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Identification of a proton-emitting isomer in ^{151}Lu

C. R. Bingham,[1,2] J. C. Batchelder,[3] K. Rykaczewski,[2,4] K. S. Toth,[2] C.-H. Yu,[2] T. N. Ginter,[5] C. J. Gross,[2,6] R. Grzywacz,[1,4] M. Karny,[4,8] S. H. Kim,[1] B. D. MacDonald,[7] J. Mas,[2,8] J. W. McConnell,[2] P. B. Semmes,[9] J. Szerypo,[8] W. Weintraub,[1] and E. F. Zganjar[10]

[1]*The University of Tennessee, Knoxville, Tennessee 37996*
[2]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*
[3]*UNIRIB/Oak Ridge Associated Universities, Oak Ridge, Tennessee 37831*
[4]*IEP, Warsaw University, 00681 Warsaw, Hoza 69, Poland*
[5]*Vanderbilt University, Nashville, Tennessee 37235*
[6]*Oak Ridge Institute of Science and Education, Oak Ridge, Tennessee 37831*
[7]*Georgia Institute of Technology, Atlanta, Georgia 30332*
[8]*Joint Institute for Heavy Ion Research, Oak Ridge, Tennessee 37831*
[9]*Tennessee Technological University, Cookeville, Tennessee 38505*
[10]*Louisiana State University, Baton Rouge, Louisiana 70803*

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An isomer of ^{151}Lu was identified by its direct proton radioactivity. It was produced by bombardment of ^{96}Ru with 266-MeV ^{58}Ni from the Holifield Radioactive-Ion Beam Facility, mass separated with a recoil separator and implanted in a double-sided silicon strip detector, which provided signals to correlate each proton decay with a particular implant. The proton energy and half-life of ^{151}Lu^m were measured to be 1310(10) keV and 16(1) μs, respectively. The half-life of the previously known $h_{11/2}$ ground state was observed to be 80(2) ms in agreement with the previously adopted value of 88(10) ms. Comparison of the half-life of ^{151}Lu^m with WKB barrier-penetration calculations leads to the conclusion that the isomer is a $d_{3/2}$ proton state. A two-potential approach predicts a half-life of $5.5^{+1.4}_{-1.1}$ μs which yields an experimental spectroscopic factor of $0.34^{+0.12}_{-0.08}$. [S0556-2813(99)50306-3]

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Proton radioactivity occurs for isotopes of an element which have large negative proton separation energies. The protons must tunnel through a combined Coulomb and orbital angular momentum barrier, making the half-life of these radioactive isotopes sensitively dependent on the proton energy and angular momentum. Because the proton emitters are far from stability and often have very short half-lives, their study was relatively slow paced until the recent developments of recoil spectrometers and Si strip detector systems at heavy-ion accelerators which enabled efficient study of this decay mode. Lu-151 was the first case of observed proton radioactivity from a nuclear ground state [1], although the proton radioactivity of a high-spin isomer in ^{53}Co had been observed earlier [2]. The proton radioactivity of ^{151}Lu has been re-investigated [3], but contrary to other proton-emitting nuclei in the mass-150 region [4] where both $h_{11/2}$ ground states and $d_{3/2}$ (or $s_{1/2}$) isomeric states have been seen to decay by proton emission, only the $h_{11/2}$ ground state was observed in ^{151}Lu. Therefore, we undertook to study the nucleus again, taking care to observe decays in the microsecond half-life range, to locate the low-spin isomer and measure its half-life. With this same system the 3.5-μs decay of ^{145}Tm was recently observed [5].

