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Internal Conversion Coefficients for Pure $E2$ and Mixed $E2+M1$ Transitions

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K-shell internal conversion coefficients have been measured for a number of pure $E2$ and mixed $E2+M1$ transitions resulting from the decay of low-lying rotational states. These states were produced either by Coulomb excitation or by radioactive decay. The experimental values for $\alpha_2{}^K$ are appreciably larger than the calculated values of Sliv and co-workers.

I. INTRODUCTION

Sliv and co-workers[1] studied the effect of the finite nuclear size on internal conversion coefficients and found in some cases, notably $M1$ transitions for high Z, appreciably different values from those calculated by Rose *et al.*[2] for a point-charge nucleus. The limited experimental evidence on $M1$ transitions seems to confirm the values obtained by Sliv and co-workers.[3-5] While making additional measurements on $M1$ transitions, we also measured a number of pure $E2$ transitions and we were surprised to find that the experimental values for the internal conversion coefficients for these $E2$ transitions were considerably larger than the calculated values of Sliv and co-workers. It is this experimental information on the internal conversion coefficients, of pure fast $E2$ transitions resulting from the decay of rotational states in even-even nuclei and of mixed $M1$ and $E2$ transitions from the decay of rotational states in odd-A nuclei, that we wish to report here.

The apparent discrepancy for $E2$ transitions is especially surprising, because the calculated values of Sliv and co-workers for $E2$ transitions differ only slightly ($\sim 2\%$) from those of Rose *et al.* and this suggests that the finite nuclear size is relatively unimportant for $E2$ transitions. The model taken for the nucleus by Sliv and co-workers was a uniformly charged sphere with radius $1.20\times10^{-13} A^{\frac{1}{3}}$ cm. The nuclear currents were taken to be on the surface of the nucleus. Only slight variations in the calculated values were observed when the nuclear radius was altered by 10% or when the nuclear currents were taken to be uniformly distributed rather than confined to the nuclear surface. They therefore conclude that the internal conversion coefficients are not sensitive to the details of the distribution of charge and current within the nucleus and that the differences from the "point charge" values are principally the result of the removal of infinities in both the transition potentials and relativistic electron wave functions.

Recently, Church and Weneser[6] have pointed out that the finite nuclear size introduces additional matrix elements for the rate of internal conversion which are different from those for γ-ray emission of the same multipole order. To illustrate the effect of these matrix elements, they considered $M1$ transitions and found that for certain types of transitions, where the gamma-ray matrix element is attenuated, one might expect appreciably different values from those given by Sliv and co-workers. Possibly these matrix elements could account for the observed discrepancy for $E2$ transitions, but the prospect is not encouraging because of the apparent unimportance of the finite nuclear size for $E2$ internal conversion coefficients. Alternatively, there could be some unrecognized systematic error in our measurements. Several investigators have previously measured internal conversion coefficients of low-lying fast $E2$ transitions and, in general, our values agree with the earlier results. However, the discrepancy was then not so easily discerned, partly because of the somewhat larger errors but mostly because exact calculations for γ rays with energies less than 150 kev have become available only within the last year.

II. APPARATUS

Singly ionized He ions of variable energy were obtained from the 5.5 million volt ORNL electrostatic generator. Targets were mounted on the target support at 45° with respect to the incident ion beam. The target support was a stainless steel tube with 0.005-inch wall thickness. By placing the detector at 235° with respect to the incident ion beam, i.e., so as to face the bombarded surface of the target, the gamma rays and x-rays could reach the detector with a minimum attenuation from the traversal of intervening material. Metallic targets were prepared either by electrodeposition onto 0.005-inch nickel, by sintering metallic powders into thin foils 0.5 inch in diameter by 75 to 150 mg/cm^2 thick, or from commercial foils.

The gamma-ray detector was a thallium-activated NaI crystal, 3 inches in diameter and 3 inches long, mounted on a DuMont type 6393 photomultiplier tube. The crystal container was prepared from 0.005-inch

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[1] L. A. Sliv, Zhur. Eksptl. i Teoret. Fiz. **21**, 77 (1951); L. A. Sliv and M. A. Listengarten, Zhur. Eksptl. i Teoret. Fiz. **22**, 29 (1952); and "Tables of K-shell Internal Conversion Coefficients" privately circulated by L. A. Sliv and I. M. Band.

[2] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951) and "Tables of Internal Conversion Coefficients" privately circulated by M. E. Rose.

[3] A. H. Wapstra and G. J. Nijgh, Nuclear Phys. **1**, 245 (1956).

[4] Nordling, Siegbahn, Sokolowski, and Wapstra, Nuclear Phys. **1**, 326 (1956).

[5] F. K. McGowan and P. H. Stelson, Phys. Rev. **103**, 1133 (1956).

