Proton Radioactivity from Highly Deformed Nuclei

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Proton radioactivity from ^{141}Ho and ^{131}Eu has been identified. The ^{141}Ho proton transition has an energy $E_p = 1169(8)$ keV, a half-life $t_{1/2} = 4.2(4)$ ms, and is assigned to the decay of the $7/2^-[523]$ Nilsson state. The ^{131}Eu transition has an energy $E_p = 950(8)$ keV and a half-life of 26(6) ms, consistent with decay from either the $3/2^+[411]$ or $5/2^+[413]$ Nilsson orbital. The proton decay rates deviate significantly from calculations assuming spherical configurations, and thus indicate the onset of large deformations in the region of the proton drip line below $Z = 69$. [S0031-9007(98)05463-5]

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The proton drip line defines one of the fundamental limits to nuclear stability. Nuclei lying beyond this locus are energetically unbound to the emission of a constituent proton from their ground states [1]. For heavy nuclei ($Z > 50$) the presence of a large Coulomb barrier reduces the proton barrier penetration probability to the extent that proton decays of nuclei from their ground states have measurably long half-lives. The relatively low mass of the proton (compared to an alpha particle) results in a high degree of sensitivity of the partial half-life $t_{1/2,p}$ to the orbital angular momentum ℓ_p of the emitted proton. For near-spherical nuclei in the region of the drip line between $Z = 69$ (Tm) and $Z = 81$ (Tl), proton decay transition rates have been shown to be well reproduced by WKB calculations using spectroscopic factors derived from a low-seniority spherical shell-model calculation [2]. This model considers the proton configuration to have a closed core at $Z = 64$, with degenerate $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ Fermi levels filling up to $Z = 82$, and the neutrons behaving as spectator particles. Subsequently, more sophisticated theoretical approaches using spectroscopic factors based on the independent quasiparticle approximation have also obtained good agreement for this region, provided spherical configurations are assumed [3]. It is now of great theoretical interest to investigate proton decay transition rates in the region of the proton drip line below $Z = 69$, where the macroscopic-microscopic mass model of Möller *et al.* [4] predicts the onset of large prolate deformations ($\beta_2 \sim 0.3$). For deformed nuclei ℓ_p is no longer a good quantum number in the parent nucleus, and significant departures from spherical decay-rate calculations would provide a signature for the onset of deformation. Anomalous proton decay rates measured for the isotopes ^{109}I and ^{113}Cs [5] have been shown to be consistent with calculations assuming relatively small deformations ($\beta_2 \sim 0.1$) [6]. Proton decay rates from highly deformed nuclei will provide a challenging test for theoretical descriptions of this process. Previous searches for proton decays from ^{142,143}Ho ($Z = 67$) and ^{132,133}Eu ($Z = 63$) using $1p3n$ and $1p2n$ heavy-ion fusion evaporation reactions have been unsuccessful [7,8], suggesting that the proton drip line has not been crossed far enough for this decay mode to compete with β^+ decay. The present paper describes successful searches for proton decay from ^{141}Ho and ^{131}Eu.

Beams of 285 and 305 MeV ^{54}Fe ions with intensity 2 particle nA provided by the Argonne ATLAS accelerator were used to bombard a 1 mg cm^{-2} thick target of ^{92}Mo for a period $\sim$10 h at each energy in order to produce ^{141}Ho nuclei *via* the $1p4n$ evaporation channel. These energies correspond to center-of-target ^{146}Er compound nucleus excitation energies of $\sim$76 and 88 MeV with a range $\sim$10 MeV across the whole target thickness. The Argonne Fragment Mass Analyzer (FMA) [9] was set to focus $A = 141$, charge state $q = 26$ recoils at the center of the focal plane, with $q = 25$ and 27 recoils also analyzed. A position-sensitive parallel grid avalanche counter located at the focal plane provided A/q, time of arrival, and energy-loss signals of the recoiling nuclei. After traversing this detector the ions traveled a further 47 cm before being implanted into a double-sided silicon strip detector (DSSD) of thickness 65 μm, area 16×16 mm^2, and having 48 orthogonal strips on the front and rear, respectively [10]. Figure 1(a) shows the energy spectrum of decay events occurring within 25 ms of an $A = 141$ recoil implanted in the same DSSD pixel. A peak is clearly visible at an energy of 1169(8) keV. The low decay energy rules out α radioactivity, and we assign this peak to proton radioactivity from ^{141}Ho, produced with a cross section $\sigma \sim 250$ nb (at both beam energies). The known ground-state proton decay line of ^{147}Tm [$E_p = 1051(4)$ keV] [8] was used to calibrate the

