Radioactive Decay of Lu^{170}

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Ytterbium oxide enriched to 81.4% in the 170 mass number was irradiated with 6-Mev protons. An activity decaying by electron capture with a half-life of (2.05±0.05) days was produced and assigned to Lu^{170} by the identification of the ytterbium K x ray and by comparison with the activities produced by similar proton irradiations of each of the other enriched isotopes of ytterbium. The observed activity consists of the ytterbium K x ray, gamma rays with energies of 84, 193, 245, 1010, 1030, 1165, 1275, 1415, 2035, 2365, 2665, 2890, and 3085 kev, and a small amount of annihilation radiation. Because no particle radiation exists, the mode of decay of Lu^{170} is solely by electron capture to Yb^{170}. Gamma-gamma coincidence measurements have led to the postulation of levels in Yb^{170} at 2120 (0), 2365 (1 or 2), 3170 (3), and 3395 (1 or 2) kev in addition to the previously assigned 84 (2+), and 278 (4+) levels. A partial energy level scheme with approximate electron capture branching ratios is proposed.

INTRODUCTION

A 1.7-DAY half-life activity decaying by electron capture and including gamma radiation of about 2.5 Mev has been assigned to Lu^{170}.[1] Conversion electron measurements following the proton irradiation of natural ytterbium oxide have resulted in the assignment of 84.2- and 193.5-kev transitions to the activity of Lu^{170} and 84- and 278-kev levels in Yb^{170}.[2] The half-life of this activity was reported as 1.9 days. Twenty-five conversion electron energies of approximately 2-day half-life found in a lutetium fraction obtained by the irradiation of tantalum with 660-Mev protons have been presented.[3] The corresponding transitions were associated with the combined activities of Lu^{169} and Lu^{170} because of their similar half-lives. In an activity of 1.5- to 2-day half-life produced in the same way as that of the preceding reference, 23 transitions were observed from conversion electron measurements.[4] Two of these were attributed specifically to the activity of Lu^{170} and 13 associated with the combined activities of Lu^{169} and Lu^{170}. Gamma rays of energies 83, 190, 245, and 2040 kev have been assigned to the activity of Lu^{170} produced by the irradiation of natural lutetium oxide with 250-Mev betatron bremsstrahlung.[5] The measured half-life of the 2040-kev gamma ray was (2.2±0.7) days and the 83-, 190-, and 245-kev gamma rays were in coincidence with the 2040-kev gamma ray.

No energy levels have been determined specifically in Yb^{170} by Coulomb excitation although a composite level of about 78 kev has been assigned to all of the even isotopes of ytterbium using the natural oxide.[6] The 84- and 278-kev levels mentioned above have been designated as the first two rotational levels of Yb^{170}.[2] The 84.2-kev transition in Yb^{170} is also observed following the β^- decay of Tm^{170}.

EXPERIMENTAL RESULTS

Ytterbium oxide enriched to 81.4% in the 170 mass number was irradiated with 6-Mev protons. The composition of the remaining protion is as follows in percent: 0.07 Yb^{168}, 7.8 Yb^{171}, 4.8 Yb^{172}, 2.3 Yb^{173}, 3.1 Yb^{174}, and 0.73 Yb^{176}. The atomic number of the resulting activity was determined by the identification of the ytterbium K x ray which was compared with the known K x rays of europium, terbium, thulium, ytterbium, lutetium, and tantalum emitted from radioactive Gd^{153}, Dy^{159}, Yb^{169}, Tm^{170}, Hf^{175}, and W^{181}, respectively. Ion-exchange separation was deemed unnecessary.

In order to determine the mass number of the activity, similar proton irradiations were performed on each of the other stable enriched isotopes of ytterbium and the resulting activities intercompared. The proton irradiations of Yb^{176}, Yb^{174}, Yb^{173}, Yb^{172}, and Yb^{171} produced the well established activities of Lu^{176}, Lu^{174}, Lu^{173}, Lu^{172}, and Lu^{171}, respectively. The initial activity produced by the irradiation of Yb^{170} was not observed in any of the activities produced by the irradiations of the other enriched isotopes of ytterbium. After sufficient decay of this initially observed activity, identifiable amounts of the activities of Lu^{171} and Lu^{172} were observed. These activities are attributable to the 7.8% and 4.8% of Yb^{171} and Yb^{172}, respectively, existing with the enriched Yb^{170}.

