DECAY OF SAMARIUM-153

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Received April 1, 1957
(Communicated by Prof. B. Peters, F.A.SC.)

ABSTRACT

Radiations emitted in the decay of Samarium-153 have been studied in the Siegbahn-Slätis *beta*-ray spectrometer. Using the internal conversion electron spectrum and the photo-electron spectrum with tin as radiator, the internal conversion coefficient α_k has been determined for 102 Kev. and 70 Kev. *gamma*-rays. The relative intensities of the three *beta*-ray branches have been determined. A weak *gamma*-ray of energy 83 Kev. has been found and can be interpreted as a transition to the ground state from the first rotational level in Europium-153. The multipole order and character of the 102 Kev. transition is discussed.

INTRODUCTION

SAMARIUM-153 (half-life 47 hrs.) decays by β^- emission to several levels in Europium-153 and has been studied by various workers.[1-9] There has been, however, considerable disagreement about the internal conversion coefficient α_k[2,4,9,10] for the 102 Kev. *gamma*-ray and some uncertainty about the relative intensities of the various *beta*-ray groups involved in the decay scheme. As a result of experiments on Coulomb excitation, rotational levels at 82 Kev. and 187 Kev. have been established in Europium-153 and it was of some interest to find out whether these levels are also formed in the *beta*-decay of Samarium-153.

Accurate determination of internal conversion coefficients has assumed special importance as recently there has been a suggestion,[12,13] with some experimental evidence[14] in its favour, that in the case of magnetic dipole (M_1) transitions, the coefficient has a smaller value than that predicted theoretically by Rose,[15] on account of the finite size of the nucleus. The 102 Kev. transition in Europium-153 has been considered by previous workers[1,2,4] to be a mixture of M_1 and E_2 types and the coefficient α_k as determined in this work is discussed from this standpoint.

The method of investigation adopted in this work consisted of three main experiments. In the first place, the continuous *beta*-spectrum was recorded and the Fermi-Kurie plot was constructed. Secondly, the internal conversion electron spectrum was investigated, giving the relative intensities of conversion lines for different transitions, K/L ratio and the Auger lines. Finally, using tin as radiator, the photo-electron spectrum was recorded, giving relative intensities of unconverted part of the transitions and X-rays in Europium, consequent on internal conversion. From these measurements, the conversion coefficient was calculated. This method of using photo-electron spectrum has not been employed by previous workers for this isotope and has the further advantage of detecting *gamma*-rays of weaker intensity and of low energy.

