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Structure Of Rare-Earth Nuclei Around The Proton Drip Line


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Abstract. Decay studies on rare earth nuclei around the proton drip line have been performed by means of the Recoil Mass Spectrometer at the Holifield Radioactive Ion Beam Facility in Oak Ridge. The proton emission from the odd-odd N=77 isotope 146 Tm was reinvestigated, resulting in the assignment of the 1.01 MeV proton line to the decay of a short-lived 146 Tm state. A new proton radioactivity of 144 Tm was identified. The decays of isomeric levels in the N=77 isotones, 140 Eu, 142 Tb and 144 Ho were remeasured using γ and electron detectors. The analysis of the structure of studied nuclei, which accounts for the coupling between the protons and neutrons and for core excitations, is presented.

INTRODUCTION

Studies of proton-radioactive nuclei have served for many years as a source of information on proton orbitals beyond the drip line, see e.g. [1]. The discovery of fine structure in proton emission from an odd-odd nucleus 146 Tm [2] allowed us for the first time to analyze the properties of excited neutron states populated by proton transitions. Five proton lines were reported in [2] as following the decay of 146 Tm.

The transitions at 1.12 MeV [3] and at 0.89 MeV [2] were assigned to the decay of a high-spin isomeric level based on the similarity of measured halflives (T 1/2 ≈ 200 ms) and on the observed intensities. Shorter-lived transitions with T 1/2 about 80 ms, at 1.19 MeV [3] and at 0.94 MeV [2], were interpreted as following the decay of a lower spin 146 Tm. The observed transition at 1.01 MeV [2] was not assigned to either 146m Tm or 146g Tm, which motivated the reinvestigation of 146 Tm.

In Ref. [2], the reference picture of the decay rates based on a spherical approach was given. Here, we present the calculations accounting for the deformed shape of the potential tunelled by the emitted protons, within the particle-core excitation model [4, 5]. Such analysis of the fine structure in proton emission is done for the first time for an odd-odd emitter.

The observation of fine structure in proton emission from 146 Tm prompts an obvious question: Is 146 Tm the only such odd-odd emitter, or can studies of odd-odd proton radioactivities serve as a tool to inspect the neutron states in exotic daughter nuclei? We have reinvestigated the decay of 150 Lu [2], for which there was no clear indication for fine
structure in proton emission. The same conclusion about $^{150}$Lu activity was obtained in Ref. [6]. We have undertaken a search for $^{144}$Tm, which is also a candidate to exhibit similar structure and decay pattern as $^{146}$Tm. The evidence of new short lived activity was discovered, as will be discussed below.

The structure of low energy levels in odd-odd nuclei depends primarily on the properties of proton and neutron orbitals near the Fermi surface and on the effects of $\pi$-$\nu$ coupling. To understand better the evolution of $\pi h_{1/2} \otimes \nu h_{1/2}$ and $\pi h_{1/2} \otimes \nu s_{1/2}$ states near the proton drip line, we have investigated the decay properties of such metastable structures in the N=77 isotones, $^{140}$Eu, $^{142}$Tb and $^{144}$Ho, in order to establish the spin and parity of the $\pi h$-$\nu h$ and $\pi h$-$\nu s$ isomers. The preliminary results on the levels in $^{142}$Tb are presented.