A 0.54-mg/cm^2-thick target of isotopically enriched ^{96}Ru deposited on a 2-mg/cm^2 Au supporting foil was bombarded with 290-MeV ^{58}Ni ions (266 MeV at the Ru target front) extracted from the Holifield Radioactive-Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory, with an average beam current on target of ~4.5 particle nA during a period of 95 h. Recoil nuclei of interest were passed through a recoil mass spectrometer (RMS) [6] and a gas-filled position-sensitive avalanche counter (PSAC) for mass/charge identification, and then implanted into a 60-μm-thick-double-sided silicon strip detector (DSSD) with 40 horizontal and 40 vertical strips covering an active area of 4 cm $\times$4 cm. This strip arrangement results in a total of 1600 (1 mm$\times$1 mm) pixels, each acting as an individual detector. The RMS was adjusted to deposit the mass-151 products on the DSSD. For each implant, the energy of the implant, the pixel in which the implant occurred, the PSAC information, and the time were recorded. If a decay occurred within a time of 240 μs after an implant during its readout, the decay energy, pixel number, and time of decay were also recorded in the same event. For decay times greater than 240 μs, the decay information was recorded as a separate event. Decays within a given pixel were correlated with the previous implants in the same pixel in order to determine the decay time of the radioactivity.

Figure 1(a) shows the low-energy spectrum of charged particles recorded in the DSSD within 400 ms of recoil implantation. The intense peak in Fig. 1(a) is that of the proton decay of the ^{151}Lu ground state; it has a full-width at half maximum of ~20 keV. Since this proton radioactivity was already known [1], its decay energy, 1233(3) keV [7,8], was used for calibration of the present experiment. The total counts in this peak (~28 000) were sufficient to tag several γ rays observed at the target position with an array of six clover Ge detectors [9]. Its half-life was measured to be 80(2) ms, which is in agreement with the adopted value of 88(10) ms [7].

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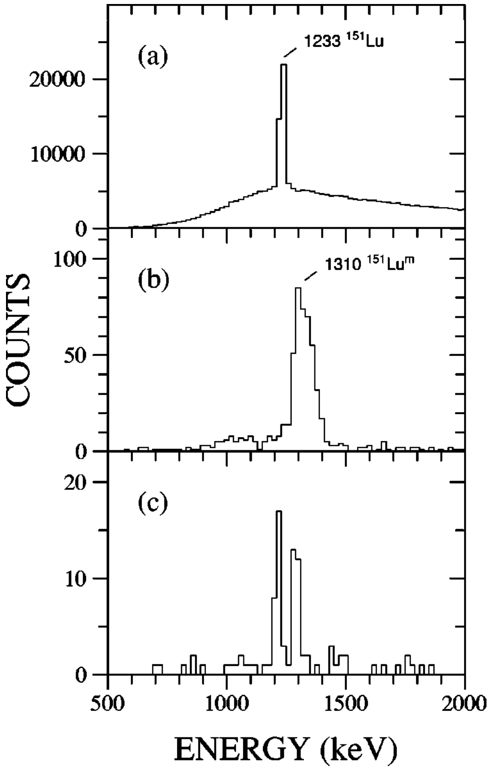

FIG. 1. Data obtained in ^{58}Ni bombardments of ^{96}Ru. Part (a) shows charged particles recorded in the DSSD within 400 ms of recoil implantation; the large peak is due to the proton radioactivity of the ^{151}Lu ground state. Part (b) shows charged particles recorded within 100 μs of recoil implantation; the peak is due to the decay of the new 16-μs isomer in ^{151}Lu. Part (c) shows the charged particles recorded between 50 and 250 μs after implantation; in this time range peaks for both the ground state and isomer decays are visible.

Figure 1(b) shows the low-energy spectrum of charged particles recorded in the DSSD within 100 μs of an implant. Once again only one peak is observed. It has about 400 counts, its energy is higher than that of the ^{151}Lu ground state, and its energy resolution is significantly worse. The resolution degradation is due to the residual pulse height in the decay amplifiers due to the implant at the time of the proton decay, with a shift in energy dependent on the time of decay and particular amplifier for the strip firing. The energy of this fast-decaying activity was determined by viewing decays that occurred at longer times after the implant, when the effect of summing was minimized, and supposedly about the same for both the 80-ms ground state and the new short-lived proton pulses. This is illustrated in Fig. 1(c) which shows decays for a period of time between 50 and 250 μs after an implant. Both the ground state proton peak and the new peak are relatively sharp in this projection, and their energy difference was determined to be 77$\pm$5 keV. This results in an energy of 1310(10) keV for the new proton decay which we assign to a transition from a previously unobserved isomeric level in ^{151}Lu. We have added an additional uncertainty of 5 keV to account for systematic uncertainties due to the pulse pileup problem. The half-life of the newly discovered isomer was determined by the method of maximum likelihood (see, e.g., [10]) to be 16(1) μs.

