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Proton radioactivity of ^{117}La

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A new more precise measurement of the ground-state proton decay of ^{117}La is presented [$E_p = 806(5)$ keV, $t_{1/2,p} = 26(3)$ ms]. ^{117}La was produced via the $p4n$ fusion-evaporation channel by bombarding a ^{64}Zn target with 310 and 295 MeV ^{58}Ni beams. The proton decay rate is consistent with emission from a prolate deformed $3/2^+$ or $3/2^-$ Nilsson state. No evidence is found for a previously reported proton decay from a high spin isomer in ^{117}La. An upper limit for the production cross section for proton decay of ^{116}La at a bombarding energy of 325 MeV was established.

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The study of proton emitting nuclei has provided valuable spectroscopic information on the structure of nuclei far from stability. Proton decays of drip-line nuclides in the $68 < Z < 82$ region are well reproduced by WKB calculations [1], assuming spherical shell model configurations. However, proton decay rates in the transitional region beyond the $Z = 50$ shell closure (^{109}I and ^{112,113}Cs [2,3]) and in the region of light rare-earth nuclei (^{131}Eu and ^{140,141}Ho [4,5]) require calculations assuming significant prolate deformations. The study of gamma transitions from a band built on the ground state of ^{141}Ho [6], and the observation of fine structure in the proton decay of ^{131}Eu [7] have provided independent confirmation of the deformed nature of these nuclei. Most recently, proton radioactivity has been reported for ^{117}La, lying between the transitional and deformed regions of proton emitting nuclei [8]. In this case proton radioactivity was claimed for both ground and isomeric state decays. The background in this experiment was reported as being high and signals were only taken from one side of the double-sided silicon strip detector (DSSD). The present Rapid Communication reports a new measurement of proton radioactivity from ^{117}La with low background and improved precision.

A 3 pnA ^{58}Ni beam from the Argonne ATLAS accelerator bombarded a 730 μg cm^{-2} thick ^{64}Zn target at an energy of 310 MeV for 10 h and 295 MeV for 14 h, producing center-of-target excitation energies of 90 and 82.5 MeV, respectively. The first beam energy was the same as that used at Legnaro National Laboratory where ^{117}La was first reported [8], the second was the energy at which a HIVAP [9] calculation predicted the maximum yield for the $1p4n$ evaporation channel required to produce ^{117}La. Fusion-evaporation residues passed through the fragment mass analyzer (FMA) [10] where they were separated in-flight according to their mass/charge ratio. The FMA was set to transmit $A = 117$ recoils with charge states +30 and +31 through two mechanical slits situated in front of a multiwire proportional counter (MWPC) at the focal plane of the FMA. The MWPC provided energy loss, timing, and position (A/Q) information. After passing through the MWPC, recoil ions were implanted into a 60 μm thick, 40×40 mm^2 DSSD with strips of 1 mm pitch. Both sides of the DSSD were fully instrumented, producing a significantly lower background than the experiment of Ref. [8] for correlations between implanted ions and subsequent decays. The energy resolution of the DSSD was ~25 keV FWHM. A large area Si detector was placed behind the DSSD to provide a veto for the 50% of β-delayed protons escaping in the forward direction, while a silicon box was used to veto events in which protons escaped in the backward direction. A 10 MHz clock was used to time-stamp the implantation and decay events, which were identified by MWPC-DSSD signal coincidences and anticoincidences, respectively. The DSSD implantation rate was typically ~1 kHz.

Figure 1(a) shows the energy spectrum for all decay events measured in the DSSD showing events from both runs, at 295 and 310 MeV. There is a broad continuum of β-delayed protons around 3 MeV, with a strong peak corresponding to the alpha decay of ^{109}Te produced as a charge state ambiguity. The continuum of events increasing in intensity below 1 MeV corresponds to escaping β-delayed protons. Despite this background a peak can be seen around 800 keV. A time condition was then applied, requiring a single decay occurring in a pixel within 60 ms of a recoil being implanted. The resulting spectrum is shown in Fig. 1(b). This clearly reveals the presence of a prominent peak with ~100 counts, corresponding to a cross section of ~240 nb (with a factor of 2 uncertainty). This is consistent with a cross section of 200 nb reported in Ref. [8] for the ground-state proton decay of ^{117}La.

