Radioactive Decay of Yb^{177}†

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The decay characteristics of the 1.8-hr negatron emitter Yb^{177} have been investigated by means of beta-ray and gamma-ray coincidence scintillation spectrometers. Gamma rays of energies 0.118, 0.140, 0.147, 0.95, 1.09, 1.12, and 1.24 Mev are found to accompany the decay. The gamma-ray energy and intensity data can be satisfied by postulating excited levels in Lu^{177} at 0.118, 0.147, 0.287, and 1.24 Mev. Beta-gamma coincidence scintillation spectrometer studies indicate that the 0.118-, 0.147-, and 1.24-Mev levels as well as the ground state of Lu^{177} are directly populated by beta decay from Yb^{177}. Tentative spin and parity assignments for the excited levels of Lu^{177} are presented.

I. INTRODUCTION

RECENT experimental work on the radioactive decay of Yb^{177} (1.8 hr) by de Waard[1] indicates that Yb^{177} decays by a 1.30±0.05-Mev negatron ground-state transition (88 percent) to Lu^{177} with the remainder of the negatron transitions leading to excited states of Lu^{177} at 0.119±0.001 Mev (3 percent) and 0.146±0.001 Mev (9 percent). Furthermore, de Waard observed that the half-life of the 0.146-Mev level is 0.122±0.005 microsecond, in good agreement with a previous measurement of 0.13±0.02 microsecond by McGowan.[2] The results of our study are in general agreement with those of de Waard except that we find evidence for two additional excited states in Lu^{177}; one occurring at 1.24 Mev, which decays by emission of four gamma rays of energies 0.95, 1.09, 1.12, and 1.24 Mev; the other occurring at 0.287 Mev, which decays by a 0.140-Mev gamma transition to the level at 0.147 Mev.[3]

II. SOURCE PREPARATION

Ytterbium-177 was prepared by thermal-neutron bombardment of Yb_2O_3[4] of natural isotopic abundance. Although a large fraction of the activity produced was Yb^{175}, the relatively long half-life of Yb^{175} (4.2 days) enabled an unambiguous separation of its emanations from those of Yb^{177} to be realized. Because of the characteristics of the Yb^{177} decay scheme, the relatively low value of the product of thermal-neutron cross section and isotopic abundance of Yb^{176}, and the available neutron flux at this laboratory, studies with our high-resolution permanent-magnet spectrographs were precluded, and the investigation reported herein was confined to the use of scintillation apparatus.

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[1] H. de Waard, Phil. Mag. **46**, 445 (1955).

[2] F. K. McGowan, Oak Ridge National Laboratory Report ORNL-952, March 13, 1951 (unpublished).

[3] Radiations from the level at 1.24 Mev have recently been observed by Cork, Brice, Martin, Schmid, and Helmer, Phys. Rev. **101**, 1042 (1956).

[4] The Yb_2O_3 of specified purity 99.95 percent was obtained from Johnson, Matthey, and Company, Limited, Hatton Garden, London.

III. GAMMA-RAY EXPERIMENTS

The results of a study of the gamma-ray spectrum of Yb^{177} are shown in Figs. 1 and 2. Data from the NaI(Tl) scintillation counters were recorded with a one-hundred-channel pulse-height analyzer. The spectra were studied as a function of time in order that contributions to the spectra from the radiations of Yb^{175} could be removed by subtraction. The relative intensities of the observed 0.118±0.002, 0.147±0.002, 0.95±0.01, 1.09±0.01, and 1.24±0.01 Mev gamma rays were measured with a 2×2 inch NaI(Tl) crystal whose detection sensitivity (photopeak area *vs* energy) is empirically known.

A series of gamma-gamma coincidence studies performed with NaI(Tl) detectors and a coincidence circuit whose resolving time was $2\tau=0.4$ microsecond revealed that the 0.118- and 0.147-Mev transitions are not in cascade. Further coincidence experiments showed that the 1.09- and 0.147-Mev transitions are in delayed coincidence and suggested that the 1.24-Mev gamma ray serves as a cross-over transition of these latter two gamma rays.