Nuclear structure information is obtained from proton radioactivity data by comparing the measured half-life with that calculated by various models for the emission of a proton with the measured energy. A simple semiclassical model, borrowed from the early theory of α-decay [11], describes the decay rate as the product of a barrier penetration probability P and a frequency factor ν. The barrier penetration is calculated in the WKB approach using the optical model potential of Bechetti and Greenlees [12]. The frequency factor ν can be obtained from the normalization of the WKB wave function of the quasibound state inside the classically allowed region. A simple analytic estimate for ν is obtained by replacing the combined nuclear + Coulomb potential inside the barrier with a square well and by ignoring angular momentum effects (s-wave emission). This simple estimate, denoted WKB1 below, has been used for many years and was discussed in the early review of Hofmann [13]. More recently, the semiclassical method was reinvestigated [14] and compared with more realistic calculations with the DWBA and the two potential approach (TPA) of Gurvitz and Kalbermann [15,16]. In this work, the frequency factor ν in the semiclassical model was calculated using the same optical model potential inside the barrier, rather than using a square well. The results of this semiclassical method using the normalization condition given by Eq. (25) of Ref. [14] are denoted WKB2 below. (Note that two different normalization conditions were considered in Ref. [14], and the labels were inadvertantly interchanged there.) In general, the semiclassical WKB approaches agree well with the other methods [14]. Furthermore, if the proton emitter is a good shell model nucleus, i.e., nearly spherical, the predicted half-lives agree well with simple shell model interpretations even though these are simple one-body models. The experimental spectroscopic factor is defined as the ratio of the calculated and experimental half-lives

$$S_p^{\mathrm{exp}}=\frac{t_{1/2}^{\mathrm{th}}}{t_{1/2}^{\mathrm{exp}}}, \tag{1}$$

and provides a measure of the fragmentation of the single-particle orbital (nlj). As explained in Ref. [14] these experimental values may be compared with spectroscopic factors from various nuclear models. For the spherical shell model with the residual pairing interaction treated in the independent quasiparticle approximation (BCS), the spectroscopic factor for a pure 1-quasiproton state is given by

$$S_p^{\mathrm{th}}=u_j^2, \tag{2}$$

where u_j^2 is the probability that the spherical orbital (nlj) is empty in the daughter nucleus. Alternatively, S_p^{th} has also been calculated in a simple low-seniority shell model where the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ orbitals are assumed to be degenerate throughout the region from $Z=64$ to $Z=82$ [17]. In this approach, the spectroscopic factors for these degenerate orbitals are simply the same, and equal to $p/9$, where p is the number of proton hole pairs (with respect to the $Z=82$ closed shell) in the even-Z daughter nucleus.

For the new 16-μs isomer in ^{151}Lu, the half-lives calculated with the WKB1 [13], WKB2, and TPA [14] methods are shown in Table I for the three subshell orbitals ($s_{1/2}$, $d_{3/2}$,and $h_{11/2}$) filling between $Z=64$ and 82, assum-

TABLE I. Half-lives from WKB1 [13] and WKB2 and TPA [14] calculations with various orbitals for comparison with the experimental half-life [16(1) μs] of ^{151}Lu^{m}.

