Recoil Decay Tagging Study Of Transitional Proton Emitters ^{145,146,147}Tm

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Abstract. Gamma rays from the transitional proton emitting nuclei ^{145,146,147}Tm have been observed using the recoil-decay tagging technique. The ground state band of ^{147}Tm was confirmed and extended and the unfavoured signature sequence was observed. A ground state rotational band with properties of a decoupled $h_{11/2}$ band was observed in ^{145}Tm. In addition coincidences between the proton fine structure line and the $2^+ \rightarrow 0^+$ γ-ray transition in ^{144}Er were detected at the focal plane of the FMA. This is the first time that coincidences between proton radioactive decays and γ rays have been seen. The particle decay of ^{146}Tm has been measured with improved statistics and a rotational band similar to ^{147}Tm has been observed.

INTRODUCTION

The phenomenon of one proton radioactivity occurs from odd-Z nuclei which are situated beyond the proton dripline, that is they are unbound to the emission of a proton from their ground state. Proton emission offers a unique laboratory in which to gain information on the structure of nuclei beyond the proton dripline. The combination of highly segmented double-sided silicon strip detectors (DSSD) with large high efficiency Ge arrays allows detailed information on the excited states of proton rich nuclei to be established.

The thulium proton emitting isotopes ^{145,146,147}Tm lie in a region of predicted shape change [1], moving from a prolate shape for ^{145}Tm to an oblate shape for ^{147}Tm. Fine structure has been observed in the decay of ^{145}Tm [2], with a branch to the first 2^+ excited state of the daughter nucleus (E_p = 1728(10) keV and $t_{1/2}$ = 3.1(3) μs, E_p = 1393(10) keV and $t_{1/2}$ = 3.1(3) μs, respectively). A total of 5 separate proton transitions were observed in ^{146}Tm [3,4]. Excited states in ^{147}Tm have been observed using the recoil decay tagging (RDT) technique with a modest array of Ge detectors [5].

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EXPERIMENTAL METHOD

In a recent RDT study a ^{92}Mo beam from the ATLAS accelerator was used with a ^{58}Ni target to produce ^{145,146,147}Tm via the *1p4n*, *1p3n* and *1p2n* fusion-evaporation channels, respectively. The Gammasphere Ge array was used in conjunction with the standard FMA and DSSD setup at Argonne National Laboratory [6]. A parallel semi-Gaussian shaping amplifier and fast delay-line amplifier system was used to instrument the DSSD allowing recoil-decay correlations to be observed for times down to 1μs [7].

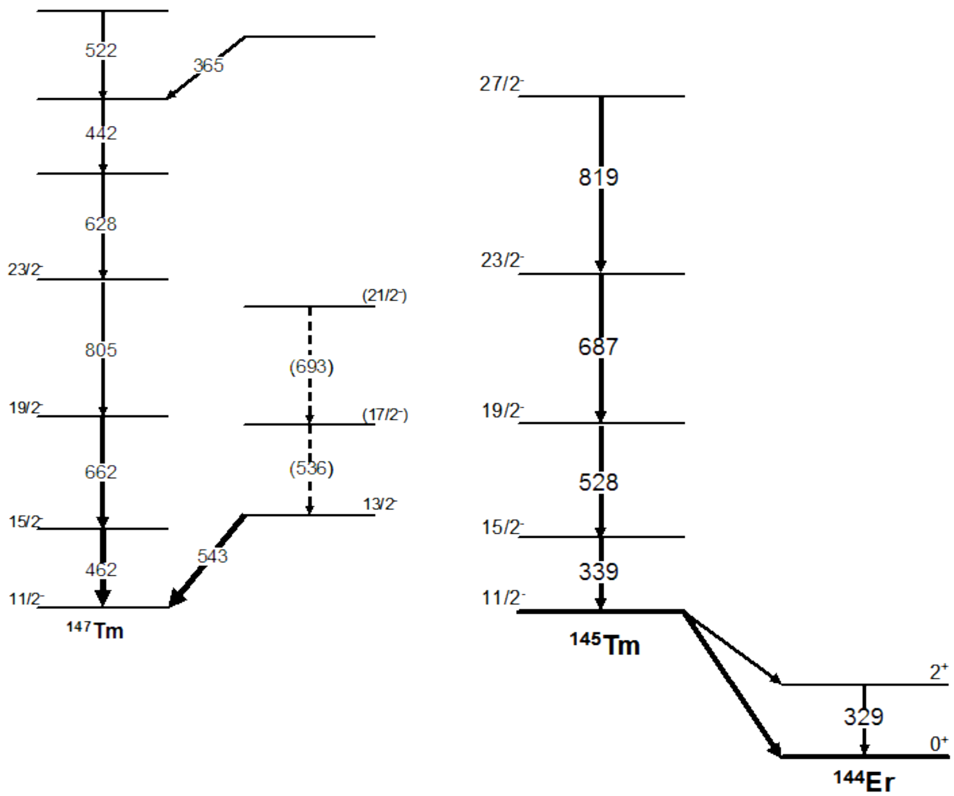

FIGURE 1. *Left*: ^{147}Tm level scheme. *Right:* ^{145}Tm level scheme.