[6] E. L. Church and J. Weneser, Phys. Rev. **104**, 1382 (1956).

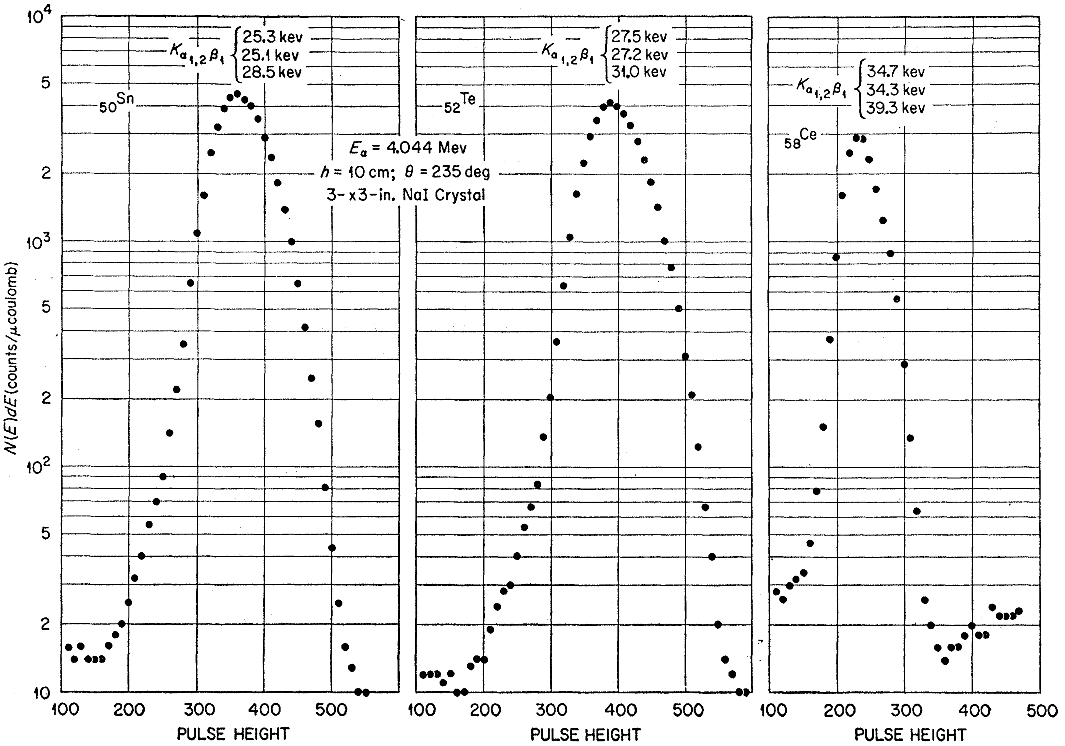

FIG. 1. Pulse-height spectrum of the gamma radiation for α particle bombardment of Sn, Te, and Ce.

aluminum foil. The inner surface of the container was sprayed with a high-efficiency diffuse reflector of alpha alumina mixed with sodium silicate. Thickness of the diffuse reflector was ~20 mg/cm^2. Pulse-height spectra were measured with a 20×120 channel analyzer.[7]

III. METHOD

The method which we have used to measure K-shell internal conversion coefficients involves the measurement of the number of K x-rays and the number of gamma rays from a source or a target. The K-shell internal conversion coefficient $(\alpha^K)_{\text{exp}}$ is given by the expression

$$(\alpha^K)_{\text{exp}}=\frac{N_x}{N_\gamma}\times\frac{R_\gamma\epsilon_\gamma A_\gamma}{R_x\epsilon_x A_x w_K},$$

where N is the number of counts in the full energy peak of the x-ray or gamma-ray pulse-height spectrum, R is the ratio of the counts in the full energy peak to the total counts in the pulse-height spectrum of the x-ray or gamma ray, ϵ is the detection efficiency of the detector, A is a correction for the attenuation of the x-ray or gamma ray by intervening material between the target and detector, and w_K is the fluorescent yield[8] for K x-rays. The number of counts in the full-energy peak is obtained from the sum of the counts in an appropriate number of channels which include the full-energy peak.

Since the measurements to be discussed involve $E_\gamma \leqslant 140$ kev, the peak-to-total ratio, R, is obtained from a knowledge of the "escape peak" intensity. For this purpose we have used a calculation of the "escape peak" intensity for the case of a collimated beam of gamma radiation entering a semi-infinite crystal of NaI normal to its plane surface. In several cases the "escape peak" intensity was measured directly from the pulse-height spectrum of x-rays incident on the detector. R_x from the computations weighted by the relative intensities[9] of 0.535, 0.267, 0.160, and 0.037 for $K_{\alpha1}$, $K_{\alpha2}$, $K_{\beta1}$, and $K_{\beta2}$, respectively, agreed with the experimental values to within 1.5%. For the purpose of assigning an error to $(\alpha^K)_{\text{exp}}$ we have taken the uncertainty in the peak-to-total ratio R to be ±2% for $E_\gamma=33$ to 70 kev and ±1% for $E_\gamma>70$ kev.

