POSITRON SPECTRUM OF $Eu^{152,154}$

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The spectrum of positrons emitted in the decay of $Eu^{152,154}$ has been studied. The spectrum consists mainly of positrons due to pair conversion of 1410-kev γ quanta and of a β^+ spectrum with an end-point energy $E_0 = 700 \pm 20$ kev. The spectrum is identified as being due to positron decay of Eu^{152} ($T_{1/2} = 13$ years), with an intensity of 1.2×10^{-4} positrons per disintegration. The value of $\log(\tau f)$ for this transition is 12.1.

1. INTRODUCTION

MANY papers (references 1 to 4 and others) have been devoted to the study of the decay of Eu^{152} which has a half-period of 13 years. However, a number of important details of the disintegration scheme remains unclear. In particular, no positron decay of Eu^{152} has yet been observed. Yet an investigation of the positron spectrum of Eu^{152} would enable us to obtain new data on its decay scheme, to determine the energy difference for the transition $Eu^{152} \rightarrow Sm^{152}$ and, consequently, to obtain more precise data on electron capture. Attempts to observe positron emission from europium by means of a magnetic-lens spectrometer did not meet with success.[5] In this paper we describe the results of an investigation of the positron spectrum of $Eu^{152,154}$ by means of a spectrometer designed for the study of weak positron spectra.

2. DESCRIPTION OF THE APPARATUS

The experimental setup with which the positron spectrum was investigated is shown schematically in Fig. 1.

We used a magnetic spectrometer of the sector type with double focusing of the beam as described in our earlier paper.[6] The radius of its mean trajectory is 250 mm. Measurements of the positron spectrum were carried out with a spectrometer solid angle equal to 1% of 4π. The relative half-width of the instrumental line was 1.5% with a source width of 1 to 2 mm and with a detector entrance slit 12 mm wide.

The focusing magnetic field of the spectrometer had the following distribution in the median plane:

$$H = H_0\left[1 - \frac{1}{2}\left(\frac{r - r_0}{r_0}\right) + \frac{3}{8}\left(\frac{r - r_0}{r_0}\right)^2\right],$$

where r_0 is the radius of the mean trajectory. The focusing magnetic field, taking into account the stray field, gives an effective focusing angle equal to $\sim 200°$. The source 1 is situated in the magnetic field (Fig. 1), while the detector situated at the spectrometer focus is outside the magnetic field. The positrons were focused by the magnetic field and passed through the entrance slit of the detector 2, to the Geiger counter 3. They were then stopped in the aluminum target where they were annihilated. The annihilation γ radiation was recorded by two CsI (Tl) crystals. Thus, a positron was recorded by the coincidence of three pulses: a pulse in the Geiger counter and two pulses in the scintillation counters. The resolving time of the coincidence circuit was chosen equal to 2×10^{-6} sec. To reduce background, the only pulses recorded were those for which the scintillation pulse corresponded to γ-

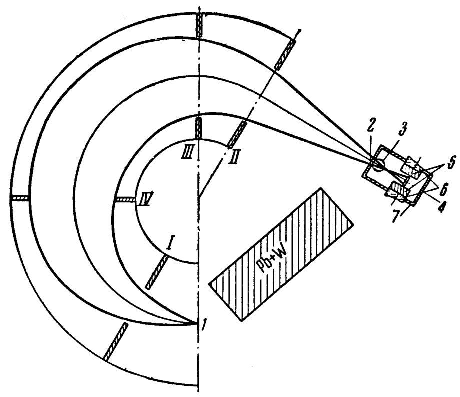

FIG. 1. The electron-optical diagram of the spectrometer. 1) source, 2) entrance slit of the detector, 3) Geiger counter, 4) aluminum target, 5) scintillators, 6) light guides, 7) detector chamber, I–IV) diaphragms.

radiation energy losses in the crystal between 100 and 600 kev.

To provide shielding from cosmic rays, a "blanket" consisting of two layers of type AMM-9 counter tubes was placed above the detector. Above the "blanket" there was a layer of lead (10 cm thick) to absorb the soft component of cosmic rays. The "blanket" was connected in anti-coincidence to the main triple-coincidence circuit, and cut off the part of the background due to showers produced by μ mesons in the neighborhood of the detector. The detector was shielded from the γ-radiation of the source by a lead-tungsten block placed between the two.

