Proton emission from drip-line nuclei ^{157}Ta and ^{161}Re

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Proton radioactivities from ^{157}Ta and ^{161}Re are reported. Fusion-evaporation residues from the reaction of 270 MeV ^{58}Ni ions on ^{102}Pd and ^{106}Cd targets were separated according to M/Q and implanted into a double-sided silicon strip detector. One line from ^{157}Ta was observed with a proton energy of 927(7) keV [$t_{1/2}=10.1(4)$ ms, $b_p=3.4(12)\%$] from the $\pi s_{1/2}$ ground state. A new alpha decay transition with energy 6117(4) keV was also observed from this state. Two proton lines from ^{161}Re were observed with energies 1192(6) keV [$t_{1/2}=0.37(4)$ ms, $b_p=100(7)\%$] and 1315(7) keV [$t_{1/2}=16(1)$ ms, $b_p=4.8(6)\%$] from the $\pi s_{1/2}$ and $\pi h_{11/2}$ states, respectively. [S0556-2813(97)50204-4]

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At the limit of nuclear stability the onset of direct proton emission from nuclear ground states defines the proton drip-line. In proton decay, unlike alpha decay, no preformation factor is required, giving a simpler decay process [1]. Measurements in this area yield much useful spectroscopic information since transition rates are extremely sensitive to the orbital angular momentum of the proton. Until recently, only a small number of ground state proton emitters, in the region $A\approx150$ and $A\approx110$ [1], had been observed due to the experimental difficulties in producing and detecting such exotic species. Production cross sections are generally very low (<100 μb) and, as well as being short lived, the desired reaction products are mixed with unreacted beam and a strong background as other products β decay towards stability. The development of the double-sided silicon strip detector (DSSD) [2] as an ion implantation detection system in conjunction with efficient in-flight separation of fusion-evaporation residues increased the sensitivity of experiments sufficiently to allow the study of short-lived (>1 μs) nuclei with submicrobarn production cross sections. This technique made possible the discovery of several new proton emitters [3,4] including the heaviest to date, ^{185}Bi [5].

The results presented in this paper are on proton emission from ^{157}Ta and ^{161}Re, both of which have 24 fewer neutrons than the nearest stable isotopes. The measurements in this work were performed using the Argonne Fragment Mass Analyser (FMA) [6] and a double-sided silicon strip detector. In the first experiment a 3 particle nA beam of 270 MeV ^{58}Ni ions from the ATLAS accelerator at Argonne National Laboratory was used to bombard a 1 mg/cm^2 thick ^{102}Pd target for a period of 33 h to produce the compound nucleus ^{160}W at a center-of-target excitation energy of 53 MeV. Fusion evaporation residues passed through the FMA where they were separated from the primary beam and then dispersed according to their mass/charge. A thin multiwire proportional counter (MWPC) at the focal plane of the FMA provided position and energy loss signals for the recoil ions, which were then defocused to illuminate a 60 μm thick DSSD uniformly over its 16$\times$16 mm^2 area [2]. A 1 MHz clock was used to time-stamp implantation and decay events, identified by DSSD-MWPC signal coincidences and anticoincidences, respectively. Mass assignments for implantation events were given by the position of the recoil ion in the MWPC. The high degree of granularity provided by the 48 orthogonally crossed strips on each face allow correlations to be made between implantation and subsequent decay events, and consequently unambiguous assignments to parent nuclei can be made for even very weak decay lines. The energy resolution from summed strips was ~30 keV FWHM.

Figure 1(a) shows an energy spectrum of all decay events in the silicon strip detector. The strong lines between about 4 and 6 MeV are predominantly the known alphas from this region of the chart of the nuclides and alphas from subsequent daughter decays. The broad ''hump'' from 1 to 3 MeV is due to alphas escaping from the front face of the detector not depositing their full energy in the silicon. Figure 1(b) shows the decay data after requiring that a mass 157 implant was the parent and that the first generation decay took place within 50 ms of the implantation. Figure 1(c) shows the same data as (b) subject to the additional requirements that a second decay occurred in the same pixel within 100 ms of the first generation decay, with an energy of 5873(4) keV, the known alpha decay of ^{156}Hf. Clearly present is a sharp peak at 927(7) keV (corresponding to a cross section $\sigma\sim20$ nb), calibrated with respect to the known ground state proton decay of ^{147}Tm [1], which on the basis of the above correlations was assigned to the proton decay of ^{157}Ta.