For the attenuation corrections, we have used the absorption cross sections for gamma rays in various materials from tables compiled by White.[10] In addition, the attenuation of the gamma rays or x-rays by the 0.005-inch stainless steel target support was measured directly by placing radioactive sources at the target position. These sources included Te^{123} (K x-rays), Ba^{133}

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[7] Kelley, Bell, and Goss, Oak Ridge National Laboratory Physics Division Quarterly Progress Report ORNL-1278, 1951 (unpublished).

[8] Steffen, Huber, and Humbel, Helv. Phys. Acta **27**, 167 (1949); Broyles, Thomas, and Haynes, Phys. Rev. **89**, 715 (1953).

[9] A. H. Compton and S. K. Allison, *X-rays in Theory and Experiment* (D. Van Nostrand Company, Inc., New York, 1935).

[10] G. R. White, National Bureau of Standards Report NBS-1003, 1952 (unpublished).

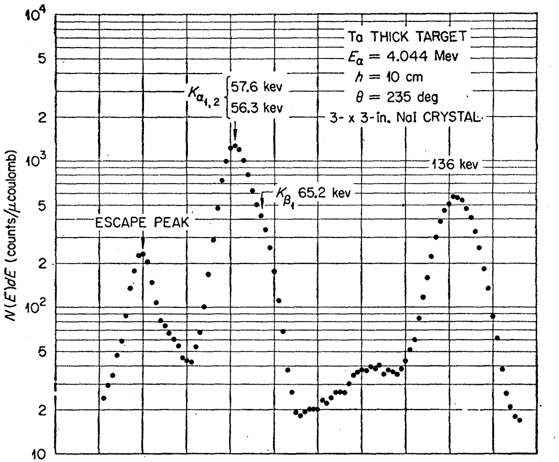

FIG. 2. Pulse-height spectrum of the gamma radiation for α particle bombardment of Ta.

(K x-rays of Cs), Lu^{177} (113 kev and K x-rays of Hf), Hf^{181} (133 and 136 kev and K x-rays of Ta), and Os^{191} (134 kev and K x-rays of Ir). For the Coulomb excitation experiments, we believe that the attenuation corrections are not uncertain by more than $\pm 2\%$ for $E_\gamma > 50$ kev.

The intrinsic detection efficiency of the detector differs from unity at most by 2% for the gamma-ray energies involved in the experiments. Insofar as the determination of $(\alpha^K)_{\text{exp}}$ is concerned, the error introduced by ϵ is negligible. Also, for the nuclei investigated the fluorescent yield w_K is probably not uncertain by more than $\pm 1\%$.

IV. MEASUREMENTS

The yield of K x-rays and gamma rays for α particle Coulomb excitation of nuclei with Z between 50 and 90 has been determined. Figures 1 to 4 show the spectrum observed when thick targets of Sn, Te, Ce, Ta, W^{186}, and Bi were bombarded by 4.044-Mev α particles. The source of the peak at 180 pulse height units, which corresponds to $\sim$25 kev, in Fig. 4 is not known. Numerous checks have been made to locate the source of this radiation. It is associated with a beam on the target and has the same intensity for a variety of targets, e.g., Bi, Pb, Tl, Au, and Pt. This would seem to exclude an impurity from a medium-weight element. In addition, medium-weight elements (such as silver solder) near the target area were shielded from possible scattered ions. This precaution did not remove the spurious peak at 25 kev. In any case this peak does not interfere with any of the measurements to be discussed in this paper.

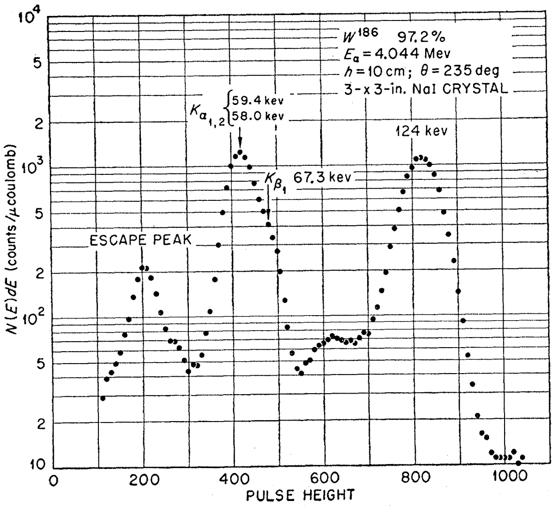

FIG. 3. Pulse-height spectrum of the gamma radiation for α particle bombardment of W^{186}.

