Physics Letters B 772 (2017) 703–707

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Spectroscopy at the two-proton drip line: Excited states in ^{158}W

D.T. Joss [a,*], R.D. Page [a], A. Herzán [a], L. Donosa [a], J. Uusitalo [b], R.J. Carroll [a], I.G. Darby [a,c], K. Andgren [d], B. Cederwall [d], S. Eeckhaudt [b], T. Grahn [b], P.T. Greenlees [b], B. Hadinia [d,e], U. Jakobsson [b,d], P.M. Jones [f], R. Julin [b], S. Juutinen [b], M. Leino [b], A.-P. Leppanen [b], M. Nyman [b], D. O'Donnell [a], J. Pakarinen [b], P. Rahkila [b], M. Sandzelius [b], J. Sarén [b], C. Scholey [b], D. Seweryniak [g], J. Simpson [h], J. Sorri [b]

[a] Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 7ZE, United Kingdom
[b] Department of Physics, University of Jyvaskyla, PO Box 35 FI-40014, Jyvaskyla, Finland
[c] Department of Nuclear Sciences and Applications, International Atomic Energy Agency, A-1400 Vienna, Austria
[d] Department of Physics, Royal Institute of Technology, Alba Nova Centre, S106 91, Stockholm, Sweden
[e] Department of Physics, University of Guelph, Guelph, Ontario N1G 2W1, Canada
[f] Department of Nuclear Physics, iThemba Laboratory for Accelerator Based Sciences, PO Box 722, Somerset West 7129, South Africa
[g] Argonne National Laboratory, Argonne, IL, 60439, USA
[h] STFC, Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, United Kingdom

ARTICLE INFO

Article history:
Received 2 June 2017
Received in revised form 5 July 2017
Accepted 15 July 2017
Available online 20 July 2017
Editor: V. Metag

Keywords:
Multiparticle excited states
Proton radioactivity

ABSTRACT

Excited states have been identified in the heaviest known even-Z $N = 84$ isotone ^{158}W, which lies in a region of one-proton emitters and the two-proton drip line. The observation of γ-ray transitions feeding the ground state establishes the excitation energy of the yrast 6^+ state confirming the spin-gap nature of the α-decaying 8^+ isomer. The 8^+ isomer is also expected to be unbound to two-proton emission but no evidence for this decay mode was observed. An upper limit for the two-proton decay branch has been deduced as $b_{2p} \leq 0.17\%$ at the 90% confidence level. The possibility of observing two-proton emission from multiparticle isomers in nearby nuclides is considered.

1. Introduction

Establishing the limits of observable nuclei is a long-standing challenge in nuclear physics. For proton-rich nuclei, theoretical predictions suggest that these limits are determined by two-proton emission in even-Z nuclei up to $Z = 82$ and by the emission of a single proton for odd-Z nuclei [1–4]. Two-proton radioactivity is a rare phenomenon and experimental discoveries from ground states has been limited to a few light nuclei. For example, two-proton emission from ^{19}Mg ($Z = 12$) [5] has been identified by measuring the decay products in flight, while two-proton decays from the ground states of ^{45}Fe ($Z = 26$) [6,7], ^{48}Ni ($Z = 28$) [8], ^{54}Zn ($Z = 30$) [9] and ^{67}Kr [10] have been observed at the focal planes of fragment separators. However, extrapolations from the table of measured masses [11] combined with advances in nuclear density functional theory have allowed candidates where two-proton radioactivity competes with α decay in heavy nuclei to be predicted [3,4].

In most cases, two-proton emission from the ground states of even-Z nuclei would occur much further from β stability than the one-proton drip line for odd-Z nuclei due to the pairing interaction. The known cases of ground state two-proton emission in light nuclei occur around two neutrons lighter than the predicted two-proton drip line [3]. Two-proton emission from the ground states of heavy nuclei would only dominate in nuclides that lie ten or more neutrons beyond the two-proton drip line [3] and are inaccessible using current experimental facilities. However, there is a possibility that direct two-proton emission might proceed from excited states in nuclei closer to stability. This would be analogous to the first observation of direct one-proton emission, which was from a $19/2^-$ isomer in ^{53}Co [12–14]. This nuclide is bound in its ground state yet its excited state at 3.2 MeV is proton unbound. In this case, the high excitation energy (and therefore large proton decay Q value) is sufficient to overcome the confining effect of the centrifugal barrier, which for ^{53}Co results in the largest spin change of any known proton emitter ($\Delta I = 9\hbar$). The discovery of