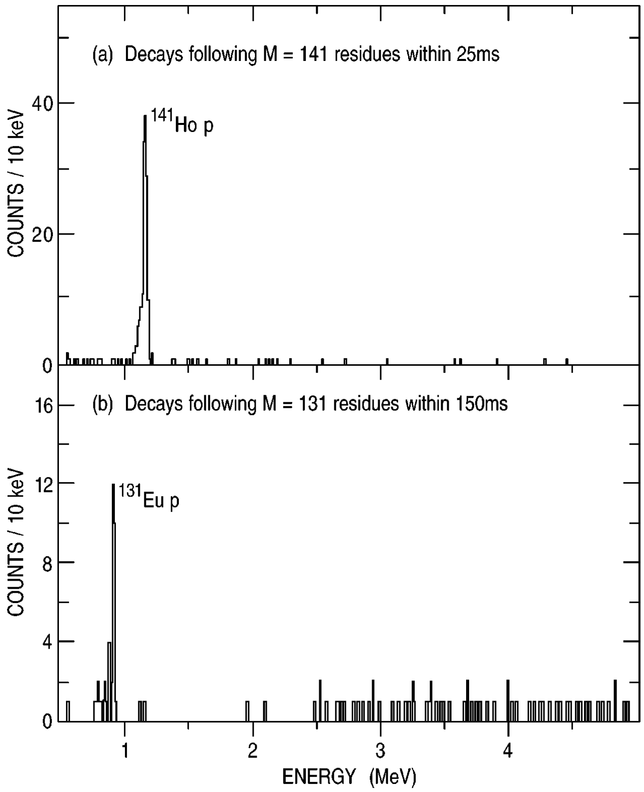

FIG. 1. (a) Energy spectrum of protons from the decay of ^{141}Ho. (b) Energy spectrum of protons from the decay of ^{131}Eu. Each spectrum shows events following the implantation into the same DSSD pixel of a reaction recoil having the specified mass and within the specified time interval.

energy of this line. The measured Q value of 1177(8) keV for ^{141}Ho is in excellent agreement with the 1.15 MeV prediction of the Liran-Zeldes shell-model based mass formula [11], which is known to reproduce proton decay Q values in this region very well. The corresponding predictions for the $A = 141$ isobars ^{141}Dy and ^{141}Tb suggest that they are proton bound, making it very unlikely that these nuclei are the source of the activity. The half-life of the proton transition was determined to be 4.2(4) ms, which is considerably shorter than the predicted β^+-decay half-life of 271 ms [12]. Therefore, we assume that the proton decay branch $b_p \approx 100\%$.

In a subsequent experiment a 222 MeV beam of ^{40}Ca ions with intensity 4.5 particle nA was used to bombard a 400 μg cm^{-2} thick ^{96}Ru target (on the back of a 700 μg cm^{-2} Al foil) for a period of $\sim$36 h in order to produce ^{131}Eu nuclei, again *via* the $1p4n$ evaporation channel. This energy corresponds to an excitation energy of $\sim$77 MeV in the ^{136}Gd compound nucleus. The FMA was set to accept $A = 131$ recoils with charge states 22 and 23 at the focal plane. Figure 1(b) shows the energy spectrum of decays occurring within 150 ms of an $A = 131$ recoil implanted into the same DSSD pixel. A peak is clearly visible at an energy of 950(8) keV (also calibrated using the ^{147}Tm ground-state proton decay line) which we assign to the proton decay of ^{131}Eu, produced with a cross section $\sigma \sim 90$ nb. This corresponds to a proton decay Q value of 957(8) keV, which compares well with the predicted value of 1.08 MeV from the Liran-Zeldes mass formula [11]. As in the case of ^{141}Ho, the neighboring isobars ^{131}Sm and ^{131}Pm are predicted to be proton bound. The observed half-life of ^{131}Eu is 26(6) ms which, when combined with the predicted β^+-decay half-life of 147 ms [12], yields a derived partial proton half-life of 32(9) ms. Using β^+-decay half-lives of 100 or 300 ms has the effect of changing the derived partial proton half-life by ±3 ms.

