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# Probing the limit of nuclear existence: Proton emission from $^{159}$Re

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**Abstract**

The observation of the new nuclide $^{159}_{75}\mathrm{Re}_{84}$ provides important insights into the evolution of single-particle structure and the mass surface in heavy nuclei beyond the proton drip line. This nuclide, 26 neutrons away from the nearest stable rhenium isotope, was synthesised in the reaction $^{106}$Cd($^{58}$Ni, $p4n$) and identified via its proton radioactivity using the RITU gas-filled separator and the GREAT focal-plane spectrometer. Comparisons of the measured proton energy ($E_p = 1805 \pm 20$ keV) and decay half-life ($t_{1/2} = 21 \pm 4$ μs) with values calculated using the WKB method indicate that the proton is emitted from an $h_{11/2}$ state. The implications of these results for future experimental investigations into even more proton unbound nuclei using in-flight separation techniques are considered.


*PACS:* 21.10.Hw; 21.10.Tg; 23.50.+z; 27.70.+q

*Keywords:* NUCLEAR REACTIONS $^{58}$Ni + $^{106}$Cd at 300 MeV beam energy; Enriched targets; Gas-filled recoil separator; Si detectors; Measured $E_p$, $t_{1/2}$

A fundamental goal in nuclear physics is to determine the limits on the number of protons and neutrons that can be bound inside an atomic nucleus. Indeed, one of the main challenges, both experimentally and theoretically, is to probe and understand nuclei with the most extreme numbers of neutrons and protons. Measurements on such nuclei have led to significant advances by challenging our understanding of nuclear properties derived from studies of nuclei close to the stability line. In the case of proton-rich nuclei, it is possible to perform experiments investigating nuclei around the proton drip line, which represents one of the fundamental limits of nuclear existence. This line is defined by nuclei with such a large excess of protons that they can decay towards stability by proton emission.

In recent years the detailed structure of the nuclear potential beyond the proton drip line has been probed via the identification of heavy proton-emitting nuclei and the measurement of their distinct decay properties [1,2]. The theoretical interpretation of proton radioactivity is comparatively straightforward, since the decay process can be treated as a simple quan-

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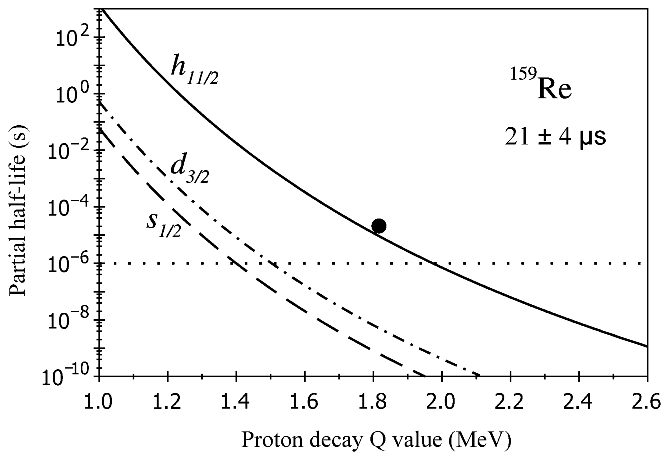


Fig. 1. Logarithm of the partial half-life as a function of the proton decay Q value calculated for decays from $\pi s_{1/2}$ (dashed line), $\pi d_{3/2}$ (dot-dashed line) and $\pi h_{11/2}$ (solid line) orbitals in $^{159}$Re. The calculations were performed using the Wentzel, Kramers and Brillouin (WKB) method and the global optical model potential of Becchetti and Greenlees [3]. No spectroscopic factor has been applied to the calculated half-lives. The filled circle represents the measured value of $21 \pm 4$ μs for the $^{159}$Re proton decay. The error bars are smaller than the size of the plotted symbol. The decreasing gradient of these curves signifies the diminishing influence of the energy on the half-life as the proton decay Q value increases. Although it is not immediately evident from these curves owing to the logarithmic scale, the orbital angular momentum also has a somewhat reduced effect on the half-life for higher Q values. The dotted horizontal line indicates the typical flight time of $\sim 1$ μs through a recoil separator.