THE ^{147}TM AND ^{145}TM NUCLEI

In the present experiment the previously observed rotational band in ^{147}Tm was extended and the unfavored signature partner band was observed, see Fig. 1. Decays correlated with the isomeric decays are not shown here. The fine structure in the decay of ^{145}Tm was confirmed and a sequence of γ-rays, with the properties of a decoupled $h_{11/2}$ band (Figs. 1 and 2), was observed in coincidence with the particle decay. Coincidences between the proton fine structure line and $2^+ \rightarrow 0^+$ γ-ray transition in the daughter nuclei were observed at the FMA focal plane, see Fig. 2. This is the first time that such a coincidence has been observed for a proton emitter and corresponds to a cross-section of ~10 nb.

It is possible to estimate the quadrupole deformation β_2 from the $2^+ \rightarrow 0^+$ transition energy. In the case of ^{144}Er; this gives a β_2 value of ~0.18, compared to a Möller-Nix prediction of ~0.25 [1]. This suggests that ^{145}Tm may be less deformed than was previously assumed. Rotational bands in odd-A nuclei, including odd-Z proton emitters, can be calculated using the Particle Rotor Model. A systematic study of the ratio of the 4^+ and 2^+ energy levels for even-even nuclei and the analogous $19/2^-$ and $15/2^-$ energy levels for odd-Z nuclei in this region suggests that ^{145}Tm and ^{147}Tm may be treated as γ-soft rotors. Particle-rotor calculations were carried out for both ^{145}Tm and ^{147}Tm using a Woods-Saxon potential with the universal set of parameters. A proton pairing strength of 0.136 MeV was used in the calculations. As in other regions of the chart of the nuclei the Coriolis interaction strength was attenuated by 15%. The comparison between the calculated levels and the measured levels in ^{145}Tm and ^{147}Tm for different values of the quadrupole deformation β_2 and the asymmetry parameter γ is shown in Fig. 3. In both cases the measured level energies agree best with the calculations at $\gamma \sim 30^{o}$.

