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Proton decay of the highly deformed nucleus ^{135}Tb

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The proton decay of the highly deformed nucleus ^{135}Tb has been observed following bombardment of a ^{92}Mo target with a 310 MeV beam of ^{50}Cr ions. This is the first instance of a proton-decaying isotope being produced via the $1p6n$ fusion-evaporation channel. Evaporation residues were separated in-flight using the Argonne fragment mass analyzer and implanted into a new design double-sided silicon strip detector. ^{135}Tb decays by the emission of a proton with energy $E_p=1179(7)$ keV $[Q_p=1188(7)$ keV$]$ and half-life $t_{1/2}=0.94^{+0.33}_{-0.22}$ms. The transition is assigned to a highly deformed $(\beta_2\sim 0.3)$ $J^\pi=7/2^-$ configuration by comparing the proton decay rate with calculations for deformed nuclei.

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Proton radioactivity has now been identified in large swathes of the proton drip-line from $Z=51-83$ [1]. Great interest has been generated by the discovery of anomalous proton decay rates in the isotopes ^{131}Eu and ^{141}Ho [2]. These decay rates were found to be consistent with deformed nuclear shapes [2]. Subsequently, the observation of proton decay fine structure [3] and in-beam gamma-rays [4] has confirmed this picture. Substantial theoretical activity has been generated on the topic of proton decays from highly deformed nuclei since they provide uniquely detailed insights into the role of nuclear shapes in proton tunneling [5–7]. However, relatively few examples of proton decays from highly deformed nuclei are known, severely limiting tests of the general validity of these different theoretical approaches. All of the few remaining undiscovered proton emitters in the region of highly deformed rare earth nuclei are expected to be produced with very small cross-sections. The present paper describes the observation of proton decay from ^{135}Tb using for the first time the very weak $1p6n$ fusion evaporation channel.

The experiment was performed using the ATLAS accelerator system at Argonne National Laboratory. A 775 μg/cm^2 thick rotating target of ^{92}Mo was bombarded for approximately five days with a ~9 pnA 310 MeV ^{50}Cr beam, forming ^{135}Tb via the $1p6n$ fusion-evaporation channel. Fusion-evaporation reaction products entered the fragment mass analyzer (FMA) [8], where they were dispersed at the focal plane by mass/charge state (A/q). After passing through a thin gas-filled position-sensitive parallel grid avalanche counter (PGAC), recoils were implanted into a new design double-sided silicon strip detector (DSSD) [9]. The DSSD consists of 80 sets of orthogonal strips with a pitch of 400 μm, forming 6400 quasipixels within which implanted nuclei and their subsequent decays are time- and position-correlated. The DSSD combines a large active area with high segmentation, and was introduced to improve the sensitivity of searches for very low cross-section proton emitters. The present experiment represented the first use of this system. In this instance, a pair of slits was placed upstream of the PGAC allowing only the passage of $A=135$ recoils with charge states q of 25 and 26 onto the DSSD. Behind the DSSD was located a large-area silicon detector of thickness 300 μm which was used to veto decay events resulting in particles (β-delayed protons and positrons) which emerged from the back of the DSSD.

Figure 1 shows the spectra of events in the DSSD following the decay of $A=135$ recoils for differing implantation-decay time intervals. There is a broad distribution of low energy events which is most probably associated with a pileup of unvetoed positrons, and β-delayed protons escaping from the front face of the DSSD. At higher energies there is an essentially flat background, which we attribute mainly to β-delayed protons. Figure 1(c), corresponding to decays occurring within 6 ms of implantation, shows clear evidence for a peak around 1.2 MeV, with very little background present. The energy is too low to be from an α-decay so we assign this to proton decay. The energy of the peak is found to be $E_p=1179(7)$ keV using the known ground-state proton decay of ^{147}Tm as a calibration. This corresponds to a proton decay Q-value $Q_p=1188(7)$ keV. The half-life of the peak is found to be $t_{1/2}=0.94^{+0.33}_{-0.22}$ ms using the method of maximum likelihood, and its production cross-section is ~3 nb. The $A=135$ isotopes ^{135}Gd and ^{135}Eu are predicted to be proton bound [10] and are therefore unlikely to be candidates for proton radioactivity. The more exotic, even Z, isotope ^{135}Dy is predicted to be slightly proton unbound [10], however it would have to be produced via the $7n$ fusion evaporation