tum tunnelling process through a potential barrier. This can be contrasted with $\alpha$ decay, where a preformation factor for the composite $\alpha$ particle is necessary. The barrier penetration probability (and so the decay half-life) is extremely sensitive to the proton decay energy ($E_p$) and the orbital angular momentum of the initial state from which the proton is emitted, see Fig. 1. This makes proton radioactivity an ideal mechanism for determining single-particle structures and characterising the nuclear potential at one of the extreme limits of nuclear stability.

In light nuclei, $Z \leqslant 50$, the relatively small potential barrier allows proton emission to occur so quickly that the limit of nuclear stability is very abrupt [1,2]. For heavier elements the proton emission process is sufficiently retarded by the potential barrier that some proton-emitting nuclei are accessible for study by current experimental techniques. Even so investigations of the structure of nuclei at the proton drip line are exceedingly difficult because their production rates are extremely low compared with other, less exotic reaction products. Fortunately, it is possible to isolate the nuclei of interest within $\sim 1$ μs of their formation using efficient recoil separators. High-granularity silicon strip detector systems installed at the focal planes of these recoil separators can then provide very clean correlations with daughter decays, allowing these nuclei to be explored. We have exploited this technique in the first identification of the proton unbound isotope, $^{159}$Re, which has 26 fewer neutrons than the lightest stable isotope.

Proton radioactivity has been observed previously in the lightest known Re isotopes, $^{160}_{75}$Re$_{85}$ [4,5] and $^{161}_{75}$Re$_{86}$ [6], which lie in a region where proton emission has been interpreted as originating from spherical configurations involving either the $\pi s_{1/2}$, $\pi d_{3/2}$ or $\pi h_{11/2}$ orbitals [1,2]. In the case of $^{160}$Re only a single state was observed that decays primarily via the emission of a $d_{3/2}$ proton, while in $^{161}$Re proton emission was observed from both the $\pi s_{1/2}$ ground state and the $\pi h_{11/2}$ isomeric state that lies at an excitation energy of 124 keV. The case of $^{161}$Re can be taken as an example to illustrate the sensitivity of proton decay half-lives to the decay energy and orbital angular momentum: increasing the proton energy by just 100 keV would reduce the calculated partial proton decay half-life by more than an order of magnitude, while increasing the orbital angular momentum quantum number by $5\hbar$ would increase the half-life by a factor of $\sim 20\,000$. Although these effects are slightly moderated as nuclei become increasingly unbound (see Fig. 1), this does serve to illustrate how quickly decay half-lives plummet once the threshold for proton emission is crossed.

The experiment was performed at the Accelerator Laboratory of the University of Jyväskylä. The $^{159}$Re nuclei were populated in the $^{106}$Cd($^{58}$Ni, $p4n$) fusion evaporation reaction. A beam of $^{58}$Ni$^{12+}$ ions at a bombarding energy of 300 MeV impinged on a 1.1 mg/cm$^2$ thick, self-supporting $^{106}$Cd target foil of 96.5% isotopic enrichment. An average beam current of 4.7 pnA was delivered during 75 hours of irradiation time. Fusion reaction products were separated in-flight from scattered beam and other reaction products by the RITU gas-filled separator [7,8] before being implanted into a double-sided silicon strip detector (DSSD) of the GREAT spectrometer [9]. All detector signals were passed to the GREAT triggerless total data readout data acquisition system [10] where they were time stamped with a precision of 10 ns to allow accurate temporal correlations between recoil implants and their subsequent radioactive decays.

Fig. 2 shows $\alpha$ and proton decays detected in the GREAT DSSDs. A calibration was performed using the characteristic $\alpha$-decay lines of implanted Tb, Dy, Lu and Hf nuclides and the proton decay line of $^{160}$Re [5]. A broad distribution is apparent in Fig. 2(a) below 4 MeV and corresponds to $\alpha$ particles that escape from the surface of the DSSD without depositing their full energy. Typical proton decay energies coincide with this distribution, rendering it difficult to observe new proton emitters directly.