In the foregoing coincidence experiments, a weak photopeak was observed at 0.118 Mev when the gate included the 1.1-Mev region. To investigate this coincidence in greater detail, two NaI(Tl) detectors were employed with a fast coincidence circuit ($2\tau=0.02$

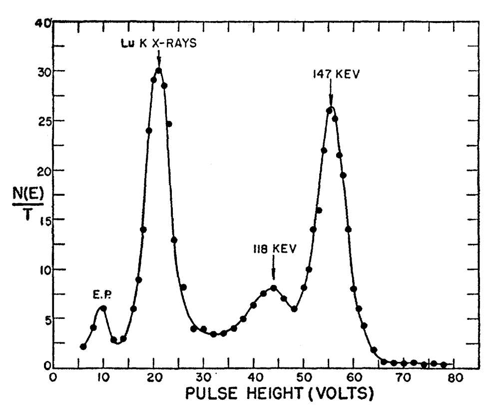

FIG. 1. Pulse height spectrum of Yb^{177} low-energy gamma rays taken with a $1\frac{1}{2}\times1\frac{1}{2}$ inch NaI(Tl) crystal.

microsecond) similar to the type described by Bell *et al.*[5] By gating with pulses corresponding to energies >1.0 Mev, thus including the 1.1-Mev region, we observed a 0.118-Mev photopeak in the resulting coincidence spectrum. Since the 0.118- and 0.147-Mev gammas are not in cascade, it seemed clear that although the 0.118-Mev gamma must be in coincidence with a gamma of energy $\sim$1.1 Mev, it is not in coincidence with the 1.09-Mev transition. Therefore, we postulate a 1.12-, 0.118-Mev cascade from the 1.24-Mev level. The sequential order of the cascade was established through beta-gamma coincidence experiments to be described in Sec. IV.

In the above fast-coincidence experiment, a 0.140 $\pm$0.004 Mev photopeak was also revealed in the resulting coincidence spectrum. Therefore, additional studies were initiated. With the gate channel of the fast-coincidence apparatus set to accept pulses corresponding to energies >1.0 Mev, it was observed that the ratio of the 0.118- to 0.140-Mev photopeak areas was greatly enhanced in comparison to the ratio obtained when the lower bound was set at 0.7 Mev. These experiments thus suggested that the 0.140-Mev gamma is in cascade with the 0.95-Mev transition. The fact that the sum of the two gamma energies equals 1.09 Mev further suggested that the 0.95-, 0.140-Mev cascade terminates at the 0.147-Mev level, and that the 0.95-, 0.140-, and 0.147-Mev triple cascade originates at the 1.24-Mev level.

To verify that the 0.140-Mev transition is indeed in coincidence with the 0.147-Mev gamma, the slow-coincidence equipment ($2\tau=0.4$ microsecond) was utilized. With the gate channel set to accept pulses in the 0.135- to 0.180-Mev region, a photopeak at $\sim$0.140 Mev was recorded in the coincidence spectrum. The gate channel was then moved to the 0.195- to 0.240-Mev region and the resulting coincidence spectrum subtracted pointwise from the spectrum obtained when the gate included pulses in the 0.135- to 0.180-Mev region. The entire coincidence experiment was repeated approximately six hours after the initial measurements in order that the Yb^{175} contribution to the spectrum could be removed. We interpret the 0.140-Mev photopeak which remained after subtraction to be engendered by coincident 0.140-, 0.147-Mev gamma rays. It is to be noted that in all coincidence experiments wherein it was possible to obtain coincidences resulting from Compton-scattered quanta, the necessary precautions both as to geometrical arrangement and shielding were taken in order to eliminate such effects. The level scheme resulting from the foregoing discussion is shown in Fig. 3. The ordering of the 0.95-, 0.140-Mev cascade shown in Fig. 3 is tentatively assigned through consideration of gamma-ray competition for depopulation of the 1.24-Mev level. Both the 0.95- and 0.140-Mev transitions precede the 0.147-Mev transition as is evidenced from the gamma-intensity relationships.