The half-life of the activity resulting from the proton irradiation of Yb^{170} is (2.05±0.05) days as determined by following the straight-line decay of the gamma-ray spectrum for six half-lives on a 100-channel scintillation spectrometer.

[1] G. Wilkinson and H. G. Hicks, Phys. Rev. **81**, 540 (1951).
[2] J. W. Mihelich, B. Harmatz, and T. H. Handley, Phys. Rev. **108**, 989 (1957).
[3] Iu. G. Bobrov, Ia. Gromov, B. G. Dzhelepov, and B. K. Preobrazhenskii, Izvest. Akad. Nauk S.S.S.R. Ser. Fiz. **21**, 940 (1957) [Translation: Bull. Acad. Sciences U.S.S.R. **21**, 942 (1957)].
[4] V. M. Kel'man, R. Ya. Metskhavarishvili, B. K. Preobrazhenskii, V. A. Romanov, and V. V. Tuchkevich, Zhur. Eksp. i Teoret. Fiz. **35**, 1309 (1958) [Translation: Soviet Phys.—JETP **35**(8), 914 (1959)].
[5] L. T. Dillman, R. W. Henry, N. B. Gove, and R. A. Becker, Phys. Rev. **113**, 635 (1959).
[6] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **100**, 150 (1955).

TABLE I. Gamma-gamma coincidence information for the activity of Lu^{170}.

	K x ray	84	193	245	511	1010, 1030	1165	1275	1415	2035	2665
84	yes	no	yes		yes	yes		yes	yes	yes	yes
511	yes	yes	yes		yes	yes					
1010 and 1030	yes	yes			*w*	yes		yes			
1275					no	yes	yes		yes		
2035	yes	yes	no	yes		yes		yes	no	no	no

L and K x rays of ytterbium were detected in the activity of Lu^{170} with a Geiger tube used with aluminum and beryllium absorbers. Figure 1 shows the gamma-ray spectrum which is complex and extends past 3 Mev. Some gamma rays are resolved in the gamma-ray spectrum and others have been observed in gamma-gamma coincidence measurements. The observed gamma rays have energies of 84 ± 1, 193 ± 5, 245 ± 5, 1010 ± 20, 1030 ± 20, 1165 ± 30, 1275 ± 20, 1415 ± 30, 2035 ± 15, 2320 ± 40, 2665 ± 20, 2890 ± 40 and 3085 ± 60 kev. No evidence of particle radiation was found by the method of plastic scintillation spectrometry nor by the use of a Geiger tube with aluminum and beryllium absorbers. A small amount of annihilation radiation does exist in the gamma-ray spectrum but was shown by absorption measurements with a plastic scintillation spectrometer to be the result of the annihilation of positrons produced by the high-energy gamma radiation. The mode of decay is therefore essentially by electron capture to Yb^{170} although the ground state of Lu^{170} is at least 3400 kev above that of Yb^{170} as discussed later.

As seen in Fig. 1, the low-energy portion of the gamma-ray spectrum consists of the ytterbium K x ray and a strong 84-kev gamma ray. Two coincidence sum peaks are also observed; one is the sum of two coincident K x rays and the other is the sum of 84-kev gamma rays and K x rays. These peaks were shown by absorption measurements to be coincidence sum peaks.

Gamma-gamma coincidence information was obtained for the activity of Lu^{170} with a coincidence circuit of resolving time $2\tau=1.5$ μsec and two $1\frac{3}{4}\times2$-inch crystals. Table I is a tabulation of this coincidence information.