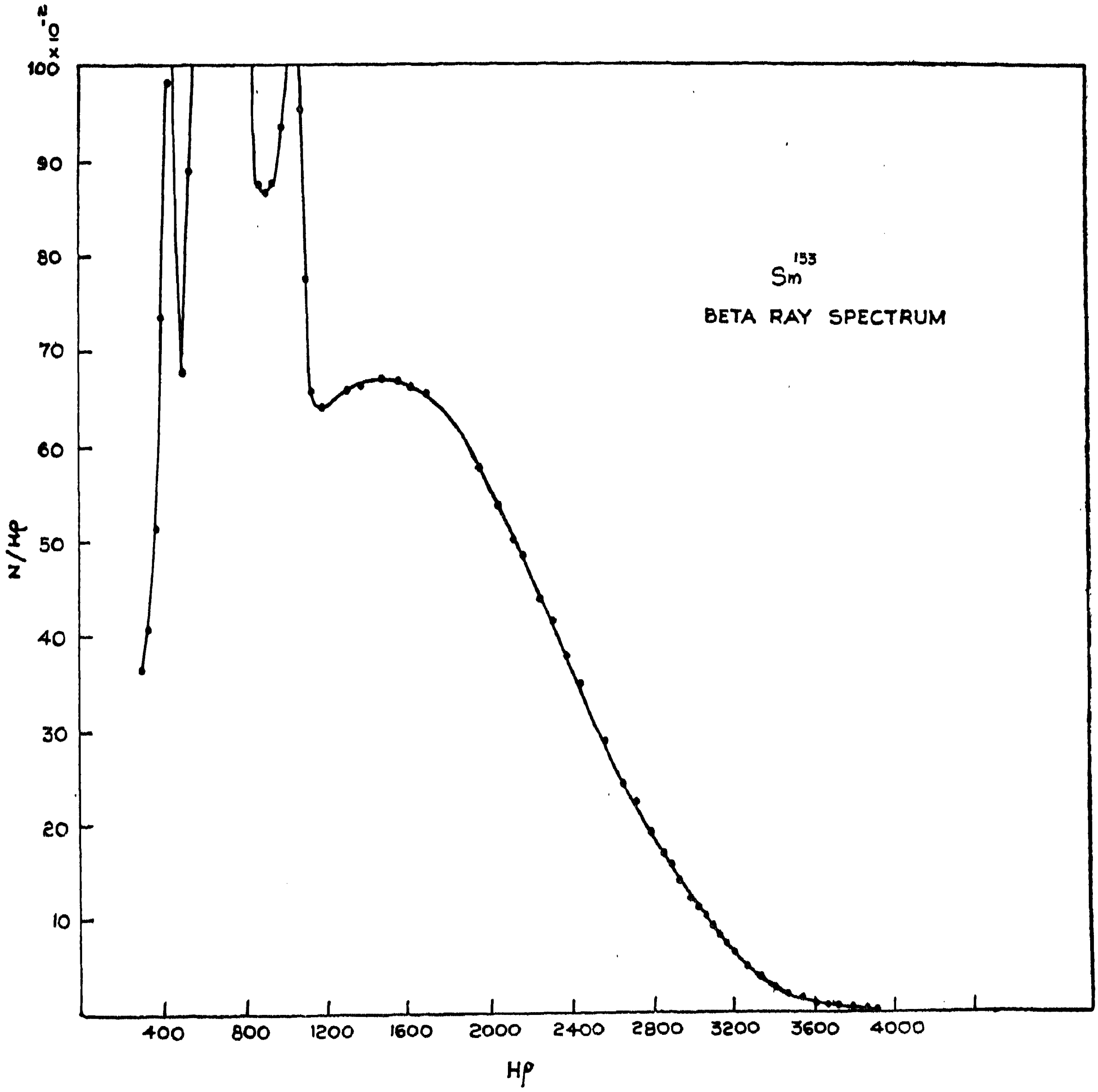

FIG. 1

EXPERIMENTAL OBSERVATIONS AND RESULTS

A source of Samarium-153 of high specific activity was obtained from A.E.R.E., Harwell. Fig. 1 shows the continuous *beta*-ray spectrum of Samarium-153, N/Hρ being plotted against Hρ, the momentum. Fig. 2

is the Fermi plot, the continuous curve having been obtained from the observed points. Assuming allowed shape for different *beta*-groups, this is seen to be made up of three *beta*-ray groups with maximum energies at 792 ± 10 Kev., 685 ± 15 Kev. and 610 ± 20 Kev. respectively. The relative intensities of the *beta*-groups and the Log ft. values for these transitions are given in Table I.

TABLE I

Group	Energy in Kev.	% Transition	log ft.
β_1	792±10	20	7·3
β_2	685±15	65	6·5
β_3	610±20	15	7·1

Fig. 3 shows the internal conversion electron spectrum. The source was deposited on a thin aluminium foil (0·13 mg./cm.^{2}), and was about 100 μg./cm.^{2} in thickness. Five electron peaks are clearly observed and are interpreted as arising from two transitions corresponding to 102 Kev. and 70 Kev. and Europium X-rays, as shown in Table II. Absorption in the counter window, which was 80 μg./cm.^{2} thick, was taken into account, using correction factors obtained from auxiliary experiments using various values for window thickness.

TABLE II

Line energy (Kev.)	Interpretation	Relative intensity	Sum (Kev.)	*Gamma* energy (Kev.)
20·3±·5	.. K_2 (K conv. of 70 Kev.)	0·29±·03	69·5	70
33±1 38±2	.. A_1 (Auger, K–2L) .. A_2 (Auger, K–L–M)	$\frac{A_1+A_2}{K_1}$ = ·19±·04		
53·3±1	.. K_1 (K conv. 102 Kev.)	1	102·5	102
62	.. L_2 (L conv. 70 Kev.)	0·06±·01	70	70
93·5±3	.. L_1 (L conv. 102 Kev.)	0·16±·02	101·5	102

Photo-electron spectrum of *gamma*-rays emitted in the decay of Samarium-153 was studied in the present investigation, using different radiators, namely, tin, uranium and gold. Fig. 4 shows the photo-electron spectrum, for tin as radiator. In this experiment, the source was kept close to an aluminium disc, thick enough to absorb all primary *beta*-rays. A layer of tin, 250 μg./cm.^{2} was deposited by evaporation, on one side of the disc, facing the spectrometer entrance slit. The line energies measured from the spectrum and their interpretation are shown in Table III. Lines due to *gamma*-rays at 102 Kev. and 83 Kev. are observed, besides the lines due to Europium K_α and K_β X-rays. The line due to 70 Kev. *gamma*-ray, which is highly converted internally, coincides in energy with the L photo-line of K_β X-ray which appears as a weak line on the high energy wing of the