The half-life measured here $t_{1/2} = 24(3)$ ms is more precise, but in excellent agreement with the value of 22(5) ms reported in Ref. [8]. These data therefore provide support for the observation of the ground-state proton decay of ^{117}La. The proton decay peak was calibrated using well-known ground and isomeric proton decays from ^{147}Tm [E_p

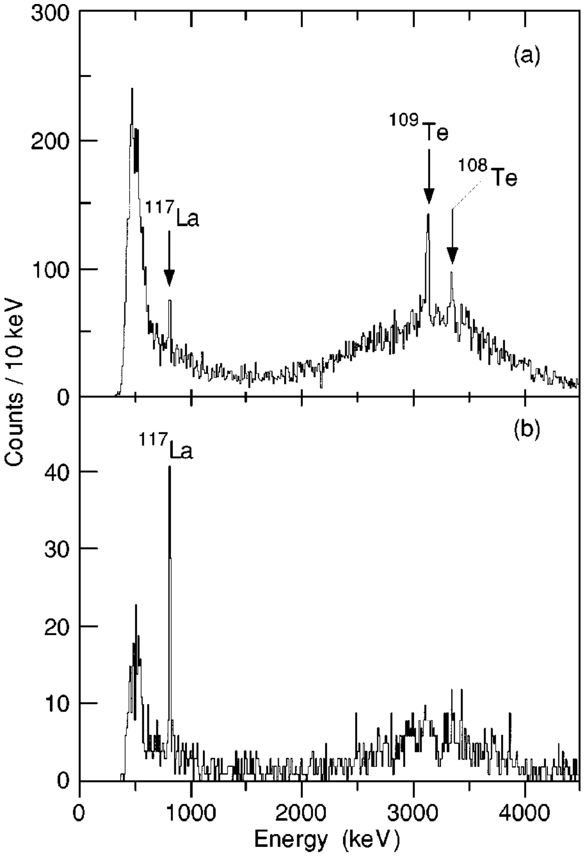

FIG. 1. Decay energy spectrum of all decays occurring within the DSSD and below 4.5 MeV, for both the 295 and 310 MeV ^{58}Ni beam bombarding a ^{64}Zn target for a combined total of 24 h with (a) no time gate and (b) a 60 ms time gate.

$=1051.0(3.3)$ keV and 1110.8(3.9) keV] and a value of $E_p=806(5)$ keV was obtained. This value is not in good agreement with the value of $E_p=783(6)$ keV obtained in Ref. [8], also calibrated using the ground-state proton decay line from ^{147}Tm. Despite this energy discrepancy it is most probable that both experiments have observed the same transition. Correcting for nuclear recoil [11], the present data give a proton decay Q value, $Q_p=813(5)$ keV. The ground-state β-decay partial half-life of ^{117}La is predicted to have a value $t_{1/2,\beta}=388$ ms [12], yielding a ground-state partial proton half-life $t_{1/2,p}=26(3)$ ms.

The $g_{7/2}$ and $d_{5/2}$ proton orbitals are expected to lie near the Fermi surface in this region. WKB calculations using the real part of the Becchetti-Greenlees optical potential [13] give proton partial half-life predictions of $t_{1/2,p}=86$ ms for a $\pi g_{7/2}$ configuration and 234 μs for a $\pi d_{5/2}$ configuration. The $g_{7/2}$ configuration can be ruled out since it implies an unphysical spectroscopic factor well in excess of unity. The $d_{5/2}$ spectroscopic factor implied by this analysis equals 0.01. This very low value indicates that the transition cannot be understood as occurring from a pure spherical shell model configuration, but must be considered as originating from a deformed configuration.

Calculations of the decay rate for ^{117}La have been performed using the adiabatic approach described in Ref. [14], which was very successful in explaining the decay rates of the deformed proton emitters ^{131}Eu, ^{141}Ho, and ^{141}Ho^m. The interaction between the quasibound proton and the deformed core includes deformed nuclear, spin-orbit, and Coulomb terms, with the parameters given in Appendix A of Ref. [14]. The depth of the nuclear potential was adjusted to reproduce the experimental energy, corrected for recoil and atomic screening effects. Candidate deformed orbitals include $K=3/2^+$, $K=3/2^-$, and $K=1/2^-$. Pairing effects have not been included (see below).

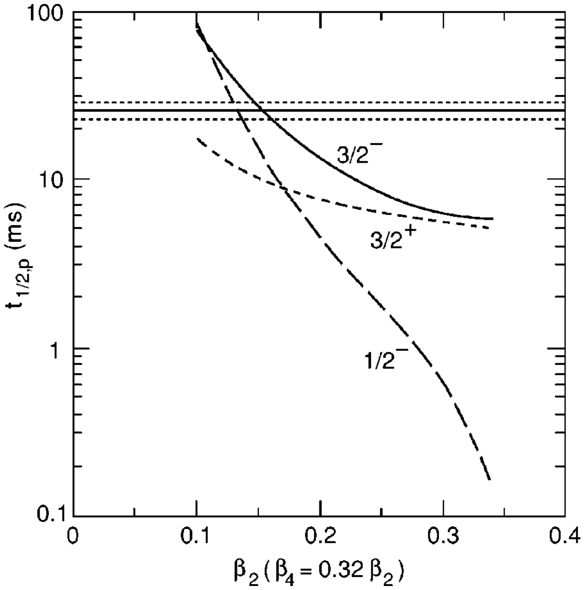

FIG. 2. Calculated proton partial half-lives for ^{117}La, for spins of $1/2^-$, $3/2^+$, and $3/2^-$. The horizontal lines represent the experimental value with uncertainties.

