STUDIES OF NUCLEI AT AND BEYOND THE PROTON DRIP-LINE WITH STABLE AND RADIOACTIVE BEAMS AT HRIBF*

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Investigations of nuclei in the proton drip-line region performed at the Holifield Radioactive Ion Beam Facility (HRIBF) within the last two years are reviewed. In particular, the discovery of five new proton radioactivities ^{140}Ho, ^{141m}Ho, ^{145}Tm, ^{150m}Lu and ^{151m}Lu is discussed. These proton emitters were produced by means of fusion-evaporation reactions and studied with a Recoil Mass Separator and a Double-sided Silicon Strip Detector. For ^{113}Cs and ^{151}Lu, the studies of level structure were extended beyond the proton-emitting states via the measurements with a clover array CLARION using Recoil Decay Tagging. The plan to use a fusion-evaporation reaction with a radioactive ^{69}As beam developed at HRIBF, in order to study the decay of a new beta-delayed proton emitter ^{125}Nd, is also described.

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1. Introduction

Investigations of nuclei at the limits of nuclear stability represent an active area of study in nuclear physics. With the development of production and detection methods allowing us to reach nuclei at and beyond the proton drip-line, information on the structure of proton rich nuclei has been greatly extended in recent years. When the intense postaccelerated radioactive ion beams become routinely available, one should be able to reach even more exotic nuclear states, see *e.g.* Ref. [1]. The structure of loosely bound nuclei and their decay modes, nucleosythesis within the rapid proton capture process and tests of fundamental processes with Fermi and Gamow–Teller beta decays are among the key themes of nuclear physics for the beginning of the next millenium [2]. These problems can be addressed via the investigations performed on nuclei near and beyond the proton drip-line.

Observation of proton radioactive nuclei plays a very important role for understanding the limits of the nuclear landscape, see *e.g.* Ref. [3]. The experiments on proton emitting states allow us to inspect and define an energy surface for very exotic nuclei with great precision. The observed decay rates contribute to our understanding of quantum tunneling through the Coulomb and centrifugal barriers for spherical and deformed shapes. Measured decay properties can be used to establish proton single-particle energies and a composition of proton emitting orbitals, both far beyond the proton drip-line.

2. HRIBF experiments on new proton radioactivities

The proton radioactivities of deformed nuclei, ^{140}Ho and ^{141m}Ho [4], and spherical ones, ^{145}Tm [5], ^{150m}Lu [6] and ^{151m}Lu [7], were discovered at the Holifield Radioactive Ion Beam Facility (HRIBF) in Oak Ridge. These results contributed to the 23 proton emitting ground states and 12 metastable states in nuclei reported till now [8–12].

Modern experiments on proton emitters at the Fragment Mass Analyzer (FMA) at Argonne [3] and at the Recoil Mass Separator (RMS) at HRIBF Oak Ridge [13] are utilizing the technique pioneered at the velocity filter SHIP (GSI Darmstadt) [14] and developed further at the Daresbury Recoil Separator [15–17]. The products of fusion-evaporation reactions are separated according to their mass–to–charge ratio (A/Q) and implanted into a Double-sided Silicon Strip Detector (DSSD) [15]. To provide an example, the details of a recent HRIBF experiment on new emitters ^{140}Ho and ^{141m}Ho [4] are given below. For this particular study, our aim was to extend the proton radioactivity studies of highly deformed nuclei to new proton emitters and to provide a theoretical model of their structure and decay process. With a *p5n* reaction channel used for the first time for the discovery of a proton emitter, it was also probing the experimental observation limits for proton emitting nuclei by means of the RMS-DSSD technique.

