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In-beam γ-ray spectroscopy of the proton emitter $^{147}_{69}$Tm using recoil-decay tagging

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Gamma rays from the decay of states in the proton unstable nucleus ^{147}Tm were observed for the first time following the ^{92}Mo(^{58}Ni,p2n)^{147}Tm reaction at 260 MeV. Prompt γ rays were detected with an array of Compton-suppressed Ge detectors, placed in front of the fragment mass analyzer at the ATLAS accelerator, and were assigned to individual reaction channels on an event-by-event basis using the recoil-decay tagging method. Gamma-ray transitions were associated with both the proton decay of the $\pi h_{11/2}$ ground state and the $\pi d_{3/2}$ isomeric state in ^{147}Tm, even though the cross sections for populating these states were only $\approx$ 16 μb and 2 μb, respectively. The level scheme which was constructed for ^{147}Tm is discussed and compared with the level structures for lighter $N=78$ isotones. [S0556-2813(97)50605-4]

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The interest in nuclei at the limits of particle stability has recently been stimulated by extensive theoretical calculations indicating that the structure of nuclei near the drip lines may be quite different from that of nuclei along the valley of stability. The prospect that high-quality spectroscopic information will become available with the use of radioactive heavy-ion beams has further enhanced this interest. However, significant progress in the drip-line area has already been made recently with stable beams because of the usage of new and refined experimental methods. For example, in-flight identification of products from projectile fragmentation has delineated the proton drip line for $50<A<80$ nuclei [1]. The combination of recoil separators with double-sided Si strip detectors has recently led to the identification of direct proton emitting nuclei as heavy as ^{185}Bi [2,3]. It is important to obtain detailed spectroscopic data on excited states in nuclei at the proton drip line and beyond as these data can shed light on possible Coulomb redistribution effects, isospin mixing, and on the influence of the continuum on loosely bound states. However, in-beam γ-ray spectroscopic studies of these nuclei using heavy-ion fusion-evaporation reactions are hampered by high fragmentation of the fusion cross section and, in heavier systems, by competition from fission. In the present work, a novel technique, the recoil-decay tagging (RDT) method [4,5], was used to select and identify in-beam γ rays. RDT combines proton and alpha decay measurements with in-beam γ-ray spectroscopic methods. It was successfully applied to the island of proton and α radioactivity above ^{100}Sn, where for the first time γ rays were identified from a proton emitter, ^{109}I [4].

The proton decay of the ground state of ^{147}Tm was originally observed using the GSI on-line mass separator [6]. A subsequent experiment with the in-flight velocity filter SHIP at GSI identified a second short-lived activity which was tentatively assigned to the isomeric proton decay in ^{147}Tm [7]. In an experiment using the Daresbury recoil mass separator [8] both activities were unambiguously confirmed as originating from ^{147}Tm. An energy of 1051(4) keV and a half-life of 580(70) ms were measured for the ground-state proton decay. The corresponding energy and half-life for the decay of the isomeric state were 1111(4) keV and 360(40) μs, respectively, in very good agreement with the previously obtained values [6,7]. Thus, an excitation energy of 60 keV was deduced for the isomer from the proton energies. Comparison between the deduced proton partial half-lives and the results of WKB calculations implied angular momenta of $l=5$ and $l=2$ for ground-state protons and protons emitted from the isomeric level, respectively. Based on these assignments, the $\pi h_{11/2}$ orbital was proposed for the ground state of ^{147}Tm and the isomeric state was interpreted as the $d_{3/2}$ proton excitation.

Proton emitters have thus far been found in two regions of the chart of nuclei: just above ^{100}Sn and around the $N=82$ and $Z=82$ shell closures. Measured proton decay transition rates are consistent with simple shell-model predictions for the proton emitters close to $N=82$ (see Ref. [8] and references therein). In contrast, the proton decay transition rates in ^{109}I and ^{113}Cs are significantly hindered [9]. These two nuclei are predicted to be situated in a transitional region between spherical and deformed nuclei. The deformation, or the change in deformation, was proposed to be responsible for the observed decay hindrance [9]. Prompt γ-ray spectroscopy allows the elucidation of the mechanism proposed for the hindrance. Discrete states in ^{109}I were observed using RDT [4] but only for a rotational band based on the excited $\pi h_{11/2}$ configuration. Transitions feeding the proton decaying ground state remained unobserved. In the present work, γ-ray transitions directly feeding both the ground state and the isomeric levels in ^{147}Tm are reported, providing insight into the structure of proton unbound states in a new region along the proton drip line.

