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Fine structure in proton emission

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Abstract. Deformations and wave functions of proton-radioactive nuclei are studied using measured fine structure properties of proton emission and microscopic theoretical models. The experimental data are available for ^{131}Eu and ^{145}Tm decays, as well as for ^{141gs}Ho, where an observation of fine structure in proton emission is reported for the first time.

The first proton-radioactive decay of an isomeric state ^{53m}Co [1] was observed over thirty years ago at Berkeley. Today, we know about thirty proton radioactive isotopes, with about forty proton-emitting ground- and isomeric-states. While the energies of the emitted protons are within 1 MeV range, the halflives vary over six orders of magnitude, from a few microseconds to seconds - see a recent compilation [2].

At the beginning of the eighties, the first ground-state proton emitters ^{151}Lu [3] and ^{147}Tm [4] were detected using the recoil velocity filter SHIP and on-line mass-separator at GSI (Darmstadt), respectively. Proton emission rates for these rare-earth nuclei, and for a number of proton emitters discovered later, were well explained within the spherical approach - see [5, 6, 7]. The identification of first shape-transitional emitters in Munich, the ^{109}I and ^{113}Cs [8], showed that a deformation of the nuclear potential can play an important role in the proton emission process. Complex structure of the wave function can substantially reduce the decay rates estimated within the simple spherical picture. Theoretical studies on deformed proton emitters were intensified in the late

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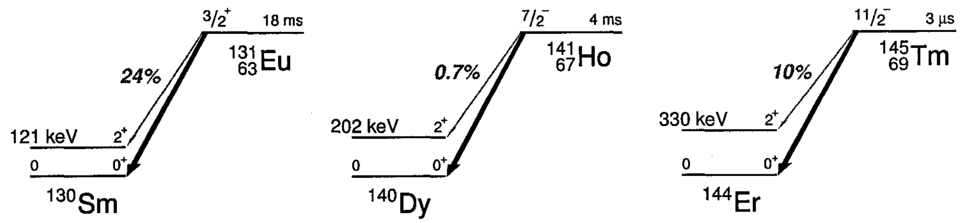

FIGURE 1. Summary of proton emission properties for the decay of ^{131}Eu,^{141gs}Ho and ^{145}Tm.

nineties after the identification of ^{131}Eu and ^{141gs}Ho [9] at Argonne and ^{141m}Ho [10] at Oak Ridge.

Particularly interesting for the analysis of a wave function of proton-radioactive nuclei is the observation of a fine structure in proton emission. There are three odd-Z even-N proton radioactivities known to date, where proton transitions to both, the 0^+ ground-state and to the 2^+ excited state in an even-even daughter nucleus were detected, see Figure 1. These experimental data include the first observation made at Argonne for ^{131}Eu [11], and the results of Oak Ridge experiments on a 3-μs activity of ^{145}Tm [12, 13] and, very recently, on ^{141gs}Ho decay. The energies of respective 2^+ states in deformed even-even daughter nuclei were estimated before the experiments by using the N_pN_n valence particle coupling scheme [14, 15, 16]. The value of 120±20 keV predicted for ^{130}Sm [17] is in a perfect agreement with observed value of 122±3 keV [11]. The 2^+ energy of 344 keV could be expected for the ^{144}Er from a direct comparison to the "N=82 mirror" nucleus ^{156}Er, close to the experimental value E_{2+}=330(10) keV deduced from the proton energy spectrum [12, 13]. However, for ^{140}Dy, the N_pN_n scheme predicts the energy of 160±20 keV [17]. The measured value of 202 keV [18, 19] is considerably larger indicating deviations from the simple valence scheme.