Additional information on $E2$ K-shell internal conversion coefficients has been obtained from $E2$ transitions following β^- decay. The intensities of K x-rays and the gamma rays have been measured for $E2$ transitions in Er^{166}, Yb^{170}, and Hf^{176}. A typical spectrum of the K x-rays and the 84.26-kev gamma ray following the β^- decay of Tm^{170} is shown in Fig. 5. To check on the method of measuring K-shell internal conversion coefficients with a scintillation spectrometer, the pulse height spectrum of the K x-rays and the 661-kev gamma ray from Ba^{137*} was measured and is shown in Figs. 6 and 7.

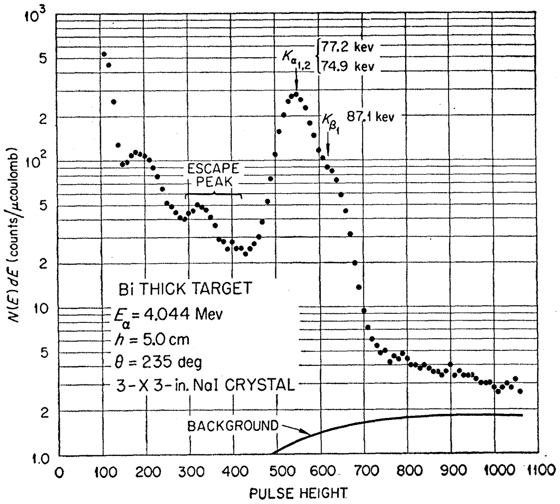

FIG. 4. Pulse-height spectrum of the gamma radiation for α particle bombardment of Bi.

V. INTERPRETATION AND DISCUSSION

A. Coulomb Excitation Experiments

From the absolute yields of K x-rays and gamma rays for α particle bombardment of nuclei, one can deduce the K-shell internal conversion coefficient $(\alpha^K)_{\text{exp}}$ for several gamma-ray transitions. The yield of K x-rays resulting from the stopping of the α particles is as much as two times smaller than the yield of K x-rays resulting from internal conversion of nuclear gamma rays following Coulomb excitation. The number of K-shell vacancies produced by the stopping of the α-particles in targets of different Z was determined for a few elements for which there is no appreciable nuclear excitation (Th, Bi, Pb, Tl, Ce, Te, and Sn). In addition, the yield of K x-rays from three targets of platinum containing different amounts of Pt^{195} was used to determine the yield of K x-rays resulting from the stopping of the α particles. For platinum there is no appreciable nuclear excitation which yields K x-rays from internal conversion except in Pt^{195}. The results from a typical set of measurements for $E_\alpha=4.044$ Mev are given in Table I. The principle uncertainty in the measurements for Ce, Te, and Sn is the attenuation correction for the material that the K x-rays must traverse between the target and detector.

In our communication[5] of the results from 3-Mev α particles incident on thick targets, we assumed that the $E2$ K-shell internal conversion coefficient $\alpha_2{}^K$ was not appreciably altered by the finite nuclear size.[1] As a result we used the data from the measurements on W^{184}, W^{186}, and Os to determine the number of K-shell vacancies I_K produced by the stopping of the α-particles because the yield of K x-rays from internal conversion could be determined from the intensity of the nuclear gamma ray of known $E2$ multipole. Our original curve[5] of I_K as a function of Z for 3-Mev α particles was adjusted to fit the data for Ce, W^{184}, W^{186}, Os, Tl, Pb, and Bi. From the more recent measurements with $E_\alpha=4.044$ Mev, it appears that our interpretation of this original yield curve is probably incorrect. The results for I_K from two different sets of measurements with $E_\alpha=4.044$ Mev are given in Fig. 8.

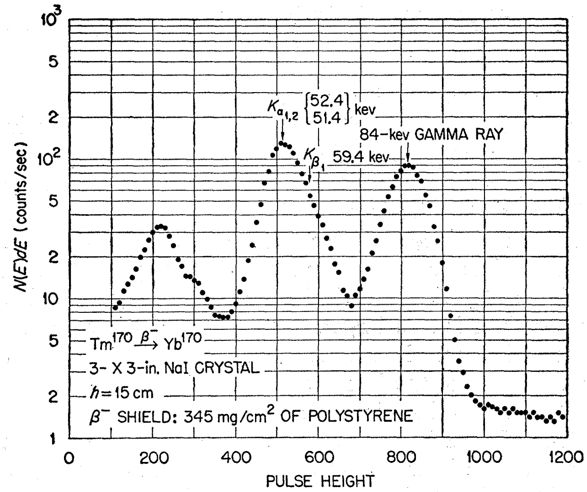

FIG. 5. Pulse-height spectrum of the gamma radiation following β^- decay of Tm^{170}.

