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GAMMASPHERE+FMA: A journey beyond the proton drip-line

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The majority of experiments performed during the 2-year long stay of GAMMASPHERE at the Argonne National Laboratory aimed to study proton-rich nuclei far from the line of stability at and beyond the proton drip-line. A high reaction channel selectivity was required to assign in-beam γ-ray transitions to weakly populated exotic nuclei in the presence of background from strong reaction channels. In many of the experiments this was achieved by using the Argonne fragment mass analyzer to separate heavy-ion fusion-evaporation reaction products from scattered beam and disperse them according to their mass-over-charge-state ratio. For medium mass and heavy α and proton emitters the Recoil-Decay Tagging method was implemented. In-beam γ-ray transitions were observed in several proton emitters between Z=50 and Z=82. Among others, rotational bands were assigned to ^{141}Ho and ^{131}Eu. A quadrupole deformation of $\beta = 0.25(4)$ was deduced for the ground state in ^{141}Ho from the extracted dynamic moment of inertia. Based on observed band crossings and signature splittings the $7/2^-[523]$ and $1/2^+[411]$ configurations were proposed for the ground state and the isomeric state, respectively. A comparison with particle-rotor calculations indicates, however, that ^{141}Ho may have significant hexadecapole deformation and could be triaxial.

1. STUDIES OF NUCLEI AT THE PROTON DRIP-LINE

Nuclei at the limits of particle stability have been the subject of intense research in recent years, thanks to new tools for production, detection and identification of nuclei with excess of neutrons or protons, large amounts of data on these exotic systems have become available. The existing and planned facilities for production of radioactive beams promise further progress in this field.

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The discovery of more than a dozen new nuclei spontaneously emitting protons is a prime example of the progress in studies along the proton drip-line [1]. From the half-life and the energy of emitted protons the proton-decay probabilities and the proton-decay Q-values have been extracted for many proton unstable rare-earth nuclei. Anomalous decay rates in ^{141}Ho and ^{131}Eu have been observed and explained by the presence of deformation [2]. Also, a first case of a proton decay to an excited state in the daughter nucleus have been reported in ^{131}Eu, presenting a stringent test for emerging models of the proton emission from deformed nuclei [3].

The proton-decay rate depends primarily on the tunneling probability through the Coulomb barrier, which is a very sensitive function of the energy of the emitted protons. Because of the centrifugal barrier, it also depends sensitively on the angular momentum of the emitted proton which is constrained by different angular momentum components in the single-particle wavefunction of the parent nucleus and the spin of the daughter nucleus. Pairing correlations lead to additional attenuation of the decay rate. In some cases, such as high-j low-K bands at lower deformations, the Coriolis interaction might play an important role as well.

Not all parameters used in the calculations of the proton-decay rates are known very well. For example, the deformation is usually obtained from microscopic-macroscopic calculations. The pairing strength and the strength of the Coriolis interaction are not known. Despite these shortcomings, the comparison between the calculations and the data allows to assign the single-particle configurations to the proton-decaying states. However, in order to be able to make a quantitative comparison between the theory and the experiment more information is needed on the proton emitters. This can be achieved by studying their high-spin states.

In an attempt to obtain independent and, in many respects, complementary information on deformed proton emitters, by learning more about their behavior at high angular momentum several experiments have been performed to study proton emitters using GAMMASPHERE and the Argonne fragment mass analyzer (FMA). These experiments will be reviewed in the next section. In the third section results obtained for the deformed proton emitters ^{141}Ho and ^{131}Eu will be presented followed by the discussion in chapter 4. The last section contains an outlook and a summary for in-beam studies of proton emitters.

2. IN-BEAM SPECTROSCOPY OF PROTON EMITTERS

Experimental studies of proton emitters are hampered by low production cross sections, ranging from hundreds of μb for the strongest channels to tens of nb for the recently discovered deformed proton emitters, and by large background from other strong reaction channels produced with cross sections of the order of hundreds of mb.