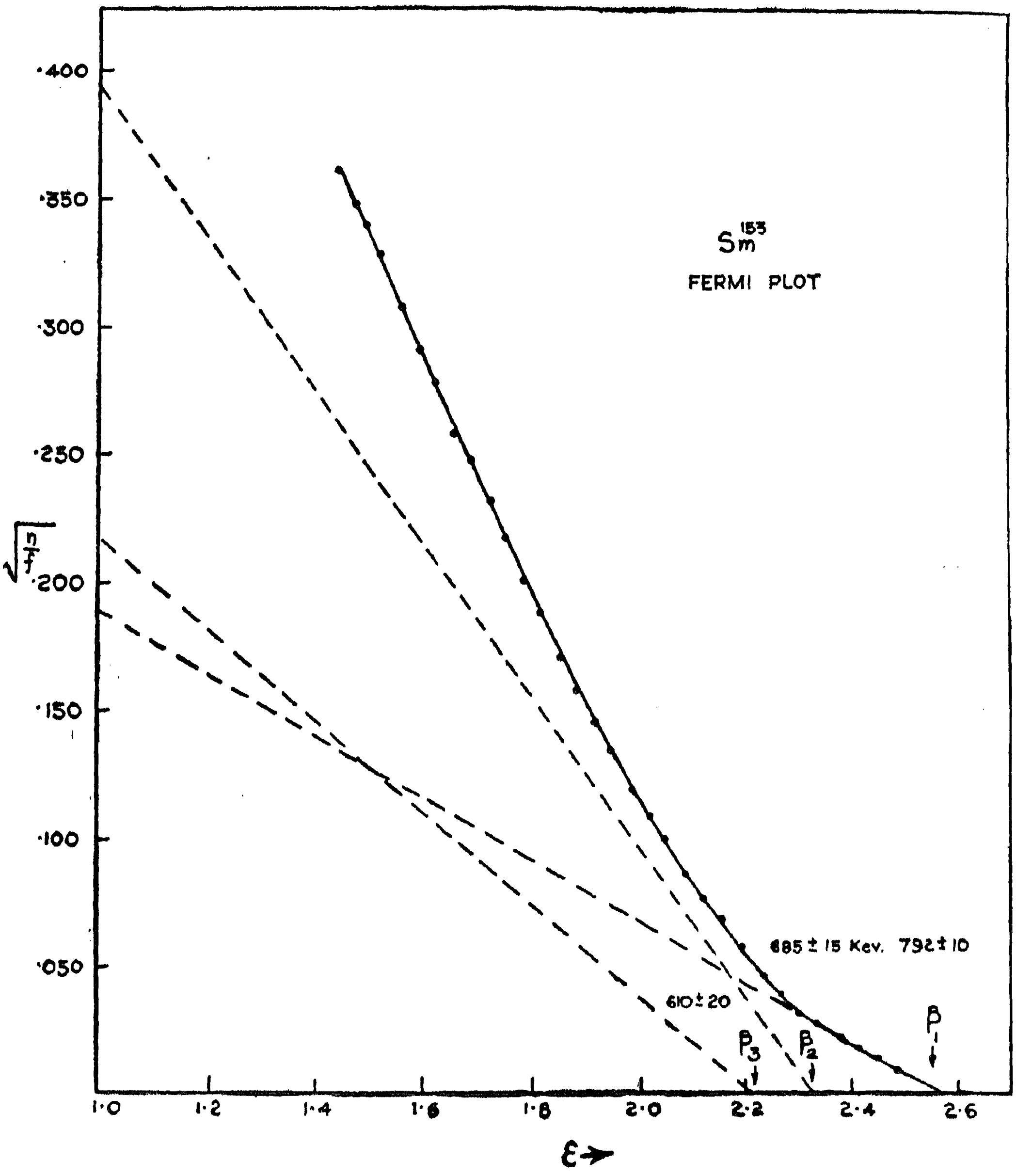

FIG. 2

intense L photo-line due to K_α X-ray in Europium. The relative intensities of the 70 Kev. and 83 Kev. *gamma*-rays, in comparison with 102 Kev. *gamma*-ray were found to be ·06 ± ·01 and < ·04 respectively, from the photo-electron spectra as well as the scintillation spectrum.

TABLE III

(Radiator: Tin)

Line energy (Kev.)		Interpretation	Sum (Kev.)	Intensity ratio N_x/N_z after necessary corrections
10·5±·8	..	K conv. Eu K X-rays	39·7	0·77±0·05
16·5±1	..	K conv. Eu K X-rays	45·7	
19±1 ..	..	Auger line in Tin	K–L–L	
35·5±1	..	L conv. Eu K X-rays	40	
55±2 ..	..	K conv. 83 Kev. *gamma*	84·2	
73·5±1	..	K conv. 102 Kev. *gamma*	102·5	
97±2 ..	..	L conv. 102 Kev. *gamma*	101·5	

Fig. 6 shows the decay scheme of Samarium-153. Three *beta*-groups leading respectively to the 170 Kev. 102 Kev and ground states in Europium and the two main *gamma*-transitions at 102 Kev. and 70 Kev. are shown. The weak radiations at 170 Kev. and 530 ± 20 Kev. which have been reported by previous workers[2,4,6] and at 600 Kev.[9] were observed neither in the photo-electron spectrum nor in the internal conversion spectrum clearly and therefore only an upper limit can be put for their intensities as 1%.

