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In-beam spectroscopy study of the proton emitter ^{151}Lu

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Gamma rays decaying from the excited states of the proton-unbound ^{151}Lu were observed for the first time in an experiment using the ^{96}Ru(^{58}Ni, $p2n$)^{151}Lu reaction. These γ rays were identified by correlating prompt γ radiations at the target position with ^{151}Lu proton radioactivities at the focal plane of a recoil mass separator. Systematic data on $N=80$ isotones suggest a possible isomeric level at high spin in ^{151}Lu. Our measurement was unable to observe such an isomer, but provided an upper limit on its half-life. The observed γ rays in ^{151}Lu can be interpreted in terms of two possible level structures. [S0556-2813(98)50812-6]

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Studies of nuclei far from the valley of stability have become an important subject in nuclear structure studies. Properties of nuclei at or beyond the proton- and neutron-drip lines often show phenomena which do not exist near the line of stability. Theoretical calculations have already predicted [1] important modifications of the familiar nuclear structure properties found near the line of stability. Experimental information on nuclei with extreme ratios of N to Z, therefore, can provide an important basis for the understanding of fundamental nuclear interactions.

Experimental access to nuclei at or beyond drip lines has always been difficult. When using the heavy-ion fusion-evaporation reactions to populate these nuclei, the production cross section for the channel of interest is usually very small (typically less than 0.1% of the total cross section), with the total cross section dominated by a large number of contaminant channels. To date, only a few cases of in-beam spectroscopy studies on proton-unbound nuclei have been reported [2–5]. These studies employed a common technique known as ''recoil decay tagging'' (RDT) [2], which correlates the prompt γ rays detected at the target position with charged-particle radioactivities detected at the focal plane of a recoil mass separator (RMS). A combination of such a correlation and mass identification with the RMS makes it possible to select the very weak signals associated with the γ decays of extremely proton-rich nuclei, providing a new way of studying nuclei beyond the proton-drip line. In this paper, we report a study of the γ decays in the proton-unbound nucleus ^{151}Lu by using the RDT technique.

Excited states of ^{151}Lu were populated using the ^{96}Ru(^{58}Ni,$p2n$) reaction. The ^{58}Ni beam was provided by the tandem accelerator of the Holifield Radioactive Ion Beam Facility (HRIBF) at the Oak Ridge National Laboratory. The target was a layer of 540-μg/cm^2 isotopically enriched ^{96}Ru metal deposited on a 2-mg/cm^2 Au supporting foil which faced the beam. The 290-MeV beam was degraded by the Au foil to an energy of approximately 266 MeV at the front of the ^{96}Ru metal. The average beam current during the experiment was about 4.5 pnA and the total beam-on-target time amounted to about 95 h.

Six clover Ge detectors were positioned at backward angles with respect to the beam direction at the target position. Each clover detector consists of four Ge crystals, and each crystal has a relative detection efficiency of about 25%. With the addback option used, the total relative efficiency of each clover detector is about 145%. The total absolute photopeak efficiency of the six clover detectors is about 1.5% for γ rays at 1.33 MeV. The clover detectors are also segmented vertically (perpendicular to the beam direction) to provide a refined polar angle resolution, and thus to reduce the Doppler broadening of the γ-ray peaks.

The RMS at HRIBF was used to select the desired mass of $A=151$, and no charge resetting foil was used. A gas-filled position sensitive avalanche counter (PSAC) was placed at the focal plane to detect the recoils and identify different groups of masses. More detailed descriptions of the RMS and PSAC can be found in Ref. [6]. Behind the PSAC, a double-sided silicon strip detector (DSSD) was used to detect the recoiling ions as well as their charged-particle decays. The DSSD is 70-μm thick and segmented into 40 horizontal strips in front and 40 vertical strips at the back. This strip arrangement results in a total of 1600 pixels, each functioning as an individual detector. More detailed descriptions on the DSSD can be found in Ref. [7].