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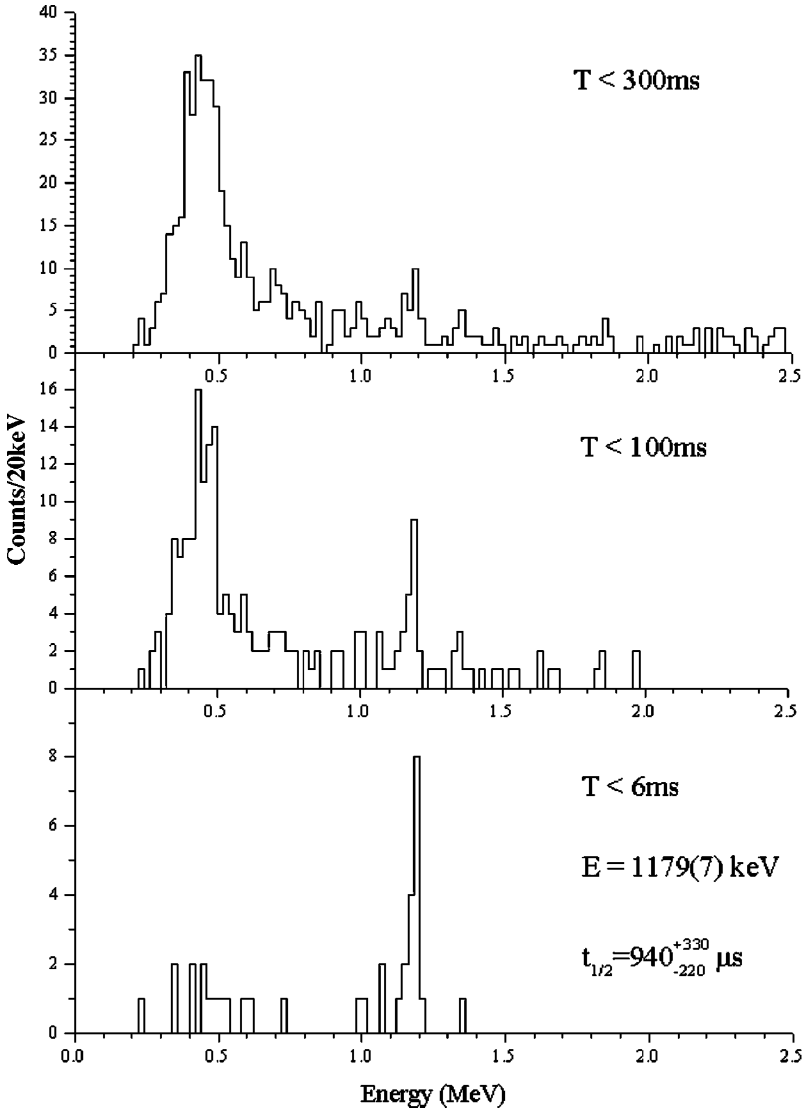

FIG. 1. Decay events from the reaction ^{50}Cr + ^{92}Mo, restricted by slits to $A=135$ recoils for (a) decay events occurring within 300 ms of an implant event in the same DSSD pixel (b) similarly for 100 ms and (c) 6 ms.

channel making the cross section unfeasibly low.

^{135}Tb is predicted to have $Q_p=1.15$ MeV by the macroscopic-microscopic mass model calculations of Möller *et al.* [10]. This model has been quite successful in predicting Q_p in this mass region, and is in excellent agreement with the experimental value reported here. No previous measurements have been made of 1p6n evaporation channels in the region of the proton drip-line. However, there have been two successful measurements of proton-decaying isotopes produced in this region via 1p5n evaporation channels (^{130}Eu [11], and ^{140}Ho [12]) with cross sections ~10 nb. This would lead to an expectation of a cross section ~1 nb for the 1p6n channel, in reasonable accord with the experimental value. On the basis of all the above evidence we assign the peak to the proton decay of ^{135}Tb. The predicted β-decay half life for ^{135}Tb [10] is 193 ms, we therefore assume for the present purposes a 100% proton decay branch.

If initially we assume a spherical shape for ^{135}Tb this implies proton decay from either $s_{1/2}$, $d_{3/2}$, or $h_{11/2}$ orbitals. However, WKB calculations give half-lives ~3 orders of magnitude too short for the low spin orbitals, and an order of magnitude too long for the high spin state. In fact, the ground state of ^{135}Tb and its daughter ^{134}Gd are both predicted to have highly deformed prolate shapes, $\beta_2 \sim 0.33$ [13]. The odd proton is predicted to occupy a $3/2^+[411]$ Nilsson configuration [10], although $5/2^+[413]$ and $7/2^-[523]$ configurations are expected to lie close to the Fermi surface.