Data on excited states of nuclei in the vicinity of ^{147}Tm are very scarce. In-beam studies of excited states in the odd-

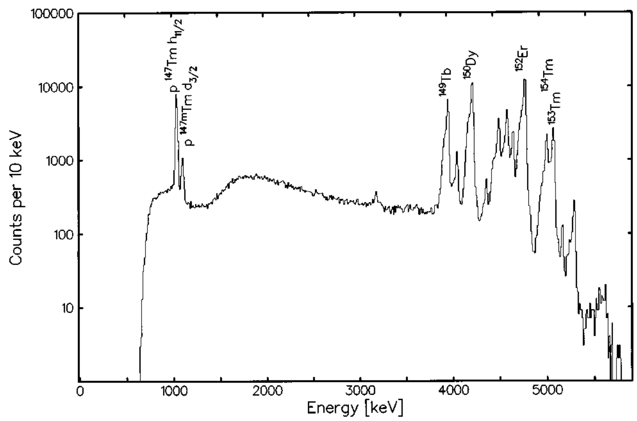

FIG. 1. Energy spectrum of protons and alpha particles measured in the DSSD for the 260 MeV-^{58}Ni+^{92}Mo reaction.

Z, $N=78$ isotones ^{143}Tb and ^{145}Ho have thus far revealed only yrast bands [10] consisting of a few transitions. The ^{144}Dy nucleus is the lightest even-even $N=78$ isotone with identified excited states [11]. Nothing is known about ^{146}Er, the immediate even-even neighbor of ^{147}Tm. The $N=82$ isotone ^{151}Tm is the lightest Tm isotope with established excited states. A sequence of transitions $27/2^- \rightarrow 23/2^- \rightarrow 19/2^- \rightarrow 15/2^- \rightarrow 11/2^-$ deexciting a $27/2^-$ isomer was observed in Ref. [12] and the proposed level structure was successfully described within the framework of the shell model assuming ^{146}Gd as an inert core and using the $(\pi h_{11/2})^5$ configuration space. Beta-decay studies of ^{151}Yb [13,14] established the low-spin single-particle states $\pi s_{1/2}$, $\pi d_{3/2}$, $(\pi d_{5/2})^{-1}$, and $(\pi g_{7/2})^{-1}$ in ^{151}Tm. In ^{147}Tm, the shell-model analysis would be more complicated due to the presence of four additional neutron holes and the less pronounced energy gap between proton shells.

Nuclei near or just below the $N=82$ shell closure favor spherical shapes. However, aided by the disappearance of the $Z=64$ energy gap, deformation sets in gradually in nuclei with $N \leqslant 82$, although the transition is not as abrupt as on the other side of the $N=82$ line [15]. The yrast level sequences observed in the odd-Z nuclei ^{137}Eu, ^{141,143}Tb, ^{145}Ho, and in the odd-N nucleus ^{145}Dy have been found to mimic the behavior of ground-state bands in neighboring even-even core nuclei and have, as a result, been interpreted as decoupled bands built on the $\pi h_{11/2}$ and $\nu h_{11/2}$ orbitals, respectively [10]. In the present article, results on excited states in the proton emitter ^{147}Tm are presented and discussed in the context of the onset of deformation in the $Z>64$, $N<82$ region.

A 260-MeV ^{58}Ni beam from the ATLAS accelerator at Argonne National Laboratory was used to bombard a 0.56 mg/cm^2 ^{92}Mo target in order to populate excited states in ^{147}Tm via the p2n fusion-evaporation channel. The experiment lasted only 33 hours and the average beam intensity on the target was approximately 9 pnA. Prompt γ rays were detected with AYEBALL [16], an array of 16 Compton-suppressed HPGe detectors and two LEPS spectrometers, placed at the target position of the fragment mass analyzer (FMA) [17]. The γ-ray photo-peak efficiency of AYEBALL was $\approx 1\%$ at 1.33 MeV. Detected γ rays were assigned to individual nuclei using the RDT method [4]. Residual nuclei were dispersed at the FMA focal plane according to their mass-to-charge state ratios and implanted into a double-sided