However, they were observed in the scintillation spectrometer with relative intensities < 1% in comparison with 102 Kev. *gamma*-ray. Since Samarium oxide (Sm_2O_3) 'spec-pure' used for neutron irradiation contains normally Europium as a small impurity, there is a need for some further investigation on these weak transitions. However, contribution due to these weak transitions to the X-ray intensity will be negligible on account of their small internal conversion coefficient, and it has been neglected in the present case. The weak *gamma*-ray at 84 Kev. is shown to be due to the de-excitation of the first rotational level above the ground state. Europium

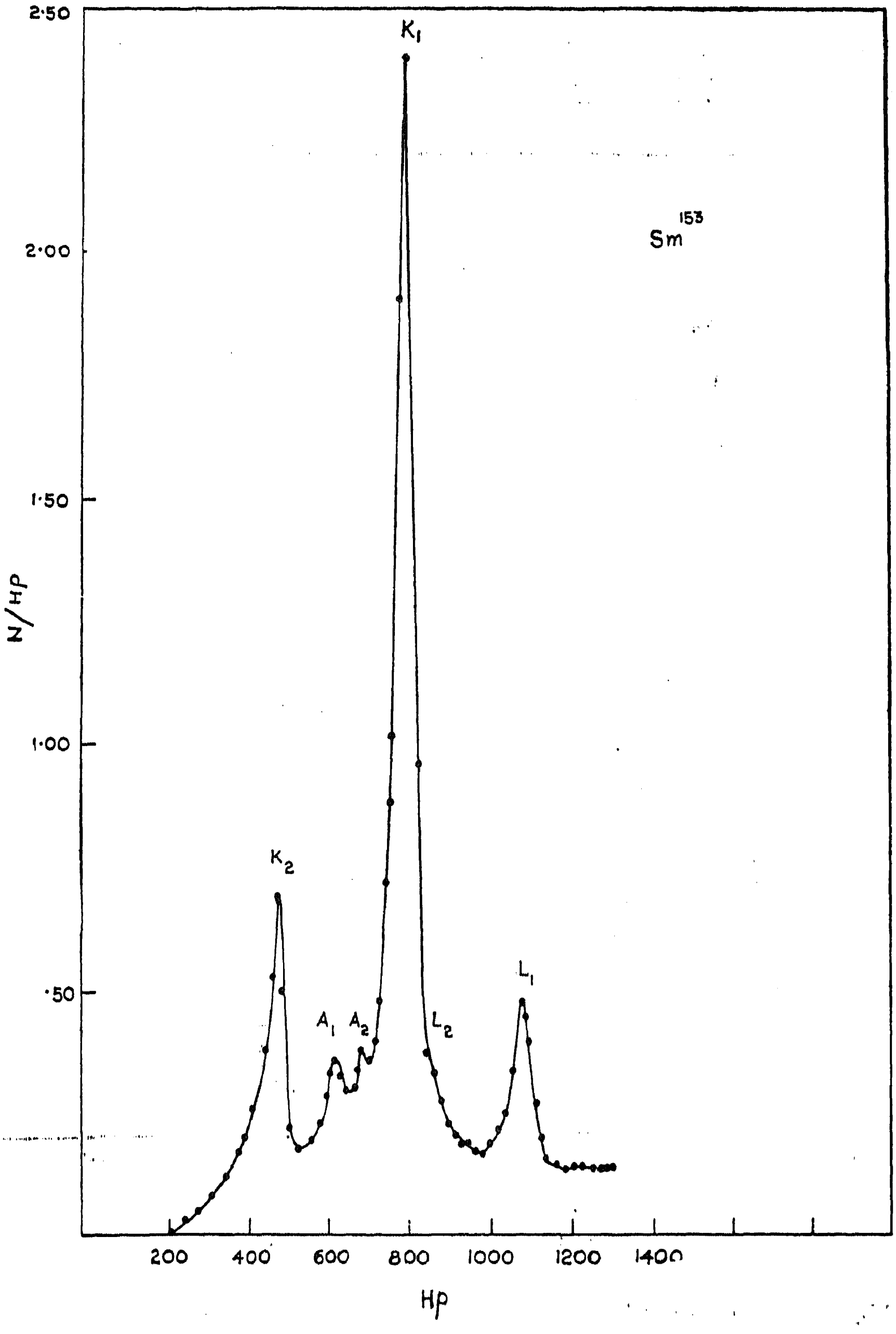

FIG. 3. Internal Conversion Spectrum

155 (half-life 1·7 years) has a *gamma*-ray at 87 Kev. and can be produced as an impurity in the sample but its activity will be less than a thousandth of that of Samarium-153. Also the relative intensities of 83 Kev. and 102 Kev. radiations are seen to remain unchanged over a period of ten days, indicating that 83 Kev. *gamma*-ray observed here is due to Samarium-153. For the purpose of estimating α_K, the conversion coefficient of 102 Kev. *gamma*-ray, and for estimating the relative intensities of the *beta*-branches, the 83 Kev. transition will not be considered. It is also assumed that all the decay is by β^- emission and that there is no decay by electron-capture.