The theoretical cross section for the ionization of the K-shell has been computed in Born approximation for nonrelativistic electron wave functions.[11] The dependence of the cross section on the Z of the target atom is Z^{-12}. The thick target yield I_K should vary approximately as $Z^{-12.5}$. However, the results in Table I with $Z\geqslant 78$ indicates that the dependence is $Z^{-13.5}$. With this dependence on Z, the points for Sn, Te, and Ce fall appreciably below a curve fitted to the data for $Z\geqslant 78$. This trend seems to be in agreement with the experimental cross sections found for protons,[12] i.e., the pre-

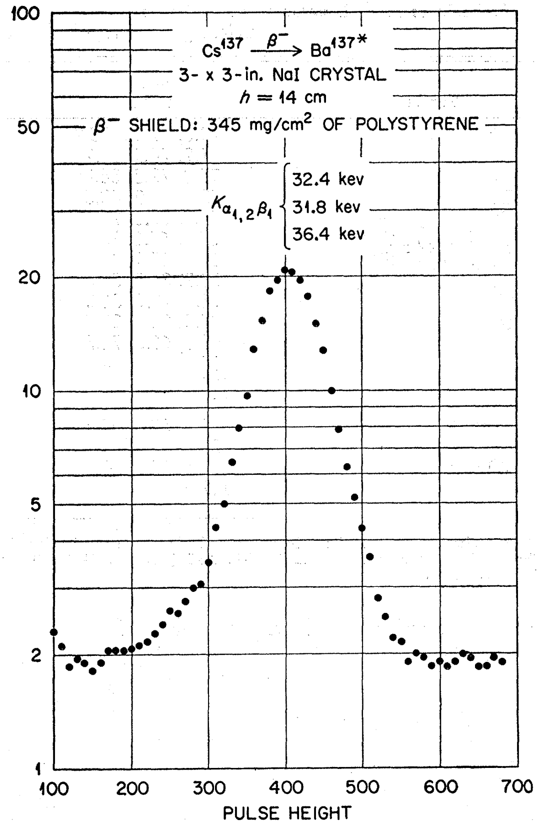

FIG. 6. Pulse-height spectrum of the low-energy radiation following β^- decay of Cs^{137}.

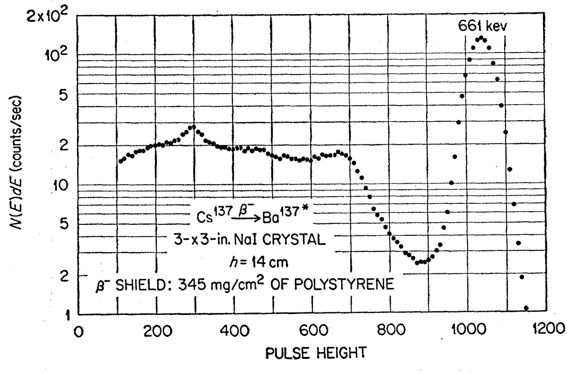

FIG. 7. Pulse-height spectrum of the 661-kev gamma ray following β^- decay of Cs^{137}.

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[12] Lewis, Simmons, and Merzbacher, Phys. Rev. **91**, 943 (1953).

TABLE I. Yield of K-shell vacancies resulting from the stopping of 4.044-Mev α particles incident on thick targets and the yield of nuclear gamma rays where there is appreciable nuclear excitation.

Target	$E_{K \text{ or } \gamma}$ (kev)	$I_{K \text{ or } \gamma}$ (excitations/μcoul)	α_2^K	I_K (internal conversion)
Th	93.5, 90.1, 105.7	$(1.10\pm0.10)\times10^4$		
Bi	77.2, 74.9, 87.2	$(3.49\pm0.21)\times10^4$		
Pb	75.0, 72.8, 84.8	$(3.98\pm0.24)\times10^4$		
Tl	72.9, 70.9, 82.5	$(4.38\pm0.31)\times10^4$		
Pt (60.1% Pt^{195})[a]	67.9, 65.1, 75.6	$(1.40\pm0.08)\times10^5$		
Pt (28.6% Pt^{195})[a]	67.9, 65.1, 75.6	$(1.07\pm0.06)\times10^5$		
Pt (33.7% Pt^{195})	67.9, 65.1, 75.6	$(1.16\pm0.07)\times10^5$		
Ce	34.7, 34.3, 39.3	$(1.95\pm0.29)\times10^6$		
Te	27.5, 27.2, 31.0	$(7.14\pm0.57)\times10^6$		
Sn	25.3, 25.1, 28.5	$(1.07\pm0.16)\times10^7$		
Os	63.0, 61.5, 71.3	$(1.79\pm0.11)\times10^5$		
	155	$(3.46\pm0.17)\times10^4$	0.323	1.12×10^4
	186	$(4.60\pm0.23)\times10^4$	0.205	0.94×10^4
	206	$(4.26\pm0.21)\times10^4$	0.158	0.67×10^4
W^{186}[a, b]	59.4, 58.0, 67.3	$(4.93\pm0.30)\times10^5$		
	124	$(4.13\pm0.21)\times10^5$	0.563	2.33×10^5
W^{184}[a, b]	59.4, 58.0, 67.3	$(5.82\pm0.35)\times10^5$		
	112	$(4.32\pm0.22)\times10^5$	0.695	3.00×10^5

[a] The enriched isotopes and the isotopic analysis were supplied by the Stable Isotopes Research and Production Division at ORNL.

