Towards digital spectroscopy of proton emitters

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Abstract

First observations of fine structure in proton emission from the isotopes ^{145}Tm and ^{146m,gs}Tm are reported. The 3 μs decay of ^{145}Tm was studied by means of the Recoil Mass Separator and digital processing of its detector signals. The structure of the proton-emitting states as well as 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.

Key words: RADIOACTIVITY ^{145}Tm [from ^{58}Ni(^{92}Mo, p4n)] and ^{146}Tm [from ^{58}Ni(^{92}Mo, p3n)]; measured E_p, recoil mass separation, Si detectors
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1 Introduction

Proton radioactivity studies offer unique data on the structure of unbound resonant nuclear states in nuclei located a few mass units beyond the proton drip-line limit. The energy of the emitted proton, usually measured with a precision on the level of ten keV, contributes to the understanding of the mass surface for exotic nuclei. The decay rate, strongly dependent on the angular momentum of the emitted proton, allows us to follow the evolution of single-particle orbitals for very proton-rich isotopes. In particular, the observation of proton emission from ground and isomeric states defines different proton orbitals in the same nucleus.

The phenomenon of proton tunneling through the spherical nuclear potential seems to be well understood, thanks to progress in experimental and theoretical studies [1,2]. The discrepancy between the observed decay rates and those calculated within the spherical approach usually indicate effects related to the deformation of proton emitters, thus contributing to our knowledge of the evolution of nuclear shapes. The deformation of a proton radioactive nucleus is more directly determined by the measurement of the excited levels built upon the p-emitting state. The Recoil Decay Tagging technique, which combines decay and in-beam spectroscopy, is a powerful tool to study such weakly produced states, see the excellent review by D. Seweryniak given at this meeting [3]. However, in the description of proton emission, the transmission probability is calculated for the proton penetrating through the potential of the daughter nucleus. Thus, information on the shape of the daughter system is also important for the proper analysis of the decay process. The nucleus created after the decay of a proton-radioactive isotope is in general also a quite exotic object, difficult to reach in experimental studies. One of the ways to obtain information on its shape is the measurement of the energy of its first 2^+ state (in the case of an odd-Z, even-N p-emitter). This energy might be used to estimate the quadrupole deformation, e.g. following Grodzins formula [4,5]. The energy of such a 2^+ state, in a favorable case, could be obtained via the observation of fine structure in proton emission - see the pioneering study of ^{131}Eu at the Fragment Mass Analyzer at Argonne [6]. In this contribution, we report the first evidence for fine structure in the proton emission from ^{145}Tm [7] (see Section 2). This experiment was performed at the Recoil Mass Separator (RMS) at the Holifield Radioactive Beam Facility (HRIBF) at Oak Ridge, using a digital processing of the detector's signals.

Proton radioactivity studies are usually considered a source of information on proton states. However, after the decay of an odd-odd proton emitter, an even-Z, odd-N nucleus is formed. It is most likely that the ground state of this even–odd isotope is populated because of the decay energy factor contributing strongly to the proton emission rate. However, the proton emission from odd-

odd nuclei may be more complex, because the proton-neutron coupling can result in isomeric configurations. Hence, the proton transitions between the isomer and excited state may occur, see e.g. [8]. In the rare-earth region the energies of neutron orbitals $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu h_{11/2}$ are similar. One can try to search for fine structure in the decays of odd-odd emitters resulting in the feeding of different final neutron states. Here, we report the first observation of fine structure in proton emission from the odd-odd isotope ^{146}Tm, interpreted as a decay to the neutron $s_{1/2}$ and $h_{11/2}$ states in ^{145}Er [9] (see Section 3).