In that case, the vacancies in the K-shell of Europium, giving rise to K_α and K_β X-rays, will all be due to internal conversion of *gamma*-rays γ_1 and γ_2 of energies 102 Kev. and 70 Kev. respectively.

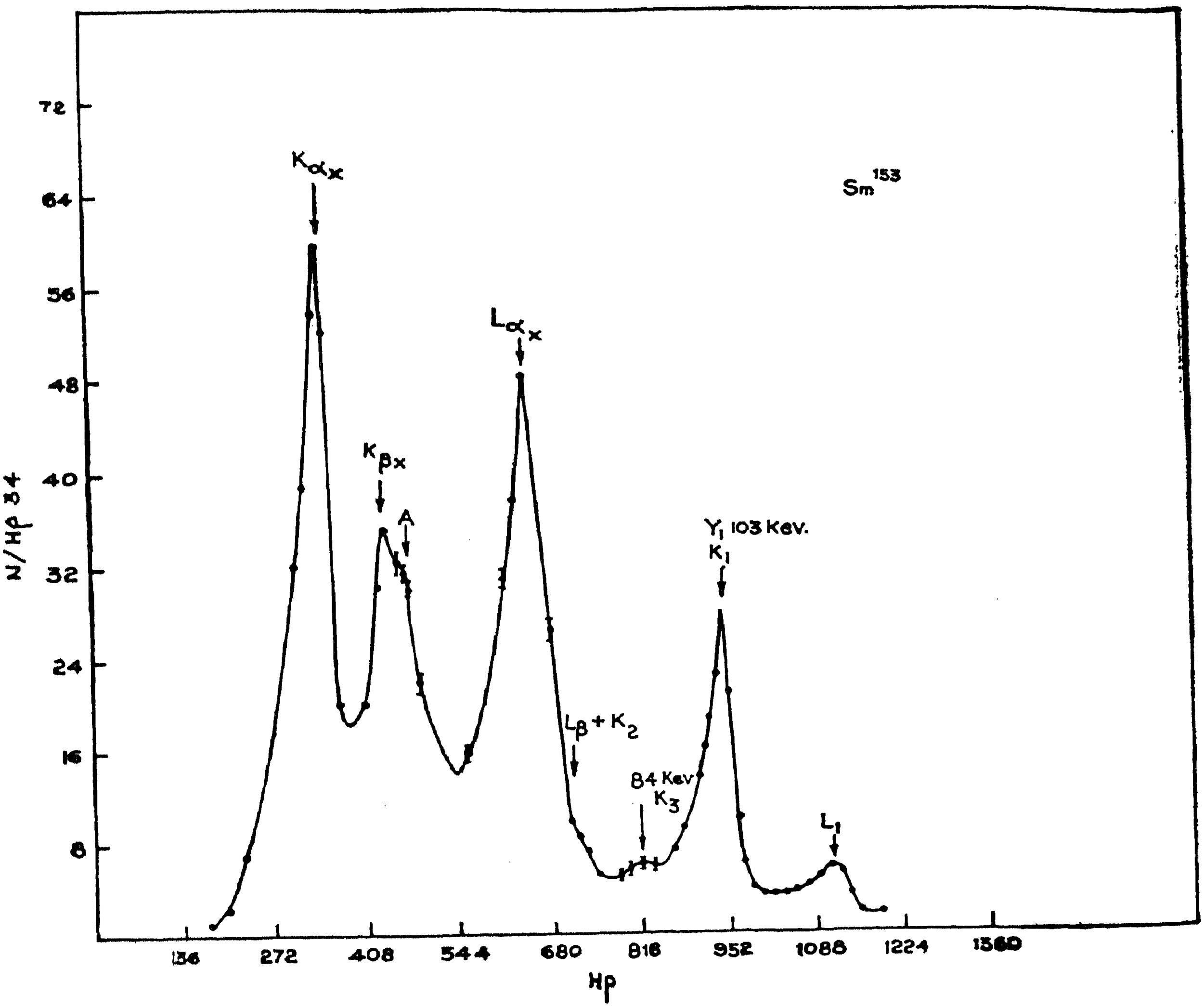

FIG. 4. Photo-electron Spectrum

N_k, the number of K-shell vacancies is given by

$$N_k = N_{ek1} + N_{ek2}$$

where N_{ek_1} and N_{ek_2} represent the number of *gamma*-rays γ_1 and γ_2 converted in the K-shell.