[b] The W^{186} target contained 97.2% W^{186}, 0.38% W^{183}, 1.94% W^{184}, and 0.5% W^{182}; the W^{184} target contained 95.7% W^{184}, 1.25% W^{183}, 2.07% W^{186}, and 0.9% W^{182}.

dicted cross sections are low, particularly for the heavy elements. For interpolation purposes a logI_K *versus* log$Z$ presentation of the data in Table I did not appear as good as the logI_K *versus* Z presentation given in Fig. 8. The curve is a straight line which seems to represent the data fairly well except for W^{184}, W^{186}, and Os. These points have already been corrected for the contribution of K-shell vacancies resulting from internal conversion of $E2$ transitions. For this purpose we have used the $E2$ internal conversion coefficients α_2^K as given by Rose *et al.*[2] and by Sliv.[1] We are inclined to consider the deviation of I_K for W^{184}, W^{186}, and Os from the straight line curve as evidence that the α_2^K are actually larger than the values calculated by Rose *et al.*[2] and by Sliv.[1] The amount of the deviation from the straight line gives the result that α_2^K for W^{184} and W^{186} are larger than the values calculated by Sliv and co-workers by $(43\pm15)\%$ and $(46\pm16)\%$, respectively. The percentage deviation for osmium is still larger, but the osmium results are rendered uncertain because of the possibly important contribution to the K x-ray intensity from excitation of states in the odd-A isotopes.

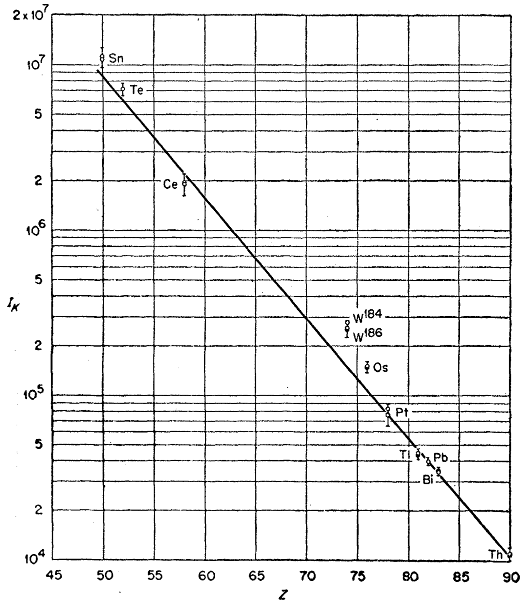

FIG. 8. Yield of K-shell vacancies resulting from the stopping of 4.044-Mev α particles incident on thick targets as a function of Z. I_K, the number of K-shell vacancies per microcoulomb of singly charged helium ions, is the yield of K x-rays corrected for the fluorescent yield.

The K-shell internal conversion coefficients deduced for several gamma-ray transitions in odd-mass nuclei are listed in Table II. The yield of K-shell vacancies resulting from the stopping of the α particles was obtained from the curve in Fig. 8. The $E2$ and $M1$ internal conversion coefficients α_2^K and β_1^K are taken from Sliv.[1] For several of these transitions the ratio $E2/M1$ is known from angular correlation measurements.[13] The values for $E2/M1$ of the transitions in Re^{185} and Re^{187} are based on an indirect determination.[13] Using these values for $E2/M1$, we have tabulated the expected values for α^K based on Sliv's values for α_2^K and β_1^K. The $(\alpha^K)_{\text{exp}}$ tend to be larger than the predicted α^K. However, these transitions are of limited value as evidence for deviations in α_2^K from the calculations by Sliv because of the rather large uncertainties in $(\alpha^K)_{\text{exp}}$ and $E2/M1$. Bernstein and Lewis[14] have observed internal conversion electrons corresponding to the Coulomb excitation of states at 82 and 73 kev in Ir^{191} and Ir^{193}, respectively. Our results for Ir^{191} and Ir^{193} would be rendered uncertain if there is appreciable

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[13] F. K. McGowan and P. H. Stelson (to be published).

[14] E. M. Bernstein and H. W. Lewis, Phys. Rev. **105**, 1524 (1957).