In order to suppress this escape background and identify any new proton emitters unambiguously, recoil-decay correlations were performed. For $^{159}$Re this was achieved by searching for correlations with the $\alpha$ decay from the ground state of the proton-decay daughter, $^{158}$W ($E_\alpha = 6445 \pm 3$ keV, $t_{1/2} = 1.5 \pm 0.2$ ms) [11]. Fig. 2(b) shows the intervening decays following a recoil implantation and preceding a $^{158}$W $\alpha$ decay. The time difference between recoil implantations and $^{158}$W $\alpha$ decays within the same pixel of the DSSD was limited to 5 ms. Fig. 2(b) highlights two groups of counts: a peak at $\approx 1.8$ MeV comprising 53 counts and a few counts around $\approx 6.6$ MeV. The 1.8 MeV peak is assigned as the proton decay from the previously unknown nuclide $^{159}$Re. This yield corresponds to one $^{159}$Re nucleus in every 4 million evaporation residues implanted into GREAT. The few counts at higher energy represent real correlations with the $6600 \pm 3$ keV $\alpha$ decay of $^{162}$Os [12] populated directly as an evaporation residue. The half-life of

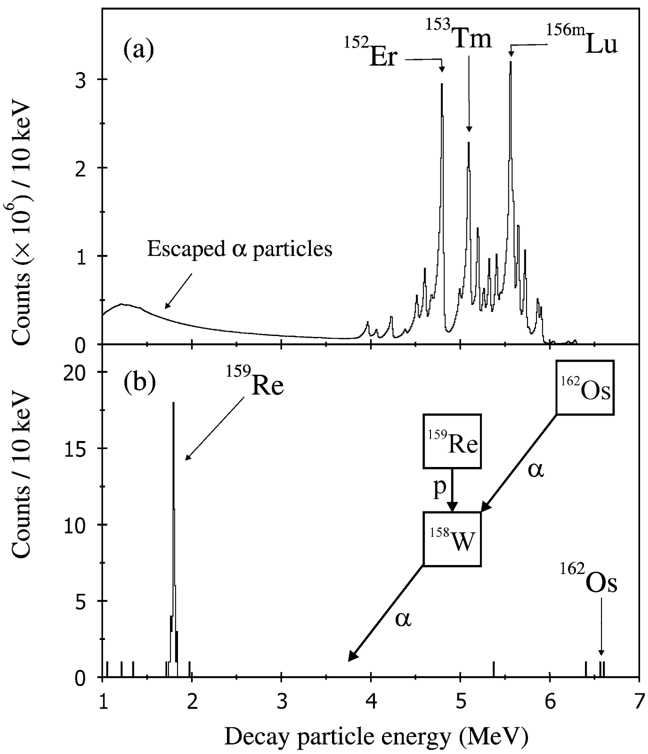


Fig. 2. (a) Decay particle energy spectrum observed in GREAT. The known $\alpha$ decays in $^{152}$Er, $^{153}$Tm and $^{156m}$Lu are indicated. The broad distribution at low energy corresponds to $\alpha$ particles escaping from the DSSDs. (b) Spectrum showing decays following a recoil implantation and correlated with subsequent $\alpha$ decays of $^{158}$W ($E_\alpha = 6445 \pm 3$ keV, $t_{1/2} = 1.5 \pm 0.2$ ms) [11] in the same pixel of the detector. The time difference between recoil implantations and $^{158}$W $\alpha$ decays was limited to 5 ms. The inset shows the proton- and $\alpha$-decaying nuclides that are expected to populate $^{158}$W.

the $^{159}$Re proton decay peak was measured as $21 \pm 4$ μs using the maximum likelihood method [13].