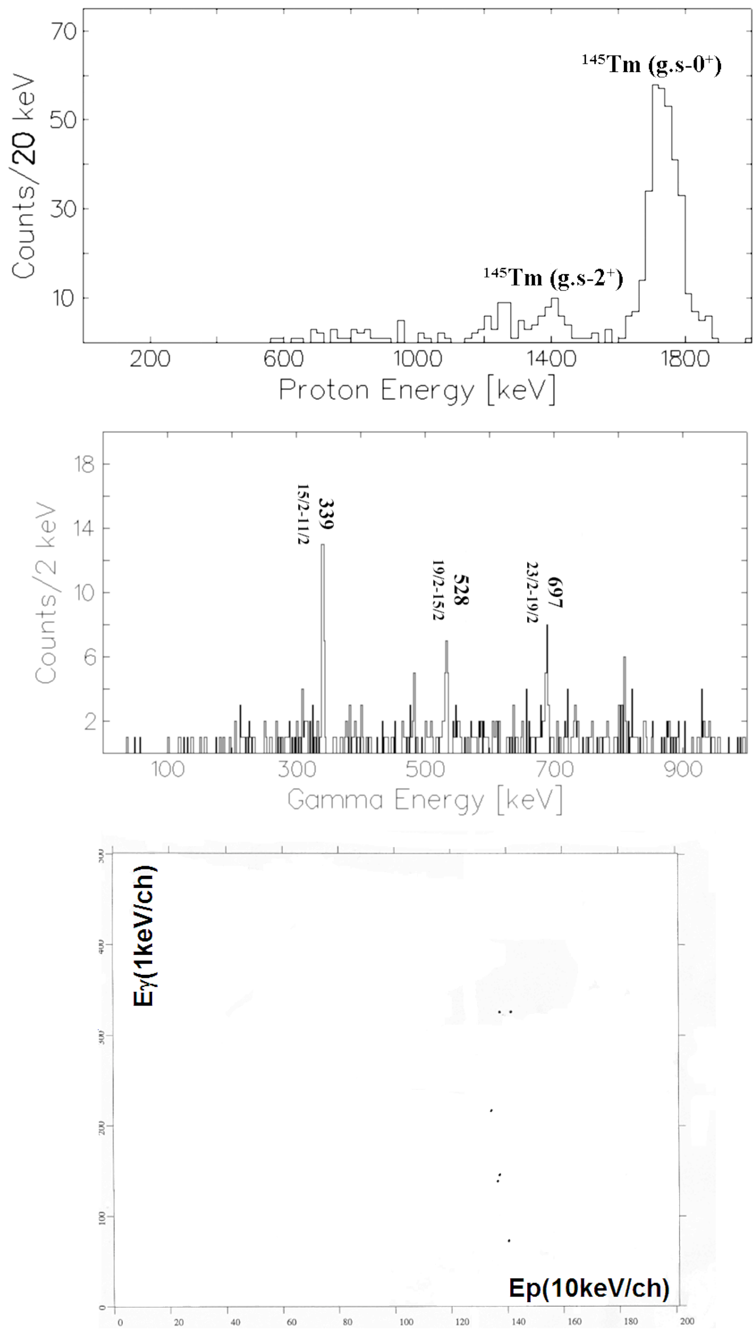

FIGURE 2. *Top*: ^{145}Tm proton spectrum, the unlabelled peak is from ^{141m}Ho leak-through [E_p = 1234(8) keV, $t_{1/2}$ = 6.6(8)μs]. *Centre:* Total γ projection for ^{145}Tm. *Bottom:* Focal plane γ-proton coincidences at rear of FMA.

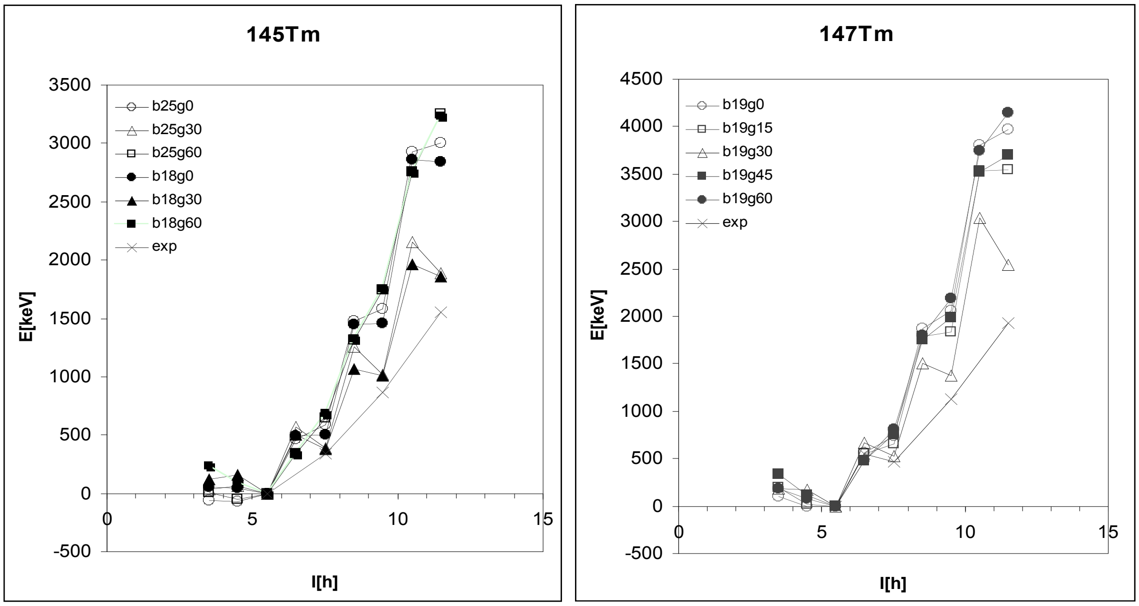

FIGURE 3. Calculated and measured (crosses) level energies in ^{145}Tm (left) and ^{147}Tm (right) for different values of β_2 (b) and γ (g) (see the legends).

THE ^{146}TM NUCLEUS

The five previously observed proton transitions in ^{146}Tm were remeasured with improved statistics, Fig. 4. The energies of the transitions were found to be in good agreement with previous measurements. New, more accurate values were measured for the half-lives of the five transitions. In addition a rotational γ-ray band, similar to ^{147}Tm, was observed in coincidence with the most intense E_p = 1122 keV proton line.

