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Discovery of the new proton emitter ^{144}Tm

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Abstract. Evidence for the proton decay of ^{144}Tm was found in an experiment at the Recoil Mass Spectrometer at Oak Ridge National Laboratory. The ^{144}Tm events were found in the weak p5n channel of the fusion reaction using a ^{58}Ni beam at 340 MeV on a ^{92}Mo target. The observed proton decay energies are 1.70 MeV and 1.43 MeV and the half-life $\sim 1.9\ \mu$s. The decay properties suggest proton emission from the dominant $\pi h_{11/2}$ part of the wave function and from the small $\pi f_{7/2}$ admixture coupled to a quadrupole vibration.

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Fine structure in proton emission can be observed only if appropriate final states are available at low excitation energies. Four out of about thirty known proton precursors are known to exhibit fine structure; these are ^{131}Eu [1], ^{141}Ho [2], ^{146}Tm [3] and ^{145}Tm [4]. The first two involve proton decay of deformed nuclei to the low lying excited 2^+ state, a member of the rotational ground-state band of the deformed daughter. The ^{145}Tm is an example of the decay to the 0^+ ground state and the 2^+ vibrational state of the ^{144}Er core. The theoretical models were developed recently [5,6] to describe such odd-Z, even-N proton emitters. However, prior to this work, only a single odd-odd nuclide ^{146}Tm, was known to exhibit fine structure in its proton emission spectra [3]. The ^{146}Tm decay scheme is complex, since the proton-emitting states involve a coupling of proton and neutron orbitals to the even-even ^{144}Er core states [7,8]. This paper reports the discovery of a new proton emitting odd-odd isotope ^{144}Tm, and evidence for fine structure in its decay pattern.

The search for the proton decay of ^{144}Tm was performed in an experiment at the Recoil Mass Spectrometer (RMS) [9] at Oak Ridge. The ^{144}Tm events were found in the weak ($\sigma \approx 10$ nb) p5n channel of the fusion reaction of a ^{58}Ni beam at 340 MeV on a ^{92}Mo target. Recoiling $A = 144$ ions in the charge states $q = 27^+$ and $q = 28^+$ were selected by adjustable slits. A Micro-Channel Plate detector system [10] was used to detect heavy ions before the implantation into a 65 μm thick Double-sided Silicon Strip Detector (DSSD). Four silicon detectors surrounding the front of the DSSD, along with thick Si(Li), mounted behind it, were used for background suppression of the proton/alpha escape signals and beta-decay radiation. All detectors were read by a fast digital-signal-processing-based acquisition system [11]. Part of the system connected to the DSSD was used in the so called "proton-catcher" mode [4,11] with an extended sensitivity range of 32 μs. We have developed a new method of pulse shape analysis, which takes into account the properties of each DSSD-strip electronic chain. The pile-up pulses for the microsecond proton emitter ^{113}Cs have been analyzed and the energy resolution was improved significantly from 75 keV FWHM reported for ~ 1.7 MeV protons [4] to 35 keV FWHM at 0.96 MeV in this work. Additional data analysis conditions have been imposed: a) pixel correlation between front and back strips of the DSSD, b) anti-coincidence condition of the proton signal with the MCP detected recoil, and c) anti-coincidence with the Si(Li) and silicon box detectors.

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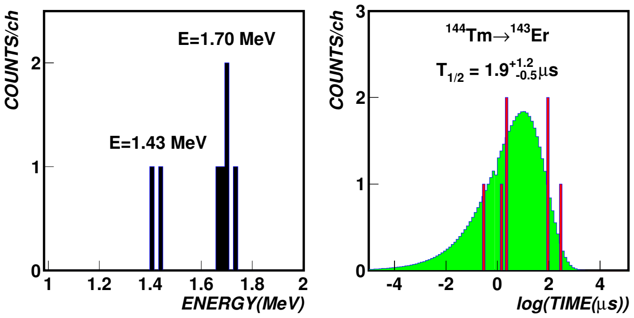

Fig. 1. Energy (left panel) and time (right panel) distribution of ^{144}Tm events. The $\log(t)$ representation is chosen for the time distribution plot [12] and the shape of the exponential decay curve with the 1.9 μs half-life is drawn.

The reliability of the electronic system and data analysis method has been verified using the known proton emitter ^{145}Tm ($T_{1/2} = 3.1 \pm 0.3\,\mu$s), which has been produced in the (^{58}Ni, p4n) reaction at 315 MeV ^{58}Ni beam energy. Twelve events have been detected during this measurement; eleven events were concentrated in the 1.73 MeV peak and one event was found at 1.4 MeV. The 1.4 MeV proton transition in the ^{145}Tm decay populates the 2^+ state in ^{144}Er with a branching ratio $I_{\rm p}(2^+) \approx 9.6\%$ [4]. The half-life of the ^{145}Tm events was determined to be $3.1^{+1.2}_{-0.7}\,\mu$s using the maximum likelihood method and the analysis of uncertainties from [12]. The energies, lifetimes and branching ratios measured for ^{145}Tm decay are in very good agreement with the values obtained in the previous measurements [4]. The same electronic system and analysis was used for the ^{144}Tm measurement.

