PHYSICAL REVIEW C, VOLUME 63, 031304(R)

New strongly deformed proton emitter: ^{117}La

F. Soramel,[1] A. Guglielmetti,[2] L. Stroe,[3,4] L. Müller,[3] R. Bonetti,[2] G. L. Poli,[2] F. Malerba,[2] E. Bianchi,[2] A. Andrighetto,[3] J. Y. Guo,[3,6] Z. C. Li,[3,6] E. Maglione,[3] F. Scarlassara,[3] C. Signorini,[3] Z. H. Liu,[5,6] M. Ruan,[5,6] M. Ivaşcu,[4] C. Broude,[7] P. Bednarczyk,[8] and L. S. Ferreira[9]

[1]*Dipartimento di Fisica and INFN, University of Udine, via delle Scienze 208, I-33100 Udine, Italy*
[2]*Istituto di Fisica Generale and INFN, University of Milano, via Celoria 16, I-20133 Milano, Italy*
[3]*Dipartimento di Fisica and INFN, University of Padova, via Marzolo 8, I-35131 Padova, Italy*
[4]*NIPNE, P.O. Box MG-6, R.O.-76900 Bucharest - Magurele, Romania*
[5]*INFN, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Padova, Italy*
[6]*CIAE, P.O. Box 275(10), Beijing 102413, People's Republic of China*
[7]*Weizmann Institute of Science, P.O. Box 26, 76100 Rehovot, Israel*
[8]*IFJ, ul. Radzikowskiego 152, 31-342 Kraków, Poland*
[9]*Centro de Física das Interacções Fundamentais, 1096 Lisboa, Portugal*

(Received 3 October 2000; published 14 February 2001)

The decay by proton emission of the ^{117}La nucleus has been studied via the 310 MeV ^{58}Ni+^{64}Zn reaction. The nucleus has two levels that decay to the ground state of ^{116}Ba with $E_p=783(6)$ keV ($T_{1/2}=22(5)$ ms] and $E_p=933(10)$ keV [$T_{1/2}=10(5)$ ms]. Calculations performed for a deformed proton emitter reproduce quite well the experimental results confirming that ^{117}La is strongly deformed ($\beta_2\sim0.3$). Spin and parity of the two p-decaying levels have been determined as well: $3/2^+$ for the ground state and $9/2^+$ for the $E_x=151(12)$ keV excited state.

DOI: 10.1103/PhysRevC.63.031304 PACS number(s): 23.50.+z, 27.60.+j, 21.10.Tg

The study of drip line nuclei is very important, since it provides a unique tool to get spectroscopic information on nuclei far away from the stability valley. From the theoretical point of view these studies permit a stringent test on models of the nuclear mean field and their dependence on isospin. Recently many proton emitters with $Z>50$ have been found and their decay properties determined [1,2]. First examples of p emitters, produced via $(p,2n)$ and $(p,3n)$ evaporation channels and located in the region $68<Z<82$, have been interpreted by means of simple WKB calculations as being spherical. However, in the region $50<Z<64$ the predicted p emitters are expected to be quite deformed in their ground state ($\beta\sim0.3$) [3], thus making their interpretation more difficult due to the complexity of the emitted proton wave function. Moreover, while many spherical p emitters are connected with other nuclei through α decay chains, in the deformed region α decay is rather uncommon and only a very restricted group of nuclei has a measurable α-decay branch. This implies that in the $50<Z<64$ region one cannot use the daughter and granddaughter α decays to tag the proton decay.

Finally, a complete explanation of the p emission process should be able to describe this decay as a function of the deformation parameter. Thus it is very important to study and characterize the p emission from deformed nuclei in order to fine tune the theoretical description of this process.