TABLE II. K-shell internal conversion coefficients deduced from Coulomb excitation experiments. The yield of K-shell vacancies I_K' resulting from the stopping of 4.044-Mev α particles was obtained from the curve in Fig. 8.

Nucleus	$E_{K \text{ or } \gamma}$ (kev)	$I_{K \text{ or } \gamma}$ (excitations/μcoul)	I_K'	$(\alpha^K)_{\text{exp}}$	α_2^K	β_1^K	$E2/M1$	α^K
Ta^{181}	57.6, 56.5, 65.2	$(5.04\pm0.30)\times10^5$	1.79×10^5					
	136	$(2.12\pm0.11)\times10^5$		1.53 ± 0.18	0.460	1.51	0.25	1.30
Re (85.4% Re^{185}, 14.6% Re^{187})[a]	60.8, 59.6, 69.1	$(4.61\pm0.28)\times10^5$	1.28×10^5					
Re^{185}	128	$(1.41\pm0.07)\times10^5$		2.43 ± 0.36	0.514	2.13	(0.025)	2.09
Re (37.3% Re^{185}, 62.7% Re^{187})	60.8, 59.6, 69.1	$(4.33\pm0.26)\times10^5$	1.28×10^5					
Re^{187}	134	$(1.34\pm0.07)\times10^5$		2.12 ± 0.32	0.464	1.90	(0.025)	1.86
Ir (85.8% Ir^{191}, 14.11% Ir^{193})[a]	64.9, 63.3, 73.5	$(2.85\pm0.17)\times10^5$	9.20×10^4					
Ir^{191}	134	$(7.04\pm0.35)\times10^4$		2.90 ± 0.58	0.445	2.20		
Ir (89.14% Ir^{193}, 10.86% Ir^{191})[a]	64.9, 63.3, 73.5	$(2.18\pm0.13)\times10^5$	9.20×10^4					
Ir^{193}	140	$(5.21\pm0.26)\times10^4$		2.24 ± 0.45	0.403	1.94	0.56	1.39

[a] The enriched isotopes and the isotopic analysis were supplied by the Stable Isotopes Research and Production Division at ORNL.

TABLE III. K-shell internal conversion coefficients deduced from a measure of the K x-ray and gamma ray intensities of transitions following β^- decay.

Source	$E_{K \text{ or } \gamma}$ (kev)	$N_{X \text{ or } \gamma}$	R	ϵ	A	w_K	α_{exp}^K	α_2^K	$(\alpha^K)_{\text{exp}}/\alpha_2^K$
$Ho^{166a}\rightarrow Er^{166}$	49.1, 48.2, 55.7	2.154×10^5	0.85	0.9965	0.851	0.923			
	80.0	1.408×10^5	0.93	0.9880	0.876		1.85 ± 0.13	1.63	1.13
$Tm^{170a}\rightarrow Yb^{170}$	52.4, 51.4, 59.4	4.507×10^5	0.86	0.9960	0.914	0.930			
	84.26	3.232×10^5	0.938	0.9858	0.931		1.65 ± 0.12	1.34	1.23
$Lu^{176a}\rightarrow Hf^{176}$	55.8, 54.6, 63.4	1.580×10^5	0.87	0.9930	0.916	0.933			
	89.0	1.389×10^5	0.945	0.9767	0.931		1.32 ± 0.11	1.10	1.20
$Cs^{137}\rightarrow Ba^{137*}$	32.4, 31.8, 36.4	6.79×10^4	0.957	0.993	0.862	0.88			
	661	3.44×10^5	0.543	0.660	0.967		0.095 ± 0.008		

[a] The samples of rare earth oxides were purified by Dr. Boyd of the Chemistry Division of ORNL.

Coulomb excitation of these states compared to the excitation of the 134- and 140-kev states in Ir^{191} and Ir^{193}.

B. $E2$ Transitions Following β^- Decay

For a simple decay scheme consisting of a single gamma-ray transition following β^- decay, the K-shell internal conversion coefficient can be obtained from a measurement of the pulse-height spectrum of the gamma radiation. Measurements of this type for $E2$ transitions with $E_\gamma \sim 85$ kev have been done earlier by several groups of workers.[15–20] At that time no calculations of α_2^K for $E_\gamma < 150$ kev were available for comparison with experiment. Within the last year both Rose *et al.*[2] and Sliv[1] have extended the calculations to lower gamma-ray energies. We have repeated our measurements with considerably better energy resolution and with a multichannel pulse-height analyzer in place of the single-channel analyzer used in the original measurements.[15] As a result the uncertainty in $(\alpha^K)_{\text{exp}}$ has been reduced from $\pm(15$ to $20)\%$ to 8%. The K-shell internal conversion coefficients deduced from the measurements of $E2$ transitions in Er^{166}, Yb^{170}, and Hf^{176} are listed in Table III along with α_2^K as given by the calculations of Sliv.[1] Only the intrinsic efficiency of the detector is given in Table III because the solid angle subtended by the detector at the source cancels out in the deduction of $(\alpha^K)_{\text{exp}}$. The experimental values for the K-shell internal conversion coefficients seem to be appreciably larger than the calculated values. The calculations by Sliv include a correction for the finite nuclear size. For $E2$ transitions and for this region of Z, the correction amounts to a 2% reduction from the values given by the point-nucleus calculations by Rose *et al.*[2]