The circuit described above for recording positrons had, in the absence of the source, a background of 0.8 to 1.0 counts per hour, and the presence of even quite strong sources of $Eu^{152,154}$ did not appreciably alter the value of the background. One disadvantage of the circuit was the relatively small efficiency for the detection of positrons, defined in our case as the ratio of the number of triple coincidences to the number of pulses recorded by the Geiger counter (with the background subtracted). In our case the efficiency amounted to 4 or 5% for positrons of energy greater than 300 kev. Owing to scattering of positrons between the Geiger counter and the target, the efficiency of positron recording depended on their energy. This dependence is shown in Fig. 2.

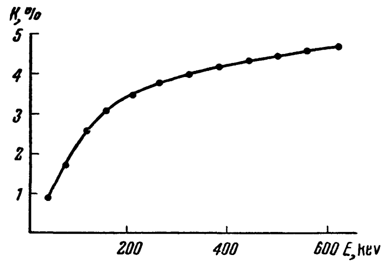

FIG. 2. Dependence of the efficiency K of the recording system on positron energy.

The source consisted of europium oxide of natural composition irradiated with neutrons. It was precipitated from an emulsion of carefully powdered europium oxide onto an aluminum foil 5 μ thick. The sources prepared in this manner had measured 4×20 mm^2 and their density did not exceed 2 mg/cm^2.

The spectrometer was calibrated against lines of conversion electrons from $Eu^{152,154}$, whose energies have been measured with sufficient accuracy.[1]

3. POSITRON SPECTRUM

To check the spectrometer we measured the well-known positron spectra of Cu^{64}, Zn^{65} and the internal-conversion positron spectrum of ThC[11]. The results obtained agree with data available in the literature. As an example, our positron spectrum and that of Owen and Primakoff[7] are compared in Fig. 3. The difference observed at $H\rho <$ 2000 Oe-cm is apparently due to the slowing down of β particles in the relatively thick sources used by us.

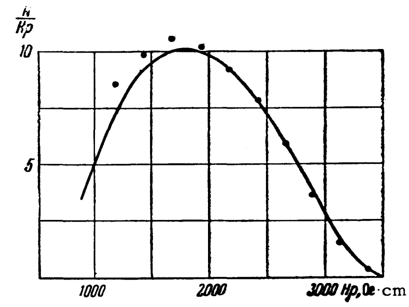

FIG. 3. The positron spectrum of Cu^{65}. Solid curve – according to Owen and Primakoff,[7] • – our results.

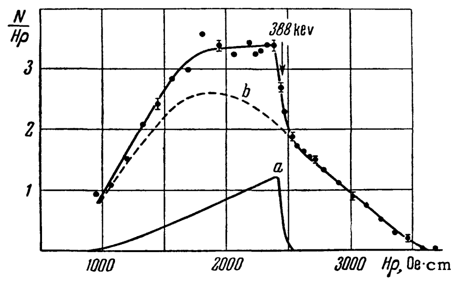

FIG. 4. The positron spectrum of $Eu^{152,154}$, a) pair conversion positrons for a 1410-kev γ quantum, b) β^+ spectrum.

The positron spectrum of $Eu^{152,154}$, reduced to equal interval widths, is shown in Fig. 4. Here a correction has already been introduced, in accordance with Fig. 2, to take into account the energy dependence of the efficiency of the recording system. The measured positron spectrum exceeds the background by 2 or 3 orders of magnitude. When the source was displaced relative to the diaphragm 1 (Fig. 1) in such a way that the β-particle beam did not pass through the spectrometer, the recorded intensity of radiation fell to background level. This shows that the observed positron spectrum is not due to the γ radiation from the source, since the conditions for irradiation of the spectrometer chamber and of the detector by γ rays practically do not change when the source is displaced. At the same time positrons production by γ quanta in the source itself (external pair production) is negligible.

A very important point is the possible presence in the composition of the source of radioactive contaminations which could give rise to emission of positrons. Some of the europium sources investigated were more than three years old, and therefore could not contain any short-lived activities. A careful study of the γ radiation from $Eu^{152,154}$ carried out by Bobykin and Novik[1] using sources prepared from the same material as used in our work, showed that this material contains insignifi-

		Results of calculations on the basis of data of references 10 to 12					Experimental results
		E1	E2	E3	M1	M2	
$\alpha_K \cdot 10^3$		0.48	1.05	2.15	1.55	3.65	
$\Gamma_p \cdot 10^4$	$Z=0$	2.2	0.63	0.21	0.28	0.08	$\Gamma_p/\alpha_K = (43 \pm 10) \times 10^{-2}$
	$Z=84$	1.2	0.42				
$(\Gamma_p/\alpha_K) \cdot 10^2$	$Z=0$	46	6	1	1.8	0.2	
	$Z=84$	25	4				

cant amounts of Eu^{155} and Cd^{153}. Positron decay of these isotopes is apparently impossible,[8,9] and the observed spectrum should therefore be ascribed entirely to $Eu^{152,154}$.

