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In-beam studies of proton emitters using the Recoil-Decay Tagging method [1]

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Abstract.
The last five years have witnessed a rapid increase in the volume of data on proton decaying nuclei. The path was led by decay studies with recoil mass separators equipped with double-sided Si strip detectors. The properties of many proton decaying states were deduced, which triggered renewed theoretical interest in the process of proton decay.

The decay experiments were closely followed by in-beam γ-ray studies which extended our knowledge of high-spin states of proton emitters. The unparalleled selectivity of the Recoil-Decay Tagging method combined with the high efficiency of large arrays of Ge detectors allowed, despite small cross sections and overwhelming background from strong reaction channels, the observation of excited states in several proton emitters.

Recently, in-beam studies of the deformed proton emitters ^{141}Ho and ^{131}Eu have been performed with the GAMMASPHERE array of Ge detectors and the Fragment Mass Analyzer at ATLAS. Evidence was found for rotational bands in ^{141}Ho and ^{131}Eu. The deformations and the single-particle configurations proposed for the proton emitting states from the earlier proton-decay studies were confronted with the assignments deduced based on the in-beam data. It should be noted that the cross section for populating ^{131}Eu is only about 50 nb, and it represents the weakest channel ever studied in an in-beam experiment.

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INTRODUCTION

The domain of nuclei situated far from the line of β stability has always been an arena of numerous experimental pursuits and a testing ground for new theoretical models of nuclear behavior. With the recent advances in experimental techniques, and with radioactive beams on the horizon, the physics of nuclei with an excess of neutrons or protons has become one of the focal points of nuclear physics. In particular, nuclei at the drip lines are expected to draw a lot of attention. They define the very limits of nuclear existence and will be susceptible more than any other nuclei to phenomena associated with low binding energy such as halos, skins or mixing with the continuum. Because protons are expected to be kept in check by the Coulomb barrier, these effects are expected to play a more important role for neutron-rich nuclei. However, the neutron drip line can be accessed experimentally only for a handful of light elements. On the other hand, the proton drip line can be studied experimentally now, as shown by recent rapid progress in proton-decay studies (see Ref. [1] for the most recent review, and several other papers in these proceedings for the latest results). In fact, more detailed studies of proton emitters are already possible. Their excited states have been studied, providing independent information on the structure of the proton emitters and elucidating their behavior at high spin. This has been made possible by combining in-beam spectroscopic techniques with the selectivity of proton and α decay studies. The experimental techniques used in these experiments will be described in more detail in the following section.

RECOIL-DECAY TAGGING

Nuclei at the proton drip line are in general produced in heavy-ion fusion-evaporation reactions using the most neutron deficient beam-target combinations available. For these reactions, the compound system emits mainly protons, rarely α particles and very seldom neutrons. The cross sections drop rapidly with the number of emitted neutrons. Typically, about 20-30 channels are open. As a result, a highly efficient and selective detection system is necessary to observe weak proton-rich evaporation channels. It is especially true for in-beam γ-ray studies where 10-20 γ-ray transitions are emitted per reaction channel, and weak γ-ray transitions are buried under Compton scattered events originating from strong reaction channels. One can reach cross sections as low as 10μb with conventional methods, such as the detection of light evaporation particles, or the measurement of the mass and the atomic number of recoils using a recoil mass separator. The cross sections for producing proton emitters do not exceed 100μb. For the deformed proton emitters discussed in this paper the cross sections are below 1μb and in the case of the isomer in ^{141}Ho only 50 nb. The required selectivity was achieved using the Recoil-Decay Tagging method. In this method, the proton or α decays detected using a recoil mass separator, equipped with a double-sided Si strip detector, are used to tag prompt γ-ray transitions. This technique was first implemented at GSI using the SHIP separator combined with NaI detectors to detect prompt γ rays [2], and independently at Daresbury using for the first time an array of Ge detectors in combination with a recoil mass separator [3]. Subsequently, the method was implemented at the Argonne National Laboratory, the University of Jyväskylä, and the Oak Ridge National Laboratory. Already in the first RDT experiment some preliminary results were reported on γ-ray transitions in the proton emitter ^{109}I [3]. In an experiment at ATLAS with the Aye-Ball array of Ge detectors and the Argonne fragment mass analyzer 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 β=0.13 was deduced for the ground state [4]. 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 [5]. Excited $h_{11/2}$ bands were found in the moderately deformed proton emitters ^{109}I [6] and ^{113}Cs [7], but the decay of these bands to the ground state was not determined. A complex level scheme including a decoupled $h_{11/2}$ band was also constructed for ^{167}Ir [8]. Finally, after the discovery of the first highly deformed proton emitters ^{141}Ho and ^{131}Eu [9], and the observation of proton fine structure in ^{131}Eu [10], attempts were made to find evidence for rotational bands in these nuclei. The following chapter reports on the results of these experiments.