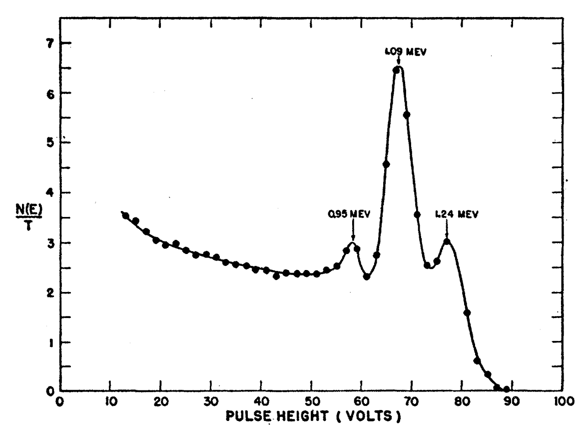

FIG. 2. Pulse height spectrum of Yb^{177} high-energy gamma rays taken with a 4×4 inch NaI(Tl) crystal. A $\frac{1}{8}$-inch thick lead absorber was placed between the source and crystal.

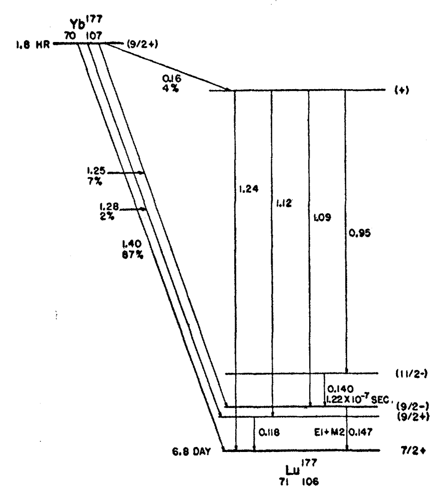

FIG. 3. Decay scheme of Yb^{177}.

The intensity of the 1.12-Mev gamma relative to that of the 0.95-Mev gamma was obtained by measuring the ratio of the intensities of the 0.140- and 0.118-Mev gammas as observed in a coincidence experiment of time resolution $2\tau=0.02$ microsecond wherein the gate circuit accepted pulses corresponding to energies >0.7 Mev. Since only the 0.140- and 0.147-Mev gamma rays were observed to be in cascade with the 0.95-Mev transition, and since the intensity of the 0.95-Mev transition relative to the sum of the intensities of the 1.09- and 1.12-Mev transitions is known from the singles spectrum, we could deduce the amount of 1.12-Mev gamma contribution to the 1.09-Mev photopeak observed in the singles spectrum. It is to be realized that because of lack of knowledge relative to the conversion coefficients of the 0.140- and 0.118-Mev transitions, their coefficients were of necessity omitted in the 1.12-Mev/0.95-Mev intensity calculation. The relative gamma-intensity data are summarized in Table I.

[5] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).

TABLE I. Gamma transitions in Lu^{177}.

Gamma energy (Mev)	Relative gamma intensities	α_K	Multipolarity
0.118 ± 0.002	13 ± 3	...	...
0.140 ± 0.004	<10[a]	...	...
0.147 ± 0.002	100	<0.4	$(M2/E1)<0.04$[b]
$0.95\ \pm0.01$	6 ± 2	...	...
$1.09\ \pm0.01$	30 ± 6	...	...
$1.12\ \pm0.01$	4 ± 2	...	...
$1.24\ \pm0.01$	27 ± 6	...	...

[a] Upper limit on the intensity value imposed by the spectrum shape of Fig. 1.
[b] With $K/(L+M)$ ratio of $3.5_{-0.5}^{+1.5}$ of reference 1.

An upper limit for the value of the K-conversion coefficient of the 0.147-Mev transition was obtained from the relative intensities of the 0.147-Mev gamma and the lutecium K x-ray. The relative intensity measurements were performed with the calibrated 2×2 inch NaI(Tl) crystal. The x-ray intensity datum was corrected for fluorescence yield.[6] A value of $\alpha_K<0.4$ was obtained. This value is an upper limit since the magnitude of K-conversion of the other gammas could not be determined. From this upper limit value on the K-conversion coefficient, the reported $K/(L+M)$ ratio of $3.5_{-0.5}^{+1.5}$,[1] and the theoretical conversion coefficients,[7,8] we conclude that the multipolarity of the 0.147-Mev gamma is $E1+M2$ with a mixing ratio $M2/E1<0.04$.