For each event, the recoiling ion passed through the RMS and the PSAC, and was then implanted in the DSSD. The time (from a continuously running clock), energy and event type (recoil or decay, depending on whether it is in coincidence with the PSAC or not) were recorded by the DSSD. γ rays correlated with at least the PSAC, or those correlated with the PSAC as well as the DSSD were recorded by the Ge detectors. During the approximately 95-h running time, a

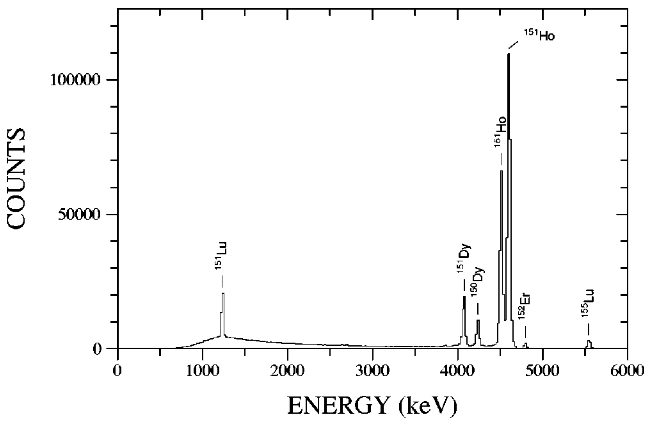

FIG. 1. Energy spectrum of the charged-particle decays from the $^{96}Ru+^{58}Ni$ reaction with the restriction of $T_d<400$ ms. The peak at 1.23 MeV is the ground state proton decay of ^{151}Lu, while the higher-energy peaks correspond to α-particle decays from neighboring nuclei.

total of about 27 million events of the following types were collected: (1) γ-γ-PSAC coincidence events; (2) γ-PSAC-DSSD coincidence events; (3) DSSD recoil events; (4) DSSD decay events.

Previous measurements [8] of the $h_{11/2}$ ground-state proton decay in ^{151}Lu established the proton energy to be $E_p=1.233(3)$ MeV and the half-life to be $T_{1/2}=85(10)$ ms. In our measurement, the previously determined E_p together with the known [9] ^{151}Ho α decay energies were used to calibrate and gain match the DSSD. Our analysis of the ground-state proton decay half-life resulted in a $T_{1/2}$ of 80(2) ms, which agrees with the previous value, but is considerably more precise. Figure 1 shows the energy spectrum of the decay particles with the restriction of decay time $T_d<400$ ms. The known [8] 1.23-MeV ground-state proton decay in ^{151}Lu is clearly seen, and it corresponds to about 28,000 protons collected during the experiment. Peaks at higher energies are identified as α decays of the neighboring nuclei of ^{151}Lu, primarily those from ^{151}Ho and $^{150,151}Dy$. This spectrum was taken by the DSSD with no specific mass gating on the PSAC. Since the RMS was tuned to position the $A=151$ recoils at the center of the focal plane, the finite size (40×40 mm) of the DSSD naturally selects this central mass with only a small amount of contamination from the neighboring masses. The small contaminant from ^{155}Lu is the result of the target impurity as well as the RMS mass-to-charge ratio (A/Q) ambiguity.

The production cross section of the ground state proton radioactivity can be estimated from the total number of proton events. Assuming that the RMS efficiency is about 3%, we estimate that this cross section is 70 ± 10 μb, which is about 0.015% of the total reaction cross section. In addition to this known 1.23-MeV proton decay, a new proton decay from an excited level of ^{151}Lu, most likely the $\pi d_{3/2}$ state, was also identified [10].

