Discovery of New Proton Emitters ^{160}Re and ^{156}Ta

R. D. Page,[1] P. J. Woods,[1] R. A. Cunningham,[2] T. Davinson,[1] N. J. Davis,[1] S. Hofmann,[3] A. N. James,[4] K. Livingston,[1] P. J. Sellin,[1] and A. C. Shotter[1]

[1]*Department of Physics, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[2]*Science and Engineering Research Council Daresbury Laboratory, Warrington WA4 4AD, United Kingdom*
[3]*Gesellschaft für Schwerionenforschung mbH, Postfach 11 05 52, D-6100 Darmstadt, Germany*
[4]*Oliver Lodge Laboratory, University of Liverpool, Liverpool L63 3BX, United Kingdom*

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The heaviest known examples of proton radioactivity, ^{160}Re and ^{156}Ta, have been discovered. Evaporation residues from fusion reactions of 300 MeV ^{58}Ni ions with ^{106}Cd targets have been mass separated in flight and implanted into a double-sided silicon strip detector. The measured proton energies, total half-lives, and proton branching ratios are 1261 ± 6 keV, 790 ± 160 μs, (91 ± 10)%, and 1022 ± 13 keV, 165^{+165}_{-55} ms, ≈ 100% for ^{160}Re and ^{156}Ta, respectively, indicating that the protons are emitted from a $d_{3/2}$ orbital in each case. An energy of 6537 ± 16 keV has been measured for the ^{160}Re alpha decay branch.

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Ground-state proton radioactivity determines the observable limit to nuclear existence for neutron-deficient nuclei. Half-lives for this inherently simple decay process are very sensitive to the available decay energy and the emitted proton's orbital angular momentum [1]. Proton radioactivity therefore offers a unique source of information on shell ordering at the extreme limits of nuclear existence. In addition, measured Q values provide very stringent tests of mass-model predictions. However, the available database of measured proton transitions is highly restricted owing to the experimental difficulties involved in measuring the decays of these typically short-lived exotic nuclei which are produced with very low yields. The few known examples of proton radioactivity were discovered in the early 1980's in the regions $A \approx 150$ [1] and $A \approx 110$ [2]. A variety of separation techniques were used to isolate these first proton emitters which were produced via $p2n$ channels in heavy-ion fusion-evaporation reactions with cross sections of ~ 50 μb. Despite considerable subsequent effort, no further progress was made in establishing new regions of proton radioactivity.

The measurements presented in this Letter were performed using a double-sided silicon strip detector (DSSSD) in an implantation detection system [3] on the Daresbury Recoil Mass Separator (RMS) [4]. The RMS separates evaporation residues in flight from the unreacted primary beam particles and from other reaction products, then disperses the selected ions in the horizontal plane according to their mass-to-charge-state ratio. These ions are implanted at the RMS focal plane into a DSSSD which comprises 48 strips on each face providing position information in two dimensions. Subsequent causally related decays are correlated using this position information and clock readings recorded with each event, in order to obtain unambiguous decay line assignments and to extract half-life and branching-ratio measurements. The DSSSD has good energy resolution ($\lesssim 20$ keV) and position resolution (strip width of 300 μm) which, combined with the fast mass separation performance of the RMS, provide a detection system sensitive enough to permit the study of short-lived ($\gtrsim 1$ μs) exotic evaporation products with cross sections of $\lesssim 1$ μb. This is sufficiently sensitive to investigate the decay properties of predicted new-proton radioactive nuclides produced via $p3n$ evaporation channels in heavy-ion fusion reactions.

In the present experiment, a 3 particle nA beam of 300 MeV ^{58}Ni ions provided by the Daresbury tandem accelerator was used to bombard an isotropically enriched 750 μg cm^{-2} thick ^{106}Cd target on a 25 μg cm^{-2} thick ^{12}C backing for a period of ~ 1 day. This beam energy produces a center-of-target excitation energy of the compound nucleus ^{164}Os of 64 MeV. This excitation energy is expected [5] to correspond to the peak cross section for the $p3n$ evaporation residue ^{160}Re which was predicted to be a good candidate for proton radioactivity [6]. Systematics [7,8] also suggested that ^{160}Re could have a significant alpha decay branch leading to ^{156}Ta, which is itself predicted to be unbound to proton emission [9].