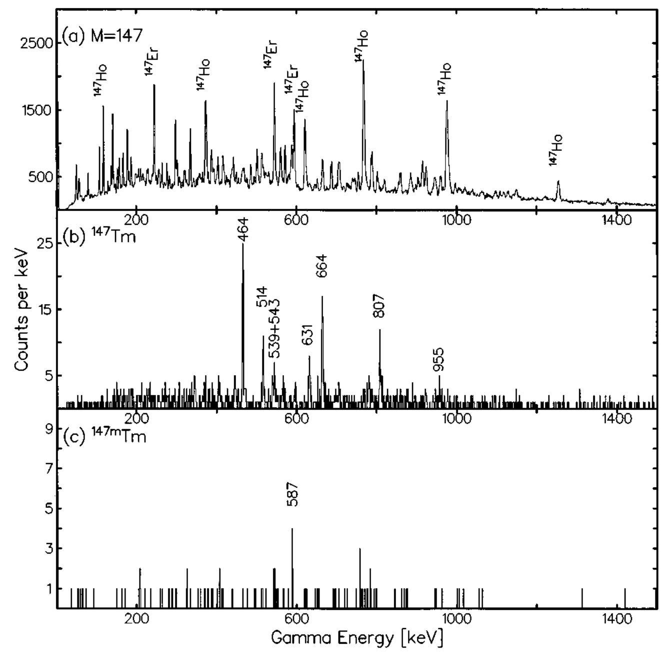

FIG. 2. (a) Gamma-ray spectrum gated with mass 147 residues. (b) Gamma-ray spectrum tagged on the proton decay of the $\pi h_{11/2}$ ground state of ^{147}Tm and (c) the $\pi d_{3/2}$ isomeric state in ^{147}Tm.

silicon strip detector (DSSD) placed behind the focal plane. The 60 μm thick DSSD had 48, 300 μm wide strips on both the front and back sides, arranged orthogonally to each other. The subsequent characteristic proton or α decays of the implants occurred in the same quasipixel of the DSSD as the implantation. Both the arrival of the implant and its decay were time stamped. By using the spatial and time correlations between implants and decays, complete identification of the implanted residues was possible. These decays were also correlated with prompt γ rays detected at the target position in coincidence with the implants.

The energy spectrum of decay particles collected in the DSSD is presented in Fig. 1. The two ^{147}Tm proton lines are clearly visible in the low energy part of the spectrum. The α lines between 3.5 and 5.5 MeV correspond to the known alpha decays of Tb, Dy, Er, and Tm isotopes which were produced due to target impurities, mainly heavier Mo isotopes. About 2000 and 16 000 protons, which deposited full energy in the DSSD, were associated with the decay of the isomeric and ground states, respectively. This corresponds to production cross sections of $\approx$ 2 μb and 16 μb for the two states.

Masses 146 and 147, corresponding to 4 and 3 nucleon-evaporation were predominantly produced under the present experimental conditions. Gamma-ray spectra measured in coincidence with mass 146 residues were dominated by transitions in ^{146}Dy (4p channel) and ^{146}Ho (3pn channel). No evidence was found for transitions in ^{146}Er (2p2n channel), but this is consistent with the expected low cross section for this channel. A γ-ray spectrum in coincidence with mass 147 is shown in Fig. 2(a). All strong transitions can be assigned either to ^{147}Ho (3p channel) or to ^{147}Er (2pn channel). Gamma-ray spectra tagged on the two ^{147}Tm proton lines are shown in Figs. 2(b) and 2(c). These γ-ray transitions were

TABLE I. Energies and intensities of γ-ray transitions assigned to ^{147}Tm observed following the ^{92}Mo(^{58}Ni,p2n)^{147}Tm reaction at 260 MeV.

Energy [keV]	Intensity	Assignment
463.7(2)	100(12)	$15/2^- \rightarrow 11/2^-$
514.3(3)	53(8)	-
538.4(3)	28(6)	-
543.4(3)	24(6)	-
587.1(8)	10(4)	$5/2^+ \rightarrow 3/2^+$
630.7(3)	53(9)	-
663.8(4)	113(13)	$19/2^- \rightarrow 15/2^-$
807.4(3)	75(11)	$23/2^- \rightarrow 19/2^-$
955.4(5)	29(8)	-

too weak to be seen in the spectrum of Fig. 2(a). At least eight γ-ray transitions, with energies indicated in Fig. 2(b), are found to be correlated with the ground-state proton decay. The γ-ray spectrum obtained for the proton decay of the isomeric state contains a single γ-ray line at 587 keV with 7 counts. It should be emphasized that the RDT spectra are virtually contaminant-free as there is no indication of strong γ-ray lines belonging to other channels. The γ-ray transition energies and intensities deduced from the RDT gated singles spectra are listed in Table I. It is worth noting that the cross section for the isomer is one of the lowest ever reported for in-beam γ-ray studies, despite the use of a rather modest array of Ge detectors and the relatively short duration of the experiment.