ROTATIONAL BANDS IN ^{141}HO AND ^{131}EU

Experiments

The Recoil-Decay Tagging method was used to study excited states in the proton emitters ^{141}Ho and ^{131}Eu. Fig. 1 shows the implementation of the Recoil-Decay Tagging at ATLAS. The prompt γ rays were detected using the array of 101 Compton suppressed HPGe detectors GAMMASPHERE. The recoiling evaporation residues were dispersed in the Argonne fragment mass analyzer (FMA) according to their mass-to-charge-state ratio. Behind the focal plane of the FMA the recoils were implanted into a double-sided Si strip detector (DSSD) where they subsequently decayed. The front and back side of the 60 μm thick, 40 mm by 40 mm DSSD were divided into 40 horizontal and 40 vertical strips, respectively, forming 1600 quasi-pixels. Using spatial and time correlation, the decays were associated with their parent nuclei and the prompt γ rays emitted from their excited states. This allowed the assignment of γ rays to particular reaction channels based on the characteristic proton decays of the implants.

Two proton lines have been observed in ^{141}Ho. The 1169(8)-keV line with a half-life of 4.4(4) ms, corresponding to the ground-state proton decay [9], and the 1230(20)-keV line with a half-life of 8±3 μs associated with an isomer [12]. In

^{131}Eu the protons have an energy of 932(7) keV and a half-life of 17.8(19) ms, and a 24(5)% decay branch to the 2^+ state in the daughter nucleus was found [10].

In the first experiment a ^{54}Fe beam at 292 MeV from ATLAS impinged on a 0.7 mg/cm^2 ^{92}Mo target to produce ^{141}Ho as the p4n evaporation channel. In order to increase the statistics, a second experiment was performed using inverse kinematics. Thanks to the increase in the efficiency of the FMA, a factor of about 4 was gained in the proton yield. In Fig. 2(a) the γ-ray spectrum tagged by the proton decay of the ground state in ^{141}Ho is shown. Fig. 2(b) shows the sum of selected γ-γ coincidence gates. The transitions marked with stars in Fig. 2(b) are in coincidence with each other and form a regular sequence, most likely the ground-state rotational band. In Fig. 3 the γ-ray spectrum tagged by the proton decay of the isomeric state in ^{141}Ho is shown. Only 4 relatively strong γ-ray transitions are present in this spectrum. Although the statistics were not sufficient to obtain coincidence relationships between these transitions, it is plausible that they are in coincidence with each other and form a rotational band built on the isomer. Assuming transport efficiency of 10% for the FMA, cross sections of 250 nb and 50 nb were deduced for populating the ground state and the isomeric state in ^{141}Ho.

In the second experiment 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. In Fig. 4 γ rays which were correlated with the ground-state proton decay of ^{131}Eu are shown. The γ-ray spectrum assigned to ^{131}Eu is much more complex than those obtained for ^{141}Ho. Already a simple inspection of Fig. 4 suggests that more than one γ-ray

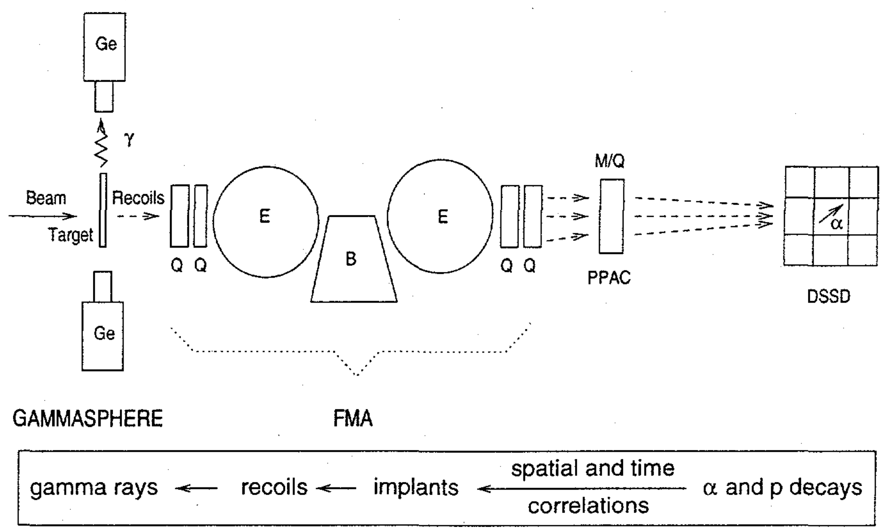

FIGURE 1. The implementation of the Recoil-Decay Tagging at ATLAS.