The energy spectrum of decays recorded in the region of the DSSSD corresponding to $A = 160$ is shown in Fig. 1(a). There is no direct evidence in this spectrum for a peak at a typical proton decay line energy [1] of ~ 1 MeV because of the background due to escaping alpha particles. If ^{160}Re is to have a significant proton decay branch it must be short lived since a partial half-life of ~ 10 ms would be expected for alpha-particle emission, the predominant competing decay mode. Therefore energy spectra of short-lived decays were analyzed in an attempt to identify a proton decay line. Figure 1(b) shows the energy spectrum of those $A = 160$ decays which occur within 3 ms of the implantation of an evaporation residue into the same area of the DSSSD. This spectrum reveals a sharp peak at an energy of 1261 ± 6 keV corresponding to a cross section of ~ 1 μb. This energy measurement was obtained using a calibration based on the energies of

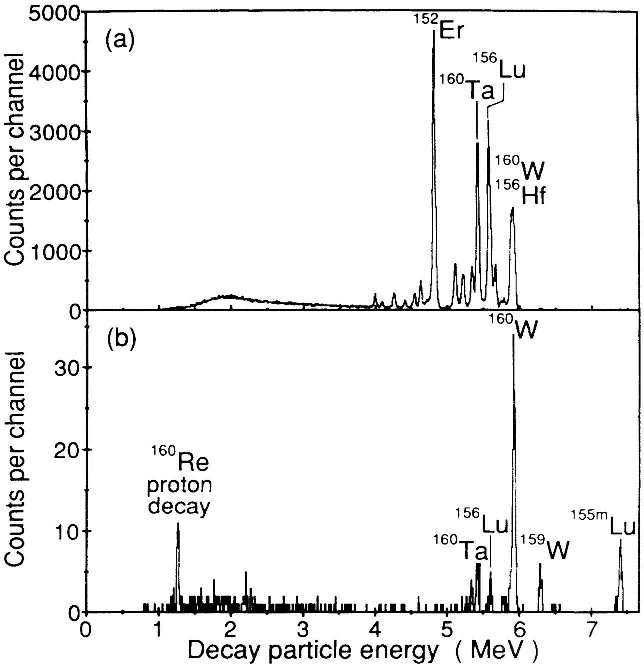

FIG. 1. (a) Energy spectrum of all decays observed in the $A=160$ region of the RMS focal plane in the reaction of a beam of 300 MeV ^{58}Ni ions on a ^{106}Cd target. Assignments are indicated for the most intense alpha decay lines. The broad bump extending from ~ 1 MeV up to the sharp alpha decay peaks is due to alpha particles which escape through the front face of the DSSSD without depositing all of their energy. (b) $A=160$ decays occurring within 3 ms of the implantation of an ion into the same area of the DSSSD. Alpha decay lines at higher energies are enhanced in this spectrum because they have shorter half-lives than those at lower energies. The ^{155m}Lu alpha decay peak arises from $A=155$ ions implanted into the $A=160$ region of the DSSSD in a lower charge state.

known alpha decay lines [10] produced in this reaction and the 1233 ± 3 keV ^{151}Lu proton decay line [1] which was produced in a separate reaction studied with the same detector. The half-life of this decay line is 860^{+230}_{-150} μs, typical of the short values characteristic of ground-state proton decays [1] but too short for the peak to be attributed to a beta delayed activity. No positrons were observed in coincidence with events in the peak, which is also consistent with it not being a beta delayed activity. The low-energy peak was shown to be correlated with subsequent alpha decays of ^{159}W ($E_\alpha = 6278 \pm 5$ keV, $t_{1/2} = 7.4 \pm 0.5$ ms) and is therefore unambiguously identified as the proton decay of ^{160}Re. The Q value measured for the correlated ^{160}Re proton decay peak was 1269 ± 6 keV.