As can be seen from Fig. 4, the positron spectrum is a complex one. The sharp falling-off of the spectrum at $H\rho \approx 2400$ Oe-cm is apparently due to the positron spectrum of the internal pair conversion of the 1410-kev γ line. The end point of this spectrum corresponds well to the energy $E_\gamma - 2mc^2 = 388$ kev. Since the energy distribution of positrons of pair conversion is known,[10] the whole pair-conversion positron spectrum can be reconstructed from the sharp discontinuity.* The spectrum constructed in this manner is shown in Fig. 4 (curve a).

The existence of this spectrum, as well as of an electron-conversion spectrum for the same transition, makes it possible to determine from the ratio of the coefficients of pair and electron conversion the multipole order of the transition. To do this, the same source was used to observe the positron spectrum and the part of the electron spectrum containing the K-conversion line for the 1410-kev transition. The results of measurements made on the electron spectrum are shown in Fig. 5. The ratio of the conversion coefficients was determined as the ratio of areas of the corresponding spectra,† the area of the conversion line being determined by interpolating the β spectrum under this line. The multipole order of the transition is determined by this method in a unique manner since, for example, in the K shell the ratio of the intensities of the internal conversion positron spectrum to that of the internal conversion electron spectrum, $I_p/I_e = \Gamma_p/\alpha_K$, falls off rapidly as the multipole order increases, since the pair-conversion coefficient Γ_p diminishes while the conversion coefficient in the K shell α_K increases. The table gives results of calculations for a number of different multipole orders, and also the value of Γ_p/α_K obtained in our experiment. The comparison of the calculated results with the experimental data gives for the multipole order of the transition the value E1, which corresponds to the data of Bobykin and Novik[1] and of Dzhelepov et al.[2] obtained from the electron-conversion coefficient in the K shell. For the pair-conversion coefficient we obtain the value $\Gamma_p = (2.0 \pm 0.5) \times 10^{-4}$ (for $\alpha_K = 0.48 \times 10^{-3}$).

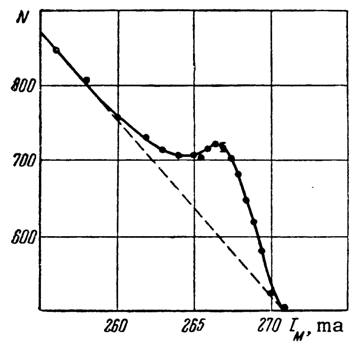

FIG. 5. Electron conversion line in the K shell for a 1410-kev γ quantum. N is the number of pulses per second recorded by the Geiger counter, I_M is the current in the winding of the spectrometer magnet.

After subtracting the pair-conversion positron spectrum belonging to the 1410 kev transition we are left with a positron spectrum (Fig. 4) that cannot be ascribed to pair conversion, both because of the shape of the spectrum (absence of a discontinuity on the high-energy side) and because of the absence of transitions with energies greater than 1410 kev in the γ spectrum of $Eu^{152,154}$. Figure 6 gives the Fermi plot for this

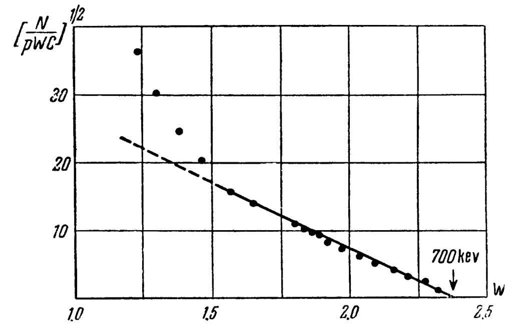

FIG. 6. Fermi plot for the β^+ spectrum. W – is the total positron energy in units of mc^2.

*The distribution of pair-conversion positrons in our case (Z = 62) was assumed to be the same as in the case Z = 84, calculations for which were made by Jaeger and Hulme.[10]

†In finding the above ratio, the difference in the efficiencies of the circuits for recording electrons and positrons was taken into account, since the electrons were recorded by a Geiger counter, while the positrons were recorded by a triple-coincidence circuit.

spectrum. It can be seen that the greater part of the spectrum lies on a straight line. This indicates that one of the europium isotopes undergoes positron β decay. The endpoint energy of the β spectrum is $E_0 = 700 \pm 20$ kev. Figure 6 shows that below 250 kev the experimental points deviate considerably from the Fermi straight line. This excess of positrons is probably due to the pair conversion of a number of weak γ lines accompanying the decay of $Eu^{152,154}$ ($E_\gamma = 1280$; 1110; 1086 kev[1,2]), and also to scattering in the source.

