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Radioactive Decay of Tm^{164} and Tm^{162}

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Erbium oxide enriched to 35.1% and 14.1% in the mass numbers 164 and 162, respectively, were irradiated with 6-Mev protons. Activities decaying by electron capture with half-lives of (2.04±0.10) minutes and (77±4) minutes were produced and are assigned to Tm^{164} and Tm^{162}, respectively, by the identification of the erbium *K* x ray, comparison with the activities produced by similar proton irradiations of each of the other enriched isotopes of erbium, and by the existence in the 2.04-minute activity of a prominent gamma ray with the energy of the first excited level in Er^{164} determined from the decay of Ho^{164}. The gamma-ray spectrum of Tm^{164} consists of only the erbium *K* x ray, a gamma ray of 91 kev, and annihilation radiation; and that of Tm^{162}, of the erbium *K* x ray and gamma rays of 102 and 236 kev. The three radiations observed in the decay of Tm^{162} are all in coincidence. Energy level schemes for the decay of these two new activities are proposed and branching ratios are estimated from relative intensities.

EXPERIMENTAL RESULTS

ALL of the enriched isotopes of erbium have been irradiated with 6-Mev protons. The well known activities of Tm^{170}, Tm^{168}, Tm^{167}, and Tm^{166} were produced from the enriched erbium isotopes with the same mass numbers by (p,n) reactions. The irradiated samples of erbium oxide enriched in the mass numbers 164 and 162 contained two activities differing from the other known thulium activities. Table I lists the percentages of erbium isotopes in the samples used. The activity resulting from the irradiation of enriched erbium 164 clearly showed a 2-minute component, and that of enriched erbium 162, a 77-minute component. The x ray in these activities was shown to be the *K* x ray of erbium by comparison with known erbium *K* x rays. The 2-minute activity exhibited a prominent gamma ray of 91 kev which is the same as the energy of the first excited level of erbium 164 determined by a study of the activity of Ho^{164} by Brown and Becker.[1] It is assumed that these two new activities also resulted from (p,n) reactions with the enriched isotopes. For these reasons, the 2-minute activity is assigned to Tm^{164} and the 77-minute activity is assigned to Tm^{162}.

The half-lives of Tm^{164} and Tm^{162} are (2.04±0.10) minutes and (77±4) minutes, respectively, as measured by following the decay of the individual *K* x rays, gamma rays, and annihilation radiation with a 100-channel scintillation spectrometer. The 2.04-minute value was obtained by the subtraction of a base line due to the longer lived thulium activities in the sample as shown in Fig. 1.

TABLE I. Composition of the enriched erbium oxide samples.

Enriched erbium isotope	Natural percentages	Percentages of erbium isotopes[a] comprising enriched samples					
		162	164	166	167	168	170
164	1.56	<0.2	**35.1**	47.4	9.8	6.2	1.5
162	0.136	**14.1**	9.0	40.0	17.1	14.6	5.2

[a] Supplied by the Stable Isotopes Division of Oak Ridge National Laboratory.

The low-energy portion of the gamma-ray spectrum of Tm^{164} is shown in Fig. 2. Only the erbium *K* x ray, a prominent gamma ray of (91±2) kev, and annihilation radiation were observed on the 2.04-minute half-life in the range 0 to 3000 kev. The relative numbers of *K* x rays, 91-kev gamma rays, and annihilation radiation photons are 100:13.5:176, respectively. The relative number of positrons can be obtained by dividing the number of counts in the spectral distribution of the annihilation radiation by two. The factor of two was confirmed with Na^{22}. An unsuccessful attempt was made to measure the energy of the positron in the 2-minute activity of Tm^{164} by the method of plastic scintillation spectrometry.