DISCUSSION

The existence of a weakly populated level at 278 kev (4+) in Yb^{170} is further confirmed here because a weak 193-kev gamma ray is in coincidence with the 84-kev gamma ray. The ratio of the number of 193- to 84-kev transitions was calculated to be 0.055 from the data of references 2 and 7 which is consistent with the fact that the 193-kev gamma ray can be seen only in the coincidence spectrum. A level with a spin of 0 is proposed at 2120 kev because (1) the 2035-kev gamma ray is in coincidence with the 84-kev but not with the 193-kev, (2) no 2120-kev crossover transition is observed, and (3) the relative number of the 2035-kev transitions is greater than any other transition except the 84-kev. Levels at 2365 and 3395 kev are suggested by the coincidences of 245-, 1030-, and 1275-kev gamma rays with the 2035-kev gamma ray. The 245-kev transition is placed lower only because a 2365-kev level allows the placement of the 2365-kev gamma ray from this level to the ground state. A spin assignment of 1 or 2 then seems consistent for both of these levels. A possible level at 3170 kev with spin 3 is suggested because the energy difference between the 2890- and 3085-kev gamma rays is 195 kev, just the energy of the second ground-state rotational transition.

The ratio of the number of counts under the spectral distribution of the K x ray to that of the 84-kev gamma ray is 100/10.2. The K, L_{I}, L_{II}, L_{III}, M, and N [7] internal conversion coefficients[8] for an 84-kev $E2$ transition in ytterbium are 1.30, 0.14, 1.76, 1.76, 1.75, and 0.50, respectively. The ratios of the total number of

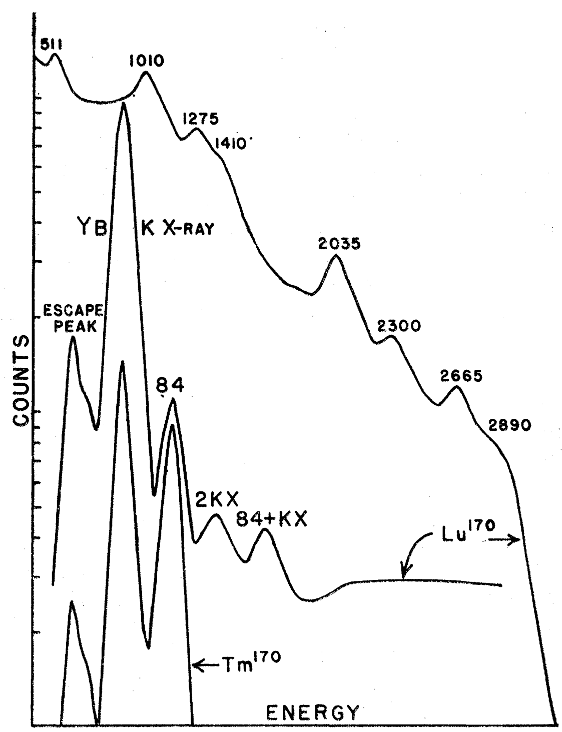

FIG. 1. Gamma-ray spectrum of Lu^{170} as measured with a 3×3 inch crystal and a 100-channel scintillation spectrometer. Sample was centered on flat face of crystal.

[7] Obtained from the data of reference 2.

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

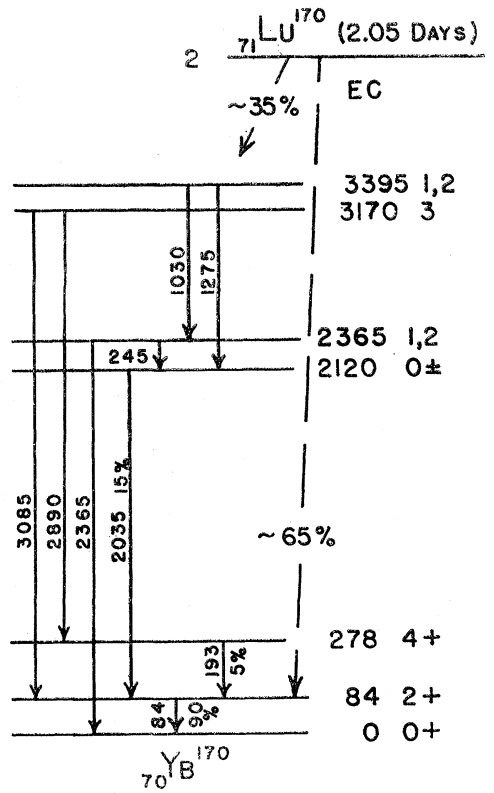

FIG. 2. Proposed partial energy level scheme for the decay of Lu^{170}.[11]

transitions to the number of corresponding gamma rays and to the number of K-converted transitions are 8.2 and 6.3, respectively. Because of K fluorescence yield in ytterbium is 0.937,[9] 107 K x-ray producing events were necessary in order for 100 to be observed.