From the half-life measured for the proton decay branch one would also expect ^{160}Re to have a significant alpha decay branch ($\sim 10\%$ for a partial alpha decay half-life of 10 ms). A weak alpha decay line was observed in the $A=160$ region of the RMS focal plane at an energy of 6537 ± 16 keV. The half-life measured for this decay line was (380^{+380}_{-130}) μs which is consistent with the value measured for the proton decay branch of ^{160}Re. The measured energy corresponds to a Q value of 6705 ± 16 keV which would fit in well with Q_α-value systematics for rhenium isotopes [7,8] and would be in excellent agreement with the value predicted by the droplet model of Myers [11] which reproduces the Q_α values of rhenium isotopes very well [7]. This new decay line is therefore assigned to the alpha decay of ^{160}Re. The half-life of this alpha decay line is much shorter than would be expected if the state decayed solely by alpha emission, indicating that the proton and alpha lines emanate from the same level in ^{160}Re. Since no other alpha decay line consistent with a decay from ^{160}Re could be identified, we conclude that the proton- and alpha-emitting state observed in this experiment represents the ground state of ^{160}Re.

Combining the data from both the proton and the alpha decay branches, a value of 790 ± 160 μs was obtained for the half-life of ^{160}Re using the method described in Ref. [12]. The branching ratios determined for the proton and alpha decays of this nuclide were $(91 \pm 10)\%$ and $(9 \pm 5)\%$, respectively, which correspond to partial half-lives for proton decay and alpha decay of $t_{1/2,p} = 870 \pm 200$ μs and $t_{1/2,\alpha} = 9 \pm 5$ ms. Assuming s-wave alpha emission, this latter result yields a reduced alpha decay width for ^{160}Re of $0.3^{+0.2}_{-0.1}$ relative to that of ^{212}Po [13]. This value agrees well with the systematic trends of reduced alpha decay widths of $N=85$ alpha emitters [7]. These trends are consistent with an increasing admixture with atomic number of the $d_{3/2}$ proton subshell, for which smaller reduced widths relative to the $h_{11/2}$ subshell have been calculated [14].

The daughter nuclide of the alpha decay branch of ^{160}Re is ^{156}Ta, which is also predicted to be unstable to proton emission [9]. Analysis of decays following ^{160}Re alpha decays revealed four correlated events at an energy of 1022 ± 13 keV, representing a branching ratio of $\approx 100\%$. These events were in turn found to be correlated with subsequent alpha decays of ^{155}Lu. The half-life of this correlated decay line was determined as 165^{+165}_{-55} ms which is significantly shorter than the value of ~ 1 s predicted for beta decay [15], the principal competing decay mode for ^{156}Ta. This new decay line is therefore assigned to the proton decay of ^{156}Ta and a Q value of 1028 ± 13 keV was deduced for these correlated proton decays. The combined Q values $Q_\alpha(^{160}\mathrm{Re}) + Q_p(^{156}\mathrm{Ta})$ and $Q_p(^{160}\mathrm{Re}) + Q_\alpha(^{159}\mathrm{W})$ are equal within the error bars, the difference being 24 ± 20 keV. Although this would be consistent with the two decay paths proceeding between the ground states of ^{160}Re and ^{155}Hf, it is not possible to establish unequivocally on the basis of the present data whether or not the observed proton-emitting state in ^{156}Ta represents the ground state.

Proton decay branches from the nuclides ^{161}Re and ^{157}Ta were also searched for in correlations with alpha decays but no evidence was found for a proton decay line in either case. Upper limits of 1% were established for the proton decay branching ratios of both nuclides from the observed yields of their alpha decays. Improved half-life measurements of 15.1 ± 3.6 ms and 5.5 ± 1.7 ms were obtained for ^{161}Re and ^{157}Ta, respectively.