Proton radioactivity studies at Oak Ridge are performed at the Recoil Mass Separator (RMS) at the Holifield Radioactive Beam Facility (HRIBF). A detailed description of the RMS-based experiments is given in [20]. Recently, a detection of recoiling ions was improved by exchanging the gas avalanche counter for a Microchannel Plate detector(MCP) [21]. MCP was originally designed to monitor the position and intensity of postaccelerated radioactive beams. This detector offers essentially 100% efficiency for recording the position and time signals of the recoils at the RMS final focus. All signals from the MCP as well as from the Double-sided Silicon Strip Detector (DSSD) and single Si veto-detector behind the DSSD are recorded using digital pulse processing electronics from XIA [22] - see [23, 24] and references therein for detailed description of the HRIBF digital data acqusition. Digital signal processing based on the Digital Gamma Finder (DGF) modules was crucial for the discovery of a fine structure in proton emission from very short-lived ^{145}Tm. The 25-μs wide traces of the preamplifier signals were recorded allowing us to analyze the recoil-proton pile-up signals. The observation window for recording proton decay events was open from 500 nanosec to 10 μs after the recoil implantation into the DSSD. It was a major factor for the increase of counting rate by about an order of magnitude, as compared to the first experiment using analog electronics [25]. Very recently, the acquisition system based on the DGF modules

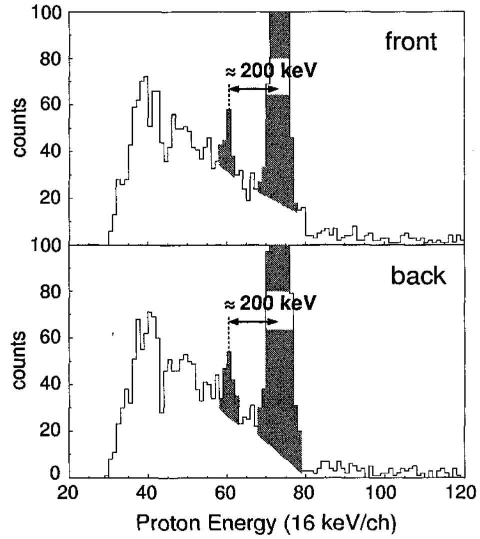

FIGURE 2. Evidence for fine structure in proton emission from ^{141gs}Ho. The 0.97 MeV proton lines were observed in the energy spectra collected at the front and at back strips of the DSSD.

allowed us to observe first ground-state two-proton radioactivity, of ^{45}Fe, produced and studied at the Fragment Separator at GSI Darmstadt [26].

For the study of 4-millisecond decay of ^{141gs}Ho, the time and amplitude of the detectors signals were analyzed on-board by the DGF modules. Good selectivity of the RMS allowed us to run with over 20 pnA intensity of 300 MeV ^{54}Fe beam on a 1mg/cm^2 thick ^{92}Mo target, without overloading the detectors and data acquisition. However, some degradation of the DSSD energy resolution was observed, and a noise level increased at low energies (below 0.7 MeV). During six days of experiment, the energy resolution of DSSD has changed from about 18 keV to about 25 keV for 1.17 MeV proton signals. A total of 7000 counts were collected at 1.17 MeV and about 50 counts in a line about 200 keV below the main transition, see Figure 2.

The energy of 202.2(2) keV for the first 2^+ state in ^{140}Dy was measured at Oak Ridge shortly before the ^{141}Ho study [18], and is also presented at this meeting [27]. The energy of the 2^+ state was deduced from the decay pattern of ^{140m}Dy interpreted as a new 7-μs, I^π=8$^-$, [ν9/2$^-$[514]$\otimes\nu$7/2$^+$[404] K-isomer at 2166 keV in ^{140}Dy. The properties of ^{140m}Dy decay [18] were already confirmed by an independent experiment at Argonne [19]. The studies on the ^{140m}Dy and ^{141gs}Ho decays suggest the interpretation of the observed 0.97 MeV proton line as the 0.7% transition to the 2^+ state in the daughter nucleus ^{140}Dy, with over 99% branching for 1.17 MeV protons populating the 0^+ ground state. The weak branching of 0.7% translates into about 2 nanobarn cross section for the fine structure line.