The effective data taking time for the $A = 144$ experiment amounted to about 80 hours at a beam intensity of 10–20 pnA. Seven events out of all detected in the experiment fulfilled the analysis requirements, see fig. 1. Five events are concentrated in the peak at 1700(16) keV and two correspond to an energy of 1430(25) keV. The half-life has been determined to be $1.9^{+1.2}_{-0.5}\,\mu$s using the previously applied method [12]. Both distributions are compatible with this half-life [13]. Despite the low statistics, by comparing these data to the known ^{145}Tm test data, we interpret these events as belonging to the decay of a single state in ^{144}Tm to two levels in ^{143}Er. Thus, the new isotope ^{144}Tm becomes the fifth proton emitter with fine structure that has been discovered.

In the discussion of the result we will be guided by the assumed similarity of the two odd-odd thulium isotopes ^{144}Tm and ^{146}Tm and by the modified particle-vibrator model [5] which now includes the coupling of protons and neutrons to the vibrational core states. The observed proton emission from ^{146}Tm [3,7,8] is thought [5] to originate from two levels, the 5^- ground state and the 10^+ isomer. The main ($\sim 50\%$) components of their wave-functions are proton-neutron configurations $(\pi h_{11/2} \otimes \nu h_{11/2})_{J^\pi=10^+}$ and $(\pi h_{11/2} \otimes \nu s_{1/2})_{J^\pi=5^-}$ coupled to the 0^+ ground state of the ^{144}Er core. The respective final states in ^{145}Er are the $(\nu h_{11/2})_{J^\pi=11/2^-}$ isomer and the $(\nu s_{1/2})_{J^\pi=1/2^+}$ ground state, where the $l = 5$ proton emission dominates the decay width. Similar to ^{145}Tm [4] the fine structure in ^{146}Tm decay is caused by an admixture of the $f_{7/2}$ protons coupled to the 2^+ core vibration. The $\sim 3\%$ configurations $(\pi f_{7/2} \otimes \nu h_{11/2} \otimes 2^+)_{J^\pi=10^+}$ and $(\pi f_{7/2} \otimes \nu s_{1/2} \otimes 2^+)_{J^\pi=5^-}$ will mix with the main configuration and lead to $l = 3$ proton emission to the $(\nu h_{11/2} \otimes 2^+)_{J^\pi=13/2^-}$ and $(\nu s_{1/2} \otimes 2^+)_{J^\pi=3/2^+}$ excited states in ^{145}Er.

According to Hagino's model calculations [5], large components ($\sim 40\%$) of the wave function for both 10^+ and 5^- states involve core vibrations: $(\pi h_{11/2} \otimes \nu h_{11/2} \otimes 2^+)_{J^\pi=10^+}$ and $(\pi h_{11/2} \otimes \nu s_{1/2} \otimes 2^+)_{J^\pi=5^-}$. These parts of the wave function would be responsible for $l = 5$ proton emission to the final $13/2^-$ and $3/2^+$ states (neutron coupled to core vibration), but this decay width is smaller than that for an $l = 3$ transition of the same energy, and does not contribute appreciably to the total decay width. On the contrary, the large contribution of such configurations reduces the total proton emission probability. The above description developed for ^{146}Tm should, in general, be valid for ^{144}Tm. Indeed, the calculation, using the same model, shows that $l = 5$ proton emission is expected from the 10^+ and 5^- states, to respective states in the daughter nucleus. However, in the experiment, there is evidence for two proton transitions originating from one level. In both scenarios, the 10^+ and 5^- lifetimes are predicted to be similar (assuming the 1.70 and 1.43 MeV energies of the protons), so it is difficult to decide which state is actually observed. Again, guided by the ^{146}Tm data we assume that we most likely observed the decay of the 10^+ state. The low-spin 5^- state is expected to have much lower population in the fusion reaction. Alternatively, the 10^+ state could be very short lived and decay in flight during the $\sim 3\,\mu$s magnetic separation process, and not be observed.

In conclusion, the new proton-emitting isotope ^{144}Tm, the fifth case of fine structure in the proton decay, has been observed. The observed decay energy of about 1.7 MeV and the half-life of $\sim 1.9\,\mu$s suggest proton emission from the dominant $\pi h_{11/2} \otimes 0^+$ and small $\pi f_{7/2} \otimes 2^+$ wave function components. Combined with ^{145}Tm and ^{146}Tm, a consistent picture of component wave function systematics is established in the ground states and long-lived isomers in the exotic Tm isotopes.

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