A 0.91 mg/cm^2 thick target of isotopically enriched ^{92}Mo was irradiated with 315-MeV ^{54}Fe ions from the HRIBF 25 MV tandem accelerator. The average beam current on target was about 13 particle nA during a period of 30 hours. Recoils of interest, of 97 $\pm$ 10 MeV, were passed through the RMS adjusted to select the mass-140 and a part of mass-141 ions in a charge state $Q = +27$. A gas-filled position-sensitive avalanche counter (PSAC) placed at the focal plane of the RMS provided time and position signals for mass/charge recoil identification. After passing the PSAC detector, products were slowed down by a 1.17 mg/cm^2 nickel foil before implantation into a 60-μm thick DSSD with 40 horizontal and 40 vertical strips covering an active area of 4 cm $\times$ 4 cm. This strip arrangement results in a total of 1600 pixels, each acting as an individual detector of 1 mm^2 [15]. For each implant, the energy of the implant, the pixel in which the implant occurred, the PSAC information, and the time were recorded. If a decay occurred within a time of 240 μs after an implant during its readout, the decay energy, pixel number, and time of decay were also recorded in the same event. For decay times greater than 240 μs, the decay information was recorded as a separate event. Decays within a given pixel were correlated with the previous implant in the same pixel in order to determine the decay time of the radioactivity.

Figure 1 shows the low-energy part of the spectrum recorded in the DSSD within the given time intervals Δt after a recoil implantation. To distinguish between A=141 and A=140, the mass gates corresponding to the dispersive plane DSSD strips, from 1 to 20 and from 24 to 37, respectively, were applied. A peak of about 100 counts in a middle section of Fig.1, obtained with $\Delta t \leq$ 25 ms and $A = 141$ condition, is that of the known proton decay [11] of the ^{141}Ho ground state. Its energy, reported in Ref. [11] as 1169$\pm$8 keV, was taken together with the measured on–line proton lines from the well-known radioactivities of ^{109}I ($E_p = 813 \pm 3$ keV), ^{113}Cs ($E_p = 959 \pm 3$ keV) [9,10] and ^{147}Tm ($E_p = 1051 \pm 3$ keV) [9,18] to calibrate the energy deposited into the DSSD. The half-life of ^{141}Ho was remeasured to be 3.9$\pm$0.5 ms, which agrees well with 4.2$\pm$0.4 ms given in [11]. By keeping the same $A = 141$ mass gate and reducing the recoil-decay correlation time Δt to 200 μs, the peak of about 10 counts at 1230$\pm$20 keV was found, see the upper part of Fig.1. The 20 keV error assigned for the peak energy is larger than purely statistical, in order to account for uncertainties in an energy shift due to the amplifier overload effects for short correlation times Δt. The proton energy shift is caused by an overlap of the proton energy signal with the tail of the high energy ion implantation signal. This effect is discussed in previous papers reporting the discoveries of new short-lived proton emitters ^{145}Tm ($T_{1/2}$ = 3.5 μs [5]) and ^{151m}Lu ($T_{1/2}$ = 16μs [7]). The energy shift