The new results presented above define a new region of proton radioactivity, establishing the heaviest limit to nuclear existence known to date. The measurements for ^{160}Re and ^{156}Ta, combined with the results of previous proton radioactivity studies [1], provide a continuous sequence of proton emitters for odd-Z elements between thulium and rhenium ($Z=69$ to 75). This offers a unique opportunity for a detailed systematic investigation into the properties of proton-emitting nuclides. Using the Q_p values obtained for ^{156}Ta and ^{160}Re one can compare the measured half-lives with calculated values in order to determine the orbital from which the protons are emitted. In this region the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ proton levels are known to be very close in energy [1]. Table I shows partial proton decay half-lives calculated for these orbitals by Buck *et al.* [16] using a quasistationary model and values calculated using the WKB approximation with the real part of a global optical-model potential [17]. The ground states of the known proton-emitting thulium and lutetium isotopes [1] comprise protons in the $h_{11/2}$ orbital which is not expected to be filled until above rhenium ($Z=75$). However, the measured half-lives for both ^{160}Re and ^{156}Ta are clearly much too short to be consistent with values calculated assuming $h_{11/2}$ proton emission. The calculated values for $s_{1/2}$ proton emission would require a factor of ~ 10 hindrance in each case to provide agreement with our measurements, but no such hindrance is expected for ^{160}Re or ^{156}Ta since none is observed for the thulium and lutetium proton emitters. However, the calculations do provide good agreement with the measured values, assuming that the protons are emitted from a $d_{3/2}$ orbital in each case. We therefore conclude that ^{160}Re has a $d_{3/2}$ proton orbital as its ground state. This result would be consistent with Nilsson-type calculations [18] which suggest that, for small prolate deformations of $\beta \approx 0.1$ [19], the $[411]\frac{1}{2}^+$ level is depressed below the $[505]\frac{11}{2}^-$ level and therefore represents the ground state. In the case of ^{156}Ta it is not possible to establish whether the $d_{3/2}$ proton-emitting state observed in the present experiment or the beta-decaying $[\pi h_{11/2} \nu f_{7/2}]9^+$ state invoked by Hofmann *et al.* [5] represents the ground state. The energy difference between these states is probably very small (~ 100 keV) so further measurements to determine the ordering of low-lying levels in $N=83$ isotones would clearly be very interesting.

TABLE I. Comparison of (a) measured partial proton-decay half-lives for the new proton emitters ^{160}Re and ^{156}Ta with (b) values calculated by Buck *et al.* [16] using a quasistationary model and (c) values calculated using the WKB approximation with the real part of the global optical-model potential of Becchetti and Greenlees [17]. Spectroscopic factors of unity have been assumed in all cases.

Proton emitter	Partial half-life (ms) (a)	(b)	(c)	Proton orbital
		0.07	0.03	$s_{1/2}$
^{160}Re	0.87 ± 0.20	0.63	0.24	$d_{3/2}$
		420	480	$h_{11/2}$
		20	10	$s_{1/2}$
^{156}Ta	165^{+165}_{-55}	200	70	$d_{3/2}$
		150000	180000	$h_{11/2}$

The new nuclei ^{160}Re and ^{156}Ta both contain 25 fewer neutrons than the corresponding nearest stable isotope for each element. In such remote regions Q_p-value data are extremely scarce so the present Q_p-value measurements provide a severe test of the predictions of mass models which are based on measurements for nuclei much closer to stability. The systematic variation of proton-decay Q values with mass number for rhenium and tantalum isotopes as predicted by four representative sets of atomic-mass estimates [11,20–22] is shown in Fig. 2. The model of Myers [11] underpredicts the measured values (assuming the ^{156}Ta transition is from the ground state) by ~ 800 keV in each case, even though the measured Q_α