The observed gamma-ray spectrum of Tm^{162} consists of the erbium *K* x ray and gamma rays of (102±2) and (236±4) kev. No other gamma rays with energies

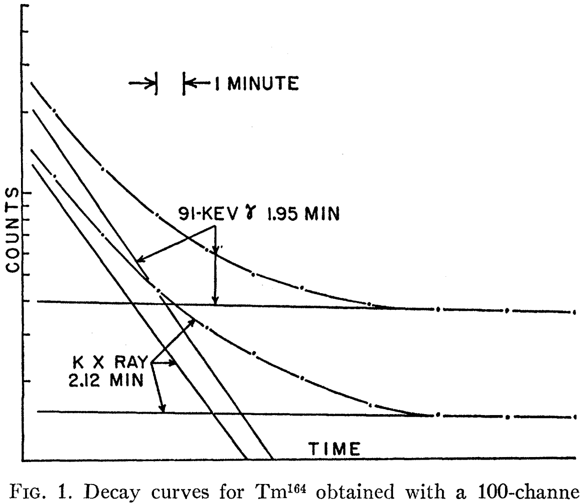

FIG. 1. Decay curves for Tm^{164} obtained with a 100-channel analyzer. A similar curve for the annihilation radiation yielded the value of 2.04 minutes. The curve for the *K* x ray has been plotted one decade low. The base line for the *K* x ray is due to the *K* x ray in the 7.7-hour Tm^{166} activity and that for the 91-kev gamma ray is the channel number where the gamma ray existed.

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[1] H. N. Brown and R. A. Becker, Phys. Rev. **96**, 1372 (1954).

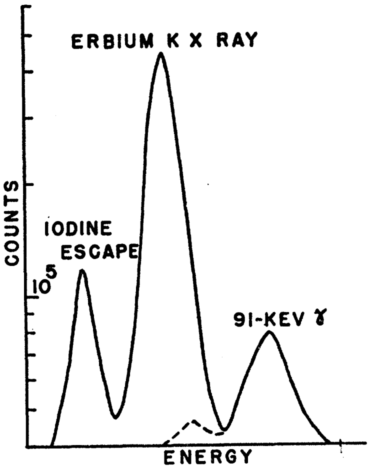

Fig. 2. Gamma-ray spectrum of Tm^{164} obtained with a $1\frac{3}{4}$ ×2 inch Na(Tl) crystal and a 100-channel analyzer.

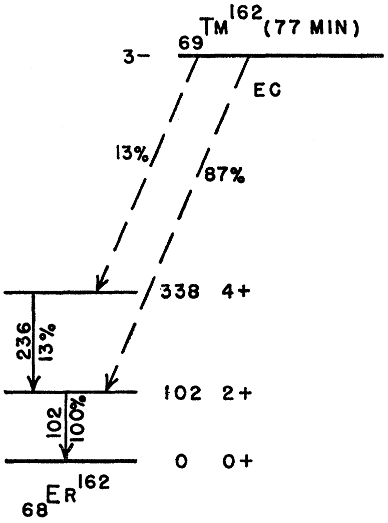

FIG. 4. Proposed energy level scheme for the decay of Tm. ^{162}

between 0 and 3000 kev were observed on the 77-minute half-life. The presence of the 112-minute positron activity of F^{18} prevented positive observation of positrons in the 77-minute activity. The relative numbers of the radiations observed in the spectrum of Tm^{162} are approximately $100:20:10=K$ x ray:102γ:236γ. Gamma-gamma coincidence measurements were performed with a circuit of resolving time $2\tau=1.5$ μsec. All three observed radiations are in coincidence.