^{146}Tm is an odd-odd proton emitter which lies in the transitional region between predicted deformed and near-spherical shapes. It is potentially a rich source of information regarding the role of the odd neutron in proton decay. The improved statistics in this experiment allow some of the long standing difficulties with the level scheme of ^{146}Tm to be addressed. The most intense ~200ms 1122 keV transition is assigned as an l = 5 transition from a (10^+, 9^+, 8^+) state based on the $\pi h_{11/2} \nu h_{11/2}$ configuration, which agrees with previous work. High spin isomer states are strongly populated in fusion-evaporation reactions.

From the half-life measurements it appears that the 937 keV, 1010 keV and 1192 keV transitions occur from the same state with a half-life of ~80ms. As in previous work the 1192 keV transition is assigned as an l = 5 transition from a (6^-,5^-) state based on the $\pi h_{11/2} \nu s_{1/2}$ configuration to the ground state of ^{145}Er. The neighboring N = 77 isotones have a number of low lying $3/2^+$ and $5/2^+$ states below the $11/2^-$ state. On the basis of this, and the delayed γ-rays seen in coincidence with the 937 keV and 1010 keV transitions (see Fig. 5) the 937 keV and 1010 keV transitions are assigned as decays from the (6^-,5^-) state in ^{146}Tm to low lying $5/2^+$ and $3/2^+$ states in ^{145}Er. This is the first example of decay to 3 states in the daughter nucleus from a proton emitter.

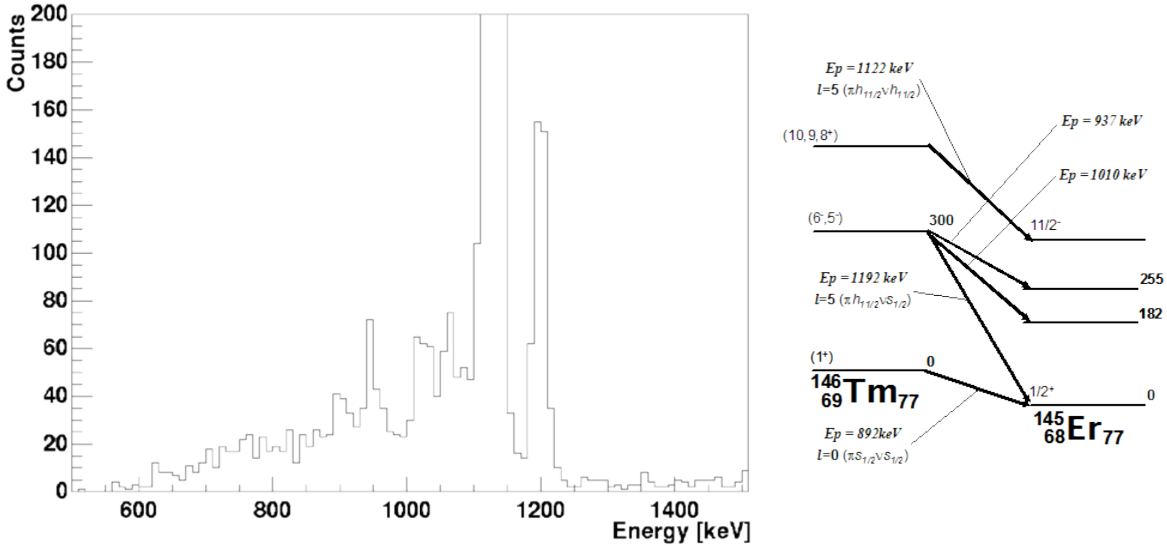

FIGURE 4. *Left*: Decays in DSSD within 500ms of A = 146 implant. *Right*: ^{146}Tm decay scheme.

The placement of the 890 keV transition is more problematic. It has previously been assigned as a decay from the (10+) isomeric state in ^{146}Tm to a 9/2$^-$ state in ^{145}Er, however this assignment would require a significant admixture of the $\pi f_{7/2}$ orbital to the emitter wave function. An alternative assignment could be the l = 0 decay of a low lying (1$^+$) state in ^{146}Tm to the ground state of ^{145}Er. A similar state is seen in neighboring odd-odd isotopes.

The half-life measured here suggests that the 890 keV transition occurs from a third state with a half-life of ~155 ms. This would seem to favor decay from a low lying 1$^+$ state in ^{146}Tm to the ground state of ^{145}Er. The recoil-decay tagged γ-ray spectra for the 890 keV transition and the 1122 keV transition are shown in Fig. 6. Despite the low statistics in the 890 keV spectrum it is clear that the most intense 476 keV transition from the 1122 keV gated spectrum is not present, again suggesting that the decays occur from two separate states in ^{146}Tm. The absence of γ-rays in coincidence with the 890 keV transitions (see Fig. 5) suggests that the decay is to the ground state. As such the transition is assigned as decay from a low lying 1$^+$ state to the ground state of ^{145}Er. The proposed level scheme for ^{146}Tm is shown in Fig. 4. A comparison of experimental partial proton decay half-lives with detailed theoretical calculations is needed to fully determine the structure of ^{146}Tm.