The half-life calculated from the protons is $12.1^{+3.1}_{-2.3}$ ms, which is not in agreement with the known α from ^{157}Ta at 6213(4) keV with a half-life of 4.3(1) ms [7]. However, it is in agreement with the half-life of 10.1(4) ms obtained from a new, much weaker alpha line at 6117(4) keV [see Fig. 1(a)] which is correlated with mass 157 recoils and was calibrated

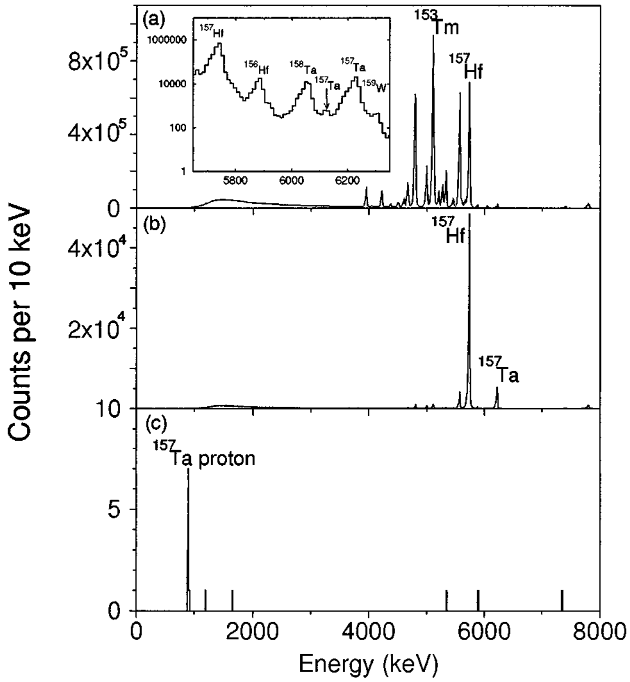

FIG. 1. (a) Energy spectrum of all decays observed in the DSSD in the reaction of 270 MeV ^{58}Ni on a ^{102}Pd target. Assignments are indicated for the most intense alpha decay lines. The inset shows the region between 5650 keV and 6350 keV, the new line from ^{157}Ta marked with an arrow. (b) Decay data after requiring that a mass 157 implant was the parent and that the first generation decay took place within 50 ms of the implantation. (c) Same data as (b) subject to the additional requirements that a second generation decay occurred in the same pixel within 100 ms of the first one, with an energy of 5873(4) keV, the known alpha decay of ^{156}Hf.

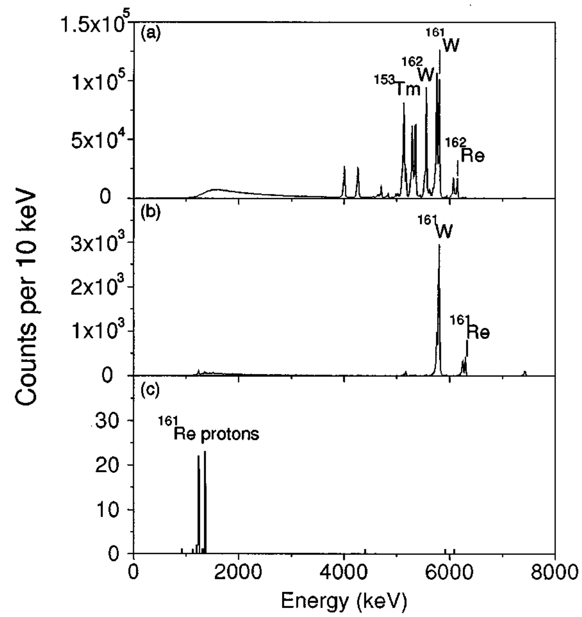

FIG. 2. (a) All decays observed in the DSSD in the reaction of 270 MeV ^{58}Ni ions on a ^{106}Cd target. (b) First generation decays occurring within 50 ms of a mass 161 implantation. (c) Same data as (b) with the extra condition that a second generation decay occurred in the same pixel within 1 s of the first one, with an energy corresponding to the known alpha decay of ^{160}W.

with respect to the known alphas decays from ^{153}Tm, ^{154}Yb, ^{156}Lu, and ^{157}Hf [7]. It is also correlated with a subsequent ^{153}Tm alpha decay, the great-granddaughter of ^{157}Ta, the two intermediate nuclei being β emitters are not observed in the DSSD. Therefore this new decay was assigned to the α decay of ^{157}Ta. The proton branching ratio from this state was calculated to be 0.034(12) and the proton partial half-life, 300(110) ms.