DISCUSSION

Figures 3 and 4 show proposed decay schemes for Tm^{164} and Tm^{162}. The 91-kev gamma ray observed in Tm^{164} probably depopulates the first ground-state rotational level of Er^{164} and is therefore assumed to be $E2$. The first rotational level of Er^{162} has not been established by Coulomb excitation but is expected to occur at about 100 kev. The 102-kev gamma ray of Tm^{162} probably depopulates this level and is also assumed to be of $E2$ character. Because the 236-kev gamma ray is in coincidence with the 102, a level at 338 kev is implied. Because the energy ratio of these two levels is that common for the first two rotational levels in even-even nuclei, the level at 338 kev is given the spin assignment 4+. The relative numbers of 91-, 102-, and 236-kev transitions shown in Figs. 3 and 4 were obtained by correcting the observed relative numbers of gamma rays for internal conversion using the data displayed in Table II.[2]

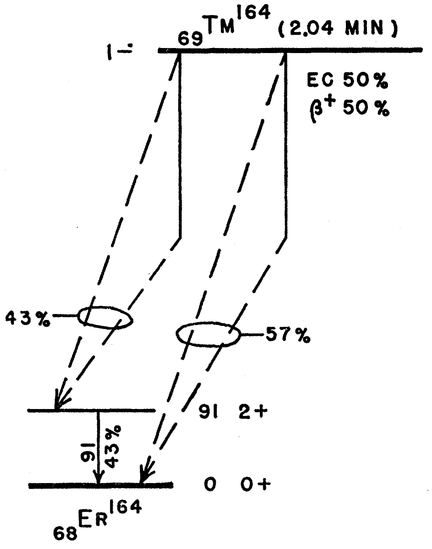

FIG. 3. Proposed energy level scheme for the decay of Tm^{164}.

The rotational spin assignments for the low lying levels in Er^{164} and Er^{162} and the branching ratios shown in Figs. 3 and 4 suggest possible spin assignments of 1− and 3− for Tm^{164} and Tm^{162}, respectively. The decay scheme for Tm^{162} as presented in Fig. 4 accounts for the relative number of K x rays observed within the experimental error which in this case is larger than for Tm^{164} because of the lower enrichment of Er^{162}. If L capture is ignored in the case of Tm^{162}, there is little or no evidence of an electron capture transition to the ground state of Er^{162}. However, if L capture is significant, the possibility of such a transition does exist. If the choice of 3 for the spin of Tm^{162} is correct, then this ground-state decay has $\Delta I=3$ and must then compete with two transitions for which $\Delta I=1$. The ground-state transition is then probably highly retarded and is not shown in Fig. 4.

TABLE II. Internal conversion coefficient data for the $E2$ transitions of 91, 102, and 236 kev in erbium. The α's are from reference 2.

E_γ	$\alpha(K)$	$\alpha(L_{\mathrm{I}})$	$\alpha(L_{\mathrm{II}})$	$\alpha(L_{\mathrm{III}})$	$\alpha(M)$	N_t/N_γ	N_t/N_K
91	1.28	0.120	1.05	1.05	1.10	5.60	4.37
102	1.00	0.094	0.606	0.591	0.615	3.91	3.91
236	0.100	0.011	0.014	0.010	0.016	1.15	11.5

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[2] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

In the decay of both Tm^{166} and Tm^{168} to the even-even isotopes of Er^{166} and Er^{168}, highly populated members of a $K=2+$ vibrational band are observed.[3] These levels are characteristically found at 750 to 1000 kev and decay to the levels of the ground-state rotational band by the emission of gamma rays of 600 to 900 kev. No gamma rays in this energy range were observed with the scintillation spectrometer following the decay of either Tm^{164} or Tm^{162}.

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[3] K. P. Jacob, J. W. Mihelich, B. Harmatz, and T. H. Handley, Phys. Rev. **117**, 1102 (1960); R. G. Wilson and M. L. Pool, Phys. Rev. **119**, 262 (1960).

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Measurements of Spatial Asymmetries in the Decay of Polarized Neutrons*

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A series of experiments has been carried out to examine the spatial symmetry properties of the beta decay of the free neutron. Measurements of angular distributions of the electrons and protons coming from the decay of polarized neutrons have shown that the correlation coefficient between the directions of electron momentum and neutron spin is -0.11 ± 0.02 and that between the antineutrino momentum and the neutron spin is 0.88 ± 0.15. The coefficient of the term proportional to the scalar triple product of antineutrino momentum, electron momentum, and neutron spin (which is not invariant under time reversal) is 0.04 ± 0.05. All these results are consistent with the $A-V$ theory of beta decay. Details of measurement techniques and the method of producing a beam of polarized neutrons are given.