The observed β^+ spectrum should apparently be attributed to the decay of Eu^{152}. The following considerations are in favor of this hypothesis. No K capture was found in an investigation[13] of the decay of Eu^{154} free of Eu^{152}. At the same time, at $E_0 = 700$ kev the intensity of K capture exceeds the intensity of β^+ decay by approximately a factor of 100. On the other hand, when the natural mixture of europium isotopes (Eu^{151} — 47.8% and Eu^{153} — 52.2%) is irradiated with neutrons, the Eu^{152} content is considerably greater than the Eu^{154} content.* Therefore, the β^+-spectrum observed experimentally cannot be attributed to the decay of Eu^{154}.

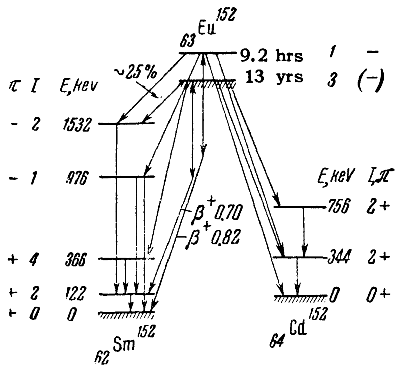

FIG. 7. The decay scheme for $Eu^{152,152m}$ with the positron decay branches according to the results of Grodzins[15] and to our data.

The intensity of the positron branch of the decay of Eu^{152} was calculated on the basis of the decay scheme shown in Fig. 7. This part of the decay scheme of Eu^{152} can at the present time be regarded as reliably established.

After having determined the intensity of the β^+ spectrum relative to the internal conversion positron spectrum (Fig. 4), we determined the intensity of the positron decay of Eu^{152}: $I = (1.2 \pm 0.2) \times 10^{-4}$ positron per decay. In this calculation the conversion coefficient for a 1410-kev γ quantum was taken to be 1.5×10^{-4} (an interpolation between the values $\Gamma_p = 2.2 \times 10^{-4}$ for $Z = 0$ and $\Gamma_p = 1.2 \times 10^{-4}$ for $Z = 84$) (cf. the table), and the intensity of electron capture into the 1532-kev level of Sm^{152} amounts to 25% of all the transitions of Eu^{152} (cf. Fig. 7). The area under the positron β spectrum was found by extrapolating the Fermi plot (Fig. 6) towards the lower energies.

As can be seen from Fig. 7, the observed β^+ decay agrees with the decay scheme of Eu^{152} confirmed by a number of workers.[1-4] The positron decay goes to the first excited state of Sm^{152}. According to the decay scheme this transition is first forbidden ($\Delta I = 1$, with a change of parity). This agrees with the experimentally-observed allowed shape of the β^+ spectrum. However, the observed value of $\log(\tau f) = 12.1$ is too large for a first forbidden transition. It should be noted that very large values of $\log(\tau f)$ are characteristic also for the other transitions in the decay of Eu^{152}, electron capture and β^- decay.

Grodzins and Kendall[15] have observed the β^+ decay of the Eu^{152m} isomer ($T_{1/2} = 9.2$ hours) to the ground state of Sm^{152}; the end-point energy of the spectrum was found to be 820 kev. The comparison of these data with those obtained in our work shows (cf. Fig. 7) that the energy interval between the ground and the isomeric states of europium is less than 20 kev.* This value differs appreciably from the value (80 ± 25 kev) obtained by Grodzins, but agrees with the value 30 ± 40 kev according to the data of Nathan and Waggoner.[4]

It should be noted that the data obtained by us on the total energy of the transition $Eu^{152} \rightarrow Sm^{152}$ do not agree with the results of the recently published paper by Bhattacherjee et al.[16]

In conclusion, the authors express their gratitude to V. M. Kel'man for his continued attention and interest in our work, and to L. A. Sliv for valuable remarks made in the course of discussing our results.

*According to reference 14 the capture cross section for Eu^{151} amounts to ~9000 barns with ≈1400 barns representing the cross section for the formation of the 9.2-hour isomer of Eu^{152}, while the capture cross section for Eu^{153} amounts to only ≈ 420 barns.

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