Proton	Half-life (μs)		
Orbital	WKB1	WKB2	TPA
$s_{1/2}$	$0.48^{+0.20}_{-0.14}$	$0.66^{+0.17}_{-0.13}$	$0.69^{+0.17}_{-0.14}$
$d_{3/2}$	$4.2^{+1.8}_{-1.2}$	$5.5^{+1.4}_{-1.1}$	$5.5^{+1.4}_{-1.1}$
$h_{11/2}$	$11\,000^{+5000}_{-3000}$	$10\,000^{+3000}_{-2000}$	9200^{+2400}_{-1900}

ing a spectroscopic factor of 1 in each case. (Similar calculations [13] for the ^{151}Lu ground state show that its spin and parity must be $11/2^{-}$.) It is clear from comparing the calculated numbers in Table I with the experimental value of 16 μs that the probable assignment for the isomer is a $d_{3/2}$ orbital rather than the $s_{1/2}$ orbital suggested in a recent review article [4]. The spectroscopic factors resulting for the three different calculated half-lives are $0.26^{+0.14}_{-0.08}$ (WKB1) and $0.34^{+0.12}_{-0.08}$ for the two newer calculational techniques, both of which are lower than the theoretical u_j^2 of 0.73 obtained following the calculations presented in, e.g., Refs. [18] and [19].

Since the proton levels filling in this region are the $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ orbitals, almost all odd-A proton emitters observed in this region have had an $h_{11/2}$ and either an $s_{1/2}$ or $d_{3/2}$ proton emitting states. Their energy systematics in the vicinity of ^{151}Lu for odd-A nuclei are shown in Fig. 2. The figure shows that the low-spin state is the ground state for ^{167}Ir and ^{161}Re. The $h_{11/2}$ state has not been observed by proton decay in ^{157}Ta, but an $s_{1/2}$ proton emitting state has been observed there indicating that it is still below the $d_{3/2}$ state. The position of the $s_{1/2}$ relative to the $h_{11/2}$ state has been determined from a combination of proton- and α-decay Q values [20]. However, as we have just shown, the $d_{3/2}$ state has fallen below the $s_{1/2}$ in ^{151}Lu and remains lower in ^{147}Tm. Thus, in going along the proton dripline from $Z=79$ to 69 the $s_{1/2}$ level seems to rise quickly with respect to the $d_{3/2}$ and $h_{11/2}$ levels. To pursue the behavior of the $1/2^{+}$

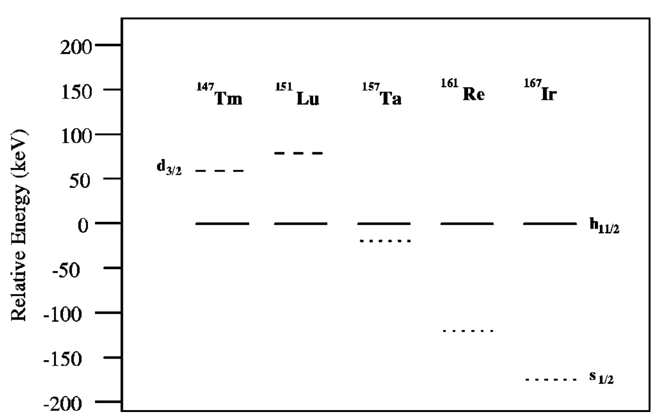

FIG. 2. Position of the $d_{3/2}$ and $s_{1/2}$ states with respect to the $h_{11/2}$ states observed by proton decay in the region from $Z=69$ to 79. Data are taken from Ref. [14] and references therein, except for the relative position of levels in ^{157}Ta which was taken from Ref. [20].

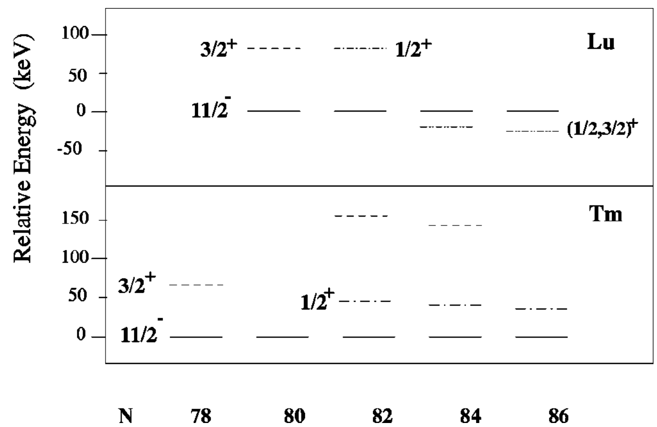

FIG. 3. Systematics of low-lying levels in Tm and Lu isotopes as a function of neutron number. These levels were taken from the current Brookhaven Nuclear Data Center ensdf data. It is noted that the $1/2^{+}$ ($s_{1/2}$) states rise significantly with respect to the $3/2^{+}$ ($d_{3/2}$) and $11/2^{-}$ ($h_{11/2}$) levels as N decreases through the closed shell at 82.

