Rotational Bands in the Proton Emitter ^{141}Ho

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Rotational bands feeding the ground state and the isomeric state in the proton emitter ^{141}Ho were observed using the recoil-decay tagging method. This constitutes direct evidence that ^{141}Ho is deformed. A quadrupole deformation of $\beta_2 = 0.25(4)$ was deduced for the ground state 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. Comparison with particle-rotor calculations for $\beta_2 = 0.25$ indicates, however, that ^{141}Ho may have significant hexadecapole deformation and could be triaxial in the $7/2^-[523]$ ground state.

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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. 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. These nuclei define the very limits of nuclear existence and will be susceptible to phenomena associated with low binding energy, such as halos, skins, or mixing between bound and continuum states.

The proton separation energy decreases with decreasing neutron number. Proton-rich nuclei, which have a negative proton separation energy and are, thus, situated beyond the proton drip-line, can spontaneously emit protons. The proton decay rate is governed by the energy and orbital angular momentum of the emitted proton. It also depends on the wave function of the proton-decaying state, which is determined by the shape of the nuclear potential and by residual interactions between valence nucleons. Most of the known proton emitters have decay rates consistent with the assumption of a spherical potential. The recent experimental effort to study proton emitters in the rare-earth region has resulted in the observation of anomalous decay rates in ^{131}Eu and ^{141}Ho [1], which were explained by assuming a large deformation for the core. In addition, proton-decay fine structure, i.e., proton emission from the ^{131}Eu ground state to the first 2^+ excited state in the daughter nucleus, has been observed for the first time [2]. This has stimulated renewed theoretical interest in the description of proton decay, especially from deformed nuclei [3–5].

Experimental studies of proton emitters are hampered by low production cross sections, ranging from hundreds of microbarns for the strongest channels to tens of nanobarns 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 millibarns. The combination of recoil mass separators with double-sided Si strip detectors (DSSD), to detect evaporation residues and their subsequent decays, has proved to be a sensitive technique to study proton and α decay along the proton drip-line. Using the recoil-decay tagging method [6], which combines the implant-decay correlation technique with the detection of prompt γ rays, excited states in some proton emitters have been studied, providing information on their structure and elucidating their behavior at high spin. For example, a ground-state γ-ray cascade in ^{147}Tm has been observed [7]. The results of this study indicated the transitional nature of the ^{147}Tm ground state between spherical and deformed shapes. Also, rotational bands based on the $\pi h_{11/2}$ orbital in ^{109}I [8] and ^{113}Cs [9] have been reported. The observed sequences indicated moderate deformation, but no connection to the proton decaying states have been proposed. The aim of the present paper is to explain the anomalous proton-decay rates in ^{141}Ho by studying its excited states. The cross section for populating ^{141}Ho is about 100 nb, i.e., 2 orders of magnitude smaller compared to previous studies.

Two proton lines have been observed in ^{141}Ho prior to this work: a 1169(8)-keV line with a half-life of 4.2(4) ms, corresponding to the ground-state proton decay [1], and a 1230(20)-keV line with a half-life of 8(3) μs associated with an isomer [10]. The proton-decay rates observed for the ground and isomeric states in the nearby nucleus ^{147}Tm are consistent with emission from the spherical $h_{11/2}$ and $d_{3/2}$ orbitals, respectively. Interpreting the ^{141}Ho proton lines as emission from the spherical $h_{11/2}$, $d_{3/2}$, or $s_{1/2}$ states would require anomalously large hindrance factors. However, a quadrupole deformation of $\beta_2 = 0.29$ has been calculated for the ground state of ^{141}Ho using a microscopic-macroscopic model [11]. At this deformation,

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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 [1] and isomeric states [10], respectively.