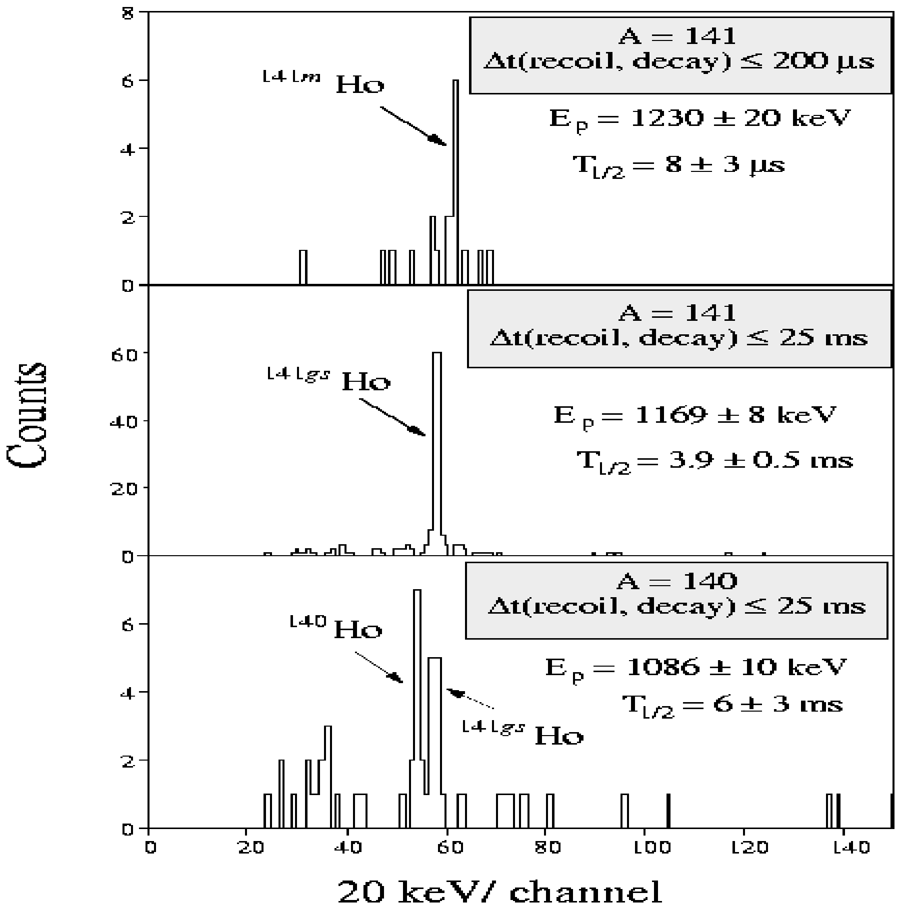

Fig. 1. The low-energy part of particle spectra recorded during 30-hours experiment with ^{54}Fe beam on ^{92}Mo target (from [4]). The given correlation time gates Δt and mass gates were applied, respectively.

can be experimentally inspected and accounted for by an on-line calibration measurement of the ^{113}Cs proton activity having a $T_{1/2} = 18.3$ μs [19]. The energy of ^{113}Cs ions deposited into the DSSD must be the same as that of the new short-lived proton radioactive nuclei. However, a mapping of the response function of the DSSD for short correlation times is very time consuming. It is difficult to reach satisfactory precision, even with a total rate of $\sim$ 5 protons per minute from the ^{113}Cs decay achieved at HRIBF. A partial solution of this problem could be obtained using new DSSD signal processing electronics to digitize the preamplifier signal [20]. The time distribution of the events displayed in the upper section of Fig.1

corresponds to a half-life of 8±3 μs. The conditions $\Delta t \leq 25$ ms and $A = 140$ mass gate applied to the same experimental data reveal two peaks, one at 1.17 MeV coming from a tail of the A=141 mass distribution, and a new one at 1086±10 keV with a decay pattern corresponding to a halflife of 6±3 ms. Since the energies of the latter 11 events obtained with relatively long recoil-decay correlation times are not modified by the amplifier overload effect, the peak energy can be given within the statistical 10 keV error.

These observed intensities of proton events correspond to the cross section values of $\approx$ 130 nb for ^{141}Ho and $\approx$ 30 nb for the new activity observed at mass $A = 141$. The cross section for the new $A = 140$ proton radioactivity is about 13 nb. All values were calculated assuming a RMS transmission of $\approx$ 3%. All of the $A = 140$ and $A = 141$ isobars, other than holmium isotopes, produced in the ^{54}Fe + ^{92}Mo fusion-evaporation reaction are stable against proton emission or have negligible production cross sections (*e.g.* ^{140}Er produced in 6p evaporation channel below the 1 pb level). Therefore, we assign the new radioactivities to ^{140}Ho and ^{141m}Ho. The predicted [21] cross sections for ^{141}Ho and ^{140}Ho, with a ^{54}Fe beam energy of 315 MeV averaged over the ^{92}Mo target thickness of 0.91 mg/cm^2, are about 300 nb and 50 nb, a factor of 2 to 4 larger than observed. However, one should remember that extrapolated mass values were used for the HIVAP calculations [21]. Also the same RMS transmission of 3% was assumed for both *p4n* and *p5n* reaction channels. The observed (small) differences between the experimental estimates and predictions for production cross sections is therefore not surprising.