Calculations of the decay rate of ^{135}Tb as a deformed proton emitter were carried out in the adiabatic limit using the Green's function technique of Ref. [5] for the $3/2^+$, $5/2^+$, and $7/2^-$ proton configurations. The calculated half-lives for ^{135}Tb proton decay are shown in Fig. 2, plotted as a function of β_2 and compared with the measured half-life (shown as a horizontal band). The calculated half-lives have been divided by the spectroscopic factor $u^2=0.57$, obtained from a BCS calculation. The inputs to the BCS calculation include single-particle energies obtained from a calculation similar to that shown for ^{131}Eu in Fig. 5 of Ref. [5]. A value of Δ_p $=0.85$ MeV was used for the proton pairing gap energy, obtained from calculated odd-even mass differences [13]. It can be seen from Fig. 2 that very good agreement is obtained for the $7/2^-[523]$ orbital with a deformation $\beta_2=0.33$, but the calculations do not agree well for the alternative $3/2^+[411]$ and $5/2^+[413]$ orbitals. On this basis we assign the proton

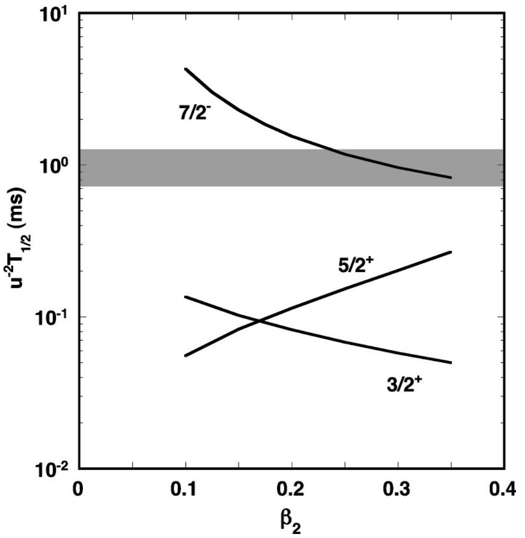

FIG. 2. Proton half-life versus quadrupole deformation β_2 for ^{135}Tb. The shaded area encloses the measurement. Calculations assuming a spectroscopic factor $u^2=0.57$ are shown for $7/2^-[523]$, $5/2^+[413]$, and $3/2^+[411]$ proton Nilsson configurations for a prolate shape.

decay transition to a $7/2^-[523]$ orbital in highly prolate deformed ^{135}Tb. The observation of proton decay from this orbital rules out a lower-lying $5/2^+[413]$ configuration since this would have a fast $E1$ gamma transition, and no proton decay branch from the $7/2^-[523]$ orbital would be observed. However, the existence of a lower lying, ground-state $3/2^+[411]$ configuration cannot be ruled out as the $E3$ transition from a $7/2^-$ isomeric state would be significantly slower than the measured proton decay branch. It is worth noting that the $3/2^+[411]$ configuration was also predicted to be the highly prolate deformed ground-state configuration of the neighboring proton emitter ^{131}Eu [10,13], which was subsequently confirmed with the observation of proton decay fine structure from this orbital [3]. It is also interesting that the proton emitting state is the same configuration as was found for the nearby proton emitter ^{141}Ho [2].

In the present case a deformation $\beta_2 \sim 0.33$ would imply an excitation energy ~120 keV for the lowest-lying 2^+ state in the daughter nucleus ^{134}Gd [14,15]. Our calculations predict an 8% fine structure branching ratio to this state. There are in fact two events corresponding to this proton energy, lying ~115 keV below the main proton decay peak in Fig. 1(c), which would imply a ~10–20% proton decay fine structure branch. However, in the absence of further statistics, no firm conclusion can be made regarding the observation of proton decay fine structure for ^{135}Tb.

In summary, proton decay has been observed from ^{135}Tb, the first example of this decay mode being produced by the very weak $1p6n$ fusion evaporation channel. A comparison with decay rate calculations supports a transition from a highly prolate-deformed $7/2^-[523]$ proton configuration. These results provide a further important test for theories of proton decay from deformed nuclei. Only two remaining elements, Pr and Pm, have yet to have proton decay branches identified in this region. The present result, and Q-value systematics, indicate it is likely that in each case at least a production reaction involving the $1p6n$ fusion-evaporation channel will be required (using stable nuclei) for proton decay to predominate. This is consistent with the recent nonobservation of proton decays from ^{126}Pm produced via the $1p5n$ evaporation channel [16].

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