Or,

$$N_k = N_{ek_1}\left(1 + \frac{N_{ek_2}}{N_{ek_1}}\right) \tag{1}$$

Now,

$$N_x = N_k \omega_k \tag{2}$$

where N_x is the number of X-rays and ω_k is the fluorescence yield. Denoting the number of unconverted transitions by N_{γ_1}

$$\frac{N_x}{N_{\gamma_1}} = \frac{N_k . \omega_k}{N_{\gamma_1}}$$

$$\frac{N_x}{N_{\gamma_1}\omega_k} = \frac{N_k}{N_{\gamma_1}} = \frac{N_{ek_1}\left(1 + \frac{N_{ek_2}}{N_{ek_1}}\right)}{N_{\gamma_1}}$$

By definition, α_{k_1}, the internal conversion coefficient of γ_1 is $\frac{N_{ek_1}}{N_{\gamma_1}}$

$$\frac{N_x}{N_{\gamma_1}\omega_k} = \alpha_{k_1}\left(1 + \frac{N_{ek_2}}{N_{ek_1}}\right) \tag{3}$$

The value of α_{k_1} is given by equation (3). The term N_{ek_2}/N_{ek_1} on the right is the ratio of intensities of K-conversion lines due to γ_1 and γ_2 and is obtained from the conversion electron spectrum (Fig. 3) N_x/N_{γ_1}, on the left is the ratio of the intensity of X-rays and of unconverted γ_1-rays and is obtained from the photo-electron spectrum, from the area of the photo-line due to γ_1 and the area under all the photo-lines due to X-rays (Fig. 4), correcting for the variation of photo-electric absorption cross-section in tin with energy. Correction has also to be applied for absorption in the aluminium absorber used for absorbing primary *beta*-rays. One obtains

$$\frac{N_x}{N_{\gamma_1}} = \frac{N_{px}}{N_{p\gamma_1}} \frac{e^{-\mu_{\gamma_1} t}}{e^{-\mu_x t}} \frac{(1 - e^{-\mu\tau_{\gamma_1} l})}{(1 - e^{-\mu\tau_x l})},$$

where N_{px} and $N_{p\gamma_1}$ are the areas under the photo-peaks due to X-rays and γ_1-rays, μ_{γ_1} and μ_x are total absorption coefficients for γ_1-rays and X-rays in aluminium, thickness t (440 mg./cm.^{2}) and $\mu\tau_{\gamma_1}$ and $\mu\tau_x$ are corresponding photo-electric absorption coefficients for tin, thickness, (0·250 mg./cm.^{2}), l, as obtained from the tables.[2]

The fluorescence yield ω_k is obtained from the internal conversion spectrum, from the equation

$$N_k(1 - \omega_k) = N_{Ae}.$$

Where N_k, the number of K-shell vacancies is given by the area under the K-conversion lines of the transitions corresponding to γ_1 and γ_2 and N_{Ae}, the number of Auger electrons, by the area under the Auger lines. The value of ω_k is found to be $0{\cdot}87 \begin{smallmatrix} + \cdot 04 \\ - \cdot 02 \end{smallmatrix}$, in agreement with $\omega_k = {\cdot}88 \pm {\cdot}02$ given by K. Siegbahn.[2] α_k for 102 Kev. *gamma*-ray as calculated in the above manner is found to be 0·69 ± ·08 which agrees with ·66 ± ·1 obtained in the usual manner from the internal conversion line and the β spectrum on which it is superposed. These present values can be compared with $\alpha_k = 0{\cdot}62 \pm {\cdot}15$ given by Lee and Katz[4] and $\alpha_k \sim {\cdot}6$ given by Siegbahn.[2] Now α_k for 70 Kev. transition can be calculated by using the α_k for 102 Kev. transition, the ratio of K internal conversion, *i.e.*, N_{ek_2}/N_{ek_1} and the ratio of *gamma*-ray intensity for these two transitions; α_k for 70 Kev. transition comes out to be $3{\cdot}5 \pm 1{\cdot}4$. This value of α_k for 70 Kev. can be compared with 3·8 given by McGowan,[10] and $4{\cdot}4 \pm {\cdot}4$ given by Dubey *et. al.*[9]

