FINE STUDIES OF PROTON RADIOACTIVITY WITH DIGITAL SIGNAL PROCESSING *

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Recent proton radioactivity studies at the Holifield Radioactive Ion Beam Facility at Oak Ridge are presented. The experiments were performed by means of a Recoil Mass Separator (RMS) and digital processing of its detector signals. Observation of fine structure in proton emission from the activities : ^{145}Tm ($T_{1/2} \approx 3\,\mu$s) and ^{146m,gs}Tm ($T_{1/2} \approx 200$ ms and 100 ms, respectively) is reported. The structure of the proton emitting states is analyzed in terms of a spherical approach. The properties of daughter states, a 2^+ state in ^{144}Er and the $s_{1/2}$ and $h_{11/2}$ neutron levels in ^{145}Er, are deduced.

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1. Introduction

Proton radioactivity was a subject of several presentations during the Zakopane meeting in 1998. The highlights included the first observation of fine structure in proton emission from ^{131}Eu [1, 2], the observation of excited states in the proton emitting nuclei by means of Recoil Decay Tagging (RDT) [3] and the discovery of several short-lived p-emitting isomeric states in known proton radioactivities [4]. For the first time, a weak $p5n$ fusion-evaporation reaction channel has been used to produce and identify a new proton emitter ^{140}Ho [4, 5]. The studies of nuclei near the proton drip-line were continued in the last two years. The contributions to Zakopane 2000 conference describe the proton decay from super deformed to normal bands near doubly-magic ^{56}Ni [6], as well as the RDT studies of proton-rich nuclei above the $N = 82$ closed shell [7]. First proton emitter discovered at Jÿvaskylä (Finland) was announced by Kettunen [8]. An odd–odd ^{164}Ir, produced in a rare $p5n$ reaction channel, was detected due to recently enhanced sensitivity of the RITU spectrometer. The observation of fine structure in the proton emission from thullium isotopes, ^{145}Tm [9] and ^{146}Tm [10], is among the subjects of this presentation. These results were achieved at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge [11].

The proton emission rate is strongly dependent on the decay energy as well as on the angular momentum of the emitted proton. In contrast to the alpha decay, the proton usually carries the non-zero orbital angular momentum (with the exception of s-wave proton emission). Having the energy of proton line measured with an accuracy of ≈ 10 keV, one can trace the evolution of single-particle proton orbitals along the drip-line region by analysing the proton decay rates. Particularly interesting are nuclei with proton emitting ground- and isomeric-state. Such observation defines the energies of proton orbitals in the same exotic nucleus.

Evolution of nuclear shapes along the drip-line region is also reflected in the proton emission probabilities. The discrepancy between the observed decay rates and those calculated within the spherical approach usually indicates the presence of deformation. Independently, the deformation of proton-radioactive nucleus could be verified via the observation of an excited band on top of the proton emitting state. This type of experiment usually requires the recoil decay tagging, see *e.g.* [3, 7]. In addition to the structure of the proton emitting state, the shape of the potential for the daughter system is crucial for the analysis of the observed decay rates. The transmission probability is calculated for the proton penetrating through the potential of the daughter nucleus. For an even–even nucleus, one can deduce information on the shape from the measurement of the energy of the first 2^+ state. This energy value yields an estimate of the quadrupole deformation [12]. It was demonstrated by the pioneering study of ^{131}Eu [1, 2] that the energy of such a 2^+ state could be obtained via the observation of fine structure in proton emission. In this contribution, we report the first evidence for fine structure in the proton emission from ^{145}Tm [9] yielding the 0.33 MeV energy for previously unknown 2^+ state in ^{144}Er. This experiment was performed at the final focus of the HRIBF Recoil Mass Separator (RMS) [11]. Digital processing of the RMS detector signals, *i.e.* the Position Sensitive Avalanche Counter (PSAC) and Double-sided Silicon Strip Detector (DSSD), was used during this study.

Proton radioactivity measurements allow us to deduce information on the structure and evolution of proton states. Whereas fine structure in the decay of an odd-mass nuclide reveals levels in the even–even daughter, fine structure in decay of odd–odd nuclei can be used to identify low-energy levels in odd-N daughters. We report here the first observation of fine structure in proton emission from the odd–odd isotope ^{146}Tm, interpreted as a decay to the $s_{1/2}$ and $h_{11/2}$ neutron states in ^{145}Er [10].

