Electron capture and β^+ decay of ^{147}Tm

K. S. Toth and D. C. Sousa*
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

P. A. Wilmarth, J. M. Nitschke, and K. S. Vierinen†
Lawrence Berkeley Laboratory, Berkeley, California 94720
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With the use of an on-line mass separator, electron capture (EC) and β^+ decay of the direct proton emitter ^{147}Tm was identified in a series of ^{58}Ni+^{92}Mo irradiations. Characteristic Er $K\alpha$ x rays and an 80.9-keV γ ray were observed to decay with the half-life of ^{147}Tm. The 80.9-keV γ ray is proposed to be the transition connecting the first-excited $(d_{3/2})$ and ground $(s_{1/2})$ neutron-hole states in ^{147}Er. The ^{147}Tm (EC+β^+)-decay strength was deduced from K x-ray and annihilation radiation intensities. A comparison of this strength with the intensity of the 1.045-MeV proton peak leads to a ^{147}Tm direct-proton-decay branch of 15(5)%.

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The $h_{11/2}$ ground state of ^{147}Tm has been known [1,2] for about a decade to be a direct-proton emitter. While production cross-section measurements, barrier-penetration calculations of the proton-decay half-life, and gross β-decay half-life predictions have all indicated that the radioactivity's dominant decay mode is electron capture (EC) and β^+ decay, this particular branch has not been observed. Herein we report the identification of the ^{147}Tm (EC $+\beta^+$) decay in a series of ^{58}Ni irradiations of ^{92}Mo with the use of the OASIS on-line separator facility [3] at the Lawrence Berkeley Laboratory's SuperHILAC.

A self-supported foil, 1.85 mg/cm^2 in thickness, of ^{92}Mo (enriched to 97.4%) was bombarded with 261 MeV ^{58}Ni ions. The ^{58}Ni energy at the midpoint of the target foil was calculated to be 245 MeV. After mass separation the $A=147$ isobars were selected by a slit in the focal plane of the separator, transported to a fast-cycling tape system, and periodically positioned between an array of detectors (see Fig. 1 in Ref. [4] for a drawing of this arrangement). A ΔE-E particle telescope and a planar hyperpure Ge detector faced the radioactive deposit while a 1-mm-thick plastic scintillator and a 52% Ge detector were located on the opposite side of the collector tape. A 24% Ge detector was situated at 90° relative to the other detectors, about 45 mm from the radioactive source. Three collection and counting cycles each of 1.28, 4.0, and 160 s were used. Coincidences between γ and x rays and positrons and protons were recorded in an event-by-event mode with all events tagged with a time signal for half-life determinations. Also, singles γ-ray data were acquired from all three Ge detectors.

One chief reason as to why ^{147}Tm (EC $+\beta^+$) decay has up to now not been observed is the low yield for producing the isotope in the various available target and projectile combinations. In our experiment, at an incident energy of 245 MeV, the calculated [5] production cross section for ^{147}Tm in the (^{58}Ni,$p2n$) reaction is 0.2 mb. This low cross section is to be compared with the much larger values of 18 and 80 mb, respectively, predicted for ^{147}Er and ^{147}Ho.

Figure 1 shows the total proton spectrum [part (a)] and protons in coincidence with positrons [part (b)] accumulated during the 4.0 s counting cycles. The 1045(10) keV peak in Fig. 1(a) is from ^{147}Tm ground-state decay while, based on coincidences with K x rays, the protons distributed from about 2 to 8 MeV are assigned to delayed protons following the (EC+β^+) decay of ^{147}Er. The time distribution of the 1045 keV peak in our data leads to a half-life of 0.64(6) s for ^{147}Tm which is to be compared with published values of 0.42(10) s [1] and 0.56(4) s [2]. The 1045 keV peak does not appear in Fig. 1(b). Its absence is a demonstration that it is not the result of proton emission following β decay but rather that it represents ground-state proton decay; we should also add that the peak was not seen in coincidence with K x rays.

A comparison of our 1.28 and 4.0 s low-energy photon spectra showed the presence of Er $K\alpha_1$ x rays in the first data set but not in the second. Also, a 0.6 s component was noted in the decay curve of the annihilation radiation seen in the 1.28 s experiments. Because the ^{147}Tm β-decay energy is higher than those of the other $A=147$ isobars investigated here, we set gates on the annihilation radiation peak and looked at coincident γ rays to emphasize the ^{147}Tm contribution. Figures 2(a) and 2(b) show these coincident spectra for the 1.28 s and 4.0 s data, respectively. In addition to γ rays belonging to ^{147}Er, ^{147}Ho, and ^{147}Dy, an 80.9(1) keV transition (and Er $K\alpha_1$ x rays) is clearly seen in Fig. 2(a) while in Fig. 2(b) the γ ray is scarcely visible. We therefore assign the 80.9 keV γ ray to the β decay of the ^{147}Tm $h_{11/2}$ ground state

*Permanent address: Eastern Kentucky University, Richmond, KY 40475.