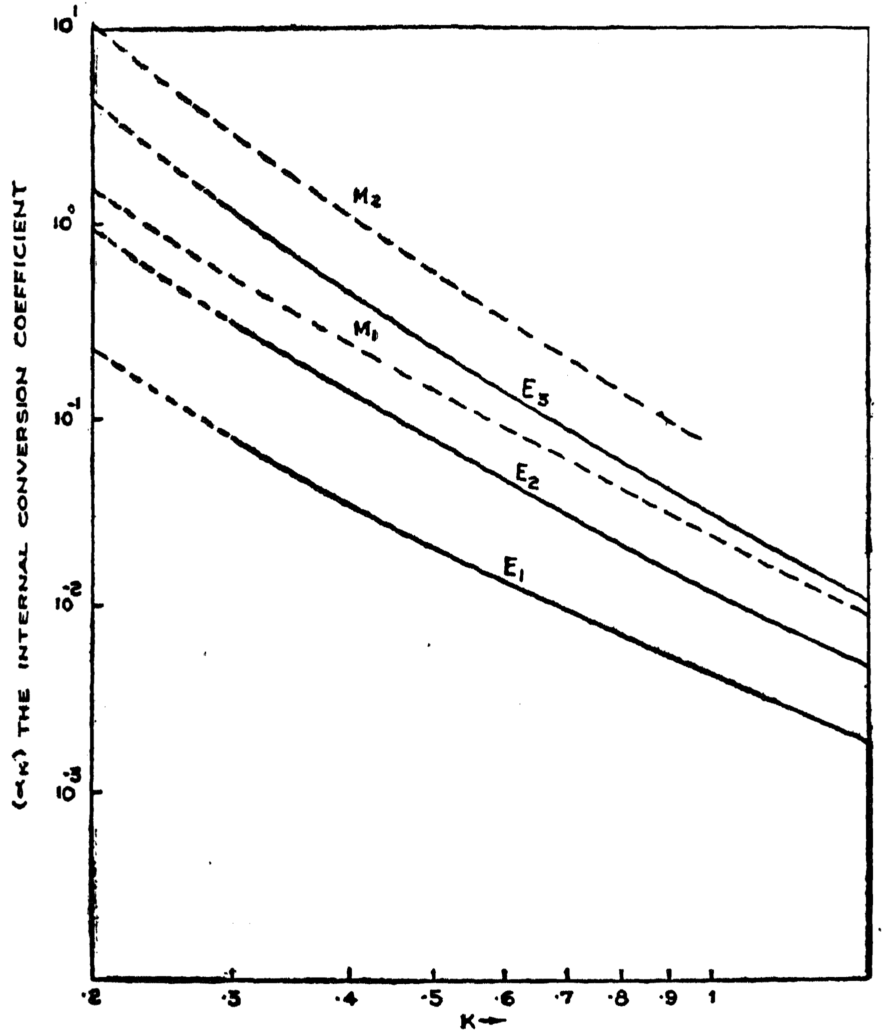

FIG. 5. Photon Energy in Units of mc.²

The branching ratio for the β_1 transition, leading to the ground state in Eu^{153}, is readily found from the Fermi plot (Fig. 2) and is 20%. One can calculate the branching ratio for β_2 and β_3 transitions, making use of the internal conversion data found from the conversion electron spectrum. Referring to the decay scheme and denoting the number of γ_1 and γ_2 transitions by N_1 and N_2 respectively, and the number of the two *beta*-transitions by $N_{\beta 2}$ and N_{β_3}, one gets,

$$N_{\beta_3} = N_2$$

and

$$N_1 = N_{\beta_2} + N_{\beta_3}$$

$$\therefore \quad \frac{N_1}{N_2} = \frac{N_{\beta_2} + N_{\beta_3}}{N_{\beta_3}} = 1 + \frac{N_{\beta_2}}{N_{\beta_3}}.$$

Also, the number of transitions N_1 equals the number of unconverted γ_1 rays, N_{γ_1}, and the number converted in K and L shells.

$$N_1 = N_{ek_1} + N_{eL_1} + N_{\gamma_1}$$

$$N_1 = N_{ek_1}\left(1 + \frac{N_{eL_1}}{N_{ek_1}} + \frac{N_{\gamma_1}}{N_{ek_1}}\right)$$

$$\therefore \quad N_1 = N_{ek_1}\left(1 + \frac{L_1}{K_1} + \frac{1}{\alpha_{k1}}\right)$$

similarly,

$$N_2 = N_{ek_2}\left(1 + \frac{L_2}{K_2} + \frac{1}{\alpha_{k2}}\right)$$

$$\frac{N_1}{N_2} = \frac{N_{ek_1}}{N_{ek_2}} \frac{\left(1 + \frac{L_1}{K_1} + \frac{1}{\alpha_{k_1}}\right)}{\left(1 + \frac{L_2}{K_2} + \frac{1}{\alpha_{k_2}}\right)}.$$

The quantities on the right, conversion coefficients, K/L ratio and the ratio of intensities of the K-conversion lines for γ_1 and γ_2 are known from the internal conversion spectrum. Hence, N_1/N_2 and N_{β_2}/N_{β_3} can be calculated. The branching ratios for β_2 and β_3 are found to be $N_{\beta 2}/N_{\beta_3} = 5$.