2. The proton emission from ^{145}Tm

The exotic nucleus ^{145}Tm ($T_{1/2}$ = 3.5 ± 1.0 μs) was the first proton emitter identified at the RMS at Oak Ridge [13]. It was discovered among the products of the ^{92}Mo (315 MeV ^{58}Ni, $p4n$) reaction despite of its low production cross section of about 0.5 μb. The time-of-flight through the RMS of $\approx$ 2.5 μs, and a blocking of the analog DSSD electronics by recoil implantation signals (over 10 μs) caused huge detection losses due to the radioactive decay. The effective detection rate was about one correlated recoil-proton event per hour in the DSSD. It allowed us to determine the energy of 1.73 MeV for the proton line. The shortest half-life ever measured for proton radioactivity, $\approx$ 3.5 μs, was deduced from the decay pattern of about fifty events. The observed transition was interpreted within a spherical approach [21] as $l = 5$ proton emission from the $\pi h_{11/2}$ ground state of ^{145}Tm [13]. In fact, the spectroscopic factor for this transition was somewhat reduced in comparison the theoretical expectation indicating that likely this emitter has a mixed wave function [4].

In order to improve the counting rates for very short-lived particle radioactivities, a new digital signal processing system for the RMS detectors has been implemented [14–16] at the HRIBF. This new set-up is based on Digital Gamma Finder (DGF-4C) units produced by the X-ray Instrumentation Associates (XIA, California, USA) [17,18]. The DGF-4C is a single-slot four-channel CAMAC module. Among available options, it can analyse the preamplified DSSD signals. The signal waveform is recorded as an amplitude *vs* time trace over a 25 μs range. The time is stamped by the DGF with a 25 ns resolution, so the 25 μs trace consists of 1000 points.

The operation mode designed for the study of very short lived particle emitters is nicknamed "proton catcher". The DGF recognizes a pile-up event in the DSSD, *e.g.* a 1.7 MeV proton signal on top of the 16 MeV ^{145}Tm ion implantation signal, and stores it until the readout occurs. Two hundred pretrigger points (5 μs) help to measure the baseline *i.e.* to define the "zero" level for the amplitude determination. Four hundred points at the end of the trace (10 μs) are used to analyze the electronic signal decay. The four hundred 25 ns samples in the center, spanning 10 μs, contain the implantation and decay pulse. Events not piled up within 10 μs, however, are rejected within this DGF operation mode.

The "proton catcher" mode of DGF operation was used during the study of the ^{145}Tm activity presented here. Thirty-two strips on each side of the DSSD were connected to the DGF channels during the ^{145}Tm run, and one DGF module was used to analyze the signals from the PSAC [11]. The proton decay signals were observed in the DSSD starting about 0.5 μs after the ^{145}Tm implantation signal. The pile-up detection rate was reduced within the first 500 ns, but the total rate of recorded proton events amounted to about ten per hour [9]. This represents an order of magnitude increase in comparison to the first experiment [13], for the identical fusion-evaporation reaction used. The RMS ion optics was tuned to focus recoiling ions in two charge states, onto the DSSD placed at the final focus. This converging solution is responsible for a factor of about 1.5 increase in spectrometer transmission, as compared to the first experiment [13]. The total event rate in the data acquisition system is very low, about 1 readout per second since

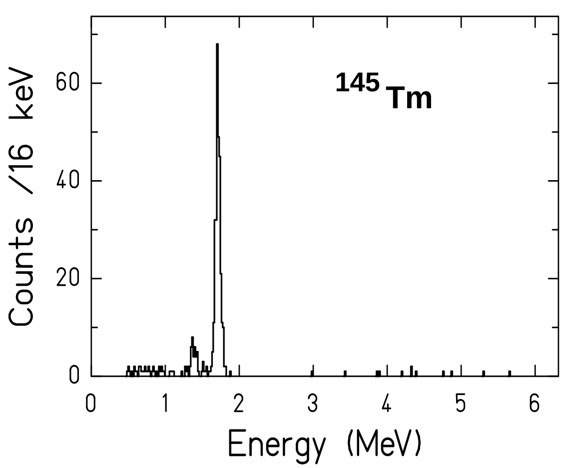

Fig. 1. The energy spectrum of proton events observed within 0.5–10 μs time interval after an implantation of $A = 145$ recoils into the DSSD [9].

the "proton catcher" mode selects up-front only the pile-up events and rejects all others. It is clear that having a system free of electronic noise is crucial for this type of operation.