sequence must be present. It is worth noting that the γ-ray spectrum tagged by the proton decay to the 2^+ excited state resembles the γ-ray spectrum correlated with the ground state-to-ground state proton decay. This confirms unambiguously that both proton lines in ^{131}Eu are emitted from the same state. This is in contrast to the situation in ^{141}Ho, where there is no overlap between the γ-ray spectra correlated with the two proton lines. Assuming an efficiency of 10% for the FMA a cross section of 90 nb was deduced for populating the ground state of ^{131}Eu.

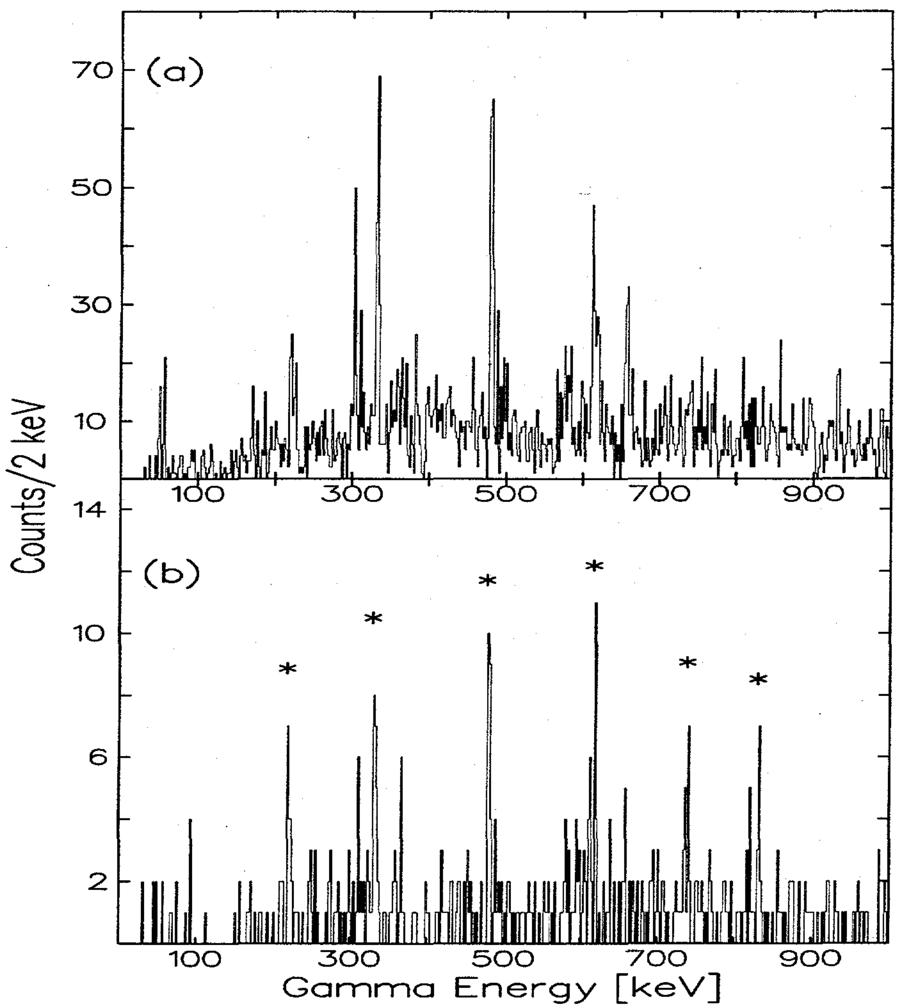

FIGURE 2. (a) The spectrum of γ rays tagged with the protons emitted from the ground state in ^{141}Ho. (b) The sum of the proton tagged γ-γ coincidence gates. The transitions used as gates are marked with stars.