In the second experiment, a 500 μg/cm^2 ^{106}Cd target was bombarded with a 270 MeV ^{58}Ni beam for a period of 38 h to search for protons from ^{161}Re. Figure 2(a) shows all the decays observed for this reaction, Fig. 2(b) shows first generation decays occurring within 50 ms of a mass 161 implantation and Fig. 2(c) shows the same data as (b) subjected to the additional requirement that a second generation decay occurred in the same pixel within 1 s of the first generation decay, with an energy of 5912(5) keV, the known alpha decay of ^{160}W. Two low-energy peaks are evident (both with cross sections $\sigma \sim 150$ nb), corresponding to proton energies of 1192(6) keV and 1315(7) keV, with half-lives of 370(40) μs and $15.4^{+1.7}_{-1.4}$ ms, respectively. The half-life measured for the higher-energy proton peak is consistent with that of the known alpha from ^{161}Re with a measured energy from the present work of 6272(7) keV and half-life of 16(1) ms [previous measurement $E_\alpha = 6265(6)$ keV, $t_{1/2} = 14(2)$ ms [7]]. We conclude that the proton and alpha come from the same state in the parent nucleus. The proton branching ratio was calculated to be 0.048(6) and the proton partial half-life, 325(44) ms. No other alpha decay branch from ^{161}Re was observed in this experiment.

A comparison of measured and calculated partial half-lives can be used to determine the orbital angular momentum of the proton-emitting states. Table 1 shows the results of calculations using the WKB barrier transmission approximation with the optical-model potential of Becchetti and Greenlees [8] for the available proton orbitals in this region, $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$. The partial half-life calculated for the $s_{1/2}$ orbital in ^{157}Ta is in good agreement with the measured

TABLE I. Comparison of measured partial proton decay half-lives for proton emitters ^{161}Re and ^{157}Ta with those calculated using a WKB approximation with the optical-model potential of Becchetti and Greenlees [8].

Nuclide	E_p (keV)	Measured partial half-life (ms)	Proton Orbital	Calculated partial half-life (ms)
			$s_{1/2}$	167
^{157}Ta	927(7) keV	300(110)	$d_{3/2}$	1470
			$h_{11/2}$	4 020 000
			$s_{1/2}$	0.142
^{161}Re	1192(2) keV	0.37(4)	$d_{3/2}$	1.18
			$h_{11/2}$	2600
			$s_{1/2}$	0.0062
^{161}Re	1315(7) keV	325(44)	$d_{3/2}$	0.051
			$h_{11/2}$	107

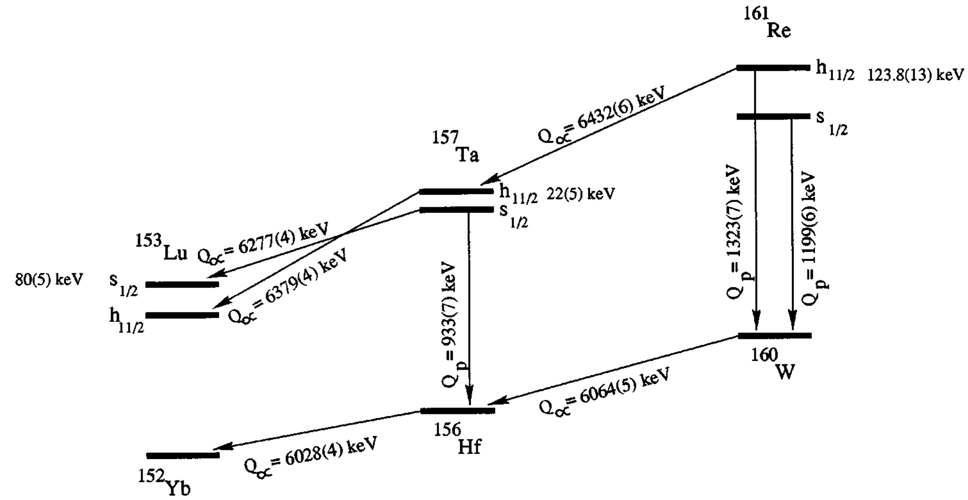

FIG. 3. Proposed decay scheme.