Spherical WKB calculations for ^{141}Ho using the Becchetti-Greenlees optical potential [13] and a spectroscopic factor of 0.89 derived from the low-seniority spherical shell-model calculations of Ref. [2] predict half-lives of 1 μs, 10 μs, and 37 ms for the $2s_{1/2}$, $1d_{3/2}$, and $0h_{11/2}$ proton orbitals, respectively. While excellent agreement was obtained for transitions in the region from $Z = 69$–81 [2], it is clear that none of these orbitals can explain the observed 4.2(4) ms half-life of ^{141}Ho. Since the major assumption in these calculations is that the nucleus is spherical or nearly spherical, the failure of the WKB calculations to account for the observed half-life strongly suggests that ^{141}Ho is highly deformed. A number of calculations point to the presence of deformation in this region. The macroscopic-microscopic mass model [4] predicts that a rapid transition between near spherical and highly deformed shapes takes place between Tm and Ho isotopes in this region of the proton drip line. A ground-state prolate deformation of $\beta_2 = 0.29$ is calculated for ^{141}Ho. Recent deformed Hartree-Fock calculations for proton-rich nuclei also predict a high deformation $\beta_2 = +0.33$ for the neighboring even-Z nucleus ^{138}Dy [14]. In addition, Ω_p^π, the angular momentum projection on the nuclear symmetry axis for the odd proton, is predicted by Möller *et al.* to be $7/2^-$ [12], corresponding to the $7/2^-[523]$ Nilsson configuration. This same configuration is observed for the deformed ground states of odd-A Ho isotopes with $N > 88$ [15]. Another possibility for the odd proton in ^{141}Ho is the nearby $1/2^+[411]$ orbital.

The predictions of Möller *et al.* place ^{131}Eu in the middle of the region of high prolate deformation with $\beta_2 = 0.33$ and an Ω_p^π value of $3/2^+$, corresponding to a $3/2^+[411]$ configuration for the ground state [4,12]. However, the nearby $5/2^+[413]$ and $5/2^-[532]$ Nilsson levels are also possibilities. In fact, the $5/2^+[413]$ configuration has been assigned to the ground states of all of the deformed odd-A Eu isotopes with $N > 88$ where known [15]. If ^{131}Eu had a spherical ground-state configuration the odd proton would occupy either a $1d_{5/2}$ or $0g_{7/2}$ state lying immediately below the $Z = 64$ shell closure. A low-seniority shell model calculation of the type successfully applied to the nuclei above the $Z = 64$ shell closure would imply spectroscopic factors of $1/3$ or $1/7$ for the $1d_{5/2}$ state, and $1/4$ or $1/7$

for the $0g_{7/2}$ state, depending on whether a subshell or supershell model space is assumed. This would give WKB half-life predictions $\sim$1 ms for the $1d_{5/2}$ state and a few hundred ms for the $0g_{7/2}$ state, neither of which is consistent with the measured value. Again the failure of these calculations can be attributed to the expected strong deformation of ^{131}Eu.

We have calculated the partial proton decay rates of ^{141}Ho and ^{131}Eu using the formalism for the proton decay of deformed nuclei developed by Bugrov and Kadmenskii [6,16,17]. This model was first developed to account for the anomalous proton decay rates of ^{109}I and ^{133}Cs, which were thought to be due to the influence of small deformations ($\beta_2 \sim 0.1$) in that region [5,6]. Their model treats the axially symmetric deformed odd-A decay parent as an inert core plus an odd proton in a quasibound state. It can be shown that this approach is equivalent to the Distorted Wave Born Approximation method of Ref. [3], adapted to deformed nuclei. The wave function of the odd proton in the intrinsic or body-centered coordinate system of the nucleus can be expressed as a sum of spherical components having constant ℓ, j, and projection Ω:

$$\Psi(N\Omega) = \sum_{j\ell} c_{j\ell}(N\Omega)\,|N\ell j\Omega\rangle,$$

where N denotes the number of oscillator quanta. Only the parity and projection Ω of the proton angular momentum j on the nuclear symmetry axis are good quantum numbers. The coefficients $c_{j\ell}(N\Omega)$ determine the probability that the proton has a given j and ℓ. For the case of ^{141}Ho, with the odd proton in the $7/2^-[523]$ orbital, the wave function consists of a sum of $1f_{7/2}$, $0h_{9/2}$, and $0h_{11/2}$ components, from which an $\ell_p = 3, j_p = 7/2^-$, proton is emitted to the 0^+ ground state of the even-even daughter nucleus ^{140}Dy.