The γ-ray spectrum gated on mass $A=151$ is shown in Fig. 2(a). This spectrum is dominated by the known [11] transitions in ^{151}Tm ($3p$ channel). The spectrum of γ rays which are correlated with the 1.23-MeV proton decay in ^{151}Lu is shown in Fig. 2(b). All strong peaks in Fig. 2(a) are absent in Fig. 2(b). Since the spectrum shown in Fig. 2(b) is

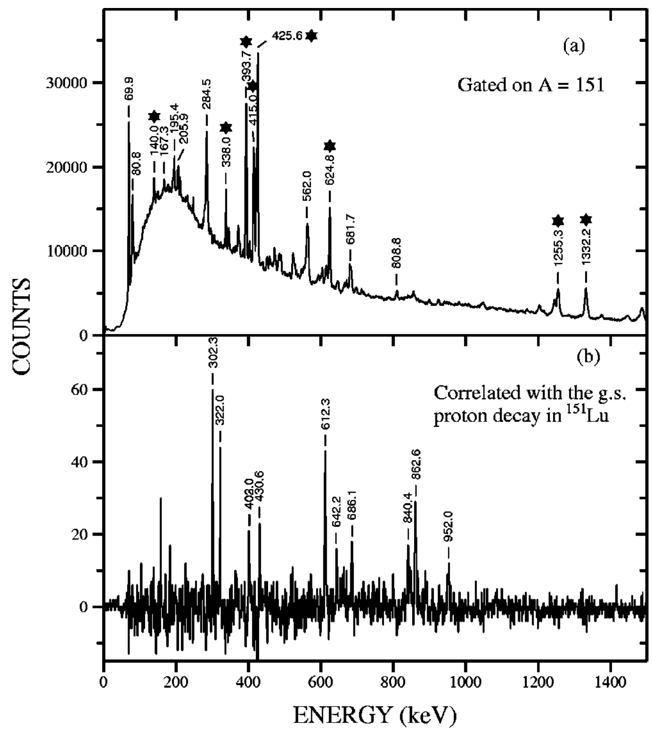

FIG. 2. (a) Gamma-ray spectrum corresponding to $A=151$ nuclei produced in the $^{96}Ru+^{58}Ni$ reaction. Peaks marked with stars are known [11] transitions in ^{151}Tm. (b) Gamma-ray spectrum correlated with the 1.23-MeV ground state proton decay of ^{151}Lu.

correlated with the ground state proton decay of ^{151}Lu, the γ rays shown in this spectrum can be firmly assigned to ^{151}Lu. The fact that the transitions shown in Fig. 2(b) are almost all invisible in Fig. 2(a) also eliminates the possibility that these transitions are residuals of the strong peaks in Fig. 2(a).

The transitions shown in Fig. 2(b) are very weak (only about 0.2% compared to γ rays in ^{151}Tm, the strongest $A=151$ nucleus populated in the reaction). The relative intensities of the ten transitions identified in Fig. 2(b) are summarized in Table I. It should be noted that since the clover detectors are all placed at backward angles, the intensities could be biased to enhance stretched $E2$ transitions. Al-

TABLE I. Energies and relative intensities of γ rays assigned to ^{151}Lu measured from the $^{96}Ru(^{58}Ni,p2n)$ reaction. The γ rays were assigned to ^{151}Lu based on their correlation with the ground-state proton decay of this nucleus.

E_γ (keV)[a]	I_γ(relative)
302.3	53 ± 6
322.0	41 ± 6
402.0	24 ± 4
430.6	26 ± 4
612.3	100 ± 12
642.2	31 ± 6
686.1	39 ± 6
840.4	31 ± 6
862.6	92 ± 16
952.0	65 ± 14

[a]Errors on these energies are approximately 0.5–1.0 keV.

TABLE II. Summary of the level energy E, spin and parity I^{π}, and half-life $T_{1/2}$ of the high spin isomeric levels in $N=80$ isotones neighboring ^{151}Lu.