IV. BETA-RAY EXPERIMENTS

The beta spectrum of Yb^{177} was studied by means of beta-gamma coincidence experiments in which scintillation spectrometers were employed. The beta particles were detected with a plastic scintillator, whereas the gamma rays were detected with a NaI(Tl) crystal. Through the use of the fast-coincidence circuit ($2\tau=0.02$ microsecond), it was observed that a beta transition of energy >0.7 Mev from Yb^{177} is in prompt coincidence with the 0.118-Mev gamma transition. A similar experiment performed with the slow-coincidence circuit ($2\tau=0.4$ microsecond) demonstrated that there exists a direct beta transition of energy >0.7 Mev to the 0.147-Mev delayed level. Thus, from the results of the foregoing fast coincidence experiment, it is obvious from energy considerations that the 1.12-Mev gamma precedes the 0.118-Mev gamma. Furthermore, by employing the fast-coincidence circuit with variable delay time, we were able to deduce that less than 0.2 percent of all Yb^{177} beta transitions directly populate the level at 0.287 Mev.

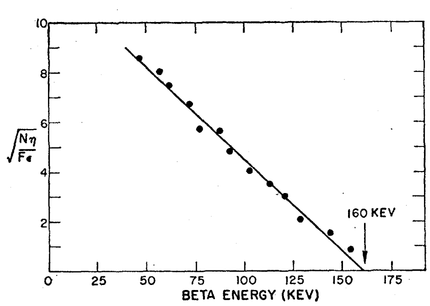

FIG. 4. Fermi-Kurie analysis of the negatron spectrum in coincidence with the portion of the gamma spectrum of Yb^{177} above 0.7 Mev.

In order to study the beta group which feeds the 1.24-Mev level of Lu^{177}, shown in the decay scheme of Fig. 3, additional coincidence experiments were performed. With the gate channel set to accept gamma pulses corresponding to energies >0.7 Mev, the coincidence spectrum was found to consist of a single beta group of end-point energy 0.16 ± 0.02 Mev. A Fermi-Kurie plot of the data is shown in Fig. 4. The end-point region of the spectrum has been corrected for resolution according to the method of Palmer and Laslett.[9] This bit of evidence, plus conclusions which can be drawn from Sec. III relative to the arrangement of levels in Lu^{177}, is indicative that the 0.16-Mev beta transition directly populates the 1.24-Mev level.

TABLE II. Beta transitions of Yb^{177}.

Beta energy (Mev)	Percent branch	$\log ft$
0.16 ± 0.02	4 ± 1	4.4
1.25 ± 0.03[a]	7 ± 2	7.2
1.28 ± 0.03[a]	2 ± 0.5	7.8
1.40 ± 0.03[a]	87 ± 3	6.2

[a] Beta energy deduced from decay scheme of Fig. 4.

A standard beta-gamma coincidence technique was utilized to determine the amount of beta branching to the 0.147-Mev level relative to the total number of betas present of energy >0.15 Mev. The beta branching to the 0.118-, 0.147-, and 1.24-Mev levels was then determined from the relative gamma intensity data of Table I. A total conversion coefficient of 1.5 was assumed for the 0.118-Mev transition in the foregoing calculation. The beta-decay data are summarized in Table II and embodied in the decay scheme of Fig. 3.

V. DISCUSSION

One of the aims of an investigation of the foregoing type is to assign spin and parity values to the excited states of the daughter nuclide. To make such assignments one must usually know the ground-state spin and parity of the parent or daughter nuclide. In the investigation reported herein, both parent and daughter nuclides are radioactive, and their ground-state spins have not been measured. However, if we associate the

[6] Broyles, Thomas, and Haynes, Phys. Rev. **89**, 715 (1953).
[7] Rose, Goertzel, Harr, Spinrad, and Strong, Phys. Rev. **83**, 79 (1951).
[8] Rose, Goertzel, and Swift (privately circulated tables).
[9] J. P. Palmer and L. J. Laslett, Atomic Energy Commission Report AECU-1220, March 14, 1951 (unpublished).

measured spin[10] of 7/2 for Hf^{177} (daughter nucleus of Lu^{177}) with the 7/2− level of an $f_{7/2}$ single-particle configuration according to deformed nuclei calculations,[11] then it is possible, from a consideration of the well-known decay scheme[12] of Lu^{177} and nuclear levels[13] of Hf^{177}, to deduce the spin and parity of Lu^{177} as 7/2+. Furthermore, a ground-state assignment of 7/2+ for Lu^{177} is in good agreement with a 7/2+ level derivable from a $g_{7/2}$ single-particle configuration for deformed nuclei.[11] Thus, from the foregoing considerations it is of interest to continue the analysis and deduce, if possible, the spins and parities of the nuclear levels in Lu^{177} and the ground-state configuration of Yb^{177}.