Figure 3 presents the proposed level scheme for ^{147}Tm. Even though the ground state is proton unbound by 1 MeV, states with $E^*=2$ MeV have been identified. It is possible that excited states which are situated more than 4 MeV above the ground state were populated as there are many other weaker γ-ray transitions in the spectrum. In Fig. 3 the γ-ray transitions were ordered on the basis of the measured γ-ray intensities and the systematics of the lighter $N=78$ isotones. Because of the low statistics only the three strongest transitions could be placed in the level scheme with confidence. The 514 keV and 631 keV γ-ray transitions could be an extension of the proposed $E2$ band which would lead to a backbending. The proposed $23/2^-$ state might also be fed by the 955 keV transition continuing the increase of the transition energy with spin. The placement of the 587 keV transition just above the isomer is uncertain. No information was obtained on the multipolarities of the γ-ray transitions due to their low intensity and the spin and parity assignments for the proposed levels are based on comparisons with the systematics in the lighter $N=78$ isotones and are, thus, tentative.

Difficulties with the interpretation of the structure of ^{147}Tm are twofold. First, the data are of low statistics and the proposed level scheme is fragmentary. Second, ^{147}Tm is a transitional nucleus and as such may be approached in several ways. In the following discussion ^{147}Tm will be interpreted in the spirit of Ref. [10] which pictures ^{147}Tm as a deformed nucleus. It should be stressed, however, that a shell-model analysis or an approach exploring vibrational degrees of freedom may prove to be equally useful. Figure 4 presents the systematics of the known low-lying yrast states

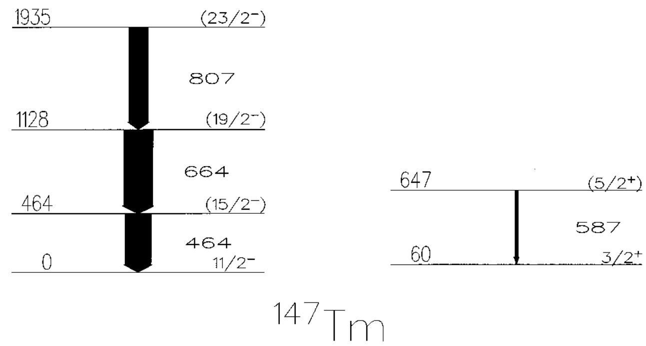

FIG. 3. Proposed level scheme for ^{147}Tm.

in the neutron-deficient $N=78$ isotones, including the three states in ^{147}Tm proposed in this work. The energy of the lowest $15/2^- \rightarrow 11/2^-$ transition in ^{147}Tm follows the decreasing trend between $Z=63$ and $Z=67$ (see Fig. 4). The energies of the $15/2^- \rightarrow 11/2^-$ transitions in these nuclei mimic very closely (to within 10 keV) the energies of the first 2^+ states in the adjacent even-even $N=78$ isotones. Unfortunately, since the energy of the lowest 2^+ state in ^{146}Er is not known, a direct comparison of ^{147}Tm with its closest even-even neighbor is not possible. Conversely, extrapolating from the lighter $N=78$ isotones one can estimate the location of the first 2^+ state in ^{146}Er to be at about 450–480 keV above the ground state. The smooth behavior of the $N=78$ isotones including ^{147}Tm suggests the same interpretation for the ground-state band in ^{147}Tm as for the lighter $N=78$ isotones, i.e., a rotationally aligned $\pi h_{11/2}$ configuration coupled to the 0^+, 2^+, 4^+, 6^+ states of the core. The energies of the 4^+ states decrease with increasing number of protons, and an estimate of about 1100–1200 keV for the energy of the first 4^+ level in ^{146}Er is proposed. The $E(19/2^-)/E(15/2^-)$ energy ratio in ^{147}Tm [equivalent to the $E(4^+)/E(2^+)$ ratio in even-even nuclei] is 2.43 and follows the slow rise with increasing number of protons for $N=78$ isotones. A moment of inertia of 5.5 $\hbar^2$ MeV^{-1} can be deduced from the energy difference of the first $15/2^-$ and $11/2^-$ states in ^{147}Tm, assuming $K=1/2$ for the projection of the angular momentum on the symmetry axis [10]. This value can be compared with that of 5.0 $\hbar^2$ MeV^{-1} for ^{145}Ho. Both the increase in the energy ratio and the rise of the moment of inertia suggest that ^{147}Tm is slightly more deformed than its less exotic neighbors, but the change with proton number is not very dramatic. Using the Grodzins formula [18] one estimates a deformation $\beta \approx 0.13$ for the ground state in ^{147}Tm. It is interesting to note that this value for the deformation is comparable to that predicted for ^{109}I. Consequently, our results cannot be used to confirm the hypothesis that deformation alone can account for the anomalous transition rates observed in ^{109}I (see discussion above).