3. Proton emission rates — spherical approach

For most of reported proton activities, the proton emission rates can be interpreted within a spherical description of the nuclei involved in the decay process [9, 22]. The spectroscopic factor corresponding to the ratio of calculated to observed partial proton half-lives represents the vacancy of the respective proton orbital in a daughter nucleus [22]. This means that the study of proton emitting states gives direct information on the composition of the wave function of the unbound proton orbital. However, it is important to notice that in several cases, including the first reported ground-state proton radioactivities ^{151}Lu [14] and ^{147}Tm [18], that it was impossible to obtain precise experimental values for the proton partial half-lives. This was due to the unknown probability of beta decay contributing to the decay process. The proton emitting orbitals were identified; however, the error bars on the spectroscopic factors were too large to make a meaningful conclusion on the structure of the wave function involved. Therefore, the study of very short-lived proton radioactivities, in which proton emission dominates the total decay width, has been initiated at HRIBF. New short-lived proton activities discovered at HRIBF, the ^{145}Tm ($T_{1/2}$=3.5 μs [5]) and ^{151m}Lu ($T_{1/2} = 16$ μs [7]), contributed to the understanding of the structure of the πh$_{11/2}$ and πd$_{3/2}$ proton emitting states.

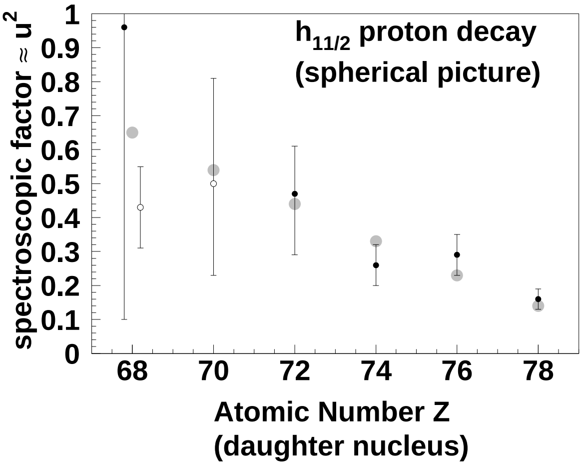

Fig. 2. Comparison of the experimental spectroscopic factors for the proton emission from the $\pi h_{11/2}$ orbital for $Z \geq 68$ nuclei and the vacancies $u^2(\pi h_{11/2})$ calculated for even-even daughter nuclei (grey dots). The HRIBF data are shown with an open circles. Odd-even emitters with well defined partial proton half-life were selected for this comparison to avoid the effects related to the proton-neutron coupling and uncertainties caused by unknown beta branching. To illustrate the latter problem, the spectroscopic factors for the ^{147}Tm ($Z = 68$, with large error bars) and ^{151}Lu ($Z = 70$) are also given.

In Fig. 2, the experimental spectroscopic factors for odd–Z, even–N $\pi h_{11/2}$ proton emitters are compared to the vacancies u^2 calculated (see *e.g.* Refs. [23, 24]) for the daughter even-even spherical nuclei. These spectroscopic factors were obtained from measured partial proton half-lives and theoretical proton rates obtained within the Two-Potential-Approach (TPA) of Ref. [22]. The radioactivities, where proton emission dominates the decay process, or the competing alpha branching was measured, are selected in this comparison. For $Z = 68$, the result for ^{145}Tm is given together with previously measured ^{147}Tm, to illustrate the importance of the recent HRIBF experiment [5]. For $Z = 70$, the spectroscopic factor includes already new halflife measurement ($T_{1/2} = 80{\pm}2$ ms) of ^{151}Lu [7], but the estimated beta branching [9] makes the error bars large. The calculated u^2 values fit very well the experimental systematics. This indicates that the spherical $\pi h_{11/2}$ orbital has a relatively pure configuration for these very exotic nuclei. The