The required selectivity can be achieved using the Recoil-Decay Tagging method (RDT). In this method, proton or α decays detected using a recoil mass separator, equipped with a double-sided Si strip detector (DSSD), are used to tag prompt γ-ray transitions [4,5]. Already in one of the first RDT experiments some preliminary results were reported on γ-ray transitions in the proton emitter ^{109}I [5]. In an experiment at ATLAS with the

Aye-Ball array of Ge detectors and the FMA a ground-state band in ^{147}Tm was observed and was interpreted as a rotationally aligned $h_{11/2}$ band, and a moderate deformation of $\beta = 0.13$ was deduced for the ground state [6]. The availability of even more efficient arrays of Ge detectors led to further advances in in-beam studies of proton emitters. Gamma-ray transitions in ^{151}Lu were identified [7] using the Oak Ridge recoil mass spectrometer

The unique combination of GAMMASPHERE and FMA made it possible to apply in-beam techniques to proton emitters produced with even smaller cross sections due to the large efficiency for detecting γ rays. Excited $\pi h_{11/2}$ bands were observed and a moderate deformation was confirmed for the proton emitters ^{109}I [8] and ^{113}Cs [9]. However, the decay of these bands to the ground state was not determined preventing direct studies of the proton emitting state. A complex level scheme was also constructed for the proton emitter ^{167}Ir [10] confirming the transitional nature of this nucleus. The following chapter presents results obtained for the deformed proton emitters ^{141}Ho and ^{131}Eu.

3. RESULTS ON THE DEFORMED PROTON EMITTERS ^{141}Ho AND ^{131}Eu

Two experiments were performed at the Argonne National Laboratory to study the decay of ^{141}Ho and its excited states In the first one, a ^{54}Fe beam at 292 MeV from the ATLAS accelerator impinged on a 0.7 mg/cm^2 thick, self-supporting ^{92}Mo target, to produce ^{141}Ho via the p4n evaporation channel. The target was irradiated for about 4.5 days with a beam intensity of about 3 pnA. In order to increase the statistics, a second measurement was performed using inverse reaction kinematics, with a 502 MeV ^{92}Mo beam and a 0.8 mg/cm^2 thick, self-supporting ^{54}Fe target. The experiment lasted 5 days and the average beam current was about 2.5 pnA. Because of the reduction of the emission cone for the evaporation residues, a factor of about 4 increase in the proton yield was achieved. In another attempt a 0.75 mg/cm^2 thick ^{58}Ni target was bombarded with a 402-MeV ^{78}Kr beam to study the p4n channel leading to ^{131}Eu.

Two proton lines have been assigned to ^{141}Ho [2]. The spectrum of γ rays correlated with the ^{141}Ho ground-state proton decay shown in Fig. 1a is fairly complex. However, a γ-ray sequence could be obtained, by summing several individual energy gates, which exhibits energy and intensity pattern characteristic of a rotational band (see Fig. 1b)

Fig 1c shows the spectrum of γ rays tagged by protons emitted from the isomeric state in ^{141}Ho Only 4 relatively strong transitions are present in this spectrum. Based on the γ-ray energies, intensities and coincidence relationships, a partial level scheme shown in Fig 2 was constructed for ^{141}Ho. The spins and parities are based on the assignments for the bandheads as described in the following section The transitions above the isomer were ordered according to the increasing energy.

The ground-state proton decay to the ground state and to the excited state have been measured for ^{131}Eu [2,3]. Figures 3a and b contain the spectrum of γ rays correlated with the ground-state to ground-state and the ground-state to the 2^+ state proton decay of ^{131}Eu, respectively The spectrum of γ rays feeding the ground state is much more complex than in the case of ^{141}Ho. This suggests that the deexcitation pattern is fragmented over several bands It should be noted, that the spectra in the Figs 3a and b resemble each other This confirms that both proton lines are emitted from the same state.