First experiments on ^{109}I [4], ^{112,113}Cs [4–6] performed at Munich and Daresbury pointed out that for these transitional nuclei an interpretation as spherical nuclei is not enough. Indeed calculations including the deformation parameter β [7,8] have been able to give a coherent description of these nuclei. Recent experiments [9,10] have measured the p decay of well-deformed nuclei such as ^{140,141}Ho and ^{131}Eu. All the proton emitters below these nuclei and with $Z>54$ are expected to have strongly deformed ground states, among them ^{117}La is predicted to have $\beta_2=0.29$ [3].

The measurement of ^{117}La decay by proton emission (a first report is given in Ref. [11]) has been carried out at the Legnaro National Laboratories. The reaction was ^{64}Zn(^{58}Ni,$p4n$)^{117}La at 310 MeV, the target was a 1 mg/cm^2 self-supporting foil. The beam was delivered by the Tandem + LINAC accelerator of Legnaro with an average intensity of 1.5 pnA. The experimental setup used the Recoil Mass Spectrometer (RMS) [12] with its maximum solid angle acceptance (10 msr), together with a DSSD (double sided silicon strip detector) placed one meter downstream of the RMS focal plane. Combining the RMS A/q selectivity, the spatial and energy information given by the DSSD, and an absolute clock (4 MHz) for half-life measurements, it is possible to measure the decay properties of nuclei with half-lives between $\sim$50 μs and a few seconds (this is a well-known technique developed and applied for the first time at the Daresbury RMS [13,14] and, later, at the Argonne FMA [15]). Among all the recoils focused on the RMS focal plane (and detected with a parallel plate avalanche counter) only those falling in the range $(A-1)/q-(A+1)/q$ with respect to the central A/q path, are implanted in the DSSD. The DSSD has (40×40) strips, 1 mm wide and a thickness of 60 μm. To reduce the high recoil energy that would saturate the amplifiers, a degrader foil of 2 mg/cm^2 natural Ni was inserted in front of the DSSD.

The DSSD signals are treated differently on the two sides; in vertical direction (x side) strips are acquired separately to get both position and energy information, while in horizontal direction (y side) all strips are read together through a delay line (2 ns per strip). Preamplifiers for vertical strips are hosted in the detector chamber. Cooling of both detector and preamplifier supports is guaranteed by Peltier elements with

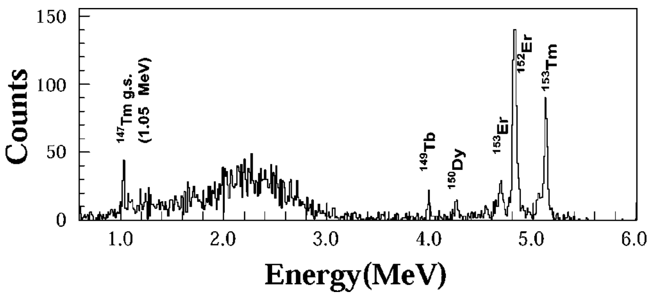

FIG. 1. Decay events from the ^{58}Ni+^{92}Mo reaction leading to the known *p*-emitter ^{147}Tm. All the events collected in the DSSD corresponding to $A/q=147/27^+$ recoils and occurring in a time interval of 1 s after a recoil implantation in a given strip are shown. The 1.05 MeV peak corresponds to the ground state *p* decay of ^{147}Tm, other lines come from α decays of indicated isotopes.

water circulation. Acquired events were those that produce at least one signal on the *x* side of the DSSD. Total measuring time for ^{117}La was 36 h.

DSSD energy calibration was obtained from an α source with three peaks, a pulser signal, and a known *p* decay. The latter one was the ^{147}Tm *p* decay which presents two protons (1.051 MeV and 1.131 MeV) [5] and was produced after $(p,2n)$ evaporation from the fusion reaction ^{58}Ni+^{92}Mo ($E_{beam}=261$ MeV) that was shortly run before the main experiment (during this run the natural Ni absorber was removed).

