3/K\alpha_1)$
Sm	0.2532	0.2525±0.0018	0.5522	0.5542±0.0075	
Ho	0.2599	0.2608±0.0012	0.5613	0.5586±0.0030	
Tm	0.2620	0.2611±0.0012	0.5653	0.5681±0.0031	
Lu	0.2645	0.2636±0.0012	0.5694	0.5698±0.0027	
Ta	0.2682	0.2682±0.0017	0.5736	0.5708±0.0027	
W	0.2698	0.2723±0.0018	0.5757	0.5761±0.0028	
Au	0.2772	0.2770±0.0023	0.5874	0.5862±0.0026	$<2.7\times10^{-4}$
Pb	0.2821	0.2826±0.0025	0.5950	0.5938±0.0026	$(1.0\pm0.5)\times10^{-3}$

[a]Reference 3.

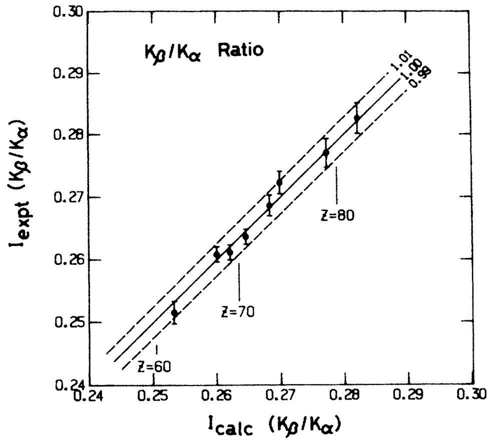

FIG. 3. $I(K\beta/K\alpha)$ intensity ratios compared with Scofield's calculations. Lines with correlation factors of 1.0 (solid) and 0.99 and 1.01 (dashed) are plotted.

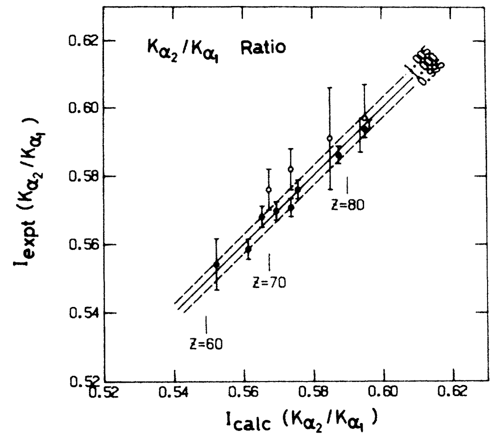

FIG. 4. $I(K\alpha_2/K\alpha_1)$ intensity ratios compared with Scofield's calculations. Values from Ref. 4 are also drawn with open circles. Lines with correlation factors of 1.0 (solid) and 0.995 and 1.005 (dashed) are plotted.

gether with Scofield's calculations. The calculated values for Sm, Ho, Tm, and Lu listed in table are estimated by interpolation from the values of neighboring elements. In Fig. 3 the $I(K\beta/K\alpha)$ ratios are compared with the calculations. A solid line with a linear correlation factor of 1.0 is drawn in the figure. Dashed lines correspond to the factors of 0.99 and 1.01. As can be seen, all the values fall between 0.99 and 1.01. This is significantly more precise than the previous results with proton bombardment for $Z \leq 47$.[5]

The comparison of the $I(K\alpha_2/K\alpha_1)$ ratios with the calculations are shown in Fig. 4. The values of Campbell and Schulte[4] are also shown in the figure with open circles. Also drawn are a solid line with the linear correlation factor of 1.0 and dashed lines with the factors of 0.995 and 1.005. The present data have less uncertainty than those of Campbell and Schulte, and fall just between the 0.995 and 1.005 lines. Thus, it can be concluded that Scofield's calculations are confirmed with an accuracy of about 0.5%. The values around $Z=72$ obtained in the present work are in excellent agreement with the calculations.

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