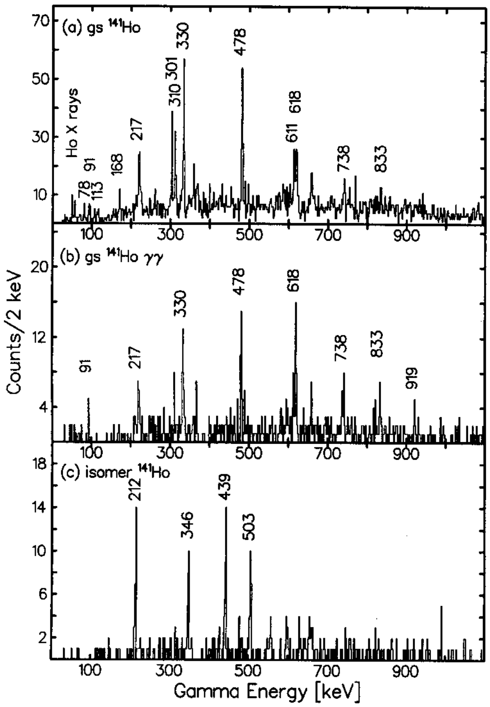

Figure 1. The spectrum of γ rays correlated with the proton decay of a) the ground state and c) the isomeric state in ^{141}Ho. b) The sum of the γ-ray gates 91, 168, 217, 330, 478, 618, 738, 833, and 919 keV correlated with the ^{141}Ho ground-state proton decay.

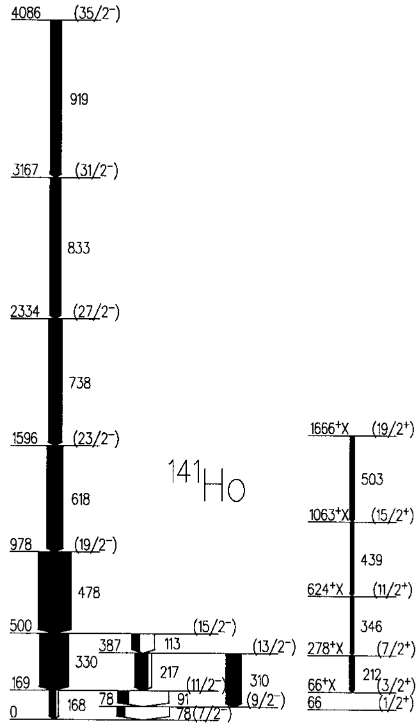

Figure 2. Partial level scheme of ^{141}Ho. The widths of the arrows are proportional to the transition intensities. The white components of the arrows reflect the calculated internal conversion contribution for the assumed multipolarity without mixing.

4. DISCUSSION

There are no data available on the excited states of ^{141}Ho and ^{131}Eu, their proton-decay daughters, neighboring odd-Z isotones, or even-N isotopes. The data on nuclei situated further away is limited to a few transitions in ground-state rotational bands for even-even systems, and in bands based on the $h_{11/2}$ proton orbital for odd-Z nuclei. This situation makes any systematic comparison difficult, especially in a region where deformation changes rapidly with the number of valence neutrons. In nuclei with Z>50 and N<82 which have enough valence protons and neutrons to develop deformation, strongly populated bands based on the $\pi h_{11/2}$ orbital are a common occurrence. In most of these cases the proton angular momentum is aligned with the axis of rotation because low-K orbitals are involved (above Z=50) or because of the small deformation (close to the

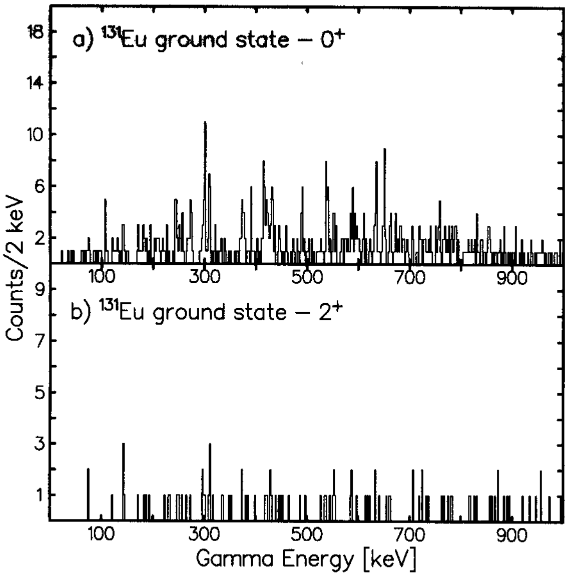

Figure 3. The spectrum of γ rays correlated with a) the ground-state to ground-state proton decay in ^{131}Eu and b) the decay to the 2^+ state in the daughter nucleus.