The data were affected by a high noise background on the *y* signal that inhibited pixel analysis, therefore only the analysis of the correlated recoil-decay events occurring in the same strip will be considered. This fact restricts the capability to measure half-lives to values below 1.5 s for ^{147}Tm and below 160 ms for ^{117}La.

Figure 1 gives an example of data from the calibration run on ^{147}Tm: Decay events in a time window of (0–1) s from the last recoil registered in the same strip are shown. The low energy peak is the ground state proton decay of ^{147}Tm which has a half-life of 560 ms. Other peaks correspond to α decays of nuclei produced in the reaction between the beam and the Mo isotopes with $A\neq 92$ present in our target. All these well-known peaks [5] have been used for internal energy calibration of the DSSD. Using shorter time gates (the pertinent spectrum is not shown) the proton line from the decay of the excited $11/2^-$ level of ^{147}Tm (1.11 MeV and 360 μs) clearly appears in the spectrum.

During the ^{117}La run RMS fields were chosen to focus $A=117$ and $q=30^+$ recoils. Figure 2 shows the data from the ^{58}Ni+^{64}Zn reaction. Panel (a) presents all decay events in the DSSD. Already from this spectrum, with no time or mass selection, a peak is emerging at ~800 keV. The peak becomes evident in Fig. 2(b) where a time requirement of $\Delta t \leqslant 100$ ms between the implanted recoil and the subsequent decay event has been imposed. Finally, in Fig. 2(c) a further condition has been added on the recoils A/q value ($A/q=117/30^+$). Despite the high background, originating mainly from β-delayed particles, the peak at 783(6) keV becomes more and more pronounced increasing the number of conditions. Therefore this peak is attributed to the decay

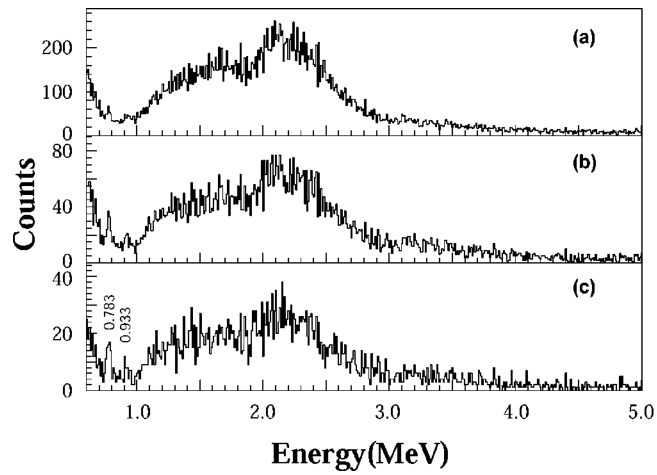

FIG. 2. Decay events collected in the DSSD during the 310 MeV ^{58}Ni+^{64}Zn run. (a) shows all the decays. (b) displays decay events occurring in a 100 ms time interval after a recoil implantation in a given strip. In (c) an additional condition $A/q=117/30^+$ for the recoils is required.

by proton emission of ^{117}La ground state to the ground state of ^{116}Ba, all other possibilities are ruled out since they correspond to nuclei closer to the stability line than ^{117}La and therefore with much lower probability to decay by *p* emission. In addition, considering an overall RMS transmission of 5–10 %, a ~60% efficiency for the DSSD, and the 75 events detected for this decay, a cross section of ~200 nb for the ^{117}La ground state is deduced, in good agreement with other experimental cross sections for $(p,4n)$ evaporation channels leading to *p* emitters in this region [9,10].

From the experimental $E_p=783(6)$ keV value a Q_p-value of 790(6) keV is obtained. Proton peak time analysis, illustrated in Fig. 3(a) together with its fit, results in $T_{1/2}=(20\pm 5)$ ms. However, since the recoil counting rate per strip during the experiment was 5 Hz, the possibility of correlating a decay event to a wrong recoil in the same strip has the effect of lowering the level half-life by 10%. After this correction the experimental half-life for this decay becomes $T_{1/2}=(22\pm 5)$ ms.