value. The calculated values for the other orbitals are clearly much larger indicating the proton decay can only be an $l=0$ transition from the $s_{1/2}$ state in ^{157}Ta to the $J=0$ ground state in ^{156}Hf. Similarly, the 1192 keV peak from ^{161}Re is best explained as the $l=0$ decay of the $s_{1/2}$ ground state and the 1315 keV peak can only be the $l=5$ decay of the $h_{11/2}$ state, both transitions going to the $J=0$ ground state of ^{160}W. The proposed decay scheme is represented in Fig. 3. Only one alpha decay transition is observed from ^{161}Re. Barrier penetration calculations, assuming a relative reduced width of unity compared to ^{212}Po, suggest an alpha partial half-life of $\sim$20 ms for an $l=0$ alpha and $\sim$400 ms for an $l=5$ alpha [compared to experimentally measured value of 16(1) ms] so the decay is assigned to a favored $l=0$ transition from the $h_{11/2}$ state to the $h_{11/2}$ state in ^{157}Ta. The excitation energy for the $h_{11/2}$ state in ^{161}Re has been determined to be 123.8(13) keV from the energy difference of the two proton transitions (the relatively small error in this number compared to those for the individual Q values reflects the insensitivity of the energy difference to the absolute energy calibration). The combined Q values

$$Q_p(\,^{161}\mathrm{Re}[h_{11/2}])+Q_\alpha(\,^{1610}\mathrm{W})-[Q_\alpha(\,^{161}\mathrm{Re})+Q_p(\,^{157}\mathrm{Ta})]$$

give an excitation energy of 22(5) keV for the $h_{11/2}$ state with respect to the $s_{1/2}$ ground state in ^{157}Ta. The energy available for proton decay from the $h_{11/2}$ state in ^{157}Ta is 955(9) keV. Using this value in a barrier penetration calculation for $l=5$ proton emission we would expect a proton partial half-life of $\sim$2000 s, which could not compete with the observed alpha with a half-life of 4.3(1) ms (expected proton branch $\sim$0.0002%). This is consistent with the nonobservation of a proton corresponding to this transition.

Further, the combined Q values $Q_p(^{157}\mathrm{Ta}[h_{11/2}])+Q_\alpha(^{156}\mathrm{Hf})-Q_\alpha(^{157}\mathrm{Ta}[h_{11/2}])$ and $Q_p(^{157}\mathrm{Ta}[s_{1/2}])+Q_\alpha(^{156}\mathrm{Hf})-Q_\alpha(^{157}\mathrm{Ta}[s_{1/2}])$ give the energy available for proton decay from the $h_{11/2}$ and $s_{1/2}$ levels in the $N=82$ closed shell nuclide ^{153}Lu as 604(10) keV and 684(9) keV, respectively. Barrier penetration calculations predict proton partial half-lives from these states of 10^{10} s and 10^4 s, therefore although the drip-line is clearly crossed, proton decay is unable to complete with β decay. Protons from these states were not observed. It is interesting to note that the above results indicate the $s_{1/2}$ state lies 80(5) keV above the $h_{11/2}$ state in ^{153}Lu, the levels being inverted with respect to ^{161}Re and ^{157}Ta. This explains why only the proton from the $h_{11/2}$ state in ^{151}Lu is observed. Assuming a similar energy gap for the $s_{1/2}$ level, the proton would have a partial half life of <1 μs, too fast to be observed.

The above results show a marked difference from those for ^{156}Ta and ^{160}Re [9,10], in which proton emission is assigned to a ground state $[\pi d_{3/2}\nu f_{7/2}]\ 2^-$ configuration. This lowering in energy of the $[\pi d_{3/2}\nu f_{7/2}]\ 2^-$ state relative to competing $[\pi s_{1/2}\nu f_{7/2}]\ 3^-$ and $[\pi h_{11/2}\nu f_{7/2}]\ 2^+$ states can be found in the Nordheim strong rule. That rule states that the interaction between an odd neutron and an odd proton occurs for the antiparallel coupling where one odd nucleon has $j=l+1/2$ (the $f_{7/2}$ neutron) and the other odd nucleon has $j=l-1/2$ (the $d_{3/2}$ proton). Therefore it is the interaction strength between the odd neutron and odd proton rather than the single particle energies that plays a decisive role in determining level ordering in the odd-odd nuclei.

In summary, direct proton decays from ^{157}Ta and ^{161}Re and a new ground state alpha line from ^{157}Ta have been identified, extending our knowledge of extremely proton-rich nuclei. Q-values, half-lives, and branching ratios were accurately measured and were consistent with emission of protons from the $s_{1/2}$ ground state in ^{157}Ta and from the $s_{1/2}$ ground state and $h_{11/2}$ state in ^{161}Re. Comparison with previous results from neighboring odd-odd nuclei demonstrates the important influence of proton-neutron residual interactions on the ordering of proton decaying states in this region of the drip-line.

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