New experimental results in proton radioactivity

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Abstract. A review of experimental data obtained recently on proton-radioactive nuclei is presented. The highlights include the observation of fine structure in proton emission, for the decays of $^{131}\text{Eu}$, $^{145}\text{Tm}$ and $^{146}\text{Tm}$, and the studies of the excited states in proton-emitting nuclei. The observation limits are extended to few nanobarns cross-sections ($^{140}\text{Ho}$, $^{164}\text{Ir}$ and $^{130}\text{Eu}$) and few microsecond half-lives (e.g., $^{145}\text{Tm}$). Measured decay properties for thirty-nine proton-emitting ground and isomeric states contributed to the understanding of nuclear masses and evolution of single-particle states at and beyond the proton drip line.

Experimental results have stimulated new theoretical approaches to proton emission and the structure of unbound narrow resonance states.

PACS. 23.50.+z Decay by proton emission – 21.10.-k Properties of nuclei; nuclear energy levels

1 Introduction: Proton radioactivity

Proton radioactivity studies provide a unique insight into the structure of nuclei beyond the drip line limit. The evolution of the single-particle structure, nuclear shapes and masses can be deduced from measured properties of proton emission. Recent progress in the experiment and theory made possible the analysis of the composition of the wave function of these narrow unbound resonance states.

The first proton-radioactive state, a metastable level in $^{53}\text{Co}$ was discovered over thirty years ago [1]. Till now, it remains the only proton radioactivity observed below $Z = 50$. All other thirty-eight experimentally known proton emitters have atomic numbers between $Z = 51$ and $Z = 83$. An experimental observation window for proton radioactivity is relatively wide for the neutron-deficient nuclei in the region from Sn to Pb elements. It is a joint effect of the mass surface and the presence of proton orbitals with a wide range of angular momentum (from $l = 0$ to $l = 5$) near the Fermi level. Also, these nuclei beyond the proton drip line can be reached and studied with fusion-evaporation reactions. For several combinations of stable projectile and target, the proton drip line is crossed far enough to detect proton emission already for $p2n$ fusion-evaporation channel. A typical cross-section is around a few tens of microbarns. Even with a small proton branching ratio caused by the competition of $\alpha$- and/or $\beta$-decay, the proton lines can be observed. Several of these emitters have half-lives in the milliseconds range. Even with a delay in the ion source, the proton activity could be detected with the on-line mass separator technique [2]. However, the proton decay width increases rapidly with the departure from the beta-stability line resulting in microsecond half-lives. Very fast separation of reaction products is necessary. Most of the known proton emitters were discovered using fusion-evaporation reactions studied by the means of recoil separation and segmented Si-detectors: at SHIP (GSI Darmstadt), at DRS (Daresbury), at FMA (Argonne), at RMS (Oak Ridge), and most recently at RMS (Legnaro) and RITU (Jyväskylä). The past few years have seen an explosion of both experimental and theoretical work on the topic of proton emission. Within the last three years new experimental data on twenty-four proton-radioactive nuclei were announced. The observation limits were extended to very low cross-sections and very short half-lives. The $p5n$ fusion-evaporation reaction channel characterized by a cross-section even below 10 nanobarns was successfully used to identify the activities of $^{140}\text{Ho}$ [3], $^{164}\text{Ir}$ [4,5] and $^{130}\text{Eu}$ [5]. The odd-odd emitter $^{164}\text{Ir}$ is the fourth isotope of iridium where proton emission was observed. Seven proton radioactivities with half-lives below 50 $\mu$s are known up to date. The first one, the 18 $\mu$s activity of $^{113}\text{Cs}$, was identified about 20 years ago in Munich [6], and later restudied at GSI, Daresbury, Oak Ridge and Argonne. The next six emitters $^{141}\text{Ho}$, $^{145}\text{Tm}$, $^{150m}\text{Lu}$, $^{151m}\text{Lu}$, $^{155}\text{Ta}$ and $^{171}\text{Au}$ were observed within the last years. The digital processing of detector signals [7] allows us to start a search for the activities with sub-$\mu$s half-lives, as demonstrated by the recent study on the decay of 3 $\mu$s activity of $^{145}\text{Tm}$ [8–10].