In addition to the known proton line at 1.73 MeV, see Fig. 1, a new transition was observed at about 0.33 MeV lower in energy [9]. The preliminary values of the half-lifes, about 3 μs, are identical (within the error bars) for the two transitions, see Fig. 2. Both transitions are associated with the decay of mass $A = 145$ recoils. It is therefore likely that both lines originate from the decay of the same state, the previously identified ^{145gs}Tm. The respective branching ratios are about 91% and 9%, respectively.

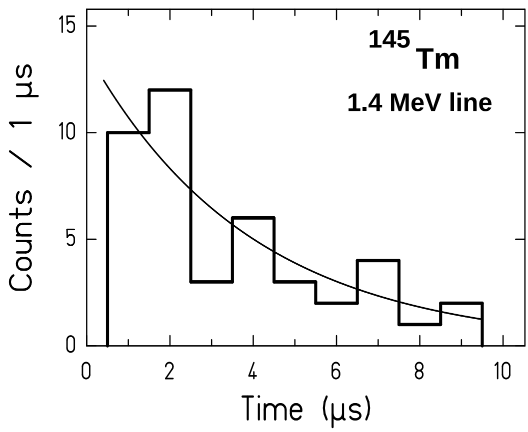

Fig. 2. The decay plot of the 1.4 MeV proton transition [9]. These decays of ^{145}Tm were detected starting 0.5 μs after the implantation of recoiling ions using new digital signal processing electronics. The detection rate was reduced within the first 500 ns of counting.

In the even–even daughter nucleus ^{144}Er, a 2^+ level is the first excited state. The value of about 0.33 MeV is close to the 2^+ energy known for three neighboring even-mass $N = 76$ isotones, ^{138}Sm, ^{140}Gd and ^{142}Dy. One can also consider ^{144}Er as a "$N = 82$ mirror" nucleus to ^{156}Er, *i.e.* the six neutron holes — six neutron particles symmetry [19, 20]. The energy of the 2^+ state is 0.344 MeV in ^{156}Er, close to the observed 0.33 MeV level in ^{144}Er.

The preliminary interpretation of the observed decay rates following the spherical approach [21], suggests an $l = 5$ ground to ground state proton decay at 1.73 MeV originating from the main $\pi h_{11/2}$ component of the ^{145}Tm wave function. Fine structure in this decay could be associated with the $\pi f_{7/2} \otimes 2^+$ configuration. Since the $l = 3$ transition at $E_{\rm p}$=1.4 MeV is about 2.5 times faster than $l = 5$ at 1.73 MeV, only a $\approx 3\%$ admixture to the main wave function explains the observed $\approx 9\%$ branching. If one assumes the $l = 5$

proton emission to be precisely described within the spherical approach [21], about 70% of pure $\pi h_{11/2}$ component in the parent wave function is necessary to explain the observed intensity of the 1.73 MeV transition. The remaining $\approx$ 30% might be at least partially related to the $\pi h_{11/2} \otimes 2^+$ configuration coupled to the $I^\pi = 11/2^-$. The latter part of the wave function would undergo a decay via $l=5$ proton emission to the 0.33 MeV 2^+ state. However, the absolute probability would be much lower, by about a factor of 500, in comparison to the $l=3$ decay of the same energy. The fraction of the $\pi h_{11/2} \otimes 2^+$ configuration in the wave function of ^{145}Tm might be up to $\approx$ 10 times larger in comparison to the $\approx$ 3% of the $\pi f_{7/2} \otimes 2^+$. However, the probability of this $l=5$ proton decay to the 2^+ state still remains about 50 times smaller with respect to the $l=3$ decay.

This spherical picture of the ^{145}Tm decay should be reanalysed with respect to the deformation effects. An application of the simple Grodzins formula [12] to the 0.33 MeV energy of the 2^+ state points to a deformation parameter β_2 of about 0.18 for the daughter nucleus ^{144}Er. This indicates a need for more advanced description of the ^{145}Tm proton decay process, within the theoretical formalism accounting for the deformation of parent and daughter states, compare [22, 23] and references therein.