**EXPERIMENTAL TECHNIQUES**

The experiments were carried out at the Holifield Radioactive Ion Beam Facility at Oak Ridge. The nuclei of interest were produced in the fusion-evaporation reactions with the intense $^{58}$Ni and $^{54}$Fe beams on a 1 mg/cm$^2$ $^{92}$Mo target. The products recoiling from the target were separated according to their mass-to-charge ratio in the Recoil Mass Spectrometer (RMS) and detected at its final focal plane [7]. The Microchannel Plate detector [8] was used to determine the position and time signal of the ions transmitted through the gaps defined by adjustable baffles. The recoils were implanted into either a 65 $\mu$m thick, 40 mm by 40 mm Double-sided Silicon Strip Detector (DSSD) with 1 mm wide strips, or the Moving Tape Collector (MTC). For proton radioactivity studies, the front of the DSSD was surrounded by a Si-box consisting of four 700 $\mu$m thick, 50-mm by 50-mm silicon detectors. A 4 mm thick, 45mm by 45 mm SiLi crystal was placed just behind the DSSD. During the studies of $^{140}$Eu, $^{142}$Tb and $^{144}$Ho, the implantation point was viewed by the $\gamma$-, X-, and conversion electron detectors mounted in a CARDS array [9]. The signals from all detectors were processed using a digital electronics, 40 MHz, 12-bit DGF4C modules manufactured by XIA [10, 11, 12]. The arrival time and amplitude of preamplifier signals were usually analyzed on-board (standard mode). For the $^{144}$Tm study, only pile-up recoil-proton signals from the DSSD preamplifiers were recorded, in a proton catcher mode [5, 11, 12]. The recoil and proton signals, spaced up to 32 $\mu$s, were identified on-board and stored as 50 $\mu$s long digital images. The MCP position and time signals as well as the Si-box and SiLi signals were collected using standard setting of the respective DGFs channels. All signals were time-stamped with a 25-nanosecond resolution.

**RESULTS**

Proton Radioactivity Of $^{146}$Tm

A recent experiment on $^{146}$Tm activity at the HRIBF used the same fusion-evaporation reactions as the earlier investigations [3, 2], with a $^{58}$Ni beam of 297 MeV on a 1 mg/cm$^2$ $^{92}$Mo target.

Since the MCP detector can run with much higher rates of transmitted ions in comparison to previously used gas detector (Position Sensitive Avalanche Counter), a $^{58}$Ni beam intensity of 20 to 25 particle-nA was used. The recoiling A=146 ions with the two charge states $^{26}$Tm and $^{27}$Tm, were implanted into the DSSD.

Fig. 1 shows clear evidence for five proton transitions at 0.89 MeV, 0.94 MeV, 1.01 MeV, 1.12 MeV and 1.19 MeV. The DSSD energy spectrum was generated by requiring a correlation time between the implanted recoil and proton signals of no longer than 200 ms. The Si-box and SiLi detectors were operated in a veto mode, suppressing a part of the DSSD particle escape background at low energies. The gates corresponding to the mass-to-charge ratios of 146/26 and 146/27 were applied to the MCP-recorded recoil position signals reducing the contamination of the spectra by a 1.05 MeV $^{147}$Tm line. The halflives of strong transitions at 1.12 MeV and 1.19 MeV were determined to be 198(5) ms and 70(5) ms, respectively. The halflife of the weakest line, of 0.89 MeV, seems to be between 180 and 250 ms, while the transitions at 0.94 MeV and 1.01 MeV display faster decay times, of about 70 ms. Therefore, we continue to interpret the decay pattern as originating from two states in $^{146}$Tm, as previously proposed [2]. The decay of 200 ms $^{146m}$Tm is followed by the 1.12 MeV ($\sim$ 99%) and 0.89 MeV ($\sim$ 1%) lines, while now we are able to assign three transitions, the 1.19 MeV (about 67%), 1.01 MeV (about 18%) and 0.94 MeV (about 15%) to the decay of 70 ms $^{146gs}$Tm. The quoted intensities and halflife values are from a preliminary analysis [13].