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The experimental investigations of proton radioactivity are not limited to the decay spectroscopy. Excited levels above proton-emitting states are deduced from prompt \( \gamma \)-radiation measured at the target area. The \( \gamma \)-cascades feeding the proton-radioactive level are selected by tagging on the proton emission signals recorded at the focal plane of recoil separators (Recoil Decay Tagging method). Powerful combinations of detectors, Gammasphere coupled to the FMA (Argonne), and CLARION coupled to the RMS (Oak Ridge) allowed us to obtain first information on the excited levels in \( ^{109} \text{I} \) [11], \( ^{113} \text{Cs} \) [12], \( ^{131} \text{Eu} \) [13], \( ^{141m,gs} \text{Ho} \) [14], \( ^{151} \text{Lu} \) [15] and \( ^{167} \text{Ir} \) [16].

Proton emission was commonly used to deduce the properties of proton orbitals. Recent observation of a fine structure in proton decay of the odd-odd isotope \( ^{146} \text{Tm} \) represents the first study of neutron states in exotic nuclei populated by proton emission.

Selected results on proton radioactivity achieved within last few years are discussed below.

### 2 Fine structure in proton emission

The decay width for proton emission depends very strongly on the available energy. Spherical even-even nuclei have their first-excited state at least at few hundred keV above the ground state. Therefore, proton transitions from (odd-Z, even-N) nuclei to the excited levels in the daughter nucleus were not observed during many years of experiments on proton radioactivities. In recent years, the proton drip line has been crossed in the region of well-deformed isotopes. The experiments at the FMA (Argonne) and RMS (Oak Ridge) reported the identification of \( ^{131} \text{Eu} \) [17], \( ^{140} \text{Ho} \) and \( ^{141gs,mg} \text{Ho} \) [17,3]. Recently, \( ^{117} \text{La} \) was identified at the RMS, Legnaro [18] and investigated at the FMA, Argonne [19].

The energies of excited first 2\( ^{+} \) state in \( ^{130} \text{Sm} \) and \( ^{140} \text{Dy} \) were expected at about 120 \( \pm 20 \) keV and 160 \( \pm 20 \) keV [20,21]. The pioneering experiment on \( ^{131} \text{Eu} \) radioactivity at the FMA resulted in the detection of two proton transitions of 932 keV and 811 keV [22]. Based on similar half-lives, these two proton lines were assigned to the decay of 18 millisecond activity of \( ^{131} \text{Eu} \) populating the \( 0^{+} \) and 2\( ^{+} \) states in \( ^{130} \text{Sm} \). The measured branching ratio to the 2\( ^{+} \) state, \( I_{\beta}(2^{+}) = 24 \pm 5\% \), together with the decay energies and half-life pointed to the 3/2\( ^{+} \) \([411]\) ground state of \( ^{131} \text{Eu} \). The low 2\( ^{+} \) energy of 121 keV in \( ^{130} \text{Sm} \) confirmed the large deformation \( \beta_2 \approx 0.34 \) expected for nuclei in this region. The most advanced theoretical analysis of this \( I^{\pi} = 3/2^{+} \) state was done within the non-adiabatic coupled-channel method [23,24]. It shows that the main components of this wave function are the \( d_{5/2} \) (67\%\), \( g_{7/2} \) (17\%) and \( g_{9/2} \) (10\%) spherical proton orbitals, see fig. 1.

However, the decay width for the ground-state proton transition in the decay of \( ^{131} \text{Eu} \) is dominated by a small admixture of the \( d_{3/2} \) orbital, of about 1\% of the total wave function. The width of the proton decay to the excited 2\( ^{+} \) state is a result of mostly \( d_{5/2} \) component, with a small part arising from \( d_{3/2} \), \( s_{1/2} \) and \( g_{7/2} \) orbitals, see fig. 2.

This rather complex picture could be at least partially corroborated by the experimental information on the excited states in \( ^{131} \text{Eu} \). A Recoil Decay Tagging experiment on \( ^{131} \text{Eu} \) radioactivity was performed with the Gammasphere and FMA [13]. Besides investigating the structure of excited states, it was an attempt to confirm independently the origin of both proton lines from the same state. Since the cross-section for production of \( ^{131} \text{Eu} \) is very low, about 70 nb, and there are several bands fractioning the total gamma intensity — the result is not conclusive yet.

The search for fine structure in the decay of both p-radioactive states in \( ^{141} \text{Ho} \) resulted in the upper limit for the branching ratio to the 2\( ^{+} \) state in \( ^{140} \text{Dy} \), of about 1\% for both emitters [14]. It is likely that the energy of this 2\( ^{+} \) state is above the expected 160 \( \pm 20 \) keV [20,21]. This conclusion follows the theoretical analysis of the observed proton decay rates, and is suggested by results of the RDT study of \( ^{141} \text{Ho} \) [14]. The \( \beta_2 \approx 0.25 \) with signif-