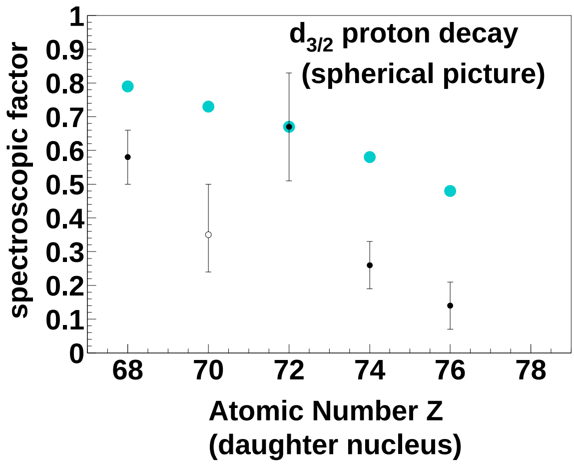

Fig. 3. Comparison of the experimental spectroscopic factors for the proton emission from the $\pi d_{3/2}$ orbital for $Z \geq 68$ nuclei and the vacancies $u^2(\pi d_{3/2})$ calculated assuming pure $\pi d_{3/2}$ configuration of the respective state in the daughter nuclei (grey dots). The HRIBF data point for ^{151m}Lu [7] is indicated by an open circle.

observed proton rates directly reflect the occupation of $\pi h_{11/2}$ along the proton drip line.

In contrast, the difference is quite striking when the spectroscopic factors for $\pi d_{3/2}$ emitters are compared to the calculated u^2 values, see Fig. 3. Here, again, the HRIBF result for ^{151m}Lu contributed to this systematics. The observed $\pi d_{3/2}$ proton rates are clearly lower than expected from the model which reproduced well the $\pi h_{11/2}$ related emission. This discrepancy indicates the level of mixing of the $I^\pi = 3/2^+$ state. The wave function component, $\pi d_{3/2}$, is responsible for the observed proton transition rate. The presence of a $\pi s_{1/2} \otimes 2^+$ component in this $3/2^+$ state is reducing the decay width to the ground-state of the daughter nucleus.

4. Deformed proton emitters

In the early proton radioactivity studies, it was found that the proton decay probabilities of ^{109}I [16, 25, 26] and ^{113}Cs [17, 19, 25, 27] could not be explained within the spherical approach. These two nuclei are located at the transitional region between the strong spherical shell $Z = 50$ and the well–deformed rare–earth nuclei midway between $N = 50$ and $N = 82$ neutron magic numbers. The structure of proton emitting states for both cases is still ambiguous. The deformed $1/2^+[420]$ Nilsson orbital originating from the spherical $\pi d_{5/2}$ level was proposed for the ground-state of ^{109}I [28, 29]. The assignment is based on the systematics of proton ground-state configurations for heavier odd-mass iodine isotopes [30, 31] and a theoretical estimate for the observed proton rate [28,29]. For the latter, the best fit to the observed half-life was obtained with a quadrupole deformation parameter β_2 of about 0.1. There is not enough experimental evidence in previous [31] or very recent [32] Recoil Decay Tagging (RDT) experiments on ^{109}I to confirm the ground-state configuration suggested in Refs. [28, 29]. In particular, the recently deduced rotational states in the $\pi h_{11/2}$ band of ^{109}I support reduced deformation for the more proton-rich iodine isotopes [32]. Even more unclear is the configuration of the proton-emitting state in the ^{113}Cs. The calculations of Ref. [29] suggest the $3/2^+[421]$ orbital originating from the $\pi d_{5/2}$ spherical state, while in Ref. [33] it is noted that the observed ^{113}Cs half-life [19] can also be explained as a proton emission from an $I^{\pi}=1/2^+$ state coming from a deformed $\pi g_{7/2}$ orbital. Recent RDT studies [19] did not establish a clear link between the dominantly populated $\pi h_{11/2}$ band and the expected ground-state of positive parity. The deformation parameters are $\beta_2 \approx 0.2$ for the discussed configurations.

Very recently, the proton radioactivity from the highly deformed nuclei ^{131}Eu and ^{141}Ho was discovered [11]. The proton emission half-lives were computed, following the DWBA approach of Refs. [28, 29], as a function of deformation for the $\pi 7/2^-[523]$ state in ^{141}Ho, and for $\pi 3/2^+[411]$ and $\pi 5/2^+[413]$ states for ^{131}Eu. The observed decay rates could be reproduced with $\beta_2 \geq 0.3$.