Discussion

A deformation of β=0.29 was calculated for the ground state of ^{141}Ho [11]. At this deformation the $7/2^-$[523] Nilsson orbital originating from the $h_{11/2}$ spherical state is predicted to be the ground state. The $1/2^+$[411] $d_{3/2}$ state is expected to be located close in energy to the ground state. In addition, several orbitals originating from the $g_{7/2}$ and $d_{5/2}$ spherical states should lie at higher excitation energies. The observed proton-decay rates from the ground state and the isomeric state in ^{141}Ho are in agreement with calculations only if the $7/2^-$[523] and $1/2^+$[411] configurations are assigned to the ground state [9] and to the isomeric state [12], respectively. In Ref. [9] a deformation of β=0.30 was found to best fit the data.

In ^{131}Eu, the $3/2^+$[411] $d_{5/2}$ state and $5/2^+$[413] $g_{7/2}$ states are predicted to be located close to the Fermi surface at the calculated deformation of β=0.33 [11]. The ground-state proton decay rate is consistent with the theory for both the $3/2^+$[411] and $5/2^+$[413] configurations and deformations of about β=0.35 [9]. However, the observed proton-decay branch to the excited 2^+ state in the daughter nucleus unambiguously favors the $3/2^+$[411] assignment [10].

There are no data available on the excited states of the proton-decay daughter nuclei, neighboring odd-Z isotones, and even-N isotopes of both ^{141}Ho and ^{131}Eu.

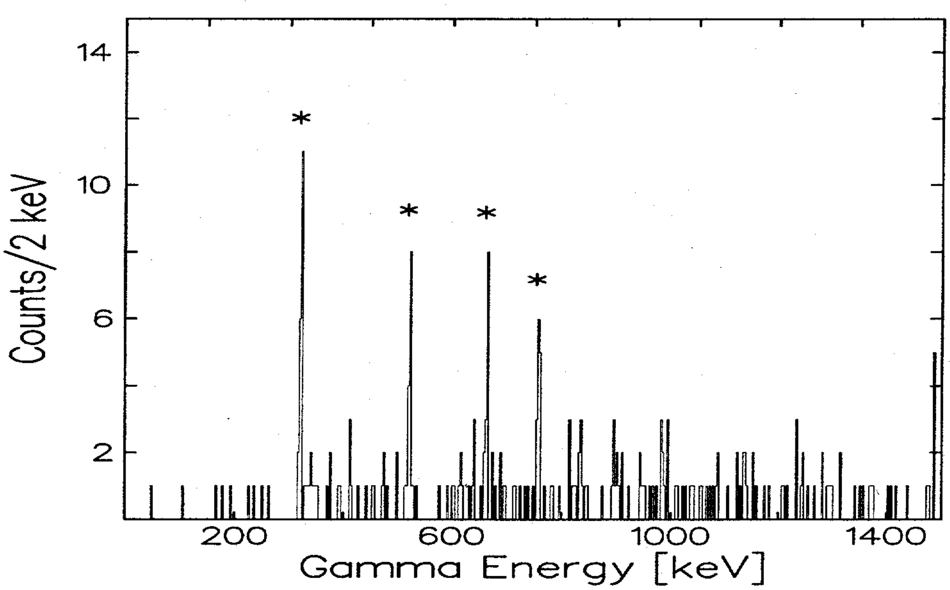

FIGURE 3. The spectrum of γ rays tagged with the protons emitted from the isomeric state in ^{141}Ho.

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 $h_{11/2}$ 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 nucleons. In nuclei with Z>50 and N<82 which have enough valence protons and neutrons to develop deformation, strongly populated bands based on the $h_{11/2}$ orbital are a common occurrence. In most of these cases the $h_{11/2}$ proton is aligned with the axis of rotation because a low-K orbital is involved (above Z=50) or because of the small deformation (along the N=82 shell gap). One expects the $h_{11/2}$ bands to be strongly populated in ^{141}Ho and ^{131}Eu as well. However, due to the larger deformation and the Fermi surface moving toward the medium-K $h_{11/2}$ orbitals, strong coupling might be energetically favored. Strongly coupled bands based on the medium-K $h_{11/2}$ orbitals have been observed on the other side of the N=82 shell gap at comparable deformation (see, for example, ^{157}Ho [13]).