The results are summarised below:

Gamma-ray	α_k	K/L	Intensity
102 Kev.	$0\cdot69 \pm 0\cdot08$	$6\cdot2 \pm \cdot8$	1
70 Kev.	$3\cdot5 \pm 1\cdot4$	$5^{+1\cdot3}_{-\cdot9}$	$0\cdot06 \pm 0\cdot01$
83 Kev.	..	..	$< \cdot04$

$$\beta_1/\beta_2/\beta_3 = 0\cdot3/1/0\cdot2$$

DISCUSSION OF RESULTS

One of the objectives of this work was to determine the K-conversion coefficient for 102 Kev. *gamma*-ray, about which there has been a lack of agreement among previous workers.[1–9] McGowan[10] and Marty[6] found it to be 1·14 ± ·2 and 1·2 ± 0·1 respectively, while Lee and Katz[4] and K. Siegbahn[2] reported it to be of the order of 0·6. The value as determined here is 0·69 ± ·08. In the light of this, it is of interest to consider the character and multipole order of the 102 Kev. transition. Previous workers have assumed this transition to be a mixture of E_2 and M_1. Table IV below gives the theoretically expected values for conversion coefficient α_k, and K/L ratio, for this energy and character E_1, E_2, M_1 and M_2. Fig. 5 gives the value of the coefficient α_k for $Z = 64$, against energy in units of mc.² down to ·3, for E_1, E_2, E_3 and M_1 and M_2 types of transition and the curves as extrapolated to 0·2 corresponding to 102 Kev. These curves are plotted from the tables of conversion coefficient by Rose *et al.*,[15] and the values for α_k in Table IV are obtained from these extrapolated curves.

TABLE IV

E	Z^2/E	α_k				K/L			
		E_1	E_2	M_1	M_2	E_1	E_2	M_1	M_2
102 Kev.	38·53	0·25	0·9	1·5	9·0	6·0	2·0	7·3	5·0

It will be seen from the above consideration that the experimental value for the conversion coefficient for 102 Kev. transition, *i.e.*, 0·69 ± ·08 is not in agreement with any one of the theoretical values for the four types of transitions. The value, however, would be consistent with a mixture of E_1 and M_2 types with a preponderant E_1 component.

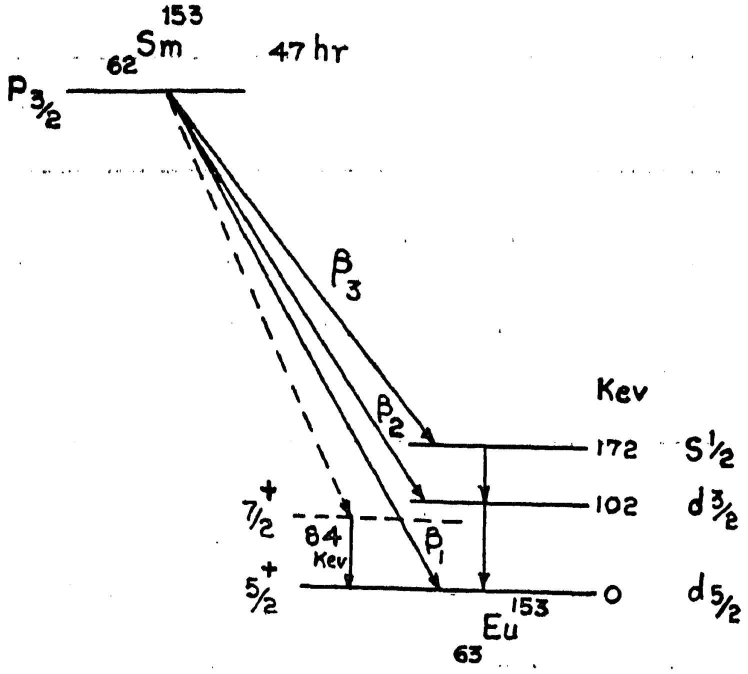

FIG. 6. Decay Scheme

The other alternative is that the transition is a mixture of M_1 and E_2 types, with a correction factor operating in the case of the M_1 coefficient, due to the finite nuclear size, as recently discussed by Sliv[12] and Church.[13] In that case, one finds that it is a predominantly M_1 type of transition and that the correction factor for the coefficient is of the order of 0·5, somewhat larger than that to be expected from Sliv's calculation for nuclei in this range of atomic number.

From shell model considerations the assignment ($d_{5/2}$ +), ($d_{3/2}$ +) and ($s_{1/2}$ +) respectively to the ground, 102 Kev. and 170 Kev. [4,6] states seems resaonable and this would favour the second alternative ($M_1 + E_2$) for the 102 Kev. transition rather than ($E_1 + M_2$), as the latter requires a change of parity.

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