Two new proton emitting states in the deformed nuclei, ^{140}Ho and ^{141m}Ho, were recently identified by their direct proton radioactivity at HRIBF [4]. The proton energies and half-lives were measured to be 1086(10) keV and 6(3) ms, and 1230(20) keV and 8(3) μs, respectively, see Fig. 1 and Section 2. The single–quasiproton band heads of rare–earth nuclei, including holmium isotopes, have been analyzed in [24]. They were calculated using the shell correction method with an average Woods-Saxon potential and a monopole pairing residual interaction. The total energy of each nucleus was minimized in the $[\beta_2,\beta_4]$ deformation lattice. For Z=67 holmium isotopes, proton orbitals were studied between mass numbers A=153 and A=171. Here, in order to assign and analyze the structure of the observed proton-emitting states, such calculations were performed for lighter holmium isotopes in an extended $[\beta_2,\beta_4,\beta_6]$ deformation space. The total energies of single-proton states in ^{151}Ho, ^{149}Ho and ^{147}Ho are minimized by the spherical shape due to the strong influence of the N=82 shell closure, with $\pi \mathrm{h}_{11/2}$ being the ground-state orbital. While ^{145}Ho can be called "transitional", the more proton rich ^{143}Ho and ^{141}Ho isotopes are clearly highly deformed. The same values of $\beta_2 \approx 0.27$, $\beta_4 \approx -0.07$ (and small $\beta_6 \approx 0.01$) were obtained for the three lowest proton orbitals in ^{141}Ho, labelled $\pi 1/2^+[411]$, $\pi 7/2^-[523]$

and $\pi 5/2^-[532]$. The negative parity Nilsson states originate from the $\pi h_{11/2}$ spherical orbital, while the $1/2^+[411]$ comes from a deformed $\pi d_{3/2}$ orbital. The two states, $\pi 1/2^+[411]$ and $\pi 7/2^-[523]$, are computed to have almost the same energy, and the $\pi 5/2^-[532]$ is about 250 keV higher. Already this level scheme suggests that in addition to the l=3 proton emission with $T_{1/2}$ $\sim$ 4 ms from the $\pi 7/2^-[523]$ ground–state, we observed a much faster l=0 decay from the isomeric $1/2^+[411]$ level in ^{141}Ho.

The width of proton resonances observed in ^{141}Ho was interpreted within the very recently developed theoretical formalism based on the coupled channel Schrödinger equation with outgoing boundary conditions, see Ref. [4] and references therein. It was concluded that the decay process of ^{141m}Ho is primarily governed by a small admixture of the $\pi s_{1/2}$ wave function in the $1/2^+[411]$ isomeric state. The corresponding spherical amplitude $(c_{lj})^2$ was calculated to be about 0.18, with the main wave function components arising from $\pi d_{3/2}$, $\pi d_{5/2}$ and $\pi g_{7/2}$ orbitals. For ^{141gs}Ho, two states with a proton width close to observed were found, namely the $\pi 7/2^-[523]$ and $\pi 5/2^-[532]$, both originating from the $\pi h_{11/2}$ orbital. However, the proton decay width for both considered Nilsson configurations is governed again by a small admixture of the $\pi f_{7/2}$ spherical state.

The structure of a proton emitting state in the odd-odd nucleus ^{140}Ho is more complex. The odd–proton, the $1/2^+[411]$ or $7/2^-[523]$ in the ground- or near ground-state configuration, is coupled to the odd–neutron. Two of the neutron single–quasiparticle states are predicted to be close to the Fermi surface for ^{140}Ho. They are the $\nu 5/2^+[402]$ and the $\nu 9/2^-[514]$ states originating from the $d_{5/2}$ and $h_{11/2}$ neutron orbitals. Since the half-life of ^{140}Ho is in the millisecond range, with an analogy to the decay of ^{141gs}Ho, the proton emitting state can have either the $\pi 7/2^-[523] \otimes \nu 5/2^+[402]$ or the $\pi 7/2^-[523] \otimes \nu 9/2^-[514]$ configuration. These π–ν states are very close in energy according to the calculations.