These recent measurements agree well with the earlier measurements. For instance, McGowan,[15] Sunyar,[17] and Graham *et al.*[20] obtained $(\alpha^K)_{\text{exp}}=1.9$ for the transition in Er^{166}. For the transition in Yb^{170} the following values have been reported: 1.5 ± 0.2 by McGowan,[15] 1.6 ± 0.15 by Graham *et al.*,[16] 1.6 by Linden and Starfelt,[18] and 1.69 by Bisi *et al.*[19]

A few check experiments with a Tm^{170} source have been done to look for systematic errors which might account for the deviations from the calculated internal conversion coefficients. At these low energies the K x-rays and gamma rays scattered from the surroundings into the detector by Compton scattering are not degraded appreciably in energy. The amount of backscattered radiation was measured directly by introducing a shadow shield of 0.010 inch of Ta+0.030 inch of Sn+0.0035 inch of Mo+0.005 inch of Cu between the source and detector. This effect of backscattering contributed 2% to the number of counts in full energy peak of the K x-ray. This correction has been included in the results given in Table III. In addition, the pulse height spectrum from Tm^{170} was measured with the source and

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[18] K. Linden and N. Starfelt, Arkiv Fysik **7**, 109 (1954).
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detector suspended in the middle of a laboratory room $24\times16\times10$ feet in order to reduce backscattering from the surroundings. From this measurement we obtained $(\alpha^K)_{\text{exp}}=1.69$. To check on the intensity of the escape peak of the 84-kev radiation, which falls at the position of the K x-ray in the pulse height spectrum, the spectrum was measured with 1.29 g/cm^2 of Pb between the source and the detector. Under these conditions the K x-rays are attenuated by a factor of 52 over that for the gamma ray. Graham *et al.*[16] also performed this measurement in their work with Tm^{170}. The escape peak intensity was in good agreement with the values used in the analysis of the data in Table III. The background from the electron bremsstrahlung and the escape peak of the gamma ray contributed 8% to the total counts observed in the full-energy peak of the K x-rays and the background in the full-energy peak of the gamma ray was about 6% for Er^{166}, Yb^{170}, and Hf^{176}.

The K-shell internal conversion for the 661-kev transition in Ba^{137} deduced from the data shown in Figs. 6 and 7 is given in Table III. This transition is generally accepted to be a $M4$ multipole based on β^--ray shape studies[21–23] and measured K-shell internal conversion coefficients.[24,25] From Sliv's calculations, the effect of the finite nuclear size on the internal conversion coefficients should be negligible for $Z=56$. This measurement of $(\alpha^K)_{\text{exp}}$ for the 661-kev transition should provide a check on the general method of measuring K-shell internal conversion coefficients with a NaI scintillation spectrometer. The calculated value[1] for $\beta_4{}^K$ is 0.094 and the experimental value agrees well with this. Our experimental value also agrees with the careful determination of $(\alpha^K)_{\text{exp}}$ by Waggoner and by Wapstra using magnetic spectrometers for the measurements.

VI. CONCLUSIONS

Information on K-shell internal conversion coefficients has been obtained from Coulomb excitation experiments and from $E2$ transitions following β^- decay. The measured $E2$ K-shell internal conversion coefficients seem to be appreciably larger than the calculations by Rose and by Sliv. Several experimental checks were done in search for possible systematic errors in the method of measurement and these errors appear to be appreciably smaller than the errors assigned to the $(\alpha^K)_{\text{exp}}$. At first sight these deviations from the calculated $E2$ K-shell internal conversion coefficients would seem to be rather large to have escaped detection by other methods. However, for these $E2$ transitions in Er^{166}, Yb^{170}, and Hf^{176} an absolute determination of the number of K-shell internal conversion electrons is not favorable because the energy of the electrons is rather small. In magnetic spectrometer measurements of internal conversion coefficients, a known $E2$ transition and the calculated internal conversion coefficient are frequently utilized to calibrate the spectrometer.

We report these results in the hope that they may stimulate and encourage others to check our results. The deviations we have observed in the values of $\alpha_2{}^K$ may be evidence for the importance of the additional nuclear matrix elements in internal conversion.[6,26] This could mean that internal conversion coefficients are not as independent of nuclear properties as previously believed.

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