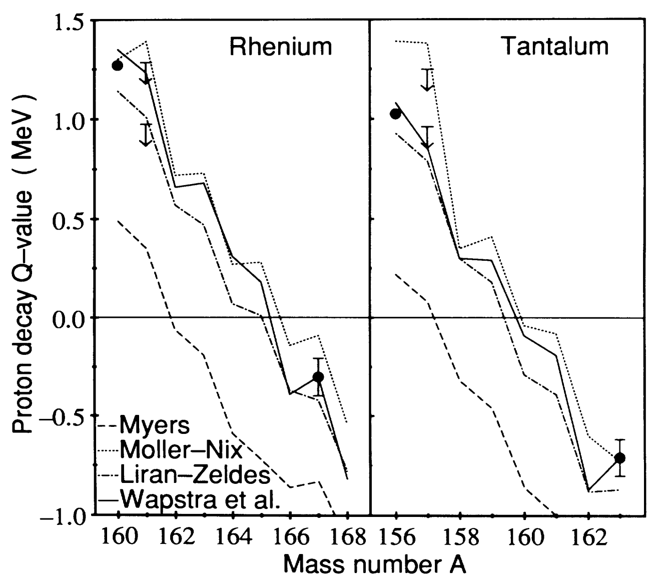

FIG. 2. Comparison of proton-decay Q-value predictions [11,20–22] for neutron-deficient rhenium and tantalum isotopes with known Q_p values. The Wapstra, Audi, and Hoekstra [22] Q_p value for ^{160}Re shown here has been obtained from their estimate of $Q_\alpha - Q_p$ and our measured Q_α value, since their tabulation does not extend to ^{156}Re. The error bars on the Q_p values measured for ^{160}Re and ^{156}Ta are smaller than the symbol size. Model-dependent Q_p-value limits determined for ^{161}Re and ^{157}Ta are marked, with nonexcluded values indicated by the arrows. The greater and the smaller limits correspond to $h_{11/2}$ and $d_{3/2}$ proton emission, respectively.

value for ^{160}Re is in good agreement with the predictions of this model. This extraordinary discrepancy is similar to those obtained for ^{147}Tm and ^{151}Lu which were attributed [7] to problems with the pairing energies in these calculations. With the exception of the Möller-Nix prediction [21] for ^{156}Ta, the remaining models provide good general agreement with the measured values.

In summary, the direct proton decays of the neutron-deficient nuclides ^{160}Re and ^{156}Ta have been identified, representing the heaviest proton emitters discovered to date. Accurate Q values have been measured and in each case the half-life and branching-ratio measurements are consistent with partial half-life estimates calculated assuming the emission of $d_{3/2}$ protons. These results illustrate how the great sensitivity of proton-decay half-lives to the orbital angular momentum of the emitted proton can be exploited to reveal detailed nuclear structure information at the extreme limits to nuclear existence.

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[1] S. Hofmann, *Particle Emission From Nuclei*, edited by D. N. Poenaru and M. Ivascu (CRC Press, Boca Raton, FL, 1989), Vol. 2, Chap. 2.

[2] T. Faestermann *et al.*, Phys. Lett. **137B**, 23 (1984); A. Gillitzer *et al.*, Z. Phys. A **326**, 107 (1987).

[3] P. J. Sellin *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **311**, 217 (1992).

[4] A. N. James *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **267**, 144 (1988).

[5] S. Hofmann *et al.*, Z. Phys. A **333**, 107 (1989).

[6] S. Hofmann *et al.*, in *Proceedings of the Seventh International Conference on Atomic Masses and Fundamental Constants, Darmstadt, 1984*, edited by O. Klepper [THD-Schriftenreihe, Wissenschaft und Tecknik **26**, 184 (1984)].

[7] S. Hofmann *et al.*, in *Proceedings of the Fourth International Conference on Nuclei Far From Stability, Helsingor, 1981*, edited by P. G. Hansen and O. B. Nielsen (CERN Report No. CERN 89-09, 1981, p. 190).

[8] U. J. Schrewe *et al.*, Z. Phys. A **315**, 49 (1984).

[9] G. D. Alkhazov *et al.*, Z. Phys. A **311**, 245 (1983).

[10] A. Rytz, At. Data Nucl. Data Tables **47**, 205 (1991).

[11] W. D. Myers, At. Data Nucl. Data Tables **17**, 411 (1976).

[12] K.-H. Schmidt *et al.*, Z. Phys. A **316**, 19 (1984).

[13] J. O. Rasmussen, Phys. Rev. **113**, 1593 (1959).

[14] R. D. Macfarlane, J. O. Rasmussen, and M. Rho, Phys. Rev. **134**, B1196 (1964).

[15] K. Takahashi, M. Yamada, and T. Kondoh, At. Data Nucl. Data Tables **12**, 101 (1973).

[16] B. Buck *et al.* (private communication).

[17] F. D. Becchetti, Jr. and G. W. Greenlees, Phys. Rev. **182**, 1190 (1969).

[18] T. Bengtsson and I. Ragnarsson, Nucl. Phys. **A436**, 14 (1985).

[19] P. Möller and J. R. Nix, At. Data Nucl. Data Tables **26**, 165 (1981).

[20] S. Liran and N. Zeldes *et al.*, At. Data Nucl. Data Tables **17**, 431 (1976).

[21] P. Möller and J. R. Nix, At. Data Nucl. Data Tables **39**, 213 (1988).

[22] A. H. Wapstra, G. Audi, and R. Hoekstra, At. Data Nucl. Data Tables **39**, 281 (1988).