As a first consideration, it is to be noted that the $E1+M2$ character of the 0.147-Mev transition demands that a spin difference of 0 or 1 and a difference in parity exist between the levels involved in that particular transition. We tentatively classify the 0.147-Mev level as 9/2− and identify it as the $h_{11/2}$ ($\Omega=9/2-$) particle excitation. The $h_{11/2}$ ($\Omega=9/2-$) state appears at 396.0 kev in Lu^{175}.[14] The inhibition of the $E1$ component of the 0.147-Mev transition relative to the prediction for single proton transitions[15] has been theoretically accounted for in a discussion of this type transition, namely a transition between $h_{11/2}$ ($\Omega=9/2-$) and $g_{7/2}$ ($\Omega=7/2+$) individual-particle states.[16]

We may also speculate that the 0.118- and 0.287-Mev states are the first rotational excitations of rotational bands whose base states occur at the ground state of Lu^{177} and the 0.147-Mev level, respectively; hence we tentatively assign spin and parity values of 9/2+ to the 0.118-Mev level and 11/2− to the 0.287-Mev level. If the above rotational analysis is correct, then it is to be noted that the level at 0.287-Mev lies within four kilovolts of the expected position of the first rotational excitation of the 0.147-Mev base state (if we assume that the rotational band based on the 0.147-Mev state has the same moment of inertia as the ground state of Lu^{177}). Unfortunately we are not able to strengthen these assignments since we have been unable to obtain information relative to the multipolarities of the 0.118- and 0.140-Mev transitions. The spin and parity assignments are, however, consistent with the apparent absence of a gamma-ray ground-state transition from the 0.287-Mev level.

To initiate the discussion of the beta transitions of Yb^{177}, we tentatively assign to the ground state of Yb^{177} a 9/2+ configuration which may be identified as the particle state $i_{13/2}$ ($\Omega=9/2+$).[11] This assignment is strengthened by the measured spin[10] of 9/2 for Hf^{179}, which has the same odd number of neutrons as does Yb^{177}. A consideration of the ft values of Table II indicates that the parities of the 1.24-Mev level in Lu^{177} and the ground state of Yb^{177} are identical. Although the ft value of the ground-state to ground-state transition is anomalously high, the ft value of the beta transition to the 0.147-Mev level is consistent with the proposed assignments. The anomalously high ft value for the ground-state to ground-state transition may result from the possibility that the transition takes place between deformed nuclei configurations which are derived from $i_{13/2}$ and $g_{7/2}$ single-particle states, respectively.[11] The beta transitions to the 0.118-Mev ($\log ft=7.8$) and 0.287-Mev ($\log ft>8.5$) levels are inhibited, however, to an unaccountable extent and might tend to indicate that the ground state of Yb^{177} is not 9/2+ but instead is 7/2−, the same as Yb^{175}.[14]

Again we wish to emphasize that the foregoing arguments should be regarded as quite provisional and are only intended to represent as near a consistent picture as we find to be in accord with experimental data and present nuclear theory. It is a pleasure to acknowledge several helpful discussions on the unified model of the nucleus with Dr. L. Wilets and Dr. D. M. Chase.

[10] D. R. Speck and F. A. Jenkins, Phys. Rev. **101**, 1831 (1956).
[11] B. R. Mottelson and S. G. Nilsson, Phys. Rev. **99**, 1615 (1955).
[12] P. Marmier and F. Boehm, Phys. Rev. **97**, 103 (1955).
[13] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **100**, 150 (1955).
[14] Mize, Bunker, and Starner, Phys. Rev. **100**, 1390 (1955).
[15] S. A. Moszkowski in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955), Chap. 13.
[16] D. M. Chase and L. Wilets, Phys. Rev. **101**, 1038 (1956).