3. The decay of an odd–odd proton emitter ^{146}Tm

The proton decay of an odd–odd nucleus leads to an (even-Z, odd-N) isotope. The proton emission rate depends strongly on the decay energy, so the transition to the ground-state is favoured. However, for the rare-earth proton drip line nuclides in this mass region, three neutron orbitals $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu h_{11/2}$ are expected to be close to the Fermi surface. Their relative excitation energies are calculated to be within a few hundred keV [24]. The same orbitals occupied by protons, the $\pi s_{1/2}$, $\pi d_{3/2}$ and $\pi h_{11/2}$ are also energetically close to each other. With $N = 77$, there will be five neutron holes in the $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu h_{11/2}$ orbitals while with $Z = 69$, there will be five proton particles beyond the $Z = 64$ subshell which occupy $\pi s_{1/2}$, $\pi d_{3/2}$ and $\pi h_{11/2}$ orbitals.

The observed rates for the $l=2$ proton emission from $I^\pi = 3/2^+$ states already indicated the configuration mixing between positive parity orbitals, the $\pi s_{1/2}$ and $\pi d_{3/2}$ [4, 25–27]. These facilitate the conditions that build the low-lying nuclear states of a complex structure. The proton–neutron pairs, with the nucleons exchanging their orbitals can be coupled to the same spin and parity. For example, one can form an $I^\pi = 6^-$ state by coupling the nucleons at the $\pi h_{11/2}$ and $\nu s_{1/2}$ orbitals as well as at the $\nu h_{11/2}$ and $\pi s_{1/2}$ ones.

For odd–odd emitters, in addition to the presence of proton emitting ground- and isomeric-states, the proton transitions between the isomer (or ground-state) and excited state in final nucleus may occur, see *e.g.* [28]. Proton radioactivity, with the decay rates reflecting the angular orbital momentum carried by the emitted proton, can help identify and map the wave functions of involved states. These considerations lead to the experiments on odd–odd proton emitters ^{146}Tm and ^{150}Lu performed at the HRIBF (Oak Ridge). The data on the decay of proton radioactive states ^{150gs}Lu [29] and ^{150m}Lu [30], were improved, but no indication for any fine structure was obtained [31, 32], see Fig. 3.

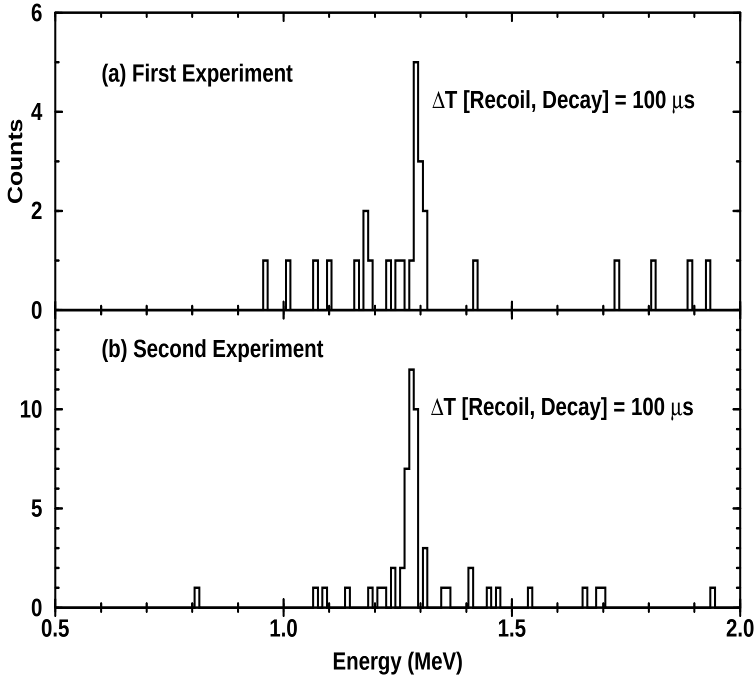

Fig. 3. The energy spectrum of proton events collected within 100 μs after an implantation of $A = 150$ recoils into the DSSD, in two similar experiments (a) and (b) using 292 MeV ^{58}Ni beam on 0.54 mg/cm^2 ^{96}Ru target [30–32]. The charge reset foil was placed 10 cm behind the target during second experiment. It restores the charge state of a recoiling ion, changed after an isomeric deexcitation involving a conversion electron [11]. Observed increase in the ^{150m}Lu proton emission suggests the presence of such isomeric level on the deexcitation path leading to the ^{150m}Lu [31,32]. Improved experiment on the ^{150}Lu activity yielded no evidence for the fine structure for displayed $l = 2$ transition as well as for the $l = 5$ proton emission from ^{150gs}Lu.