Owing to the short half-life of the proton-emitting state, the detected energies need to be corrected for a pile-up effect [14, 15]. This effect originates from the proton being emitted before the corresponding recoil energy signal from the shaping amplifier has been fully restored to the baseline. This effect was corrected by analysing the pulse height measured as a function of time for the $^{160}$Re proton decay line ($E_p = 1263$ keV, $t_{1/2} = 790$ μs [4,5]) that was produced strongly in this experiment. Following this correction procedure, the energy of the $^{159}$Re proton decay line was determined to be $1805 \pm 20$ keV.

The present data were also analysed for other possible proton- and $\alpha$-decaying states in $^{159}$Re. Correlations were sought with the 8.3 MeV $\alpha$-decaying isomer in $^{158}$W [5,11,16], the proton decay of $^{155}$Ta [17] and the $\alpha$ decay of $^{154}$Yb, which would follow the proton decay of any state in $^{155}$Ta. However, no evidence for any other decay branch from $^{159}$Re could be identified. Since the $\beta$-decay half-life of $^{159}$Re is expected to be $\sim 0.2$ s [18], the proton decay branching ratio of the observed peak was assumed to be 100%.

The measured partial half-life for the proton decay of $^{159}$Re is compared in Table 1 with WKB calculations for the different possible proton orbitals using the measured proton decay energy. The column labelled WKB1 uses the potential of Becchetti and Greenlees [3], while a mean-field potential from a Skyrme Hartree–Fock calculation using the SkP force [19] and BCS pairing were used for the column labelled WKB2. With either WKB potential, the measured half-life is only compatible with that calculated for the $\pi h_{11/2}$ orbital, see Fig. 1. The half-lives calculated for the other, lower-spin orbitals are far too short and would be expected to decay in flight long before reaching the focal plane of RITU. From the ratio of the calculated and measured half-lives, a spectroscopic factor associated with the WKB1 calculation of $0.45 \pm 0.10$ can be deduced. This compares with the value of 0.44 expected from a low-seniority shell model calculation for a rhenium isotope [20]. For the WKB2 calculation, the BCS occupation probabilities give a spectroscopic factor calculated self-consistently alongside the potential used. When applied to correct the half-lives, the Skyrme + BCS calculation yields a half-life of 28 μs for the $\pi h_{11/2}$ state, which is also in excellent agreement with the experimental result.

Table 1
Measured and calculated decay properties of $^{159}$Re. The calculated half-life values were obtained using the WKB method and either the global optical model potential of Becchetti and Greenlees [3] (WKB1), or a Skyrme Hartree–Fock potential, (WKB2) [19]. In order to estimate experimental half-lives, these calculated values should be divided by the relevant spectroscopic factor. For the WKB1 calculations, a spectroscopic factor of 0.44 would be expected for all three orbitals from a low-seniority shell model calculation [20]. In the case of the WKB2 calculations, the spectroscopic factors deduced from the BCS occupation probabilities are 0.224, 0.156 and 0.473 for the $s_{1/2}$, $d_{3/2}$ and $h_{11/2}$ orbitals, respectively

| Partial half-life $t_{1/2}$ | | | | |
|---|---|---|---|---|
| $E_p$ (keV) | Exp (μs) | WKB1 (μs) | WKB2 (μs) | Proton orbital |
| | | 0.00064 | 0.0020 | $s_{1/2}$ |
| | | 0.012 | 0.012 | $d_{3/2}$ |
| 1805(20) | 21(4) | 9.4 | 13.2 | $h_{11/2}$ |

In addition to providing spectroscopic information beyond the proton drip line, proton decay measurements can also provide precise measurements of proton separation energies. When combined with $\alpha$-decay measurements it is possible to build up a more comprehensive systematic picture of nuclear binding energies beyond the drip line. Fig. 3 shows the measured proton separation energies plotted as a function of neutron number for odd-$A$ and for odd–odd nuclides of elements from Ta ($Z = 73$) to Tl ($Z = 81$). The filled symbols are for $\pi h_{11/2}$ states, while those for low-spin ($\pi s_{1/2}$ or $\pi d_{3/2}$) states are given by the open symbols. This plot shows clearly the monotonic decrease of proton separation energies with increasing neutron deficiency, with the notable exception of $^{155}Ta_{82}$ [17]. This anomaly could be explained if the proton in this case were emitted from a higher-lying isomer comprising an $h_{11/2}$ proton.