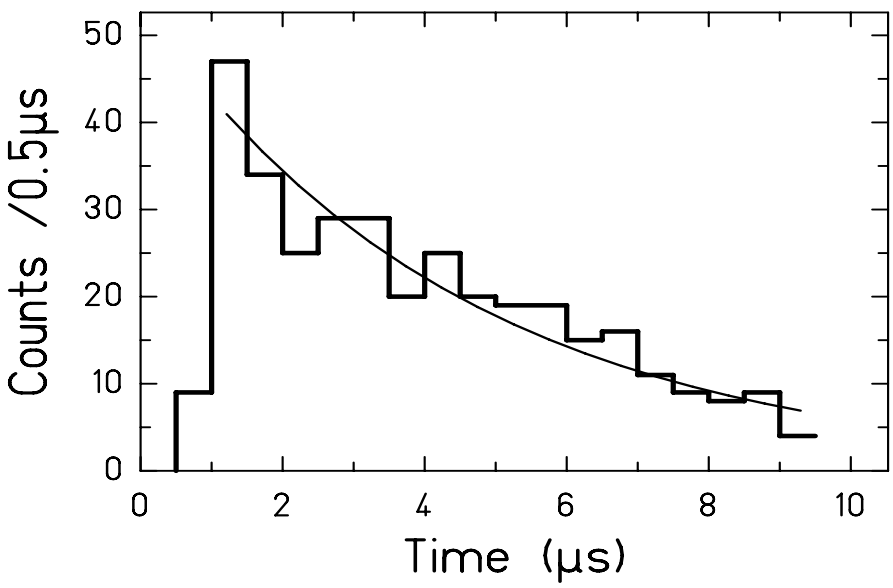
2 Fine structure in proton emission from ^{145}Tm

The proton emitter ^{145}Tm was first identified at the RMS [10] among the products of the ^{92}Mo(^{58}Ni,*p4n*) reaction. The 1.73 MeV proton transition was interpreted within a spherical approach as *l=5* proton emission from the $\pi h_{11/2}$ ground state of ^{145}Tm. With ≈ 0.5 μbarn cross section, about one proton event per hour was counted by the Double-sided Silicon Strip Detector (DSSD). This low detection rate was largely caused by the very short halflife of 3.5 ± 1.0 μs (the shortest-lived proton emitter observed). Due to the time-of-flight through the RMS (≈ 2.5 μs), and mostly because of a blocking of the analog DSSD electronics by recoil implantation signals (over 10 μs), the decay events were effectively counted starting from about 13μs after production in the target. In order to overcome the latter deficiency, a new digital signal processing system for the RMS detectors has been implemented [11–13] at the HRIBF. This new electronics is based on 4-channel Digital Gamma Finder (DGF-4C) single–slot CAMAC units [15,16]. The so called "proton catcher" mode of DGF operation was used during the study of the ^{145}Tm activity presented here. This mode is designed for the study of very short lived particle emitters. Each channel of the 4-fold DGF is connected to the preamplifier card of a DSSD strip. Thirty-two strips on each side of the DSSD were connected to the DGF channels during the ^{145}Tm run. One DGF module was used to analyze the signals from the position sensitive avalanche counter PSAC [14]. 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). It records the signal waveform as an amplitude vs time trace covering 25 μs.

The 25 μs trace consists of 1000 points, 25 ns apart. Two hundred pretrigger points (5 μs) help to measure the baseline, and 400 points at the end (10 μs) help to determine the electronic signal decay. The 400 samples in the center, spanning 10 μs, contain the implantation and decay pulse. In the real experimental conditions of the ^{145}Tm experiment, decay signals were observed starting about 0.5 μs after the implantation signal (see Fig. 1), with some detection rate reduction within the first 500 ns. The total rate of recorded proton events amounted to about ten per hour [7], an order of magnitude increase in

comparison to the first experiment [10]. The same ^{58}Ni beam energy of 315 MeV and intensity of 15 to 20 pnA were used as well as the same ^{92}Mo target of 0.91 mg/cm^2 thickness. The RMS was tuned to focus two charge states of the recoiling mass A=145 ions onto the DSSD placed at the final focus. This converging solution for the RMS ion optics gave a factor about 1.5 increase in spectrometer transmission, compared to the first experiment [10]. The total event rate in the data acquisition is very low, about 1 readout per second since the "proton catcher" mode selects up-front only the pile-up events and rejects all others.