However, for ^{146}Tm, in addition to the two known transitions at 1.12 MeV and 1.19 MeV [33], three new lines were identified at 0.89, 0.94 and 1.01 MeV, see Fig. 4. The counting statistics have been increased at the HRIBF by over an order of magnitude in comparison to the earlier Daresbury experiment. The contributing factors were the high selectivity and good transmision ($\approx$ 5%) of the RMS. It allowed us to use about three times higher beam intensity, about 15 pnA of 292 MeV ^{58}Ni on the ^{92}Mo target, without overloading the RMS final focus detectors.

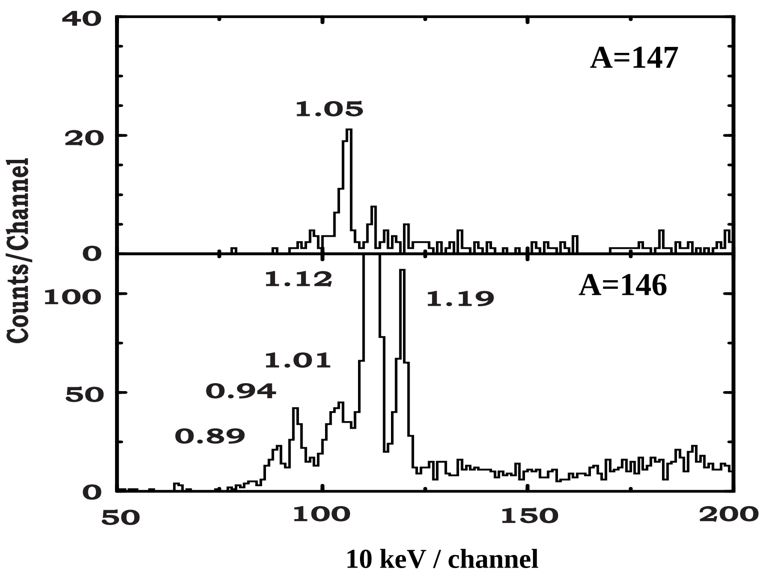

Fig. 4. The energy spectrum of protons measured in correlations with the implantation of mass $A = 147$ (upper panel) and $A = 146$ (lower panel) recoils. A correlation time of 100 ms between the recoil and decay events was applied.

The present status of the data analysis suggests that all observed proton lines can be assigned to the decay of previously observed states [10, 33]. This conclusion is based on the decay pattern and the correlations with $A = 146$ recoils. The state with a half-life of about 100 ms emits 0.94 and 1.19 MeV protons, and the $T_{1/2}\approx$ 200 ms was measured for the 0.89, 1.01 and 1.12 MeV proton transitions. The intensities of observed lines indicate that the direct population of the 200 ms state is about 10 times stronger than the shorter-lived state. There is no evidence in the decay pattern for the transition between the two proton emitting states suggesting large spin difference and/or small energy difference.

Energy level systematics of the states in neighboring nuclei (closer to β-stability) helps to understand the ^{146gs,m}Tm decay scheme. The odd-mass proton emitters ^{145}Tm and ^{147}Tm have $I^{\pi} = 11/2^{-}$ ground-state.

Their proton and beta decay rates are explained by the $\pi h_{11/2}$ configuration dominating the ground-state. The level systematics of N=77 isotones suggests the sequence of neutron levels in N=77 daughter nucleus ^{145}Er. The ground-state configuration is likely $\nu s_{1/2}$, as it is known for all odd-mass N=77 isotones from $Z = 56$ barium to $Z = 66$ dysprosium. The $\nu d_{3/2}$ and $\nu h_{11/2}$ states could be expected at about 100–200 keV and 200–300 keV above the ground-state, respectively. For odd–odd thulium isotopes, the isomeric 10^+ state (^{148}Tm and ^{150}Tm) and the 6^- ground-state (^{150}Tm) are known.

The ground-state configuration of the ^{146}Tm is likely to contain a large $I^\pi = 6^-$ $[\pi\, h_{11/2} \nu\, s_{1/2}]$ component, while the higher spin isomer (likely 10^+ or 9^+) is mostly made out of the $[\pi\, h_{11/2}\, \nu h_{11/2}]$ proton–neutron pair. Much stronger direct population of 200 ms state suggests the high spin (*e.g.* 10^+) assignment to the isomeric state and the lower spin (*e.g.* 6^-) for the 100 ms ground-state. The tentative 10^+ and 6^- assignments follow the spin and parities known for the ground- and isomeric-states in neighboring ^{148}Tm and ^{150}Tm.

