A Search for Neutron Single-Particle States Populated Via Proton Emission from ^{146}Tm

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Abstract. We studied the proton emission from $^{146}_{69}Tm_{77}$ and observed three new transitions. New transitions at 0.89 and 0.93 MeV have half-lives similar to that of the previously observed transition at 1.19 MeV, while a new transition at 1.02 MeV has a half-life similar to that of the previously observed transition at 1.12 MeV. These new transitions indicate the population of excited neutron single-particle states in $^{145}_{68}Er_{77}$.

INTRODUCTION

A previous study [1] of the proton emission from ^{146}Tm identified two proton transitions: one at 1119 ± 5 keV with a half-life of 235 ± 27 ms and the other at 1189 ± 5 keV with a half-life of 72 ± 23 ms. Both transitions are interpreted as originating from $h_{11/2}$ orbitals based on the comparison of their measured half-lives to predictions from simple WKB calculations.

In ^{145}Er, the proton decay daughter of ^{146}Tm, the three active neutron single-particle states (one of which is the ground state) are the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ states. Calculations performed based on the microscopic-macroscopic model presented in Ref. [2] indicate that these three states lie close to each other — within an energy range of 200 keV. It is thus conceivable that these states can be populated in the decay of ^{146}Tm by proton emission. We have re-studied the proton emission from ^{146}Tm to search for proton transitions populating excited states in the daughter and to look for new proton emitting states with half-lives down to the microsecond time scale.

THE EXPERIMENT

We produced ^{146}Tm via the $p3n$ reaction channel using a beam of ^{58}Ni on a ^{92}Mo target of thickness 0.91 mg/cm^2. The beam was delivered at an energy of 292 MeV and with an intensity of 10 particle nA by the Holifield Radioactive Ion Beam Facility's 25 MV tandem accelerator located at Oak Ridge National Laboratory. The total beam-on-target time was about 72 hours.

We used the HRIBF Recoil Mass Spectrometer (RMS) to separate mass 146 ions for implantation into a double-sided silicon strip detector (DSSD) to study their subsequent decay by proton emission. A thin carbon foil was placed 10 cm downstream from the target position in front of the RMS to re-establish charge state equilibrium for any recoils that may have decayed by internal conversion before reaching the foil to prevent such recoils from being lost in the spectrometer. The RMS was scaled to accept recoils with a central energy of 90 MeV. The RMS was run in the converging mass mode to deliver two charge states of mass 146 recoils — 26^+ and 27^+ — into the DSSD. Baffles at the focal plane were used to prevent recoils from masses other than 146 from reaching the DSSD.

A multi-wire, gas-filled position sensitive avalanche counter (PSAC) was used at the focal plane in front of the DSSD. The PSAC not only provided mass identification of the recoils based on their observed positions, but it also was used to distinguish between decay and implantation events in the DSSD by whether or not these events were observed in coincidence with events from the PSAC.

Signals from the DSSD were processed using electronics provided by the University of Edinburgh. This system features Silena ADC's with FERA readout. The components of this system are discussed in detail in Ref. [3]. Use of this setup for observing proton activity at the RMS focal plane — particularly its effectiveness for observing short-lived activities with half-lives down to a few microseconds — has been discussed on several occasions [4–7].

The energy with which recoils were implanted into the DSSD was either well below 20 MeV or above 60 MeV depending on whether or not a 2.27 mg/cm^2 thick Cu foil was used between the PSAC and DSSD to reduce the energy of the recoils.

RESULTS

The overall gain in counts obtained in the two strong proton peaks from this experiment was about a factor of 20 over the previous work [1]. This gain resulted from extending the running time by a factor of four, from doubling the beam current used, from the collection of two charge states of mass 146 at the focal plane, and from use of a thicker target.

Although we obtained no evidence for new proton transitions with half-lives on the microsecond time scale, we did observe three new transitions at lower energies than the ones previously identified. Two transition at 0.89 and 0.93 MeV have half-lives in the range of 100 ms; the other transition at 1.02 MeV has a half-life in the range of 200 ms. This experiment will also provide more precise half-life values for the two previously identified transitions. Note that all new energy and half-life values stated here are preliminary.

To ensure that the new decay peaks were not somehow created by the way protons from the strong peaks at 1.12 and 1.19 MeV escaped from the surface of the DSSD on which the recoils were implanted, we varied the implantation depth of the recoils by using or not using the Cu foil to reduce the energy of the recoils. The new peaks remained under both experimental conditions.

Figure 1 shows the decay events observed in the DSSD within the first 100 ms after the arrival of a recoil when no Cu foil was used in front of the DSSD. The peaks above 4 MeV are from the α-decay of heavier nuclei. These nuclei arise from isotopic impurities within the target and reach the DSSD because they have mass-to-charge ratios similar to those of the mass 146 recoils.

As Fig. 1(a) illustrates, the background arising from escaping α-particles peaks at an energy well above the proton transitions near 1 MeV; very little of this background is present around the proton peaks. When the degrading foil was used, the α-escape background peaked on top of this crucial energy range. Deep implantation of recoils shifts the peak in the α-escape background to higher energies because the α-particles deposit a larger portion of their energy before they reach the surface of the DSSD to escape.

A disadvantage of deep implantation is the shift in energy observed for decay events which occur within a couple of hundred microseconds after the recoil is implanted into the DSSD. This shift occurs because of the extra time it takes the decay amplifiers to recover from the larger overload resulting from the higher implantation signal. For the case of ^{146}Tm, this overload effect turns out not to be an important issue since no short-lived proton transitions are present.

Figure 1(b) provides an expanded view of the energy range of interest. The three new peaks are clearly visible.