Our interpretation of the structure of involved states is based on the systematics of proton and neutron states derived from neighboring nuclei. The $\pi h_{1/2}$ orbital is known as the ground-state in neighboring Tm isotopes, $^{145}$Tm [5] and
The isomeric state goes down along with increasing mass of the odd-A N=77 isotones, from 520 keV in 137 Nd down to 316 keV in 143 Dy. The \(1.12\) MeV transition populating the \(3/2^+\) pattern for the 70 ms low spin state, see Fig. 2. The expected total wave function and it is distributed over roughly equal parts of \(\pi h_{11/2} \otimes vs_{1/2}\) and \(\pi h_{11/2} \otimes 2^+ \otimes vs_{1/2}\). The 1.01 MeV transition is caused by a small 4% admixture of a \(\pi f_{3/2} \otimes 2^+ \otimes vs_{1/2}\) component. The calculated branching ratio of 17.7% fits perfectly to the preliminary experimental value of 18%. As in Ref. [2], the 0.94 MeV line is ascribed to the small admixture of isospin-mirror component, the \(\pi s_{1/2} \otimes vs_{11/2}\). The 2% fraction of the wave function explains the 15% intensity of the \(l=0\) 0.94 MeV transition to the \(h_{11/2}\) isomer in 145 Er. This results in defining the energy levels of 145 Er, with the \(h_{11/2}\) state 250 keV above the \(vs_{1/2}\) ground-state. However, the presence and magnitude of this isospin-mirror component doesn’t come directly from the model calculations, and needs further theoretical investigation. The 146Er decay scheme, with a \(l^2=5^+\) coupling option, is displayed in Fig. 2. Note the \(l=3\) 1.01 MeV transition populating the \(3/2^+\) state at 180 keV. The decay of the 6\(^-\) 146Er would have a similar pattern, with the \(l=3\) 1.01 MeV transition populating the 5/2\(^+\) state. Since the energy of 180 keV fits somewhat better to the 3/2\(^+\) level energy systematics, we postulate \(l^2=5^+\) for the 70-ms 146Er.

FIGURE 1. Energy spectrum of proton events observed within 200 ms after the implantation of the selected recoils.
In our previous work [2], an $I^\pi = (8^+) \text{ state}$, resulting from the $\pi h_{11/2} \otimes h_{11/2}$ coupling, was suggested for the spin and parity of $^{146m}$Tm, which was produced in the reaction at about an order of magnitude stronger than the lower spin $^{146g}$Tm. The 1.12 MeV line was recognized earlier [3, 2] as an $l=5$ proton transition decaying to the spectator $h_{11/2}$ state in $^{145}$Er. The fine structure line at 0.89 MeV was ascribed to the small $\pi f_{7/2}^+ \otimes h_{11/2}$ component in the $^{146m}$Tm wave function populating the $(9/2^-) [h_{11/2} \otimes 2^+]$ excited state in $^{145}$Er. However, the possible contribution of the $\pi f_{7/2}^+ \otimes h_{11/2}$ configuration coupling to the $I^\pi = (8^+)$ was omitted in the interpretation. The recent calculations with particle - core excitation [4, 5] indicated that a 2-3% $\pi f_{7/2}^+ - 0^+ \otimes h_{11/2}$ component is expected to be present in $^{146m}$Tm wave function. This triggers faster $l=3$ proton transitions to the $h_{11/2}$ state resulting in a much shorter halflife (about 50 ms) of the isomeric state and much too small fine structure branching ratio at the $10^{-2}$ % level.

It became clear that the spin of $^{146m}$Tm must be higher than 9, disallowing a contribution of $\pi f_{7/2}^+ - 0^+ \otimes h_{11/2}$ configuration in the wave function. As it could be expected, the calculated structure of the $10^+$ state is dominated by the 55% $\pi h_{11/2} \otimes h_{11/2}$ and 42% $\pi h_{11/2} \otimes 2^+ \otimes h_{11/2}$ components. The 0.89 MeV line originates from about 2.5% $\pi f_{7/2}^+ \otimes h_{11/2}$ part, and populates the 13/2− (or 15/2−) $h_{11/2} \otimes 2^+$ excited state in $^{145}$Er. The estimated fine structure branching ratio is about 1.2%, close to the observed value of 1 to 2%. The calculated proton partial halflife of the $10^+$ isomer is about 750 ms, confirming that the decay of this state is dominated by beta decay. The allowed Gamow-Teller transformation of the $h_{11/2}$ proton to the almost-empty $h_{9/2}$ orbital is likely to have a partial halflife of about 200 - 300 ms.

