Available online at www.sciencedirect.com
ScienceDirect
PHYSICS LETTERS B
Physics Letters B 641 (2006) 34–37
www.elsevier.com/locate/physletb

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

D.T. Joss [a,b,*], I.G. Darby [a], R.D. Page [a], J. Uusitalo [c], S. Eeckhaudt [c], T. Grahn [c], P.T. Greenlees [c], P.M. Jones [c], R. Julin [c], S. Juutinen [c], S. Ketelhut [c], M. Leino [c], A.-P. Leppänen [c], M. Nyman [c], J. Pakarinen [a,c], P. Rahkila [c], J. Sarén [c], C. Scholey [c], A. Steer [c,1], A.J. Cannon [d], P.D. Stevenson [d], J.S. Al-Khalili [d], S. Ertürk [e], M. Venhart [c,f], B. Gall [g], B. Hadinia [h], J. Simpson [b]

[a] Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom
[b] CCLRC Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, United Kingdom
[c] Department of Physics, University of Jyväskylä, PO Box 35, FIN-40014, Jyväskylä, Finland
[d] Department of Physics, University of Surrey, Guildford, GU2 7XH, United Kingdom
[e] Nigde Universitesi, Fen-Edebiyat Falkültesi, Fizik Bölümü, Nigde, Turkey
[f] Department of Nuclear Physics and Biophysics, Comenius University, Mlynska Dolina, 842 48 Bratislava 4, Slovakia
[g] IPHC, CNRS-IN2P3, ULP Strasbourg, 23 rue du Loess, 67037 Strasbourg cedex 2, France
[h] Department of Physics, Royal Institute of Technology, SE-106 91, Stockholm, Sweden

Received 4 July 2006; accepted 9 August 2006

Available online 18 August 2006

Editor: V. Metag

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-

* Corresponding author.
E-mail address: dtj@ns.ph.liv.ac.uk (D.T. Joss).

[1] Present address: Department of Physics, University of York, Heslington, York, Y010 5DD, United Kingdom.

0370-2693/$ – see front matter
doi:10.1016/j.physletb.2006.08.014

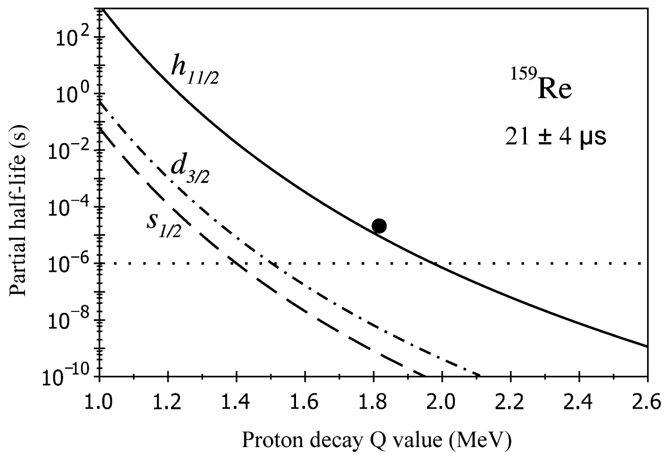

Fig. 1. Logarithm of the partial half-life as a function of the proton decay Q value calculated for decays from $\pi s_{1/2}$ (dashed line), $\pi d_{3/2}$ (dot-dashed line) and $\pi h_{11/2}$ (solid line) orbitals in ^{159}Re. The calculations were performed using the Wentzel, Kramers and Brillouin (WKB) 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 ± 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 ~ 1 μs through a recoil separator.

tum tunnelling process through a potential barrier. This can be contrasted with α decay, where a preformation factor for the composite α 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 ~ 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, $^{160}_{75}\mathrm{Re}_{85}$ [4,5] and $^{161}_{75}\mathrm{Re}_{86}$ [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 α and proton decays detected in the GREAT DSSDs. A calibration was performed using the characteristic α-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 α 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 α 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 α decay. The time difference between recoil implantations and ^{158}W α decays within the same pixel of the DSSD was limited to 5 ms. Fig. 2(b) highlights two groups of counts: a peak at ≈ 1.8 MeV comprising 53 counts and a few counts around ≈ 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 ± 3 keV α decay of ^{162}Os [12] populated directly as an evaporation residue. The half-life of