DISCUSSION

It should be noted that the previous work on ^{146}Tm is consistent with our observation of new proton transitions. Extra counts are visible in the region just below the proton peak at 1.12 MeV in Fig. 1 of Ref. [1].

The fact that the half-lives of the new transitions at 0.89 and 0.93 MeV seem to match that of the transition at 1.19 MeV suggests that all three transitions originate from the same state in ^{146}Tm; this implies that the new transitions are to

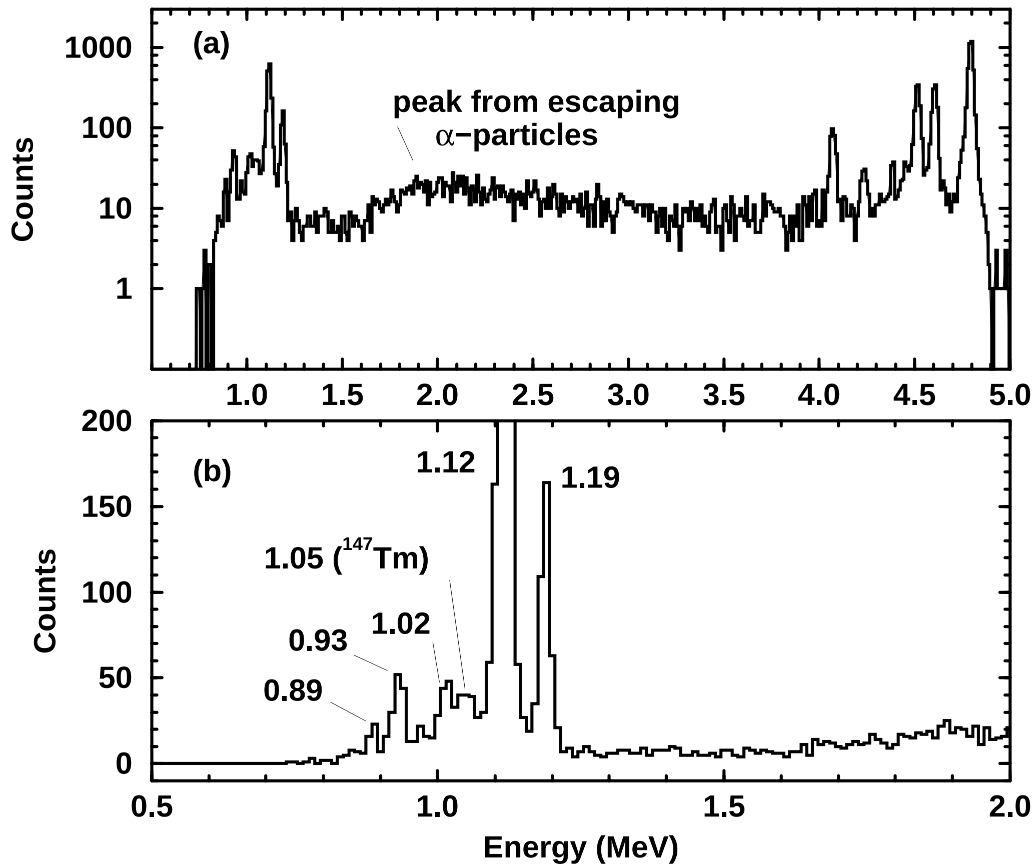

FIGURE 1. Decay events occurring within the first 100 ms after the arrival of a recoil at the DSSD. This data was generated with no Cu foil used in front of the DSSD to reduce the energy of the implanted recoils. The peaks above 4 MeV are from α-decay events, while those around 1 MeV are from proton emission events. The peak in the background from escaping α-particles is visible in (a) and clearly lies above the proton peaks. An expanded view of the energy range containing the ^{146}Tm proton peaks is given in (b).

TABLE 1. Simple WKB calculation of half-life as a function of angular momentum l for the five ^{146}Tm proton transitions. The new experimental energy and half-life values listed here are preliminary.

		WKB Half-Life Estimate (ms)		
Energy (MeV)	Measured $t_{1/2}$ (ms)	$\Delta l = 0$	$\Delta l = 2$	$\Delta l = 5$
0.89	~ 100 [a]	32	280	740,000
0.93	~ 100 [a]	7.2	63	160,000
1.02	~ 200 [a]	0.34	3.0	7,400
1.12	235 ± 27 [b]	0.018	0.16	370
1.19	72 ± 23 [b]	0.0029	0.025	57

[a] Preliminary half-life estimate.
[b] Value from Ref. [1]

excited states in ^{145}Er. The analogous argument implies that the new transition at 1.02 MeV is also to an excited state in ^{145}Er. The energy relationship that exists among the five transitions indicates that we are observing at least two new excited states in ^{145}Er.

If the new transitions are not to excited states in ^{145}Er, then they must be from previously unidentified states in ^{146}Tm. This would be the first instance in which a proton emitter has been observed with more than two proton emitting states.

Table 1 presents the half-lives as a function of angular momentum l as predicted using a simple WKB calculation for all four proton transitions. (The three proton orbitals active in this region of nuclei are $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$.) The table suggests that the 0.93 MeV transition could arise from a state involving the $d_{3/2}$ proton orbital.

SUMMARY

Three new proton transitions have been identified in the decay of ^{146}Tm: ones at 0.89 and 0.93 MeV with half-lives of approximately 100 ms and one at 1.02 MeV with a half-life of approximately 200 ms. Whether these transitions arise from new excited states in ^{146}Tm or result from decays to new excited states in ^{145}Er, this work demonstrates that proton emission studies have advanced to the stage of multi-level decay spectroscopy.

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