N=82 shell gap). One expects a $\pi h_{11/2}$ band to be strongly populated in ^{141}Ho. However, due to the large deformation and the Fermi surface situated closer to the medium-K $h_{11/2}$ orbitals, coupling of the angular momentum to the deformation might be energetically favored. Such strongly coupled bands, based on the medium-K $h_{11/2}$ orbitals, have been observed on the neutron-rich side of the N=82 shell gap at comparable deformations. See, for example, the $7/2^-[523]$ ground-state band in ^{157}Ho [11]. In ^{131}Eu the Fermi surface is closer to the $3/2^+[411]$ $d_{5/2}$ and $5/2^+[413]$ $g_{7/2}$ orbitals at the deformation of about $\beta = 0.33$ calculated by Möller and Nix [12]. The bands built on these bandheads are strongly coupled. The $\pi h_{11/2}$ band in ^{131}Eu is expected to be yrast at higher spins and should also be populated in a heavy-ion induced reaction.

4.1. Proton emitter ^{141}Ho

Fig. 4 shows the dynamic moment of inertia as a function of rotational frequency, ω, for the rotational bands in ^{141}Ho. For the ground state band, $\mathcal{J}^{(2)}$ increases gradually up to $\hbar\omega \approx 0.25$ MeV and then rises more steeply, to start leveling off at about 0.4 MeV. In this region of nuclei, the first band crossing is normally due to the alignment of a pair of $h_{11/2}$ protons, and has been observed to take place at a frequency of about 0.25 MeV [13]. It manifests itself by a dramatic change in $\mathcal{J}^{(2)}$, as illustrated in Fig. 4 by the behavior of the $d_{5/2}$ band in ^{133}Pm [14]. The dynamic moment of inertia of the ^{141}Ho ground-state band does not exhibit a crossing at such a low rotational frequency. This observation suggests that the crossing is blocked, as would be expected for the band built on the

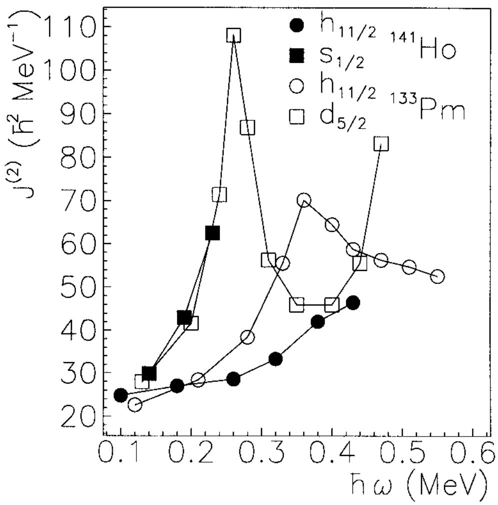

Figure 4. Dynamic moments of inertia as a function of the rotational frequency for the rotational bands in ^{141}Ho, and the $\pi h_{11/2}$ and $3/2^+[411]$ bands in ^{133}Pm.

$\pi h_{11/2}$ orbital. The increase of $\mathcal{J}^{(2)}$ at $\hbar\omega \approx 0.35$ MeV could be caused by the alignment of a second pair of $h_{11/2}$ protons or/and by the alignment of a pair of $h_{11/2}$ neutrons [13]. This second crossing can be seen in the $d_{5/2}$ band in ^{133}Pm [14] (Fig. 4). Thus, we propose that the strong sequence of transitions correlated with the ground-state proton decay is a $\pi h_{11/2}$ band.

It was shown [15] that in rare-earth, even-even and odd-Z, even-N nuclei the deformation can be correlated with the J_0 parameter in the Harris expansion of the dynamic moment of inertia: $\mathcal{J}^{(2)} = J_0 + 3J_1\omega^2$. Using this approach, a deformation of $\beta_2 = 0.25 \pm 0.04$ was deduced for the ground-state band in ^{141}Ho. The uncertainty reflects the spread of the J_0 parameter as a function of deformation in known rotational bands. This value is slightly lower then the value of $\beta_2 = 0.29$ calculated by Möller and Nix [12].