and $3/2^{+}$ states in another dimension, plots are shown of their positions as a function of neutron number for the Tm and Lu isotopes in Fig. 3. The results for Tm reveal that the $1/2^{+}$ levels are lower than the $3/2^{+}$ levels for neutron numbers of 82 and higher, while the $3/2^{+}$ has come lower at $N=78$ (^{147}Tm). In ^{155,157}Lu ($N=84,86$) the ground states have $(1/2,3/2)^{+}$ assignments. If these are assumed to be $1/2^{+}$ from analogy with the Tm isotopes at these N values, then it is observed that the $1/2^{+}$ rises dramatically at $N=82$, and at $N=80$ the $3/2^{+}$ level is lower than the $1/2^{+}$.

In Fig. 4 the ^{151}Lu^{m} spectroscopic factor is plotted along with other values in the subshell between $Z=64$ and 82 and compared with theoretical values [14]. It is observed that the spherical shell model predictions in this region are in reasonable agreement with the experimental values for $h_{11/2}$ and $s_{1/2}$ states. However, the experimental $d_{3/2}$ spectroscopic factors are systematically smaller than the calculated values (note that the data point for $Z=72$ resulting from ^{156}Ta decay represents the upper limit for S_p^{exp} since it was calculated assuming a 100% proton branch). These systematic discrepancies are difficult to explain satisfactorily, but one simple possibility is that the single-particle energy of the spherical $d_{3/2}$ state, which is calculated about 600 keV above the $h_{11/2}$ and about 80 keV above the $s_{1/2}$, is too high in the Woods-Saxon model. If the proper $d_{3/2}$ single-particle energy is below the $h_{11/2}$, then the fractional occupancy of the $d_{3/2}$ orbital would be greater than for the $h_{11/2}$, and thus the emptiness (and hence the spectroscopic factor) would be smaller for the $d_{3/2}$ than for the $h_{11/2}$. If the $d_{3/2}$ orbital is arbitrarily shifted 400 keV below the $h_{11/2}$, a spectroscopic factor of 0.44 can be obtained that just overlaps the experimental error bar. However, the overall good agreement between calculated and experimental quasiproton bandheads in the deformed rare earth region [19] seems inconsistent with such a large shift of the spherical $d_{3/2}$ state.

A second possible explanation is that the $3/2^{+}$ states might not be pure $d_{3/2}$ quasiproton states, but are mixed with other configurations, and thus only a portion of the expected $d_{3/2}$ strength is present in the lowest $3/2^{+}$ state. For example, in a weak-coupling model, one could devise other low-lying