Bugrov and Kadmenskii give an expression for the proton decay amplitude B [6], from which the width Γ and the decay half-life $t_{1/2}$ may be obtained:

$$B = \left[\frac{2(2J_f+1)}{2J_i+1}\right]^{1/2} \langle J_f j_p 0 K_i \,|\, J_i K_i\rangle U_f(K_i) \sum_{\ell j, m_s} c_{j\ell}(NK_i) \left\langle \ell_p \, \frac{1}{2} \, K_i - m_s m_s \;\middle|\; j_p K_i \right\rangle$$
$$\times \left\langle \ell \, \frac{1}{2} \, K_i - m_s m_s \;\middle|\; jK_i \right\rangle \left\langle Y_{\ell_p}^{K_i - m_s}(\theta',\phi') \frac{F_{\ell_p}(kr,\eta)}{r} \;\middle|\; V_{pA}(\mathbf{r}) + V_{\mathrm{Coul}}^{\mathrm{nonspher}}(\mathbf{r}) \;\middle|\; \frac{R_{n\ell j}(r)}{r} Y_\ell^{K_i - m_s}(\theta',\phi') \right\rangle.$$

Here J_i and K_i are the total angular momentum and its projection on the symmetry axis for the deformed parent nucleus, J_f is the angular momentum of the daughter nucleus, $U_f(K_i)$ is the probability amplitude that the K_i orbital in the daughter nucleus is not occupied, $F_\ell(kr,\eta)$ is the (regular) Coulomb function, and $R_{n\ell j}(r)$ is the radial part of the proton quasibound state wave function. In our calculations, the potential $V_{pA}(\mathbf{r})$ consists of the real part of the deformed optical potential between the proton and the daughter nucleus, and includes the spin-orbit term. The nonspherical Coulomb potential $V_{\mathrm{Coul}}^{\mathrm{nonsph}}(\mathbf{r})$ is comprised of quadrupole and hexadecapole components. The effect of having $Y_{20}(\theta')$ terms in the deformed nuclear potential $V(\mathbf{r}) = V_{pA}(\mathbf{r}) + V_{\mathrm{Coul}}^{\mathrm{nonsph}}(\mathbf{r})$ is to permit angular momentum exchange between the outgoing proton and the core during the decay. Thus, the decay amplitude contains the diagonal matrix element $\langle \ell_p j_p | V | \ell j\rangle$ with $\ell = \ell_p$ and $j = j_p$, as well as nondiagonal matrix elements having other ℓ values of the same parity as ℓ_p and $j = \ell \pm 1/2$ with $N + 1/2 \geq j \geq K_i$.

The $c_{j\ell}(NK_i)$ spherical expansion coefficients were obtained using the eigenvalue procedure described by Andersen, Back, and Bang [18]. The advantage of this method is that it allows the same potential to be used for the calculation of both the spherical expansion coefficients and the spherical wave functions. The $c_{j\ell}(NK_i)$ coefficients obtained in this way are similar to those obtained using a deformed harmonic oscillator potential [19].

Proton partial half-lives have been calculated for the decays of ^{141}Ho and ^{131}Eu, for β_2 values between 0.25 and 0.35. An examination of the radial behavior of the decay amplitudes shows that the region within a few fm on either side of the nuclear surface accounts for $>$95% of the strength. Half-lives have been calculated for ^{141}Ho assuming that the odd proton occupies the $7/2^-[523]$ and $1/2^+[411]$ Nilsson orbitals, and for ^{131}Eu assuming the $3/2^+[411]$, $5/2^+[413]$, and $5/2^-[532]$ orbitals. For ^{141}Ho, the $1/2^+[411]$ case is ruled out because the calculated half-lives are in the vicinity of 15 μs, and for ^{131}Eu the $5/2^-[532]$ case is ruled out because the calculated half-lives are greater than 0.5 s. In these calculations, we have neglected both the effects of pairing in the daughter wave function [by setting $U_f(K_i)^2 = 1$], and possible small shape differences between parent and daughter nuclei. Incorporating pairing increases the calculated half-lives by a factor of $1/U_f(K_i)^2$.