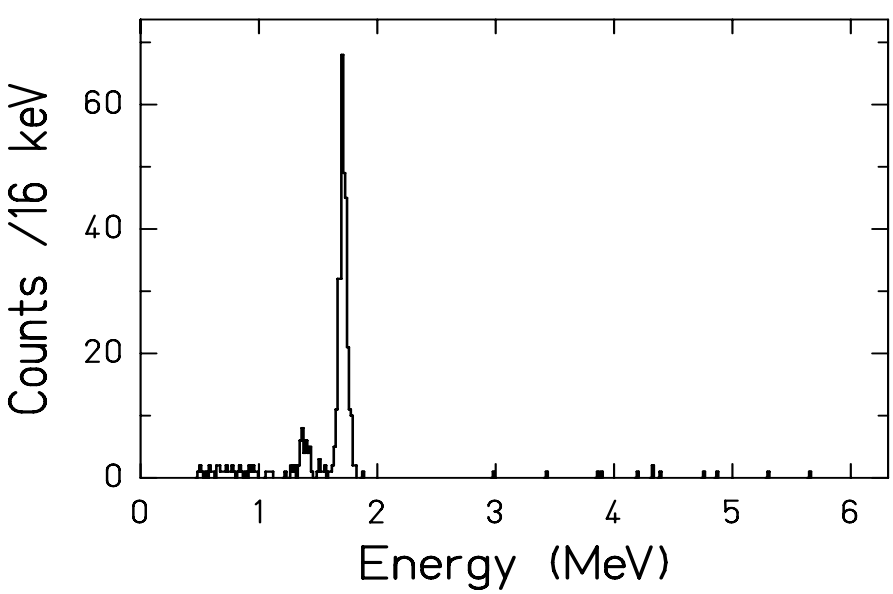
Figure 1. The decay plot of the 1.73 MeV proton transition. These decays of ^{145}Tm were detected starting 0.5 μs after the implantation of recoiling ions using new digital signal processing electronics. The detection rate was reduced within first 500 ns of counting.



In addition to the known proton line at 1.73 MeV, a new transition was observed at about 0.33 MeV lower in energy [7], see Fig. 2. The preliminary values of the halflifes, about 3 μs, are identical (within the error bars) for the two transitions, and both 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 branching ratios are about 90% and 10%, respectively. In the Z=68, N=76 daughter nucleus ^{144}Er, a 2^+ level is clearly the first excited state. The energy of about 0.33 MeV would fit to the

general systematics of such states in N=76 isotones (compare this to the 2^+ energies of 0.347 MeV, 0.329 MeV and 0.316 MeV for ^{138}Sm, ^{140}Gd and ^{142}Dy, respectively). Also, within a simple perspective of N_pN_n systematics [17,18], one finds a 2^+ state at 0.344 MeV in ^{156}Er - a "N=82 mirror" for ^{144}Er. The preliminary interpretation of the observed decay rates, within the spherical approach, 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 $2^+ \otimes \pi f_{7/2}$ configuration. Since the *l=3* transition at E_p=1.4 MeV is faster than *l=5* at 1.73 MeV, only about a 3% admixture to the main wave function is necessary to explain the observed $\approx$ 10% branching.

Figure 2. The energy spectrum of protons emitted within 0.5 μs to 10 μs after implantation of A=145 ions. Two transitions, a known one at 1.73 MeV and a new one at 1.4 MeV are clearly visible. The energy of 0.33 MeV for the E2 transition between the 2^+ and 0^+ states is too high to cause a substantial summing of the low energy protons and respective K-conversion electrons in the DSSD counter.



However, one should note that the application of the simple Grodzins formula [4,5] 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 suggests a further analysis within the theoretical formalism accounting for deformation as presented at

this meeting by B. Barmore, see [19,20] and references therein.