According to single-particle energies calculated using a Woods-Saxon potential with the 'universal' set of parameters [16] the $7/2^-[523]$ Nilsson orbital is expected to be the ground-state in ^{141}Ho for deformations around $\beta_2 = 0.29$. Thus the bandhead of the ground-state band was assumed to have spin and parity $7/2^-$. Contrary to expectations the sequence based on the $9/2^-$ level is shifted up in energy, resulting in a large signature splitting. The discussion so far did not consider the hexadecapole degree of freedom or the presence of triaxiality. Both these factors could lead to additional mixing of low-K components resulting in increased signature splitting. Möller and Nix [12] calculated $\beta_4 = -0.06$ for the $7/2^-$ ^{141}Ho ground state. The $7/2^-[523]$ bands in ^{157}Ho[11] and ^{159}Tm[17] were found to have sizable values of the γ parameter, $\gamma \approx -15°$, at comparable

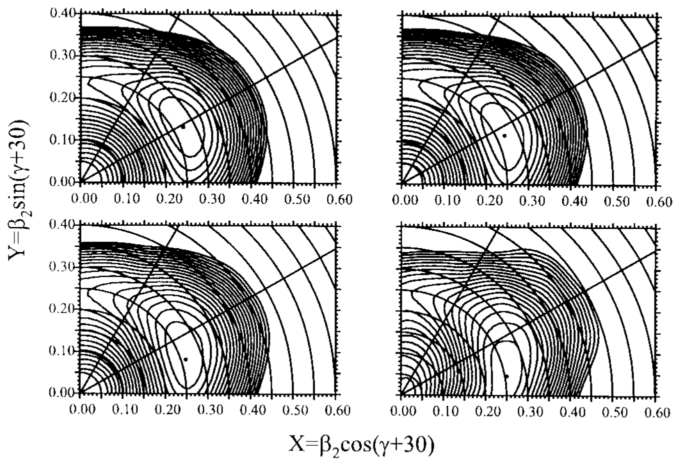

Figure 5. Results of the Total Routhian Surface calculations for the $7/2^-[523]$ configuration in ^{141}Ho. The top two panels correspond to the rotational velocity $\omega = 0.05$ MeV and 0.15 MeV, while the bottom ones were obtained for $\omega = 0.25$ MeV and 0.35 MeV, respectively.

quadrupole deformation. The results of the Total Routhian Surface calculations for the ground state band in ^{141}Ho are shown in Fig. 5. As can be seen in Fig. 5 the ground state of ^{141}Ho appears to be γ-soft and then gradually a shallow minimum develops with increasing rotational velocity for negative γ values.

In order to understand the role of more complicated shapes in ^{141}Ho, particle-rotor calculations were performed for the ground-state band. For negative parity states, the $\pi h_{11/2}$ band corresponding to K=7/2, was calculated to be the ground-state band. Using $\beta_2 = 0.29$ and $\beta_4 = -0.06$, the excitation energies of the $9/2^-$, $11/2^-$, $13/2^-$ and $15/2^-$ states relative to the $7/2^-$ ground state were compared with the calculations and the best agreement was obtained for $\gamma \approx -20°$. On the other hand, a deformation of $\beta_2 = 0.25$ leads to a lower value of $\gamma \approx -10°$. In Fig. 6 the experimental and calculated energy splittings for the $7/2^-[523]$ band in ^{141}Ho are compared.

It is worth noting that the calculated B(M1)/B(E2) ratios for the $11/2^-$, $13/2^-$, $15/2^-$ states in the $7/2^-[523]$ band approach the measured values, although the experimental uncertainties are quite large.

As can be seen in Fig. 4, the dynamic moment of inertia for the band based on the isomer starts to increase at $\hbar\omega \approx 0.2$ MeV, indicative of a low-lying band crossing. Since only one signature partner is observed for this band, it must have significant signature splitting. Among the non-$h_{11/2}$ orbitals located near the Fermi surface only the $1/2^+[411]$ band is expected to exhibit a large signature splitting. The particle-rotor calculations predict for $\beta_2 = 0.29$ and $\beta_4 = -0.06$ that the $3/2^+$ state is situated only 10 keV above the $1/2^+$ bandhead. Thus, the observed γ-ray transitions most likely feed the $3/2^+$ state. The low energy transition between the $3/2^+$ and the $1/2^+$ state remains unobserved.