I. INTRODUCTION

Besides the decay rate λ and the spectrum $N(p_e)$, the fundamental process of beta decay,

$$n\rightarrow p+e+\bar{\nu}, \tag{1}$$

is further characterized by certain angular correlations (asymmetries) between such physically observable quantities as the spins and momenta of the particles involved. A complete theory of beta decay should predict all of these observable effects quantitatively. Conversely, the empirical knowledge of all such correlations (in addition to that of the decay rate and of the spectrum) should specify, and possibly overdetermine, all the free parameters of the theory (i.e., the so-called coupling constants). The fact that the neutron undergoing beta decay is, in most experiments, embedded in nuclear matter should not affect this statement. However in order to interpret such experiments, one must have a valid description of nuclear structure. Lacking this knowledge, further free parameters (i.e., the nuclear matrix elements) appear in the theoretical predictions for the observable effects, without essentially increasing the number of experimentally observable quantities.

At the time of the discovery of the breakdown of invariance under space inversion (P) and charge conjugation (C) in weak interactions,[1] Robson and others[2] had already shown that measurements on the decay of free neutrons are experimentally feasible. We therefore decided to investigate in this process those asymmetries which arise from the failure of P and C invariance, and also a particular asymmetry which could arise[3] if time-reversal invariance (T) also failed in beta decay.

The probability of emission of electrons and antineutrinos from polarized nuclei is given by Jackson, Treiman, and Wyld[3] as

$$\begin{aligned}\omega(\langle\mathbf{J}\rangle E_e,\Omega_e,\Omega_{\bar{\nu}})dE_e d\Omega_e d\Omega_{\bar{\nu}} &= \frac{1}{(2\pi)^5}p_e E_e(E^0-E_e)^2\\ &\times dE_e d\Omega_e d\Omega_{\bar{\nu}}\xi\left\{1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_{\bar{\nu}}}{E_eE_{\bar{\nu}}}+b\frac{m}{E_e}\right.\\ &+c\left[\frac{1}{3}\frac{\mathbf{p}_e\cdot\mathbf{p}_{\bar{\nu}}}{E_eE_{\bar{\nu}}}-\frac{(\mathbf{p}_e\cdot\mathbf{j})(\mathbf{p}_{\bar{\nu}}\cdot\mathbf{j})}{E_eE_{\bar{\nu}}}\right]\left[\frac{J(J+1)-3\langle(\mathbf{J}\cdot\mathbf{j})^2\rangle}{J(2J+1)}\right]\\ &\left.+\frac{\langle\mathbf{J}\rangle}{J}\cdot\left[\mathcal{A}\frac{\mathbf{p}_e}{E_e}+\mathcal{B}\frac{\mathbf{p}_{\bar{\nu}}}{E_{\bar{\nu}}}+\mathcal{D}\frac{\mathbf{p}_e\times\mathbf{p}_{\bar{\nu}}}{E_eE_{\bar{\nu}}}\right]\right\}.\end{aligned} \tag{2}$$

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[*] Work performed under the auspices of the U. S. Atomic Energy Commission.

[†] Presently at Ramo-Wooldridge, Canoga Park, California.

[1] C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. **105**, 1413 (1957); R. L. Garwin, L. M. Lederman, and M. Weinrich, Phys. Rev. **105**, 1416 (1957); J. I. Friedman and V. L. Telegdi, Phys. Rev. **105**, 1681 (1957).

[2] J. M. Robson, Phys. Rev. **83**, 349 (1951); A. H. Snell, F. Pleasonton, and R. V. McCord, Phys. Rev. **78**, 310 (1950).

[3] J. D. Jackson, S. B. Treiman, and H. W. Wyld, Phys. Rev. **106**, 517 (1957).