In Figs. 2(b) and 2(c) a second proton peak can be seen in the region immediately above 900 keV. Though it is not a high statistics peak, its analysis gives positive results, the peak turns out to correspond to $E_p=(933\pm 10)$ keV and $T_{1/2}=(10\pm 5)$ ms (including the random coincidence correction). After the usual corrections a $Q_p=(941\pm 10)$ keV is deduced. This second peak is populated with ~1/3 of the 783 keV peak cross section. The time analysis of the peak is shown in Fig. 3(b). Experimental data do not show evidence for α lines which might come from ^{117}La decay.

It can be seen that both experimental *Q* values lie in between the range determined by existing mass predictions and calculations: Audi and Wapstra [16] give $Q_p=(471\pm 1021)$ keV, Möller and Nix [3] predict $Q_p=501$ keV, Liran and Zeldes [17] $Q_p=1011$ keV, and Jänecke and Masson [18] $Q_p=1021$ keV.

From Ref. [3] the ^{117}La nucleus should be strongly deformed with $\beta_2=0.29$ and $\beta_4=0.1$ and calculations done for

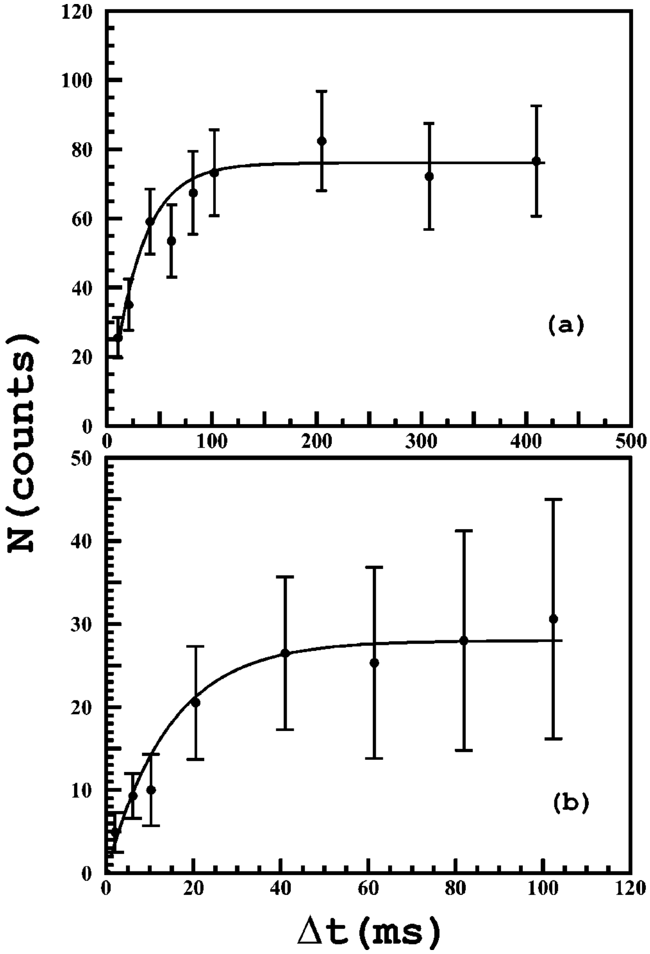

FIG. 3. Time analysis of the 783 keV (a) and 933 keV (b) proton peaks of ^{117}La.

a proton emitted from a spherical nucleus should be used only to fix a range for the possible half-lives. With a code [19] based on a simple WKB spherical model the Q_p^{nucl} $=800$ keV (which results from the sum of Q_p value and 10 keV electron screening effect) should correspond either to $T_{1/2}=0.33$ ms if the ground state were a $d_{5/2}$ or to $T_{1/2}$ $=110$ ms if it were a $g_{7/2}$ level, these being the only candidates for the ground state configuration of ^{117}La in the spherical approximation.