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 292-MeV^{54}Fe beam 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. 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. The recoil-decay tagging method was implemented to select γ-ray transitions belonging to ^{141}Ho. Prompt γ rays were detected using the GAMMASPHERE array [12] equipped with 97 Compton-suppressed high-purity Ge detectors and four low-energy photon (LEP) spectrometers. The recoiling evaporation residues were dispersed according to their mass-to-charge-state ratio at the focal plane of the Argonne fragment mass analyzer (only mass-141 recoiling nuclei with charge states 36^+ and 37^+ were collected during the second experiment). After passing through a position-sensitive parallel-grid avalanche counter placed at the focal plane, the recoils were implanted into a DSSD where they subsequently decayed. The front and back sides of the 60 μm thick, 40×40 mm^2 DSSD were divided into 40 horizontal and 40 vertical strips, respectively, forming 1600 quasipixels. Using spatial and time correlations, the decays were associated with their parent nuclei and with the prompt γ rays emitted at the target. This allowed the assignment of γ rays to particular nuclei based on the characteristic proton decays of the implants.

Insets in Figs. 1(a) and 1(c) show the proton spectra associated with the decay of the ground state and the isomeric state in ^{141}Ho, respectively. From the relative positions of the two lines an isomer excitation energy of 66(2) keV was deduced. Using the ground-state proton energy of 1169(8) keV obtained in Ref. [1] as a reference, an energy of 1235(9) keV was obtained for the protons emitted from the isomer. In addition, a half-life of $6.5(-0.7 + 0.9)$ μs was measured for the isomer. Both values are in agreement with the previous measurement [10], but the uncertainties were reduced in the present work. No evidence was found for fine structure lines within 250 keV of the ground state and the isomer line, and in both cases an upper limit of about 1% was derived for decay branches to the first 2^+ state in the daughter nucleus. In Fig. 1(a) the γ-ray spectrum tagged by the ^{141}Ho ground-state protons is shown. The 91-keV transition was also detected in the LEP spectrometers. Note that Ho x rays are present in the spectrum, supporting the as-

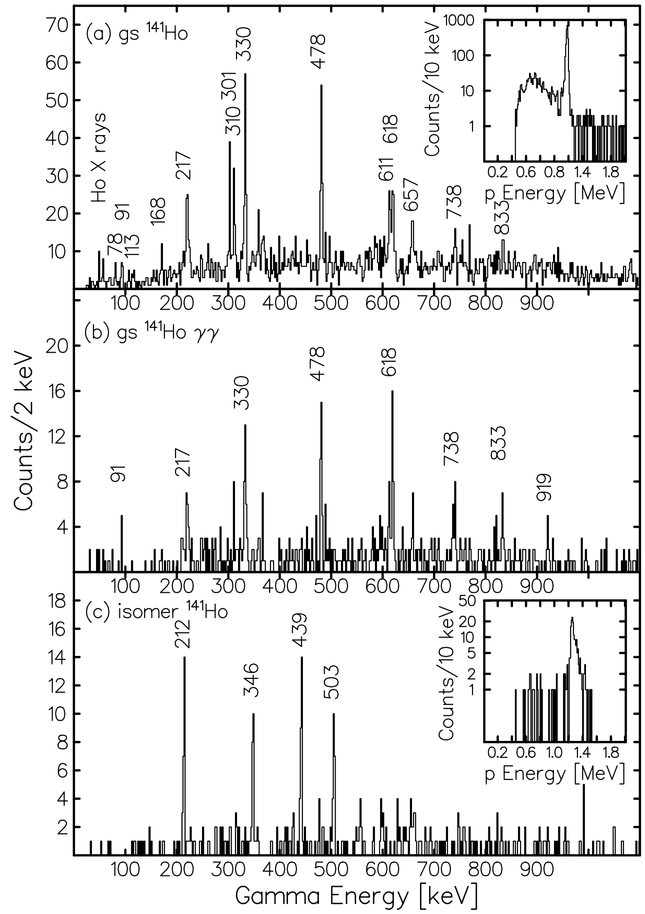

FIG. 1. (a) The γ-ray spectrum tagged with protons emitted from the ground state in ^{141}Ho. The ground-state protons emitted within 50 μs and 25 ms after implantation are shown in the inset. (b) The sum of selected γ-γ coincidence gates (91, 168, 217, 330, 478, 618, 738, 833, and 919 keV) tagged by the ground-state proton decay. (c) The γ-ray spectrum tagged with protons emitted from the isomeric level in ^{141}Ho. The spectrum of protons emitted from the isomer within 40 μs after implantation is shown in the inset. The broadening of the line is caused by pileup of the recoil and proton signals occurring within 10 μs of each other.

signment and indicating the presence of strong converted low-energy transitions. Figure 1(b) contains the sum of selected γ-γ coincidence gates tagged by the ground-state protons. Gamma rays correlated with the proton decay of the isomer are given in Fig. 1(c). Only four relatively strong γ-ray transitions are present in the spectrum. The statistics were not sufficient to obtain coincidence relationships between these transitions.

