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Study of fine structure in the proton radioactivity of ^{146}Tm

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Abstract. Measurement of fine structure in proton emission allows one to deduce the composition of the parent and daughter state's wavefunction populated by proton emission. This paper presents new experimental data on the fine-structure decay of ^{146}Tm, and a new interpretation of its decay properties.

PACS. 23.50.+z Decay by proton emission – 27.60.+j $90 \le A \le 149$ – 21.10.Pc Single-particle levels and strength functions

Proton emission from a spherical (odd-Z, even N) nucleus typically occurs to the 0^+ ground state of the even-even daughter. The situation with the decay of an odd-odd nucleus to an (even-Z, odd-N) isotope is quite a bit more complicated. The proton-emitting state consists of coupled proton and neutron states, with the final state being a low-energy neutron state in the daughter nucleus. The study of fine structure in the decay of these odd-odd nuclei can be used to identify and determine the relative energies of these low-energy neutron levels.

In a previous experiment by this research group [1], fine structure in the proton radioactivity of ^{146}Tm was observed, which populated excited neutron states in ^{145}Er. Three fine-structure transitions of energies 0.89(1), 0.94(1) and 1.014(15) MeV were observed. Due to the low statistics of the data, only the 0.89 and 0.94 MeV transitions could be assigned based on their measured half-lives. Because of this, we re-investigated the decay of ^{146}Tm.

Thulium-146 was produced via the ^{92}Mo(^{58}Ni, p3n) reaction with a beam energy of 297 MeV (292 MeV at the target mid-point), at the Oak Ridge Holifield Radioactive Ion Beam Facility (HRIBF), using the 25 MV Tandem Accelerator. Recoil nuclei of interest were separated by the HRIBF Recoil Mass Spectrometer (RMS) [2]. A microchannel plate detector (MCP) [3] at the focal plane was used to identify the A/Q of the recoils. Following the MCP, the ions were implanted into a $\approx 65\,\mu$m thick double-sided silicon strip detector (DSSD) [4] with 40 horizontal and 40 vertical strips. Signals from the DSSD are read by the preamps and then fed directly into a digital spectroscopy system using 25 DGF-4C modules (produced by X-ray Instrumentation Associates) [5,6]. It uses 40 MHz flash ADCs and on-board digital signal processors. In this experiment, a "Si-box" consisting of four $700\,\mu$m thick Si detectors was added to the system to veto escaping alphas and protons. With these detectors, we were able to significantly clean up the proton spectra.

The existence of these three fine-structure peaks were confirmed, as is shown in fig. 1. The measured energies and half-lives are detailed in table 1. Based on the half-lives, we assign the 0.89 MeV transition to the 198 ms high-spin state (along with the 1.12 MeV line). The 0.94 and 1.01 MeV transitions are assigned to the 75 ms low-spin state (along with the 1.19 MeV line).

From a simple shell model picture, one expects that ^{146}Tm would have 5 proton particles above the $Z = 64$ proton subshell, and 5 neutron holes below the $N = 82$ closed shell. The available single particle orbitals for both protons and neutrons are therefore $h_{11/2}$, $d_{3/2}$ and $s_{1/2}$.

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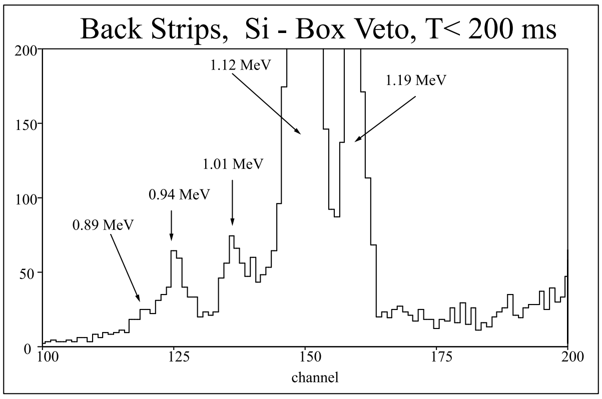

Fig. 1. Spectrum of proton events obtained in this study.

Table 1. Preliminary values for the proton energies, half-lives, and counts from ^{146}Tm. Intensities for the isomer and ground state are calculated relative to the 1.12 MeV and 1.19 MeV transitions, respectively.