Nucleus	E (keV)	I^{π}	$T_{1/2}$	Ref.
$^{142}_{62}$Sm	3662	10^+	480 ns	[12]
$^{143}_{63}$Eu[a]	-	-	-	[15]
$^{144}_{64}$Gd	3433	10^+	131 ns	[12]
$^{145}_{65}$Tb[a]	-	-	-	[16]
$^{146}_{66}$Dy	2935	10^+	150 ms	[13]
$^{147}_{67}$Ho[b]	~2700	$(27/2^-)$	315 ns	[14]
$^{148}_{68}$Er	2915	10^+	13 μs	[14]
$^{149}_{69}$Tm[c]	-	-	-	-
$^{150}_{70}$Yb[c]	-	-	-	-
$^{151}_{71}$Lu[d]	-	-	-	This work

[a]Excited states known, but no high spin isomers observed.
[b]The energy and spin of the isomer were not precisely determined, but the half-life was measured [14] to be 315(30)ns.
[c]Excited states not known.
[d]See text.

though all ten transitions indicated in Fig. 2(b) can be confidently assigned as depopulating excited states of ^{151}Lu, the ordering of these transitions is less transparent. Due to low statistics, gating on these transitions in the mass-gated γ-γ matrix produced no useful result. Therefore, spin and parity assignments for levels associated with these γ rays have to be made based on comparisons with states in the neighboring nuclei, and on considerations of our measured relative γ-ray intensities.

Previous studies of $N=80$ isotones have shown the existence of a 10^+ isomer in the even-even isotones [12–14]. The study of ^{147}Ho, the only $Z>64$, odd-Z, $N=80$ isotone with known excited states, also showed [14] the existence of an isomer at spin $27/2^-$ with the $(\pi h_{11/2})^3$ configuration. A summary of information on these isomers is tabulated in Table II. These isomers have half-lives ranging from 130 ns to 150 ms. The common occurrence of a high spin isomer in these nuclei suggests the possible existence of a similar isomeric level in ^{151}Lu around spin $27/2^-$. Unfortunately, our experimental setup was not suitable for measurements of such an isomer. However, if the isomer does exist, it is possible to estimate the upper limit of its half-life from our measurement. According to the observed time spectrum for the ground state proton decay of ^{151}Lu, there was no clear sign of delays preceding the proton decay. This allowed us to put the upper limit of the half-life of any possible high spin isomer at $T_{1/2}<7$ ms.

Since only a thin target was used and no Ge detectors were placed at the focal plane during our experiment, the γ rays we observed must be prompt transitions. However, depending on the specific level structure, these γ rays can be placed either above or below the suspected isomer. Two most likely possibilities are described in the following:

Possibility 1: Most or all of the decays from high spin states go through this isomeric level. In this case, γ rays directly above the ground state (and below the isomer) are all delayed and therefore could not be observed in our experiment. Thus the transitions we observed must be those above the isomeric level. For heavy $N=80$ isotones, the decay patterns above the isomers are all irregular and complicated (see Refs. [12–15]). Our lack of coincidence data, therefore, makes it impossible to construct a meaningful level scheme in such a case. If the half-life of the isomeric level is longer than a few microseconds, then a future experiment with the same setup plus an additional Ge array at the RMS focal plane would be able to establish the isomeric level as well as the level structure below the isomer.