Figure 2 shows the predicted proton decay half-lives for these spins, plotted as a function of β_2. The corresponding value of β_4 was set to $0.32\beta_2$. Smith *et al.* [15] have extracted β_2 values of 0.24–0.27 for ^{124,122,120,118}Ba from experimental 2^+ excitation energies. These are consistent with the predictions of Möller *et al.* [16] for these even-even neutron-deficient Ba isotopes. Möller *et al.* [16] predict deformations for the daughter nucleus ^{116}Ba of $\beta_2=0.28$ and $\beta_4=0.09$, and a ^{117}La ground-state spin of $3/2^+$. At this deformation, $J=3/2^-$ and $J=1/2^-$ are also expected to be close to the Fermi surface. Thus, for deformations $\beta_2>0.2$, as we expect is the case for ^{116}Ba, the $J=1/2^-$ option for ^{117}La appears to be ruled out. Under these circumstances, Fig. 2 suggests that the ground-state spin of ^{117}La is either $3/2^+$ or $3/2^-$. The experimental spectroscopic factors using $\beta_2=+0.28$ and $\beta_4=+0.09$ [16] are 0.23(5) and 0.27(6) for $J=3/2^+$ and $J=3/2^-$, respectively, with the uncertainties reflecting experimental half-life and proton energy uncertainties. BCS calculations give a spectroscopic factor for the ground-state decay of ~ 0.6. For either spin the calculated branching ratio for decay to the 2^+ state of the daughter nucleus is too small to be observed, since the excitation energy is expected to be ~ 200 keV or higher.

The isomeric state proton decay reported for ^{117}La in Ref. [8] was not observed in the present work. According to [8], it was produced with a cross section $\sim 1/3$ that of the ground-state peak at an energy $E_p = 933(10)$ keV, or 150 keV above the ground-state transition, with a half-life $t_{1/2} = 10(5)$ ms. Such a peak should be clearly visible in Fig. 1(b) but there is no evidence for it. Our data indicate an upper limit on the cross section for producton of an isomeric transition of < 10 nb, or $\sim 4\%$ of the ground-state yield. In [8] the isomer was identified as a $9/2^+$ configuration. This is an unusual result since in previous studies of proton emitters produced using heavy ion fusion-evaporation reactions, high-spin states were produced more strongly than low-spin states. We note that a $9/2^+$ assignment for our 806(5) keV transition is ruled out because the predicted partial proton half-life is 350 ms for $\beta_2 = +0.28$, implying a combined half-life approximately an order of magnitude larger than the measured value.

A search for the proton decay of ^{116}La was also undertaken during the same experiment. The 773 μg cm^{-2} thick ^{92}Mo target was bombarded by a 325 MeV ^{58}Ni beam for 29 h, and no identifiable proton peak was observed. This sets an upper limit on the cross section at that bombarding energy for producing ^{116}La at ~ 5 nb for proton decays with half-lives 20 $\mu\text{s} \leqslant t_{1/2} \leqslant 20$ ms. This limit could imply a reduction in cross section by a factor of greater than 50 for the $1p5n$ compared to the $1p4n$ evaporation channel. Information on the relative yields of these evaporation channels is limited in this region of the proton drip-line, but where information is known it suggests a factor ~ 30 reduction is more typical [5,17]. Generally speaking, odd-odd proton emitters have very similar decay energies to neighboring odd-even proton emitters lying closer to stability and, for the same proton configuration, have similar half-lives. However, the nearby I and Cs isotopes are found to have significantly reduced proton decay Q-values for the odd-odd partner [3]. The nonobservation could also therefore be due to a relatively low proton energy for ^{116}La, in which case (nonobservable) β-decay modes could become competitive. Proton decay Q-value systematics suggest it is unlikely that the proton decay is too short-lived to be observed.

In summary, we have observed the ground-state proton decay of ^{117}La, confirming an earlier measurement [8], but do not observe the isomeric state decay reported in that work. Proton decay calculations for a deformed emitter indicate that the ground-state spin of ^{117}La is $3/2^+$ or $3/2^-$.

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