The proposed decay scheme is shown in Fig. 5.

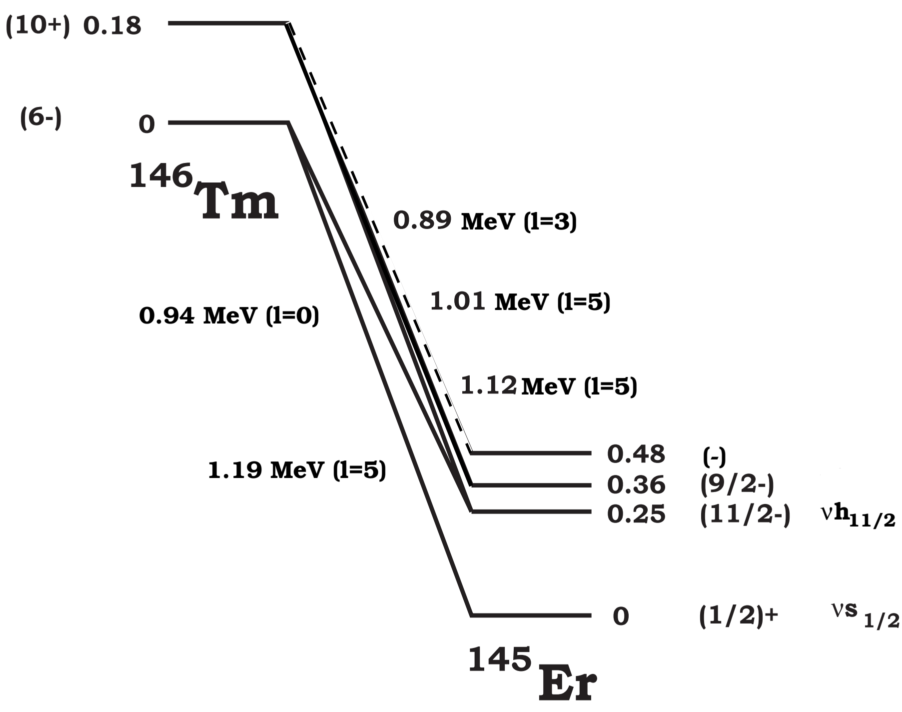

Fig. 5. Partial decay scheme of the ^{146gs}Tm, $I^\pi = (6^-)$ and $T_{1/2} \approx$100 ms, and of ^{146m}Tm, $I^\pi = (10^+)$ and $T_{1/2} \approx 200$ ms. The energies are given in MeV.

The 6^-, $T_{1/2} = 100$ ms ^{146gs}Tm decays by the main $l = 5$ transition of 1.19 MeV to the $\nu s_{1/2}$ ground-state of ^{145}Er. The second, weaker, proton line could be associated with $l = 0$ emission to the $\nu h_{11/2}$ level at the excitation energy of about 0.25 MeV. The $[\pi s_{1/2}\, \nu s_{11/2}]$ fraction of the ^{146gs}Tm wave function would be responsible for the transition to the 0.25 MeV state. It is enough to have the latter component about 60 times smaller in comparison to the dominating $[\pi h_{11/2}\, \nu s_{1/2}]$ one to explain the observed intensity ratio of about 5 : 2. The smaller proton decay energy value is compensated by the lowering of the angular momentum barrier. The existence and beta decay of the $I^\pi = (11/2^-)$, $T_{1/2} \approx 0.9$ second state in the ^{145}Er has been reported earlier [34].

The $l = 5$ proton decay of the $10^+[\pi\, h_{11/2}\, \nu\, h_{11/2}]$ state should lead to the $11/2^-\, \nu\, h_{11/2}$ state in ^{145}Er. This explains the main 200 ms line at 1.12 MeV. The new weaker lines are interpreted as the $l = 5$ and $l = 3$ decays to two levels: a $9/2^-$ state at 0.36 MeV and to the negative parity state at 0.48 MeV. The very weak $l = 3$ transition might originate from the fraction of the 10^+ state wave function which is identical to the one responsible for the fine structure in the ^{145}Tm decay, the $11/2^-[2^+ \otimes \pi f_{7/2}]$ configuration "replacing" the $\pi h_{11/2}$ part in the 10^+ isomeric state. Contribution from the $[2^+ \otimes \pi f_{7/2}]$ below 10% is needed to explain the observed intensity ratio 36 : 3 : 1 for the decay of 200 ms ^{146m}Tm, this isomeric state being about 0.18 MeV above the 6^- ground-state. All calculated half-lifes of the discussed proton transitions were estimated within the spherical WKB approach [21] taking into account respective proton vacancy factors [24].