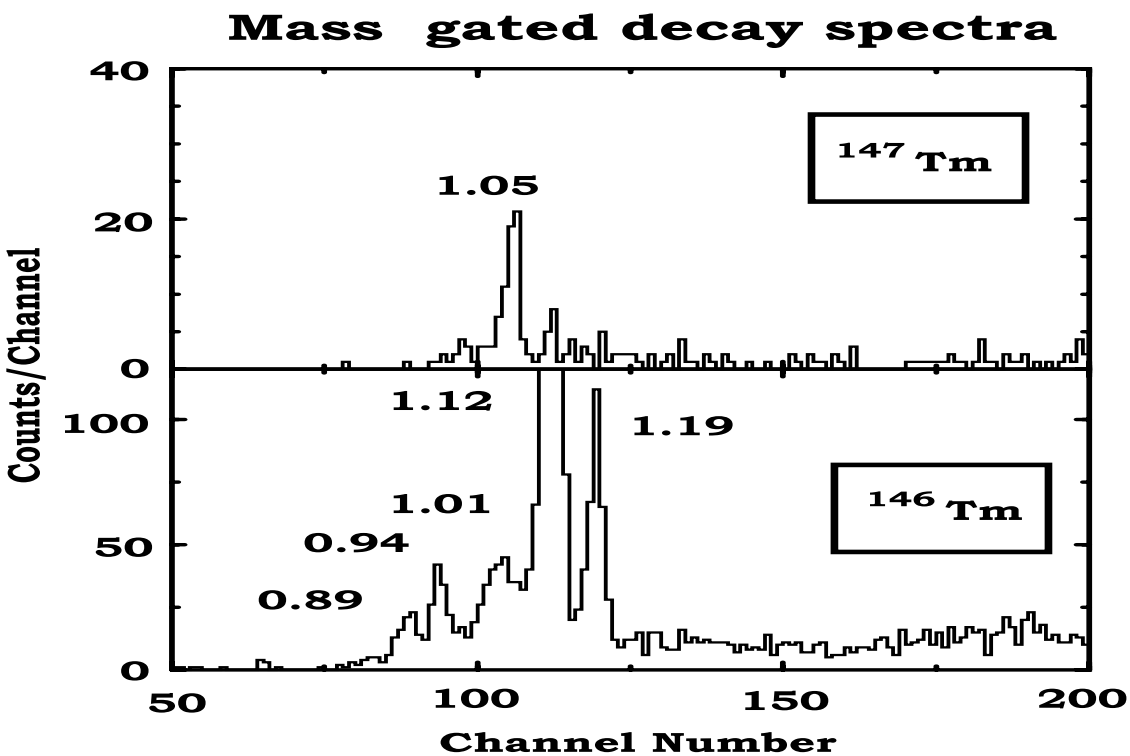
3 Fine structure in proton emission from odd-odd ^{146}Tm

Three close-lying single-particle orbitals, the negative parity $h_{11/2}$ and positive parity $s_{1/2}$ and $d_{3/2}$, are near the Fermi surface for spherical proton drip-line nuclei between Z=64 and Z=82. This fact holds for both protons and neutrons. The configuration mixing of $\pi s_{1/2}$ and $\pi d_{3/2}$ reduces proton emission rates from $I^{\pi}=3/2^{+}$ states (see e.g. ^{151m}Lu [21]), as discussed by P. Semmes during this meeting [22]. One can envision more complex configurations for odd-odd nuclei, e.g. with both proton and neutron on the mixed $s_{1/2}$ and $d_{3/2}$ orbitals. The proton and neutron can also "exchange" orbitals but still be coupled to the same final spin. For example, one can form an $I^{\pi}=6^{-}$ state by coupling both $\pi h_{11/2}\nu s_{1/2}$ and $\nu h_{11/2}\pi s_{1/2}$. Since all discussed orbitals are relatively close in energy, such states can be mixed to a large degree in the odd-odd systems. However, proton radioactivity with its angular momentum dependent emission rates can help to map the wave function components.