Based on the γ-ray energies, intensities, and coincidence relationships, the partial level scheme shown in Fig. 2 was constructed. The transitions above 300 keV marked with energies in Fig. 1(b) are coincident with each other. Their regular energies and intensity pattern indicate that they form a rotational band. The energy spacings suggest that they are of quadrupole character. The 168-keV γ ray is proposed to feed the ground state. Based on

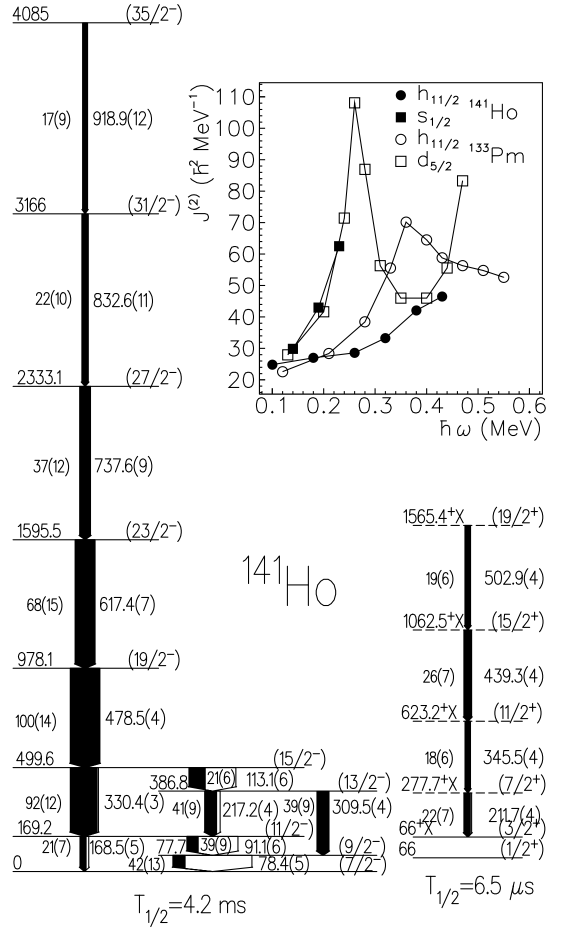

FIG. 2. Partial level scheme of ^{141}Ho. γ-ray transition energies and intensities are specified on the right and left sides of the arrows, respectively. The white components of the arrows reflect the calculated internal conversion contribution for the assumed multipolarity without mixing. Dynamic moments 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 [13] are shown in the inset.

their energy sum, the 91- and 78-keV transitions are proposed to form a parallel $\Delta I = 1$ cascade. The 217-keV γ ray is suggested to be a stretched $\Delta I = 1$ transition feeding the $11/2^-$ state. Its placement is supported by the presence of the 113- and 310-keV transitions. Spin and parity assignments are based on the assumption that the observed cascade feeds a $7/2^-$ bandhead (see discussion below). Because of low statistics in individual γ-ray gates the 301-, 611-, and 657-keV transitions which can be seen in Fig. 1(a) and are weak in Fig. 1(b) were not placed in the level scheme. The transitions correlated with the proton decay of the ^{141}Ho isomer have energies similar to those in the ground-state band and, most likely, also form an E2 cascade. As their relative intensities are very similar, they were ordered according to increasing energy. The proposed spin and parity assignments assume that the observed cascade terminates on a $3/2^+$ state (see discussion below).