†On leave from University of Helsinki, SF-00170, Helsinki, Finland.

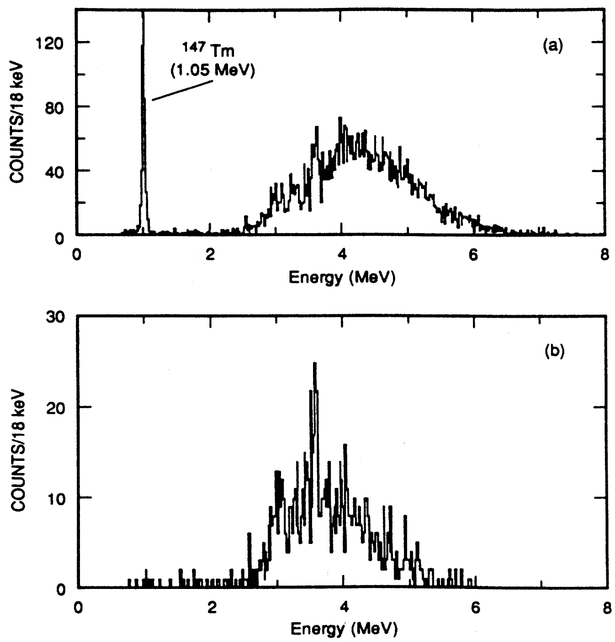

FIG. 1. Proton spectra measured for $A=147$ nuclides; (a) shows the total proton spectrum while (b) shows protons recorded in coincidence with positrons. Note that the 1.05 MeV peak in (a), which is from ^{147}Tm ground-state decay, does not appear in (b).

and propose that it connects the ^{147}Er first-excited $d_{3/2}$ neutron-hole level with its $s_{1/2}$ ground state.

This placement is based on systematics of $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ neutron-hole states in this mass region that were recently updated [6] following our study of the decay of ^{145}Ho ($h_{11/2}$), the $N=79$ isotone just below ^{147}Tm. Figure 3 shows these systematics. One notes that the 80.9 keV energy for the $d_{3/2}$ level in ^{147}Er fits well into the overall picture, i.e., this level is at 1.58 keV in ^{141}Sm, and then increases in excitation energy to 45.1 and 66.3 keV in ^{143}Gd and ^{145}Dy, respectively. As in the case of ^{145}Ho decay [6], the $d_{3/2}$ level in ^{147}Er is probably populated by a γ ray from a $d_{5/2}$ state which in turn is fed by cascades from higher-lying levels with still higher spins; however, we could not observe this $d_{5/2} \rightarrow d_{3/2}$ transition nor any other γ rays that could be assigned to ^{147}Tm decay. The interested reader is referred to our earlier discussion [6] of these neutron level systematics.

We used the intensity of the 0.6 s component in the time distribution of the annihilation radiation recorded during the 1.28 s counting cycles to determine the ^{147}Tm β^+-decay strength. This intensity was corrected (using the prescription described in Ref. [7]) for positron annihilation in flight and for the efficiency of stopping positrons in the particular detector geometry that we used. To this we added the EC strength which was deduced from the Er $K\alpha_1$ peak intensity corrected for K-shell electron conversion of the 80.9 keV γ ray (assumed to be an $M1$ tran-

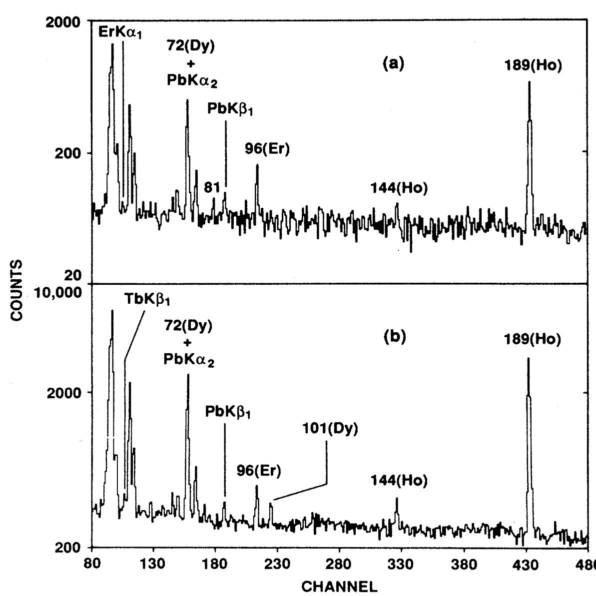

FIG. 2. Gamma-ray spectra observed in coincidence with annihilation radiation for $A=147$ nuclides during (a) 1.28 s and (b) 4.0 s counting cycles. The 81 keV γ ray in (a) is assigned to ^{147}Tm (EC+β^+) decay. Transitions assigned to the decays of ^{147}Dy, ^{147}Ho, and ^{147}Er are labeled by their elemental symbols.