Beta decay in the region of ^{146}Tm is governed by the well-known Gamow–Teller transformation of $\pi h_{11/2}$ into $\nu h_{9/2}$. It contributes to the ^{146gs,m}Tm decay rate. The beta partial half-lifes can be expected at the level of 200 to 500 ms. The observed ^{146gs,m}Tm states are clearly not pure proton emitters.

We estimated that beta decay is responsible for about 30% of the branching for the decay of the 100 ms state, and for about 70% of the branching for the 200 ms state. The configuration of the $I^\pi = (6^-)$ state is proposed to be about 60% $[\pi\, h_{11/2}\, \nu\, s_{1/2}]$ and 1% $[\pi\, s_{1/2}\, \nu\, h_{11/2}]$ for the proton emitting part, with the remaining ≈ 40 % of $[\pi\, h_{11/2}\, \nu\, d_{3/2}]$. The latter fraction of the ^{146gs}Tm wave function contributes to Gamow–Teller beta decay, but its $l = 5$ proton decay to the excited $\nu\, d_{3/2}$ state in ^{145}Er has a very low branching ratio. This is due to the energy factor, since the $\nu d_{3/2}$ state is likely about 150 to 200 keV above the $\nu s_{1/2}$ ground state. It is a challenge to determine the energy of this neutron $d_{3/2}$ level — it might be a subject in an improved experiment on the ^{146}Tm proton radioactivity.

The configuration of the $I^\pi = (10^+)$ isomer is somewhat simpler, with the dominant (over 90%) $[\pi\, h_{11/2}\, \nu h_{11/2}]$ part, and the smaller fraction (below 10%) of $2^+ \otimes \pi\, f_{7/2}$ coupled to $\nu\, h_{11/2}$.

4. Summary

The proton radioactivity studies between the magic numbers $Z = 50$ and $Z = 82$ are moving towards "complete spectroscopy". Information on the structure of proton emitters deduced from the observed rates of proton emission is complemented by the studies of excited states in the parent nuclei (via RDT measurements) and in the daughter nuclei (via fine structure in proton emission). The exploration of other drip-line regions, *e.g.* below doubly-magic ^{100}Sn, may become possible. The digital signal processing of the detector signals allows us to extend the observation window for proton emission, with respect to the short half-lifes and energy thresholds.

Fine structure in proton emission was found in the decays of ^{145}Tm, ^{146gs}Tm and ^{146m}Tm. For the 3 μs activity of ^{145}Tm this observation was possible thanks to an order of magnitude increase in proton detection rate resulting from new digital signal processing electronics applied to the PSAC-DSSD setup at the RMS.

The structure of ^{145}Tm and the measured decay rates were interpreted within the spherical approach. The proton emitting state in ^{145}Tm is dominated by the $\pi\, h_{11/2}$ orbital, with a few percent admixture of the $2^+ \otimes \pi\, f_{7/2}$ configuration. However, the observed 2^+ level energy of 0.33 MeV in ^{144}Er suggests deformation $\beta_2 \approx 0.18$. There is a need for advanced analysis of the ^{145}Tm decay accounting for the deformation effects.

For the first time, the properties of neutron states in an exotic drip-line nucleus have been deduced via proton radioactivity studies. The $\nu\, s_{1/2}$ orbital has been assigned to ^{145gs}Er, and the excited $\nu\, h_{11/2}$ level was found at 0.25 MeV — which is likely the $T_{1/2} \approx 0.9$ second isomer identified earlier via its beta decay. $I^\pi = 6^-$ is proposed for the ground state of ^{146gs}Tm, while the $I^\pi = 10^+$ is assigned to the 0.18 MeV isomeric state.

Information obtained from proton radioactivity studies is no longer limited to the evolution and structure of proton orbitals. We should revisit known odd–odd emiters and study new ones in order to deduce the properties of neutron states in exotic nuclei. The energies on the neutron excited states obtained during the proton radioactivity studies, could be helpful for further, more precise investigations with large γ-detector arrays.

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