A calculation which is able to take into account the ground state deformation becomes necessary to understand ^{117}La structure. Using the approach of Maglione *et al.* [8], which assumes that the emitted proton is moving in a deformed single particle Nilsson level and its wave function is obtained by solving exactly the Schrödinger equation for a deformed Woods-Saxon potential with a deformed spin-orbit term and realistic parameters, it is possible to establish the ^{117}La Fermi surface. At large deformation ($\beta_2=0.3$ and β_4 $=0.1$) the ground state is likely a $K=3/2^+$ state coming from the spherical $d_{5/2}$ level (this result agrees with that expected from [3]). Figure 4(a) shows the result obtained performing a calculation for this level using the method of Ref. [8]. The calculation includes the Q_p experimental error (gray band) and the spectroscopic factor estimated as in [20]; the spectroscopic factor turns out to be 0.6 ± 0.1 for deformations $\beta_2=(0.2-0.4)$. The agreement with the experimental results is good for $\beta_2>0.16$ with $\beta_4=\beta_2/3$.

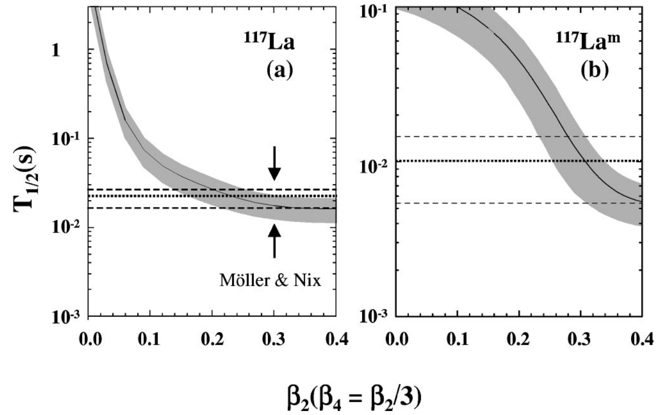

FIG. 4. Calculated proton partial half-life as a function of the deformation parameter for 783 keV (a) and 933 keV (b) proton decay levels of ^{117}La. Gray bands reflect the experimental error for the Q_p^{nucl} values, while the horizontal dashed lines correspond to the experimental errors for the half-lives. For the ground state decay the value obtained from Ref. [3] is also indicated.

Similar calculations performed for the second peak, assuming that this proton is emitted from a $K=9/2^+$ state coming from the $g_{9/2}$ spherical level, give the result of Fig. 4(b): the agreement with experimental data is quite good also in this case, and the deformation for the level emitting the 933 keV proton is $\beta_2>0.24$ (always with $\beta_4=\beta_2/3$).

It is worth noting that negative parity states originating from the spherical $h_{11/2}$ level, though lying close to the Fermi surface, do not reproduce the data in either case.

At this point a few words on the relative population of the two proton decaying levels are necessary. In fact one expects that the higher spin level, being yrast, would have a higher population than the ground state, opposite to the experimental observation. Two different explanations are possible. The $h_{11/2}$ band is the yrast band in neutron deficient Cs, La, Pr nuclei, and its decay might feed the $3/2^+$ band. This would explain our results on the proton intensities. However, there is a second possibility of an $M3$ transition from the $9/2^+$ to the $3/2^+$ state competing with the $9/2^+$ proton decay. This transition is indeed observed in ^{121}Cs [21]. For ^{117}La a 150 keV $M3$ transition would have a partial half-life of ~3.5 s (Weisskopf estimate corrected for internal conversion). Taking into account that maximum enhancement for an $M3$ is 10 [22], the partial half-life becomes 350 ms, i.e., 35 times slower than the experimental $9/2^+$ half-life. This result rules out the second possibility.