The differences between transition energies in the $h_{11/2}$ band marked in Fig. 2(b) suggest that it is a cascade of stretched quadrupole transitions. Fig. 5 shows the dynamic moment of inertia $\mathcal{J}^{(2)}$ as a function of rotational frequency ω for the rotational bands in ^{141}Ho and ^{131}Eu. $\mathcal{J}^{(2)}$ increases gradually up to $\omega \approx 0.4 MeV$

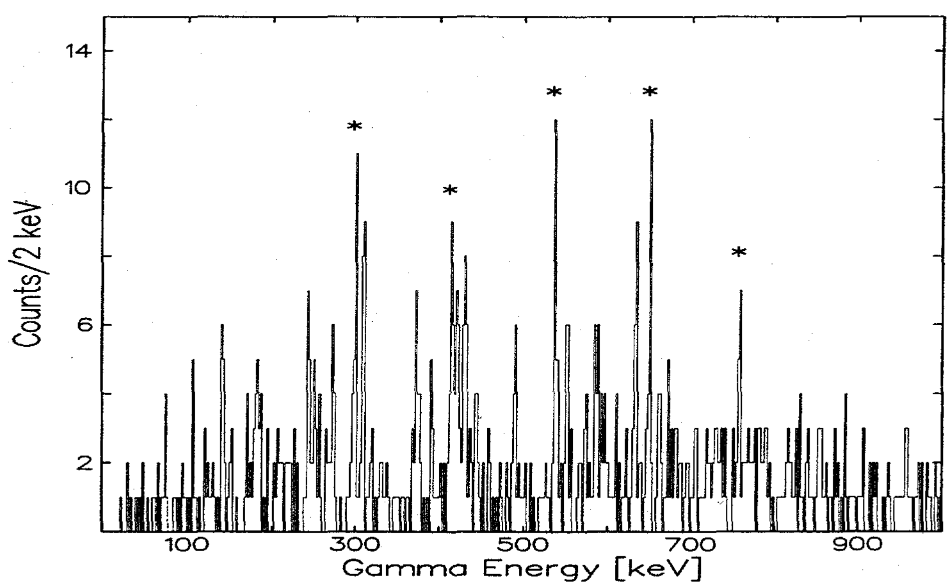

FIGURE 4. The spectrum of γ rays tagged with the protons emitted from the ground state of ^{131}Eu. The transitions marked with stars could possibly form an $h_{11/2}$ band.

for the ground-state band. The first crossing is expected to be due to the alignment of a pair of $h_{11/2}$ protons and was observed to take place at a rotational frequency of about $0.25 MeV$ in this region. The dynamic moment of inertia of the ground-state band does not exhibit any crossing at such a low rotational frequency. This suggests that the band is built on the $h_{11/2}$ orbital since, as a result, the crossing is blocked. The observed transitions could form the favored sequence $27/2^- \rightarrow 23/2^- \rightarrow 19/2^- \rightarrow 15/2^- \rightarrow 11/2^- \rightarrow 7/2^-$ of the $7/2^-[523]$ band. Contrary to expectations the unfavoured signature partner does not seem to be populated. Triaxiality could explain a larger than expected signature splitting.

It was shown by Mueller [14] that deformation is correlated with the J_0 parameter in the Harris expansion of the dynamic moment of inertia as a function of the rotational frequency: $\mathcal{J}^{(2)} = J_0 + 3J_1\omega^2$. Using this approach a deformation of β=0.28±0.04 is deduced for the ground state band in ^{141}Ho.

The transitions correlated with the proton decay of the ^{141}Ho isomer have similar energy spacings as seen in the ground-state band at low energies, but there is a compression at higher energies. As can be seen in Fig. 5, the dynamic moment of inertia for this band starts to increase at $\omega \approx 0.2 MeV$, indicative of a low-lying band crossing. In fact, a careful inspection of Fig. 3 reveals several weak transitions in the region where the backbending takes place. Since we observed only one signature partner for this band it must have a significant signature splitting. Among the non-$h_{11/2}$ orbitals which are located near the Fermi surface only the $1/2^+[411]$