The 10.2 84-kev gamma rays result from $10.2\times8.2=84$ transitions which also produce $84/6.3=13$ K x-rays by K conversion. If internal conversion of the other weak transitions is neglected, $107-13=94$ K x rays result from K capture to the levels of Yb^{170}. These figures indicate that a large fraction of the electron capture transitions result in an 84-kev transition. It is estimated that approximately two-thirds of the electron capture transitions of Lu^{170} occur to the 84-kev level of Yb^{170}, the remainder populating higher-energy levels or occurring directly to the ground state. Some flexibility must be allowed in this division because the fraction of L capture is not known nor are the positions of the numerous but weak high-energy transitions certain. The intensities of all of these high-energy radiations are small compared with the 84-kev, and the amount of L capture should be a minimum because of the large decay energy.

Figure 2 shows a proposed partial energy level scheme for the decay of Lu^{170}. The coincidence information and the high-energy radiations emitted in the decay of Lu^{170} require an energy difference of about 3395 kev between the ground states of Yb^{170} and Lu^{170}. Because approximately two-thirds of the electron capture disintegrations of Lu^{170} occur to the 84 kev 2+ level of Yb^{170}, a spin of 2 is favored for the ground state of Lu^{170}.

Three other lutetium activities previously reported upon[10] yield information about the energy level structure of the even-even isotopes of ytterbium with mass numbers 168, 172, and 174. The ground-state spins of all four of the radioactive lutetium isotopes, 168, 170, 172, and 174, are important factors in determining which parts of the even-even level structure of the ytterbium isotopes are excited. Lu^{172} has a ground state with a spin of 4, the decay of which excites the first three members of the ground-state rotational band, a $K=3$ vibrational-rotational band at 1172 kev, and an apparently single-particle level at 2072 kev. Lu^{174} and Lu^{168} have ground-state spins of 1− and their decays excite a much smaller part of the level structure of the daughter isotopes; only the first member of the ground-state rotational band, a 0+ vibrational level at 1305 kev in Yb^{174}, and a level at 987 kev in Yb^{168} which is probably the ground state of the $K=2+$ vibrational band.

As discussed above, Lu^{170} may have a ground-state spin of 2 and is at least 3.4 Mev above the ground state of Yb^{170}. A departure from the portion of the level structure which is excited occurs in this case. The first two members of the ground-state band are the only levels below 2 Mev which are excited.[11] The complex, low-intensity, and high-energy gamma-ray spectrum of Lu^{170} seems to result from the population of low-spin levels in Yb^{170} with energy greater than 2 Mev. A minor closed shell or magic number occurs when the one-hundredth neutron fills the $^2f_{7/2}$ state. The (p,n) reaction with Yb^{170} requires the removal of this "closed shell" neutron which may account for the energy difference of 3.4 Mev.

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[9] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam 1959).

[10] R. G. Wilson and M. L. Pool, Phys. Rev. **117**, 517 (1960); **118**, 227 (1960); and **118**, 1067 (1960).

[11] *Note added in proof.* Ninety conversion electron transitions between 0 and 3000 kev have recently been reported [B. Harmatz, T. H. Handley, and J. W. Mihelich, Phys. Rev. **119**, 1345 (1960).] for the activity of Lu^{170}. A large number of levels below 2 Mev probably do exist in Yb^{170} which are weakly populated from above. A weak crossover transition from the 2123-kev level is observed which suggests that the spin of this level is 2 rather than 0. More accurate energies for the levels shown in Fig. 2 are 84.2, 277.7, 2123, 2359, 2956, and (3389 and 3421) kev. Other possible levels are suggested at 941, 1141, 1232, 1483, 1515, 1537, 2512, 2767, 2836, and 3348 kev.