Concluding, we have found that ^{117}La has two p-decaying levels that populate the ground state of ^{116}Ba: the ground state with $J^\pi=3/2^+$ decays via a (783 ± 6) keV proton with $T_{1/2}=(22\pm5)$ ms, while the excited level decay, with E_x $=151(12)$ keV (this value corresponds to the difference between the Q_p values) and $J^\pi=9/2^+$, is characterized by E_p $=(933\pm10)$ keV and $T_{1/2}=(10\pm5)$ ms. Since the data do not show evidence of α decays, and since a possible β decay would have $T_{1/2}^{\beta}\sim338$ ms [23], we attribute 100% branching to each of the two *p* decays. In addition ^{117}La is quite deformed in agreement with what is expected from [3].

In summary, the decay by proton emission of the proton rich ^{117}La nucleus has been studied, characterizing the energy and the half-lives of the two experimentally measured decays, and determining spin, parity, and deformation of the decaying levels.

We would like to acknowledge the skillful technical help of A. Dal Bello, C. Boiano, G. Fattori, R. Isocrate, and M. Malatesta in setting up the whole experiment. We are grateful to C.N. Davids for his continuous support and valuable discussions. One of the authors (L.S.F.) acknowledges the support by the Fundação de Ciência e Tecnologia (Portugal), Grant No. 36575/99-Sapiens99.

[1] S. Hoffmann, in *Nuclear Decay Modes*, edited by D. N. Poenar (IOP, Bristol, 1996), p. 143.
[2] P.J. Woods and C.N. Davids, Annu. Rev. Nucl. Part. Sci. **47**, 541 (1997).
[3] P. Möller *et al.*, At. Data Nucl. Data Tables **59**, 185 (1995).
[4] T. Faestermann *et al.*, Phys. Lett. **137B**, 23 (1984).
[5] P.J. Sellin *et al.*, Phys. Rev. C **47**, 1933 (1993).
[6] R.D. Page *et al.*, Phys. Rev. Lett. **72**, 1798 (1994).
[7] V.P. Bugrov and S.G. Kadmensky, Yad. Fiz. **49**, 1562 (1989) [Sov. J. Nucl. Phys. **49**, 967 (1989)].
[8] E. Maglione, L.S. Ferreira, and R.J. Liotta, Phys. Rev. C **59**, R589 (1999).
[9] C.N. Davids *et al.*, Phys. Rev. Lett. **80**, 1849 (1998).
[10] K. Rykaczewski *et al.*, Phys. Rev. C **60**, 011301(R) (1999).
[11] F. Soramel *et al*, in *Proton-Emitting Nuclei*, 1999, edited by J.C. Batchelder, AIP Conf. Proc. No. 518 (AIP, Melville, NY, 2000), p. 68.
[12] P. Spolaore *et al.*, Nucl. Instrum. Methods Phys. Res. A **238**, 381 (1985).
[13] P.J. Sellin *et al.*, Nucl. Instrum. Methods Phys. Res. A **311**, 217 (1992).
[14] A.N. James *et al.*, Nucl. Instrum. Methods Phys. Res. A **267**, 144 (1988).
[15] C.N. Davids *et al.*, Nucl. Instrum. Methods Phys. Res. B **70**, 358 (1992).
[16] G. Audi *et al.*, Nucl. Phys. **A624**, 1 (1997).
[17] S. Liran and N. Zeldes, At. Data Nucl. Data Tables **17**, 431 (1976).
[18] J. Jänecke and P.J. Masson, At. Data Nucl. Data Tables **39**, 289 (1988).
[19] G.L. Poli, Ph.D. thesis, University of Milan, 1998.
[20] L.S. Ferreira and E. Maglione, Phys. Rev. C **61**, 021304(R) (2000).
[21] J. Genevey *et al.*, Z. Phys. A **338**, 405 (1991).
[22] P.M. Endt, At. Data Nucl. Data Tables **26**, 47 (1981).
[23] P. Möller, J.R. Nix, and K.L. Kratz, At. Data Nucl. Data Tables **66**, 131 (1997).