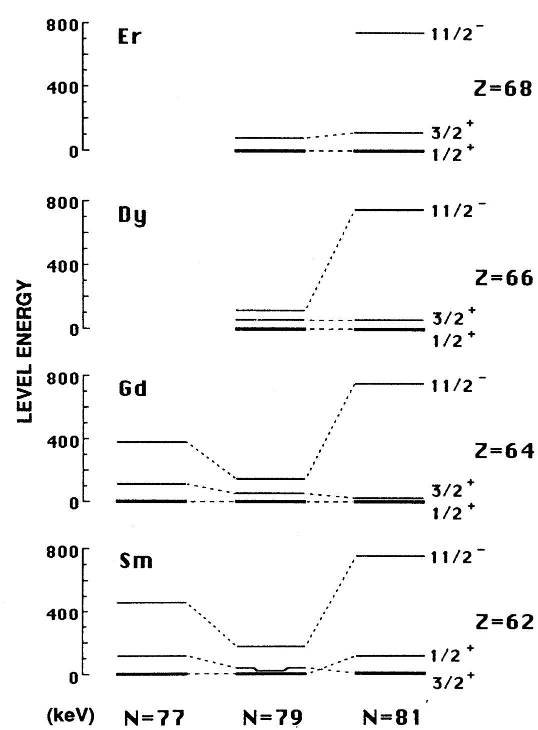

FIG. 3. Systematics of excitation energies for the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ neutron-hole states in Sm, Gd, Dy, and Er nuclei with $N=$ 77, 79, and 81.

sition). Then, from this total (EC + β^+)-decay strength and the intensity of the 1045 keV proton peak, the proton-decay branch of ^{147}Tm was calculated to be 15(5)%. Previously, an estimate of 20% had been deduced [2] based on a comparison of the observed yield of 1.05 MeV protons with the predicted cross section for the production of ^{147}Tm. Barrier-penetration calculations (see, e.g., Refs. [8–10]) have shown that to obtain a half-life of ~3 s for a 1.05 MeV ^{147}Tm proton decay to the ^{146}Er 0^+ ground state a Δl value of $5\hbar$ has to be invoked. This result strongly suggests that the parent level is the $h_{11/2}$ proton state which is found at low excitation energies in neighboring odd-Z nuclei. The $h_{11/2}$ level is presumably the ground state since a second, higher-energy ($E_p = 1.12$ MeV) proton decay has been assigned [11] to a 360 μs state in ^{147}Tm. The 360 μs half-life of this isomer has been compared [8–10] with half-lives calculated for protons originating from various proton orbitals and has been found to be most consistent with a $d_{3/2}$ assignment. Note that the 360 μs half-life is much too short for us to have observed this 1.12 MeV proton emitter with our experimental apparatus.

Figure 4 summarizes the known decay properties of ^{147}Tm. We have indicated in Fig. 4 that the excitation energy of the $\nu h_{11/2}$ ^{147}Er level is less than 118 keV. This upper limit is based on systematics for $N = 79$ isotones (see Fig. 3 and Ref. 6) which indicate that the $h_{11/2}$ state decreases in excitation energy as Z increases. It is located at 231.2, 175.8, 152.6, and 118.2 keV in ^{139}Nd (not shown in Fig. 3), ^{141}Sm, ^{143}Gd, and ^{145}Dy, respectively.

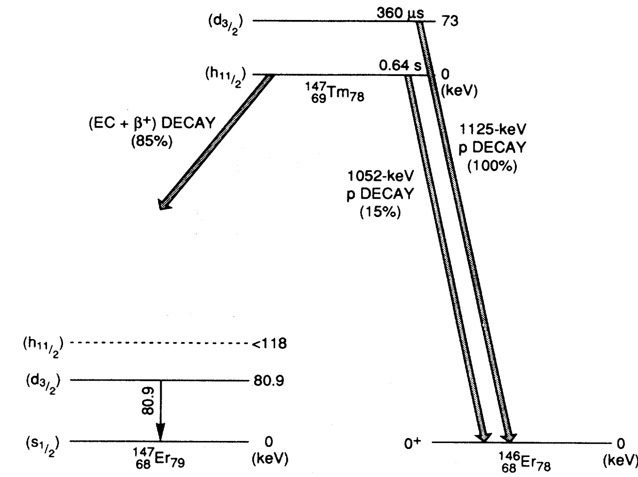

FIG. 4. Schematic summary of the ^{147}Tm decay properties.

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