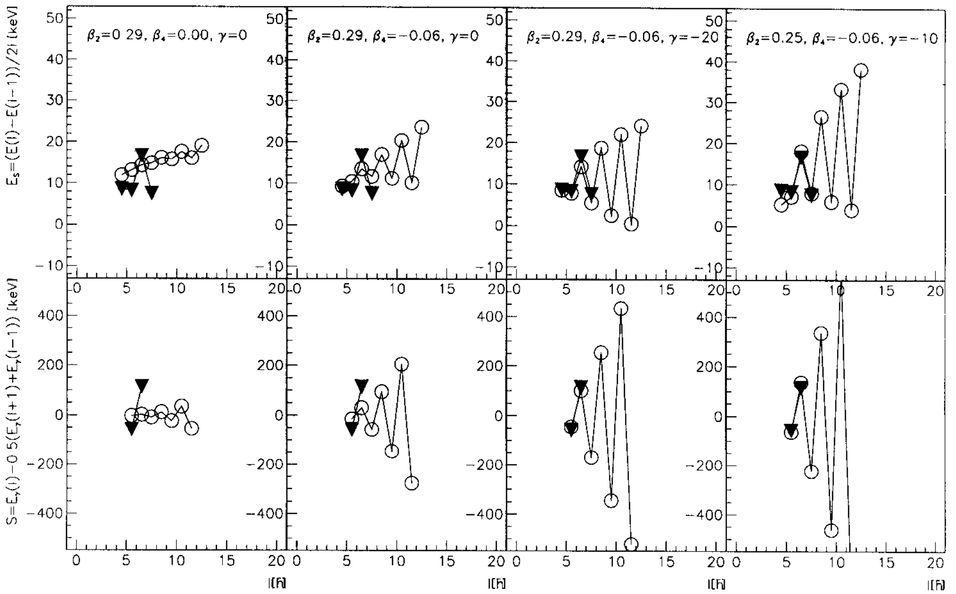

Figure 6. Results of the particle-rotor calculations for the $7/2^-[523]$ band in ^{141}Ho. The strength of the Coriolis interaction was attenuated by 15% in the calculations. Full triangles and open circles correspond to the experimental and calculated values, respectively.

4.2. Proton emitter ^{131}Eu

Due to lower statistics and a complexity of the measured γ-ray spectrum band assignments for ^{131}Eu are difficult. The number of γ-ray transitions in the spectrum indicates that at least 3 bands are populated with comparable intensities. In particular, transitions below 120 keV present in the spectrum could be the lowest lying M1 transitions connecting the two signature-partner bands in the $d_{5/2}$ or the $g_{7/2}$ band. Exact placement of the transitions in ^{131}Eu will require observation of γ-γ coincidences with better statistics.

5. OUTLOOK AND SUMMARY

The Recoil-Decay Tagging method has established itself as a powerful technique for in-beam studies of proton emitters. With state-of-the-art detection systems, reaction channels with cross sections as low as 50 nb have been observed. In ^{141}Ho and ^{131}Eu rotational bands were observed. A deformation of $\beta = 0.25 \pm 0.04$ were deduced in agreement with the value obtained from experimental proton-decay rates and proton-decay calculations. In addition, the dynamic moments of inertia extracted for the bands in ^{141}Ho support the configuration assignments proposed from the analysis of the proton-decay rates. Because of low statistics and a more complex γ-ray spectrum in ^{131}Eu, firm band assignments have not yet been made. The study of excited states in deformed proton emitters has already proven to be a source of valuable information on the structure of the proton decaying states, and has shed light on the response of proton emitters to the stress of rotation.

To draw more firm conclusions on the structures observed in ^{141}Ho and ^{131}Eu one needs data with better statistics. In particular, γ-γ coincidence relationships are needed for ^{131}Eu. This would require a detection system with higher efficiency and/or a system which can handle more intense beams. Several other deformed proton emitters can also be studied in-beam. The nuclei ^{117}La [18] and ^{145}Tm [19] are the most promising cases since their production cross sections are comparable to those of ^{141}Ho and ^{131}Eu. Other, not yet discovered, Pr, Pm and Tb proton emitters are another possibility, although the cross sections might be prohibitively low if p6n reaction channels have to be used. Finally, one could search for light deformed proton emitters below ^{100}Sn.

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