Two proton emitting states, with halflives of 235 $\pm$ 27 ms and 72$\pm$23 ms, in odd-odd ^{146}Tm were identified at Daresbury [23] among the products of a ^{58}Ni beam (287 MeV) and a ^{92}Mo target reaction. Profitting from the high selectivity and good transmision of the RMS, we used about three times higher beam intensity and have increased the counting statistics by over an order of magnitude.

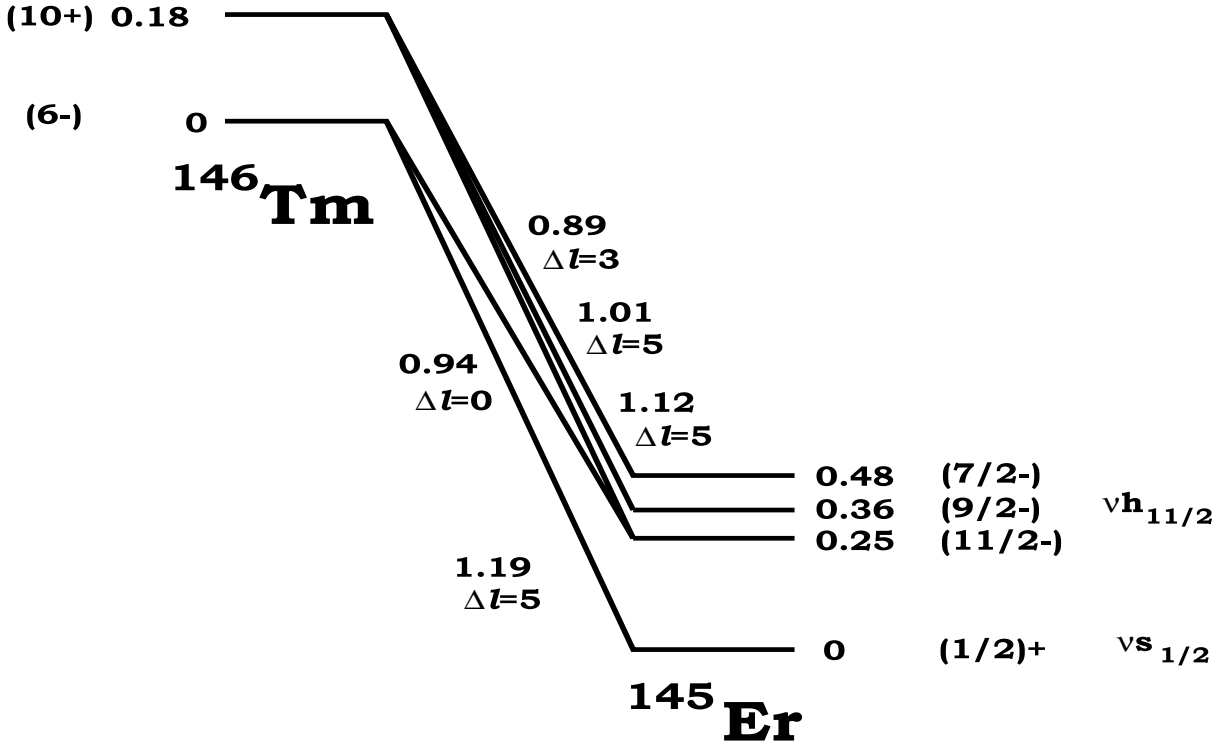
The measured particle energy spectrum, gated by the mass A=146 ions, is given in Fig. 3. Three new proton lines were identified, at about 0.89, 0.94 and 1.01 MeV (rounded preliminary values). Based on the similar decay patterns, all lines are assigned to the decay of previously observed states [23,9]. The state with a halflife of about 100 ms emits 0.94 and 1.19 MeV protons, and the $T_{1/2}\approx$ 200 ms state decays via 0.89, 1.01 and 1.12 MeV proton transitions. In the *p3n* reaction channel the 200 ms state is populated about 10 times more strongly than the shorter-lived state. Information on neighboring nuclei closer to β-stability is very helpful for the construction of the ^{146gs,m}Tm decay scheme. In the heavier odd-odd thullium isotopes, the isomeric 10^{+} (^{148}Tm and ^{150}Tm) and ground-state 6^{-} (^{150}Tm) configurations are known. Neighboring odd-mass thullium isotopes, the proton emitters ^{145}Tm and ^{147}Tm, have $I^{\pi}=11/2^{-}$ ground-states dominated by the $\pi h_{11/2}$ orbital. The sequence of neutron states in the odd-N daughter nucleus ^{145}Er could be extrapolated from the experimental level systematics of less exotic N=77 isotones. The $\nu s_{1/2}$ orbital is known as the ground-state for all odd-mass N=77 isotones from Z=56 barium to Z=66 dysprosium.