Energy (keV)	$T_{1/2}$ (ms)	Counts	Rel. Intensity
888(10)	190(80)	170(30)	1.8(3)
1119(5)	198(5)	9450(250)	100
938(10)	60(20)	290(30)	22(2)
1016(10)	70(15)	370(40)	28(3)
1189(5)	75(5)	1350(80)	100

From the experimental level systematics of heavier odd-odd Tm isotopes and $N = 77$ isotones, one would expect an isomer with a spin of 8^+ to 11^+ ($\pi h_{11/2} \otimes \nu h_{11/2}$), and a ground state of 5^- or 6^- ($\pi h_{11/2} \otimes \nu s_{1/2}$). These states can have a complex structure with admixtures of $\pi s_{1/2} \otimes \nu h_{11/2}$, $\pi d_{3/2} \otimes \nu h_{11/2}$, and $\pi h_{11/2} \otimes \nu d_{3/2}$ contributing to their wave functions. The possible wave function compositions of both the isomer and ground state of ^{146}Tm were analyzed in the particle-core vibration coupling model [7,8] and compared with the experimental data (see table 2). In the case of the high-spin isomer, the calculations show that if the level was 8^+ as previously assigned [1], both the branching ratio for the fine-structure decay and the half-life would be much smaller than the experimental data. The wave function composition that gives values most consistent with the experimental values is fine-structure decay from a 10^+ state in the parent to the $13/2^-$ state in the daughter. The relatively long proton half-life (compared to the measured half-life) indicates that the decay of this state proceeds mostly (≈ 75 percent) via beta decay. For the low-spin ground state, the two possibilities that agree with experiment for the 1.02 MeV transition are $5^- \rightarrow 3/2^+$ and $6^- \rightarrow 5/2^+$. From the systematics of the $N = 77$ isotopes, one would expect the $5/2^+(\nu s_{1/2} \otimes 2^+)$ state to be greater than 200 keV, and the $3/2^+(\nu s_{1/2} \otimes 2^+)$ state to lie somewhere between 160 and 180 keV. We therefore assign the 1016 keV transition to the $3/2^+$ state. The $\ell = 0$ 0.94 MeV transition is ascribed to a small ($\approx 2\%$) admixture of $\pi s_{1/2} \nu h_{11/2}$ in the ground state as in ref. [1]. The proposed decay scheme with the composition of the various levels is shown in fig. 2.

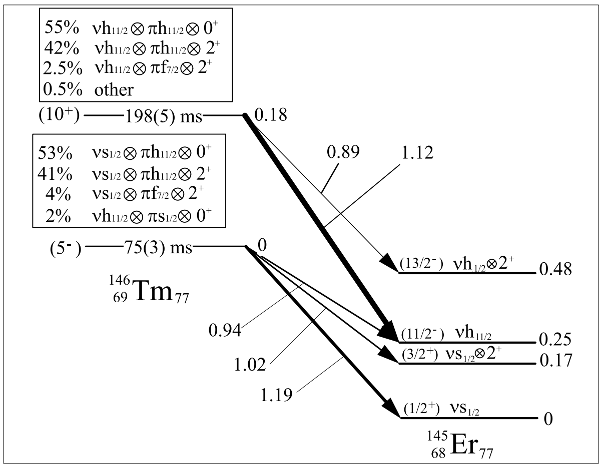

Fig. 2. Partial decay scheme of ^{146}Tm. All energies are listed in MeV.

Table 2. Possible initial- and final-state configurations for ^{146}Tm analyzed in the particle-core vibration coupling model [7,8]. The experimental half-life values are the total half-life for the state. The proton partial $T_{1/2}$ is adjusted for the experimental branching ratio ($\approx 15\%$) of the 0.94 MeV transition.

i. s.	final states	f. s. BR	p $T_{1/2}$(ms)
	0.18 MeV Isomer		
8^+	$11/2^-$, $7/2^-$; $\nu(_{11/2}) \otimes 2^+$	0.004%	68
8^+	$11/2^-$, $9/2^-$; $\nu(_{11/2}) \otimes 2^+$	0.011%	51
9^+	$11/2^-$, $7/2^-$; $\nu(_{11/2}) \otimes 2^+$	0.002%	28
9^+	$11/2^-$, $9/2^-$; $\nu(_{11/2}) \otimes 2^+$	0.002%	44
10^+	$11/2^-$, $9/2^-$; $\nu(_{11/2}) \otimes 2^+$	0.04%	758
10^+	$11/2^-$, $13/2^-$; $\nu(_{11/2}) \otimes 2^+$	1.24%	746
10^+	$11/2^-$, $15/2^-$; $\nu(_{11/2}) \otimes 2^+$	1.07%	740
11^+	$11/2^-$, $13/2^-$; $\nu(_{11/2}) \otimes 2^+$	0.048%	807
11^+	$11/2^-$, $15/2^-$; $\nu(_{11/2}) \otimes 2^+$	2.33%	683
	Experimental values:	1.7(3)%	198(5)
	Ground State		
5^-	$1/2^+$, $3/2^+$; $\nu(s_{1/2}) \otimes 2^+$	15.3%	79
5^-	$1/2^+$, $5/2^+$; $\nu(s_{1/2}) \otimes 2^+$	3.0%	87
6^-	$1/2^+$, $3/2^+$; $\nu(s_{1/2}) \otimes 2^+$	0.38%	96
6^-	$1/2^+$, $5/2^+$; $\nu(s_{1/2}) \otimes 2^+$	15.6%	74
	Experimental values:	19(2)%	75(3)

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