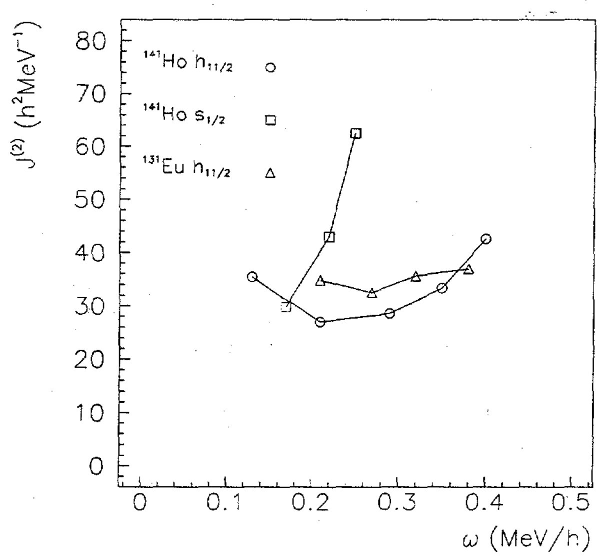

FIGURE 5. The dynamic moments of inertia as a function of rotational frequency for the rotational bands in ^{141}Ho and ^{131}Eu.

band is expected to exhibit a large signature splitting. Thus, the observed γ-ray transitions could form the $15/2^+ \rightarrow 11/2^+ \rightarrow 7/2^+ \rightarrow 3/2^+$ favored signature band. The low energy transition to the $1/2^+$ band-head and the unfavored signature band have so far remained unobserved.

Due to lower statistics and the complex γ-ray spectrum 4, band assignments in ^{131}Eu are more difficult. The γ-ray transitions marked in Fig. 4 could be good candidates for an $h_{11/2}$ band. Their regular spacing indicates that the first crossing is blocked. The dynamic moment of inertia for this band is larger than that for the analogous $h_{11/2}$ band in ^{141}Ho. As a result, a slightly higher deformation of β=0.34$\pm$0.05 was obtained using the same method as for ^{141}Ho. The remaining transitions in Fig. 4 most likely form a strongly coupled band. They could correspond to the members of the $3/2^+[411]$ $d_{5/2}$ band which was observed in ^{133}Pm [15]. In particular, transitions below 120 keV could be the lowest lying M1 transitions connecting the two signature-partner bands. At the moment the structure of this band is not known, but the data analysis is still in progress.

OUTLOOK

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 relations are needed for ^{131}Eu. This would require a detection system with higher efficiency and/or a system which can handle more intense beams. In principle, several other deformed proton emitters could be studied in-beam. ^{117}La [16] and ^{145}Tm [17] nuclei are the most promising cases for in-beam studies 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 could be 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 between ^{56}Ni and ^{100}Sn, provided that their half-lives lie within the observation window of the existing detection systems. Obviously, intense radioactive beams will help to study all the cases listed above by means of much larger cross sections.

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 and deformations of $\beta \approx 0.28$ and $\beta \approx 0.34$, respectively, were deduced in agreement with the values obtained from experimental proton-decay rates and theoretical 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 conclusions on 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.

REFERENCES

1. P.J. Woods and C.N. Davids, *Annu. Rev. Nucl. Part. Sci.* **47**, 541 (1997).

2. R.S. Simon et al., *Nucl. Phys.* **A325**, 197 (1986).

3. E.S. Paul et al., *Phys. Rev.* **C55**, R2137 (1997).

4. D. Seweryniak et al., *Phys. Rev.* **C56**, R723 (1997).

5. C.-H. Yu et al., *Phys. Rev.* **C58**, R3042 (1998).

6. C.-H. Yu et al., *Phys. Rev.* **C59**, R1834 (1999).

7. C.J. Gross et al., in *Proceedings of the 2nd International Conference on Exotic Nuclei and Atomic Masses*, Shanty Creek, USA, 1998, edited by B.M. Sherrill, D.J. Morrissey and C.N. Davids (AIP, New York, 1998), p. 444.

8. M.P. Carpenter et al., *Acta Physica Polonica* **30**, 581 (1999).

9. C.N. Davids et al., *Phys. Rev. Lett.* **80**, 1849 (1998).

10. A.A. Sonzogni et al., *Phys. Rev. Lett.* **83**, 1116 (1999).

11. P. Möller et al., *At. Nucl. Data Tables* **59**, 185 (1995).

12. K. Rykaczewski et al., *Phys. Rev.* **C60**, 011301 (1999).

13. D.C. Radford et al., *Nucl. Phys.* **A545**, 665 (1992).

14. W.F. Mueller, PhD thesis, University of Tennessee, Knoxville, May 1997.

15. A. Galindo-Uribarri et al., *Phys. Rev.* **C54**, 1057 (1996).

16. F. Soramel, these proceedings.

17. J.C. Batchelder et al., *Phys. Rev.* **C57**, R1042 (1998).