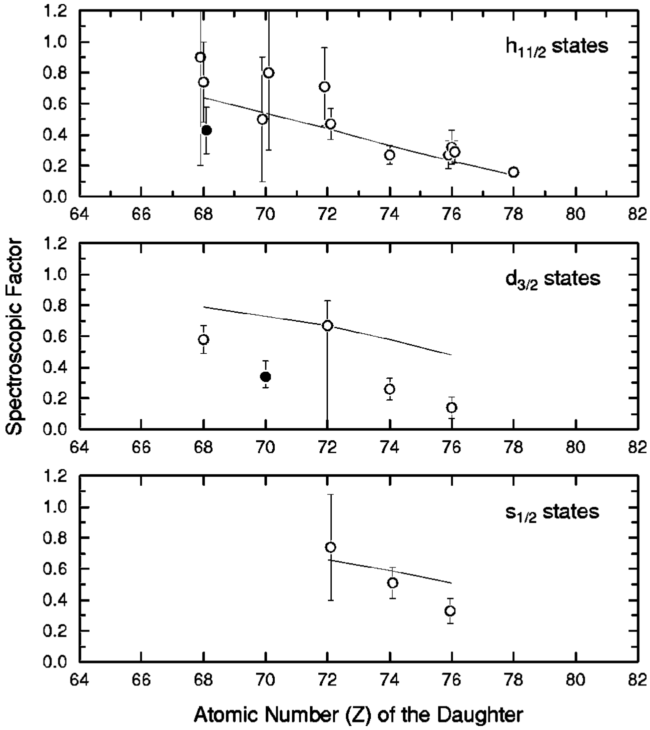

FIG. 4. Comparison of experimental (dots) and theoretical (lines) spectroscopic factors for the region with $64<Z<82$ for $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ states. The present spectroscopic factor and one for ^{145}Tm from Ref. [5] are shown as solid points and the other data were taken from Ref. [14] and references therein.

$3/2^+$ states by coupling an $s_{1/2}$ or a $d_{3/2}$ proton to the first 2^+ level of ^{150}Yb. If we consider a three level mixing model composed of $\pi d_{3/2}\otimes 0^+_{\rm core}$, $\pi d_{3/2}\otimes 2^+_{\rm core}$, and $\pi s_{1/2}\otimes 2^+_{\rm core}$ components, only the first would decay to the 0^+ ground state of the daughter nucleus. Since the observed spectroscopic factor for ^{151}Lu is about half the theoretical value, the squared amplitude for the $\pi d_{3/2}\otimes 0^+_{\rm core}$ component should be approximately 0.50. Interestingly, the last component would lead to an unhindered decay to the 2^+ level of ^{150}Yb via emission of the $s_{1/2}$ proton, thus producing a fine structure line in the proton spectrum. However, the 2^+ state is estimated to be about 600 keV above the ground state in ^{150}Yb, and consequently the decay to the 2^+ state would not compete with the ground state decay due to the decreased Q_p value. This weak-coupling scenario is qualitatively plausible, but some difficulties remain. First, for such a high 2^+ energy, the 50% mixing with other components seems unlikely in a spherical nucleus. Also, if such a weak-coupling calculation could provide the necessary mixing for the lowest $3/2^+$ state, it is not obvious whether the analogous mixing for the lowest $1/2^+$ state (from $\pi s_{1/2}\otimes 0^+_{\rm core}$ and $\pi d_{3/2}\otimes 2^+_{\rm core}$ components) would spoil the agreement currently obtained for the $1/2^+$ states. Furthermore, three of the five cases of $d_{3/2}$ proton emission shown in Fig. 4 are for odd-odd nuclei, where complicated mixings might be expected due to the higher level density at low energy and the proton-neutron residual interaction.

Finally, proton activity was recently reported for the ground states of ^{141}Ho and ^{131}Eu [21] and a new short-lived isomer ^{141}Ho^m and ^{140}Ho [22]. The Ho nuclei fall in the range $64<Z<82$ being discussed here, but the Ho half-lives are not fit by the spherical shell-model picture. This is indicative of an onset of deformation in this region of the periodic chart which results in greater mixing of states involving protons with different orbital angular momenta.

In summary, the new proton-decaying ^{151}Lu^m [$t_{1/2}=16(1)\ \mu$s] was identified and the half-life of the ground-state proton emitter ^{151}Lu was remeasured. The new isomer was given a $d_{3/2}$ proton assignment indicating that the $s_{1/2}$ state is above the $d_{3/2}$ in this nucleus. While the $h_{11/2}$ and $s_{1/2}$ decay rates are predicted very well in this region by a simple spherical shell model, the spectroscopic factor for the $d_{3/2}$ state observed here is smaller than predicted with this model. This reduction suggests that either the $d_{3/2}$ spherical single particle state is shifted below the $h_{11/2}$, or that the isomeric state wave function is not a simple 1-quasiparticle state but also contains significant components with core excitations, e.g., $\pi s_{1/2}$ or $\pi d_{3/2}$ coupled to the 2^+ state of the ^{150}Yb core.

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