The inset in Fig. 2 presents the dynamic moment of inertia, $\mathcal{J}^{(2)} = [(1/\hbar^2)d^2E(I)/dI^2]^{-1}$, 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. 2 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 $\pi h_{11/2}$ 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. 2), although it is not fully delineated. 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 $\beta_2 = 0.25 \pm 0.04$ is 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. 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 $\beta_2 = 0.25$. The proton-decay rate calculations confirm this assignment [1]. Additional input on the value of deformation can be derived from the absence of proton decay to the first 2^+ state in the daughter nucleus. No information is available on the energy of the 2^+ state in ^{140}Dy. According to the Grodzins formula [17], which correlates energies of 2^+ states with deformation, $\beta_2 = 0.25$ would imply $E(2^+) = 190$ keV. This value agrees also with extrapolations of the 2^+ energies in neighboring nuclei. Using the adiabatic approach a branching ratio of about 1%, equal to the upper experimental limit, is calculated for the ^{141}Ho ground state to the ^{140}Dy 2^+ excited state [$\beta_2 = 0.29$ and $E(2^+) = 140$ keV gives 5%] [4].

Two $\Delta I = 2$ bands corresponding to two signatures, interconnected by $\Delta I = 1$ transitions, are expected to be built on medium-K $\pi h_{11/2}$ orbitals at the deformations considered. See, for example, the $7/2^-[523]$ ground-state band in ^{157}Ho [18] on the neutron-rich side of the $N = 82$ shell gap. Contrary to expectations, the sequence based on the $9/2^-$ level is shifted up in energy, resulting in a large signature splitting. This unusually large signature splitting can be caused by even lower deformation, by hexadecapole deformation or by the presence of triaxiality.

Möller and Nix [11] calculated $\beta_4 = -0.06$ for the $7/2^-$ ^{141}Ho ground state. The $7/2^-[523]$ band in ^{157}Ho [18] was found to have a sizable γ parameter $\gamma \approx -15°$ at comparable quadrupole deformation. In order to understand the role of more complicated shapes in ^{141}Ho, particle-rotor calculations were performed for the ground-state band [19]. For negative parity states, band based on a $7/2^-$ state of the $\pi h_{11/2}$ $K = 7/2$ band, was calculated to be the ground state. Using $\beta_2 = 0.25$ and $\beta_4 = -0.06$, the excitation energies of the $9/2^-$, $11/2^-$, $13/2^-$, and $15/2^-$ states were compared with the calculations and the best agreement was obtained for $\gamma \approx -10°$ ($\beta_2 = 0.29$ leads to a larger value of $\gamma \approx -20°$). In addition, the calculated $B(M1)/B(E2)$ ratios for the $11/2^-$, $13/2^-$, $15/2^-$ states in the $7/2^-[523]$ band (0.31, 0.097, 0.36 μ_N/e^2b^2) [20] approach the measured values [0.23(10), 0.20(7), 0.42(16) μ_N/e^2b^2], although the experimental uncertainties are quite large.

As can be seen in Fig. 2, 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 $\beta_2 = 0.25$ that the $3/2^+$ state is situated only 20 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.

In summary, two rotational bands were observed in ^{141}Ho. A deformation of $\beta_2 = 0.25(4)$ was deduced for the ground-state band. This value is somewhat lower than that inferred from the microscopic-macroscopic calculations [11]. The observed band crossings and signature splittings agree with the configuration assignments proposed for the ground state and the isomer from the analysis of the proton-decay rates [1,10]. Consequently, the present results support strongly the hypothesis that the anomalous proton-decay rates result from the onset of deformation. However, evidence was found that the ground state of ^{141}Ho may have even lower deformation, a significant hexadecapole deformation and may well be triaxial. Therefore, a new challenge is posed to include nonaxial degrees of freedom in the nuclear potential in calculations of proton-decay rates. The present experiment is the best illustration so far of the sensitivity of the recoil-decay tagging method. It shows that, with a state-of-the-art detection system, excited states in nuclei produced with cross sections below 100 nb can be studied. Further advances will require, however, detection systems which are more efficient or can cope with more intense beams.

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[20] The results were obtained using $\beta_2 = 0.25$, $\beta_4 = -0.06$, $\gamma = -10°$, $Q_0 = 5.56$ eb, $g_R = 0.48$, and $g_K = 1.265$.