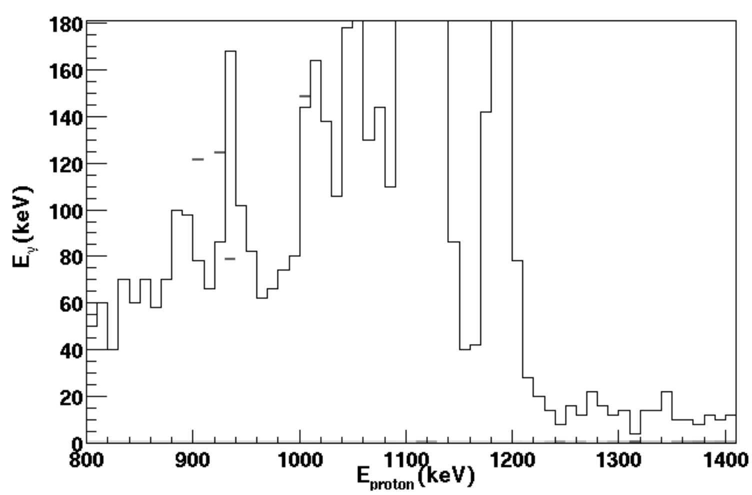

FIGURE 5. Delayed γ-rays in coincidence with particle decays detected at the FMA focal plane. The particle decay spectrum from Fig. 3 is shown overlaid.

SUMMARY

The combination of the FMA – DSSD system with Gammasphere provides a powerful tool for studying excited states in proton rich nuclei. The ground state band of ^{147}Tm has been confirmed and extended and the unfavored signature partner has been observed. The ground state rotational band in ^{145}Tm has been observed with properties of an $h_{11/2}$ decoupled band. The first example of decay to 3 states in the daughter nucleus from a proton emitter has been seen in ^{146}Tm. For the first time all observed proton transitions from this nucleus have been placed in a level scheme.

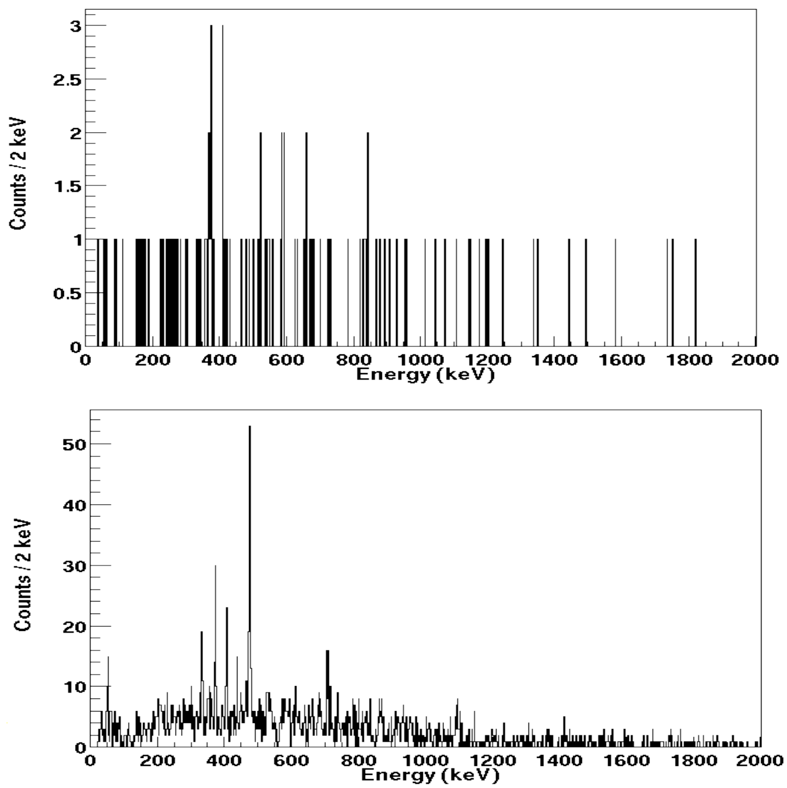

FIGURE 6. Recoil-decay tagged γ-rays for 890 keV proton transition (top) and 1122 keV proton transition (bottom).

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