Possibility 2: There are strong prompt transitions bypassing the isomeric level and feeding the low-spin states directly. In this case, the strong γ rays shown in Fig. 2(b) could be the lowest cascade of transitions feeding the $\pi h_{11/2}$ ground state. In particular, we could assign the 612-keV and 862-keV transitions as the $15/2^- \rightarrow 11/2^-$ and $19/2^- \rightarrow 15/2^-$ transitions. Such an assignment would fit the systematic trend of the $N=80$ isotones, see Fig. 3. When comparing the low-spin transitions in ^{147}Ho to its even-even core, ^{146}Dy, we see that the $15/2^- \rightarrow 11/2^-$ and $19/2^- \rightarrow 15/2^-$ transitions in ^{147}Ho closely resemble the $2^+ \rightarrow 0^+$ and the $4^+ \rightarrow 2^+$ transitions in ^{146}Dy. This suggests that the low-spin levels in ^{147}Ho are formed simply by coupling the odd $h_{11/2}$ proton to the 2^+ and 4^+ states of the even-even core. Meanwhile, the 4^+ and 2^+ energies decrease with increasing proton number. If we extrapolate these decreasing energies to $Z=70$, we would put the 2^+ level of ^{150}Yb at about 600 keV, and the 4^+ level at about 1400 keV. Our tentative assignment of the $15/2^- \rightarrow 11/2^-$ and $19/2^- \rightarrow 15/2^-$ transitions in ^{151}Lu would then resemble the lowest two transitions in its even-even core, ^{150}Yb, similar to the way ^{147}Ho resembles ^{146}Dy.

It should be pointed out that our experimental data do not provide strong evidence to favor either the first or second possibility. Our analysis shows that for every hundred ground-state proton decays in ^{151}Lu, there are only about twenty prompt 612-keV γ rays observed. The difference of the cross sections between the ground-state proton decay and the prompt 612-keV γ decay could support possibility 1, in

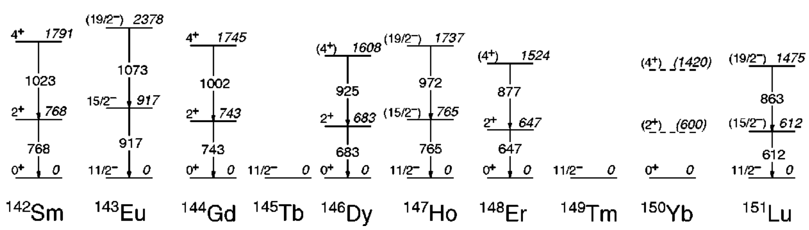

FIG. 3. Proposed level scheme of ^{151}Lu in case of possibility 2 (see text), together with those of lighter $N=80$ isotones. No excited states are known in ^{150}Yb, and dashed levels shown in the figure for this nucleus are extrapolations from the systematic trend of the lighter even-even isotones. Data for ^{142}Sm, ^{143}Eu, ^{144}Gd, ^{146}Dy, ^{147}Ho, and ^{148}Er are taken from Refs. [12–15].

which the γ rays we observed are all above the isomeric state. Since the decay scheme above the isomer is complex and often has parallel paths feeding the isomeric level, the 612-keV γ ray could be one of several γ rays feeding the isomeric state in parallel. The intensity of the 612-keV γ ray is, therefore, only a fraction of that feeding the ground state. However, the cross section difference could also support possibility 2, in which the 612-keV transition is the $15/2^{-} \rightarrow 11/2^{-}$ transition observed through the prompt transitions bypassing the isomer. The intensity of the 612-keV transition is reduced since the prompt γ rays bypassing the isomer are only part of the total γ transitions feeding the ground state.

In conclusion, excited states in the ground-state proton emitter ^{151}Lu were populated using the ^{96}Ru(^{151}Lu,$p2n$) reaction. Gamma rays in ^{151}Lu were identified for the first time by using the recoil-decay tagging technique. Ten γ rays were unambiguously assigned to ^{151}Lu. Systematic data suggest a possible isomeric level at high spin in ^{151}Lu. While we were unable to determine whether or not such an isomer exists, an upper limit on its half-life was estimated. The γ rays assigned to ^{151}Lu can be interpreted in terms of two possible level structures: they can either be γ decays above the unidentified high spin isomeric level, or be a cascade of transitions directly above the $h_{11/2}$ ground state. In the latter case, the tentatively assigned low-spin transitions fit the decay patterns in the neighboring nuclei of ^{151}Lu. The experimental data, however, are insufficient to favor either possibility 1 or possibility 2.

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