Figure 3. 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 $\nu d_{3/2}$ and $\nu h_{11/2}$ states could be expected at about 100 - 200 keV and 200 - 300 keV above the ground-state, respectively. 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 10^{+} isomer is mostly made out of the $[\pi h_{11/2}\nu h_{11/2}]$ proton-neutron pair. The difference in the direct population of these two states is consistent with an assignment of the 200 ms activity to the 10^{+} isomeric state, and the 100 ms activity to the 6^{-} ground-state. Combining this information with the observed energies and intensities of proton lines we come to the consisitent decay scheme shown in Fig.4. 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 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 [24]. For the decay to the 0.25 MeV level, the smaller proton decay energy value is compensated by the lowering of the angular momentum barrier.

Figure 4. 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 small fraction of the ^{146gs}Tm wave function responsible for this branch would be formed by a mirror proton-neutron pair, the $[\pi s_{1/2} \nu s_{11/2}]$. This component needs to be 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 *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 explained as the *l=5* and *l=3* decays to two levels: a $9/2^- \nu h_{11/2}$ state at 0.36 MeV and a $7/2^- \nu h_{11/2}$ state at 0.48 MeV. The very weak *l=3* transition is related to a configuration 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 halflives of the discussed proton transitions were estimated within the spherical WKB approach [2] taking into account respective proton vacancy factors [25].

It is clear that large beta decay probabilities, governed in this region by the well-known Gamow-Teller transformation of $\pi h_{11/2}$ into $\nu h_{9/2}$, contribute to

the ^{146gs,m}Tm decay. The beta partial halflives 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 beta decay to be 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 $\approx$ 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. An experiment on the ^{146m}Tm, with even better statistics, offers a unique chance for determining the energy of this neutron $d_{3/2}$ level in the exotic drip-line nucleus ^{145}Er, in addition to the observed $\nu s_{1/2}$ and $\nu h_{11/2}$ states. 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 investigation of proton radioactivity between the magic numbers Z=50 and Z=82 is moving from the exploration phase towards deatiled studies. The structure of proton emitters is deduced now not only from the observed rates of proton emission, but also from the studies of excited states in the parent nuclei (via RDT measurements) and daughter nuclei (via fine structure in proton emission).

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 system 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. The corresponding $9/2^-$ and $7/2^-$ states, originating from the $\nu h_{11/2}$ orbital, are found at 0.36 MeV and 0.48 MeV. $I^\pi=6^-$ is proposed for the ground state of ^{146gs}Tm, while the $I^\pi=10^+$ is likely the 0.18 MeV isomeric state.

Both studies reported here, proton emission from ^{145}Tm and ^{146gs,m}Tm, should be consider as the starting points for a series of investigations beyond the proton drip-line. New submicrosecond proton radioactivities should become detectable thanks to a new generation of digital signal processing electronics. 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. Once established during proton radioactivity studies, the information on the neutron excited states could be used for more precise investigations with large gamma arrays.

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