Extrapolating these trends to the $\pi s_{1/2}$ state in $^{159}$Re, one expects that this state would represent the ground state, with the $\pi h_{11/2}$ state observed in the present Letter lying at an excitation energy of $\approx 120$ keV. The corresponding half-life of the $\pi s_{1/2}$ state in $^{159}$Re would be expected to be $\sim 10$ ns from WKB calculations. Since this is far shorter than the flight time through RITU this provides a natural explanation for the non-observation of this decay in this experiment. It should be noted that this

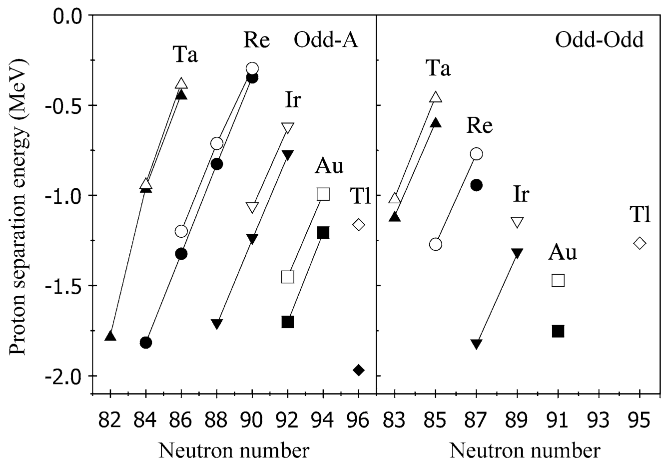


Fig. 3. Experimental proton separation energies deduced from proton decay measurements plotted as a function of neutron number for odd-$Z$ elements from Ta to Tl. The left-hand panel is for odd-$A$ nuclides, while odd–odd nuclides are shown in the panel on the right. The filled symbols denote $\pi h_{11/2}$ states, whereas low-spin states are indicated by the open symbols. In odd-$A$ nuclei the low-spin states have an unpaired $s_{1/2}$ proton while in odd–odd nuclei the odd proton occupies a $d_{3/2}$ orbital. The lines connect states of the same odd-proton configuration for a given isotopic chain. Data are taken from references [5,6,14, 17,20–24]. The error bars are smaller than the size of the plotted symbols.

phenomenon where an excited state survives long enough to be observed while the proton decay of the ground state is too short to observe is not unique to $^{159}$Re: the same pattern is thought also to occur in the odd-mass proton emitters $^{145}$Tm [15], $^{155}$Ta [17] and $^{165}$Ir [20].

It is interesting to speculate whether $^{159}$Re might be the lightest Re isotope that could be observed. The $\pi d_{3/2}$ proton- and $\alpha$-decaying state known in $^{160}$Re has a half-life of only 790 μs [4]. If the proton decay energy is increased by $\approx 500$ keV, as suggested by the systematics plotted in Fig. 3, one would expect the half-life to be only $\sim 10$ ns (the weak dependence of the calculated half-lives on the mass number of the proton emitter means that the values for $^{158}$Re are only a few per cent larger than those plotted for $^{159}$Re in Fig. 1). However, if there were a proton-emitting $\pi h_{11/2}$ state in $^{158}$Re, the effect of the angular momentum barrier may be sufficient to increase the half-life to $\sim$ μs in spite of the increase in decay energy. Even so, this would be an extremely challenging experiment because the production rate would be even lower than that for $^{159}$Re. In addition, the unique identification through correlation techniques would be hampered by the relatively slow $\beta$ decay of $^{157}$W intervening between the $^{158}$Re proton decay and the $\alpha$ decay of $^{157}$Ta.

More generally, progress in the study of proton emission in this region appears to be very difficult using recoil separators owing to the limitation imposed by the flight time. To push these studies further beyond the proton drip line it may be necessary to focus attention on detecting protons close to the target [25–27]. Although this should reduce the lower lifetime limit for nuclei accessible for study, obtaining the sensitivity and precision offered by recoil separators will be a major challenge.