The measured energy of the 2^+ state of an even-even nucleus is commonly used to estimate the deformation [28, 29]. Following the recent publication of Raman *et al.* [29], we can derive values of β_2=0.33-0.34 for ^{130}Sm, β_2=0.23-0.24 for ^{140}Dy, and β_2=0.18

for ^{144}Er. The result for ^{140}Dy indicates somewhat smaller quadrupole deformation than earlier anticipated β_2 values of 0.27-0.28 [10, 30, 31]. However, the β_2 value of 0.23-0.24 is close to β_2=0.25 derived for ^{141gs,m}Ho [32] from the observed level scheme. This constitute first time experimental evidence that there is no dramatic shape change during proton emission process from ^{141}Ho parent to the ^{140}Dy daughter. The latter is a commonly used assumption during theoretical analysis of proton radioactivity. However, one should remember that there are model assumptions made during the conversion of measured 2^+ energies values into the quadrupole deformation parameters [28, 29]. The measurement of the B(E2) γ-transition probabilities for discussed 2^+ states could provide more solid experimental basis for the determination of the shape of the potential tunneled by the protons.

The interpretation of the structure of proton emitting states in ^{131}Eu and ^{141gs}Ho and their decay probabilities was recently made within the non-adiabatic coupled-channel method [33, 34]. The respective composition of the wave function and corresponding decay width were obtained. The wave function of emitting states, the $3/2^+[411]$ for ^{131}Eu and $7/2^-[523]$ for ^{141gs}Ho, is expressed as a sum of spherical components lj coupled to the I^π=0^+, 2^+, 4^+,6^+,8^+ rotational states of the ground state band in the daughter even-even nucleus, with respective c^2_{Ilj} coefficients. The corresponding decay width Γ_{Ilj} for each component is also calculated. One finds the proton emission from ^{131}Eu to be dominated by 1% of the total wave function, the small $\pi d_{3/2}$ component ($c^2_{0,2,3/2}$=1%). The fine structure can be explained by the presence of $\pi d_{5/2}$ orbital in the wave function, with the $c^2_{2,2,5/2}$ value of 60%. The observed partial halflives are reproduced within 50% of the measured values. For ^{141gs}Ho, the main part ($\approx$80%) of the wave function is composed of the $\pi h_{11/2}$ orbital, but the observed decay is governed by a few percent admixture of the $\pi f_{7/2}$ component. However, the fine structure branching ratio is overestimated by a factor of three, and the total decay probability is underestimated by a factor of ten. Very likely, this disagreement is caused by the more complex shape, in comparison to the considered [β_2,β_4] deformation space. There are preliminary indications that calculations done with a triaxial shape of the tunneling potential improve greatly the agreement between the observed and theoretical decay rates [35].

For the transitional nucleus ($\beta_2 \approx$0.18) ^{145}Tm, the calculations of K. Hagino [36] indicate over 97% of $\pi h_{11/2}$ component in the wave function. Most of $\pi h_{11/2}$ (73%) is coupled to the ground-state of ^{144}Er, i.e., to the 0^+ core, while $\pi h_{11/2} \otimes 2^+$ accounts for 24% component. The observed 10% fine structure branching ratio results from the presence of a small 1% component, of the $\pi f_{7/2}$ coupled to the 2^+ excited core of ^{144}Er.

The results on ^{131}Eu, ^{145}Tm, and particularly on the pair of parent ^{141}Ho and daughter ^{140}Dy nuclei pave ground for the directions for future studies at the proton drip line. The experimental investigations will aim at the complete spectroscopy, including the proton emission rates, and the excited levels in the proton emitters (obtained via recoil Decay Tagging methods) and in the daughter nuclei. Hopefully, with the help of the Rare Isotope Accelerator, we will be able to reach and study new regions of proton- and two-proton radioactivities.

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