Additional information related to the energy surface of proton drip line nuclei is also gained from our study. The energy of the proton line from odd-odd ^{140}Ho decay is lower than the one from the neighbouring, less exotic odd-even ^{141}Ho. Such a pattern was already observed [17] for nuclei in the transitional region above Z=50, *i.e.* for ^{104}Sb - ^{105}Sb, ^{108}I - ^{109}I and for ^{112}Cs - ^{113}Cs. For ^{104}Sb and ^{108}I, only the upper limits for proton decay energy, 460 keV and 600 keV respectively, were derived from the experimental data. However, these are already below the energies of protons emitted from the ^{105}Sb (E_p = 478±15 keV [34]) and ^{109}I (E_p = 813±3 keV [17]). The energies of the proton lines for ^{112}Cs and ^{113}Cs are 807±7 keV [17] and 959±4 keV [9], respectively. For spherical proton emitters with $Z\geq 69$, this energy dependence is reversed, *i.e.* the proton decay energy always increase as the neutron numbers decrease, see *e.g.* Ref. [10]. An observation of a proton line for the ^{140}Ho decay at almost 100 keV below that for ^{141}Ho, suggests an interpolation of this energy pattern for the deformed region between $Z = 55$ and $Z = 67$. This observed structure of the energy surface beyond the proton drip-line, probably connected to the $\pi - \nu$ correlations, does not show up to such extent in mass formulas and advanced nuclear structure models [35–37]. It actually can be related to the presence and population in heavy-ion reactions of high spin states in odd-odd nuclei resulting from the odd proton–odd neutron coupling. Such a state may decay via proton emission to an excited state in the daughter nucleus resulting in the observed energy pattern. It may explain the non-observation of a proton decay of ^{136}Tb and ^{137}Tb. Following the ^{140}Ho and ^{141m}Ho experiment, the proton decay of these terbium isotopes was searched for over 35 hours with a 15 pnA ^{50}Cr beam on a 0.91 mg/cm^2 ^{92}Mo target. The beam energy, 290 MeV, was optimized [21] for ^{136}Tb production, but a part of $A = 137$ recoils were also implanted into the DSSD similar to the $A = 140$ *vs* $A = 141$ mass distribution, see Section 2. No evidence for these decays were obtained indicating that the beta-decay channel is dominant, for both ^{136}Tb and ^{137}Tb. While the various mass predictions point to the proton energies well below 1 MeV for ^{137}Tb, the more proton rich ^{136}Tb was calculated to be more proton-unstable. The results for ^{140}Ho — ^{141}Ho proton emitters might indicate an opposite pattern. The validity of such an interpolation might be tested, in principle, with an investigation of proton emission from ^{130}Eu allowing a comparison to the observed decay [11] of ^{131}Eu ($E_p = 950\pm10$ keV). However, if indeed the proton decay energy is lower by more than 100 keV, the beta decay may again dominate the weakly produced ^{130}Eu activity making detection of the proton line very difficult.

5. Recoil decay tagging experiments at HRIBF

The HRIBF experiments on the nuclei beyond the proton drip line were recently extended to the excited states in proton-emitting nuclei. The studies applying the Recoil Decay Tagging method [31, 38] were performed for ^{113}Cs [19] and ^{151}Lu [39]. Only a part of Oak Ridge Germanium Array for Spectroscopic Measurements (CLARION), consisting now of eleven 145% Clover detectors with BGO shields, was used for γ–counting at the target position. In principle, such experiments should allow us to establish the level sequence above the proton unstable state and to deduce the deformation of the investigated nucleus. However, since these experiments usually suffer from low statistics, particularly for γ–γ coincidences, the configuration assignment to the identified levels is not unambiguous [19, 39]. For ^{113}Cs, the γ-cascade interpreted as a $\pi h_{11/2}$ band was observed. However, the link to the proton decaying ground-state is not clear — a low energy transition(s) might remain unobserved [19]. For ^{151}Lu, two concepts of data interpretation were presented in [39]. To clarify the situation, a complementary search for a short–lived γ–decaying isomeric state in ^{151}Lu has been recently proposed [40], to be performed at the final focus of the RMS with a part of the CLARION array.