In this Letter proton emission from the new isotope $^{159}$Re has been observed. The measured decay energy and half-life are consistent with those expected from a $\pi h_{11/2}$ configuration assuming a spherical nucleus. The prospects for investigating even more proton unbound nuclei in this region using recoil separators appear rather limited, owing primarily to the short half-lives expected for the proton-decaying states involved. New experimental techniques may therefore have to be developed in order to explore even more loosely bound nuclei, where the influence of coupling to the continuum of unbound states is expected to become important and pairing interactions could be dramatically affected by diffuse proton distributions [28].

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## References

[1] S. Hofmann, Particle Emission From Nuclei, vol. 2, CRC Press, Boca Raton, Fl, 1989, p. 25.
[2] P.J. Woods, C.N. Davids, Annu. Rev. Nucl. Part. Sci. 47 (1997) 541.
[3] F.D. Becchetti, G.W. Greenlees, Phys. Rev. 182 (1969) 1190.
[4] R.D. Page, P.J. Woods, R.A. Cunningham, T. Davinson, N.J. Davis, S. Hofmann, A.N. James, K. Livingston, P.J. Sellin, A.C. Shotter, Phys. Rev. Lett. 68 (1992) 1287.
[5] R.D. Page, P.J. Woods, R.A. Cunningham, T. Davinson, N.J. Davis, A.N. James, K. Livingston, P.J. Sellin, A.C. Shotter, Phys. Rev. C 53 (1996) 660.
[6] R.J. Irvine, et al., Phys. Rev. C 55 (1997) R1621.
[7] J. Uusitalo, et al., Nucl. Instrum. Methods Phys. Res. B 204 (2003) 638.
[8] M. Leino, Nucl. Instrum. Methods Phys. Res. B 126 (1997) 320.
[9] R.D. Page, Nucl. Instrum. Methods Phys. Res. B 204 (2003) 634.
[10] I.H. Lazarus, et al., IEEE Trans. Nucl. Sci. 48 (2001) 567.
[11] H. Mahmud, et al., Phys. Rev. C 62 (2000) 057303.
[12] D.T. Joss, et al., Phys. Rev. C 70 (2004) 017302.
[13] K.-H. Schmidt, Z. Phys. A 316 (1984) 19.
[14] A.P. Robinson, et al., Phys. Rev. C 68 (2003) 054301.
[15] J.C. Batchelder, et al., Phys. Rev. C 57 (1998) R1042.
[16] S. Hofmann, et al., Z. Phys. A 333 (1989) 107.
[17] J. Uusitalo, et al., Phys. Rev. C 59 (1999) R2975.
[18] M. Hirsch, A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus, At. Data Nucl. Data Tables 53 (1993) 165.
[19] J. Dobaczewski, H. Flocard, J. Treiner, Nucl. Phys. A 422 (1984) 103.
[20] C.N. Davids, et al., Phys. Rev. C 55 (1997) 2255.
[21] H. Kettunen, et al., Acta Phys. Pol. B 32 (2001) 989.
[22] H. Kettunen, et al., Phys. Rev. C 69 (2004) 054323.
[23] H. Mahmud, et al., Eur. Phys. J. A 15 (2002) 85.
[24] G.L. Poli, et al., Phys. Rev. C 59 (1999) R2979.
[25] T. Faestermann, A. Gillitzer, K. Hartel, P. Kienle, E. Nolte, Phys. Lett. B 137 (1984) 23.
[26] A. Gillitzer, T. Faestermann, K. Hartel, P. Kienle, E. Nolte, Z. Phys. A 326 (1987) 107.
[27] D. Rudolph, et al., Phys. Rev. Lett. 80 (1998) 3018.
[28] J. Dobaczewski, I. Hamamoto, W. Nazarewicz, J.A. Sheikh, Phys. Rev. Lett. 72 (1994) 981.