As indicated earlier, the assignment of the weak lines of 0.89 MeV, 0.94 MeV and 1.01 MeV as depopulating the states decaying by the 1.12 MeV and 1.19 MeV transitions is entirely based on the similarity of observed halflives. This is not an unambiguous assignment. In principle, other scenarios are possible [2, 20]. In particular, one can debate about a third proton emitting state in $^{146}$Tm, even below the 70-ms (5−) level. Such states, with $I^\pi = 1^+$, were identified in N=77 isotones $^{140}$Eu and $^{142}$Tb. However, already for $^{144}$Ho, the presence of the $I^\pi = 1^+$ state below the h-h and h-s isomeric levels is not experimentally demonstrated. The proton partial halflife of the $1^+ [\pi d_{3/2} h_{1/2}]$ state in $^{146}$Tm, emitting an $l=2$ 0.89 MeV proton would be about 400 ms. However, the beta branching contributing to its decay can make the halflife shorter, even down to about 200 ms. More data are needed to define the decay pattern and level properties of $^{146}$Tm, see [20]. In particular, the identification of the level scheme of $^{145}$Er would be beneficial.

FIGURE 2. The proposed decay scheme of $^{146m,gr}$Tm.
New Proton Radioactivity Of $^{144}\text{Tm}$

Using a $^{58}\text{Ni}$ beam energy of 340 MeV, we have performed a search for $^{144}\text{Tm}$ radioactivity. The experiment was done at the RMS in a similar way to the $^{146}\text{Tm}$ study (see previous sections). The proton catcher operation mode of the DGFs was used, since the half-life of $^{144}\text{Tm}$ was expected to be in the (sub)microsecond region. The events identified during the experiment as an overlapping recoil and proton signal are given in Fig. 3.

**FIGURE 3.** The results of the on-line analysis of the DSSD preamplifier signals containing a proton decay overlapping with an A=144 recoil implantation pulse, within the several $\mu$s range. The time difference between the recoil and proton signals is plotted against the pairs of corresponding proton (around 1.7 MeV) and recoil (scattered from 10 to 17 MeV) amplitudes.

Evidence for a short-lived (about 3 $\mu$s) 1.7 MeV proton transition correlated with the decay of A=144 recoils can be seen. The calculations within the particle - core excitations model assuming a decay pattern similar to the (10$^+$) $^{146m}\text{Tm}$ yield a half-life of about 4 $\mu$s and a large fine structure branching ratio of about 30%. Further off-line analysis is being performed in an attempt to verify this scenario.

The Level Scheme Of $^{142}\text{Tb}$

Experiments on the metastable states in $^{140}\text{Eu}$, $^{142}\text{Tb}$ and $^{144}\text{Ho}$, involving conversion-electron counting, were performed at the RMS. These studies were aimed at determination of the multipolarities of the transitions deexciting the isomers, and thereby the spin and parity of the levels. As an example, the conversion electron energy spectrum from the study of the $\pi h_{11/2} @ v h_{11/2}$ $^{142m}\text{Tb}$ is given in Fig. 4.

The half-life of the decaying state was remeasured to be 25(1) $\mu$s [28], which is longer than the value of 15(4) $\mu$s reported earlier [29]. The observed K/L ratio for the 303 keV transition indicates a rather pure E2 character, while mixed multiplicities of E2/M1 were deduced for the 137 keV and 165 keV lines. This information, combined with the suggested E1 character of the 37 keV isomeric transition [29, 26], leads to a spin difference of three between the $\pi h$-$v h$ and $\pi h$-$v s$ isomers. The $\pi h$-$v s$ level is known to decay via two cascades of two transitions each, to the $1^+ = 1^+$ ground-state. The most likely sequence of the spin/parity for the metastable levels in $^{142}\text{Tb}$ is therefore $1^+$, $5^-$ and $8^+$.

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FIGURE 4. Energy spectrum of conversion electrons measured with a conversion electron spectrometer BESCA [27] within 90 µs after the implantation of the RMS-selected A=142 recoils [28].

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