6. HRIBF experiments with radioactive postaccelerated beams

First generation radioactive ion beam facilities (RIB-I) are expected to deliver beams of unstable nuclei of moderate intensities of the order of 10^7 to 10^8 particles per second (pps). This is about three to four orders of magnitude lower than the intensities of respective stable beams routinely used for the studies of neutron-deficient nuclei far from beta stability. This means that the overall production rate of exotic new nuclei will be lower when using RIBs. However, even low intensity RIBs have important advantages with respect to stable projectiles. The compound nucleus made out of a RIB plus stable target combination is further away from beta stability in comparison to the corresponding stable beam-stable target fusion product. The evaporation channel leading to the final exotic product is more favoured with respect to the total reaction cross section. The signals corresponding to the decay of the studied nucleus occur with much cleaner background conditions. The lower total production of recoiling evaporation residues from a RIB experiment will also permit correlation studies with the counter telescope over a much broader half-life range. With higher production rates during the experiment based on stable beam, such correlations will likely be lost for $T_{1/2}$ above ≈100 ms. Therefore, the overall detection power of the RIB-based experiment is increased in comparison to the stable beam study. The perfect "demonstration case" is realized, when a specific, unique radiation occurs among the separated isobaric chain only in the decay of the isotope of interest, due to the removal of background radiation by the RIB based production method. This background radiation would be present with the best stable beam choice. However, even with enhanced selectivity, the lower limit for the cross section providing still enough activity for the decay studies is about a few tenths of a millibarn for the RIB intensities of the order of a few times 10^7 pps.

The considerations presented above are foreseen to be demonstrated by the proposed identification and investigation [41] of a new isotope, the beta-delayed proton (βp) precursor ^{125}Nd selectively produced with the ^{69}As radioactive beam [42] at HRIBF. In the isobaric chain $A = 125$ the only known βp precursor is ^{125}Ce [43]. Its energy window for βp emission is Q_{EC}-$S_p \approx$ 5 MeV and the branching ratio is calculated to be $I_{\beta p} \approx 0.014\%$ [44–46]. The protons emitted during ^{125}Nd and ^{125}Ce decays are partially within the same energy range.

The ^{125}Ce nucleus is not produced in the fusion-evaporation reaction with a radioactive ^{69}As beam on a ^{58}Ni target. The corresponding search for ^{125}Nd without radioactive beams would require, *e.g.*, a ^{40}Ca beam on a ^{92}Mo target. With the 260 MeV energy of a ^{40}Ca beam optimized [21] for the production of ^{125}Nd, its cross section amounts to 8 μb. The ^{125}Ce production is 1000 times stronger in the same ^{40}Ca + ^{92}Mo reaction. The number of βp signals resulting from ^{125}Nd and ^{125}Ce decays will be comparable, making the identification of ^{125}Nd decay very difficult.

The cross section for ^{125}Nd produced using the reaction ^{69}As (300 MeV) on a 1 mg/cm^2 ^{58}Ni target is calculated to be about 1 mb [21]. An experiment with $3*10^7$ pps of ^{69}As should provide enough data for the identification and measurement of the main decay properties of ^{125}Nd in about one week.

The experiments with the ^{69}As projectiles are planned for 1999, after the currently running projects using radioactive ^{17}F beam at HRIBF are concluded.

7. Summary

The studies of proton radioactivity have became a part of the scientific program at Oak Ridge National Laboratory. The experiments performed at HRIBF have added important data to experimental systematics. Advanced theoretical interpretion of spherical [22] and deformed emitters [4] has been carried out by the UTK/ORNL Theory Group in collaboration with physicists from Hungary, Romania, Sweden and US universities.

The future studies at HRIBF based on a radioactive beams like ^{69}As and ^{56}Ni (under development) should allow us to reach even more exotic nuclei near and beyond the proton drip-line.

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