The assignment of the 587 keV transition which was correlated with the proton decay of the $\pi d_{3/2}$ isomeric state is more speculative because transitions feeding the corresponding $\pi d_{3/2}$ level in lighter odd-Z $N=78$ isotones are not known. Here, the observation of the 587 keV transition was possible only because of the additional selectivity offered by the RDT method. It is possible that the 587 keV transition corresponds to the deexcitation of the $(\pi d_{5/2})^{-1}$ state in

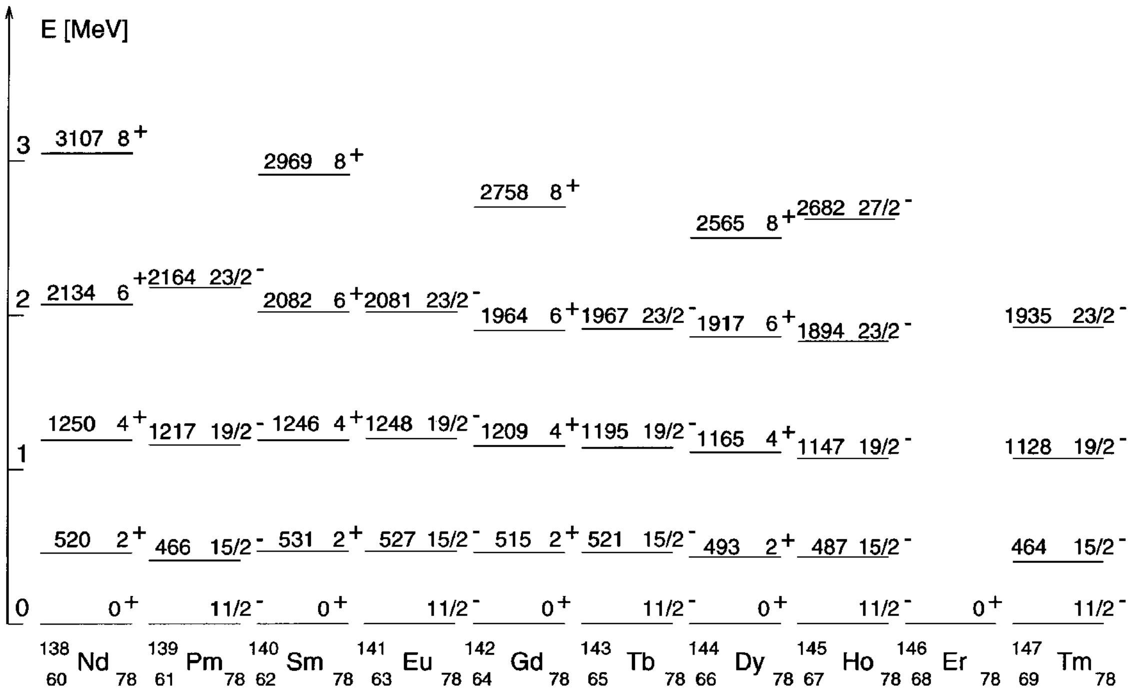

FIG. 4. Systematics of yrast states in neutron-deficient $N=78$ isotones.

^{147}Tm. An analogous transition has been observed in ^{151}Tm following the β decay of ^{151}Yb [13,14].

In the present experiment, γ-ray transitions correlated with the ground-state proton decay as well as with protons emitted from the isomeric state in ^{147}Tm were identified. This truly represents in-beam γ-ray spectroscopy beyond the proton drip line, and clearly illustrates the potential of the RDT method. The observed yrast ground-state band follows the systematics of the lighter odd-Z $N=78$ isotones and could be interpreted as a rotationally aligned $h_{11/2}$ proton configuration coupled to the 0^+, 2^+, 4^+ and 6^+ states of the core.

The present work is the first one in which γ-ray transitions feeding the ground state of a proton emitter were observed. In addition, a γ ray feeding a low-spin isomer was observed, allowing studies of low-spin excited states that would otherwise be very difficult to observe. The isomer was populated with a cross section of $\approx 2\ \mu$b, one of the lowest cross sections ever reached in in-beam γ-ray studies. With the planned coupling of a much larger multidetector array (GAMMASPHERE) to the FMA, it is estimated that it will be possible to identify γ rays from reaction channels populated with cross sections of the order of 100 nb. High-statistics γ-γ-coincidence data can be obtained because of the factor of 50 increase in γ-γ coincidence efficiency over the capabilities of AYEBALL. It will then be possible to study in detail the structure of nuclei beyond the proton drip line to high excitation energies, where new nuclear structure effects may emerge.

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