Figure 2 shows the calculated proton partial half-lives for ^{141}Ho and ^{131}Eu as a function of deformation. The $7/2^-[523]$ calculations for ^{141}Ho are consistent with the observed half-life over a wide range of high β_2 values. For this nuclide the contributions to the decay amplitude from the diagonal matrix element $\langle \ell_p = 3, j_p = 7/2 | V | n\ell j = 1f_{7/2}\rangle$ [$c_{j\ell}(NK_i) = 0.18$–0.21] and the nondiagonal matrix element $\langle \ell_p = 3, j_p = 7/2 | V | n\ell j = 0h_{11/2}\rangle$ [$c_{j\ell}(NK_i) = 0.97$] are approximately in the ratio 1.5:1. In the case of ^{131}Eu, good agreement is obtained using the $3/2^+[411]$ configuration with a deformation $\beta_2 \gtrsim 0.3$, for which the $1d_{3/2}$, $1/d_{5/2}$, and $0g_{7/2}$ spherical states make comparable contributions to the decay amplitude. This is consistent with the predictions of Möller *et al.* [4,12], which indicate a $3/2^+[411]$ ground-state configuration with a corresponding deformation

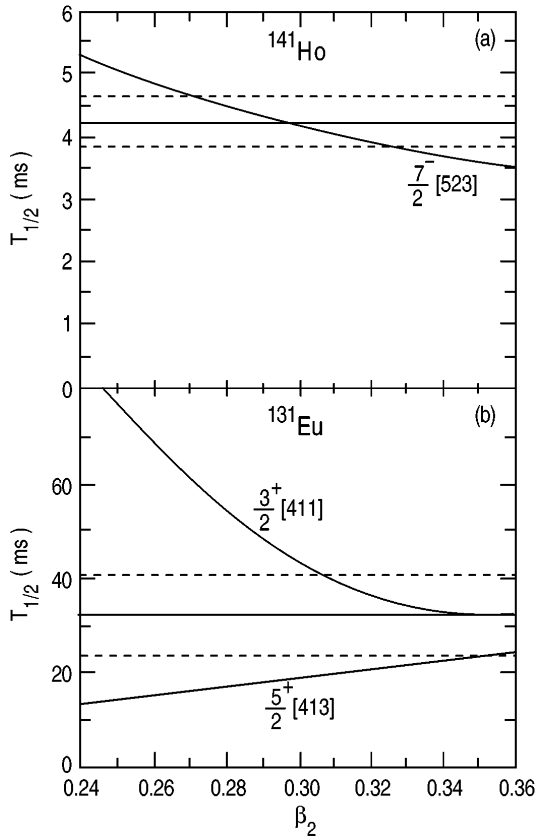

FIG. 2. (a) Calculated proton decay half-life for ^{141}Ho based on the $7/2^-[523]$ Nilsson orbital. The observed half-life lies in the band between the dashed lines. A β_2 value of 0.29 is predicted by Ref. [4] for ^{141}Ho. (b) Calculated proton decay half-life for ^{131}Eu based on the $3/2^+[411]$ and $5/2^+[413]$ Nilsson orbitals. The observed half-life lies in the band between the dashed lines. A β_2 value of 0.33 is predicted by Ref. [4] for ^{131}Eu. Pairing has been neglected $[U_f(K_i)^2 = 1]$ in both (a) and (b) (see text for details).

$\beta_2 = +0.33$. However, it can be seen from Fig. 2 that the $5/2^+[413]$ configuration also gives reasonable agreement for high deformations, and cannot be ruled out as a possibility. The dominant contribution for this decay comes from the $\langle \ell_p = 2, j_p = 5/2 | V | n\ell j = 1d_{5/2}\rangle$ diagonal matrix element, with $c_{j\ell}(NK_i) = 0.24$–0.30.

In summary, the proton decays of ^{141}Ho and ^{131}Eu have been identified. The decay rates are consistent with emission from highly deformed nuclear configurations, indicating the rapid onset of large deformations below $Z = 69$, as has been predicted theoretically for this region of the proton drip line. These measurements have provided clear evidence of the effect of large deformations on proton decay rates. In particular, the ^{141}Ho result is a dramatic departure from previous proton decay measurements which were well reproduced assuming a spherical shell model space for the $Z = 64$–82 region of the proton drip line. It is important to find further examples of proton decays in this region in order to further test and develop theoretical models of proton decays from highly deformed nuclei. In addition, gamma-ray studies of such nuclei would be extremely valuable since they can be used to independently determine the ground-state deformation and, hence, to constrain theoretical calculations.

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