---

[*] Corresponding author.
E-mail address: david.joss@liverpool.ac.uk (D.T. Joss).

http://dx.doi.org/10.1016/j.physletb.2017.07.031

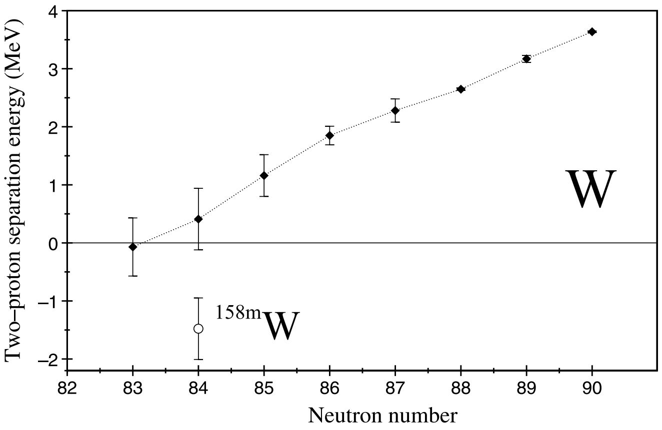

Fig. 1. Two-proton separation energies for the neutron-deficient W isotopes. The solid diamonds denote ground-state two-proton separations energies taken from the atomic masses table [11]. The unfilled circle denotes the two-proton separation energy of the 8^+ isomer in ^{158}W deduced using references [11,24].

direct two-proton emission from a multiparticle isomer has been claimed in a study of the 21^+ isomer in ^{94}Ag [15] although more recent measurements suggest this observation is doubtful [16–19].

The focus of this letter is ^{158}W ($Z = 74$), which is predicted to lie at the two-proton drip line [20]. Its adjacent isotones ^{159}Re and ^{157}Ta are both single-proton emitters [21,22]. Its neighbour, ^{157}W, is the lightest-known tungsten isotope [23] and is predicted to be just unbound to two-proton emission [20]. Although ^{158}W may also be unbound to two-proton emission [11] it is observed to undergo α decay with a half-life of 1.5(2) ms [24]. In general, most known excited states of proton-unbound nuclei decay preferentially by γ-ray emission. However, there is a second α-emitting state in ^{158}W at an excitation energy of 1888(8) keV [24] that would be unbound to two-proton emission by 1478(530) keV [20], see Fig. 1. A simple barrier penetration calculation suggests that ^{2}He emission is unlikely to complete with α decay from this state but other mechanisms exist for two-proton emission, which makes predicting half-lives challenging [25]. The corresponding isomer in the lighter $N = 84$ isotone ^{156}Hf lies at an excitation energy of 1959(1) keV [26] and is bound to both one- and two-proton emission, reflecting the rarity of accessible two-proton emission candidates in heavy nuclei.

This letter reports the identification of excited states built above the ground and isomeric states in ^{158}W and the search for two-proton emission from the 8^+ isomer. Prior to this work no other low-lying excited states had been identified in ^{158}W although three γ rays above the α-decaying 8^+ state were reported in an earlier experiment [27]. Our measurements indicate how the excited states could evolve in nearby even-Z nuclides, which could also be two-proton decay candidates.

2. Experimental details

The experiment was performed at the University of Jyvaskyla Accelerator Laboratory. The ^{158}W nuclei were produced in fusion–evaporation reactions induced by 255 MeV ^{58}Ni ions bombarding an isotopically enriched, self-supporting ^{102}Pd target foil of nominal thickness 1 $\mathrm{mg\,cm^{-2}}$. An average beam intensity of 4.3 particle nA was delivered for 139 hours. Prompt γ rays were measured at the target position using the Jurogam array, which comprised 43 Compton-suppressed Ge detectors [28]. The ^{158}W ions recoiled out of the target and were transported within ~0.5 μs by the gas-filled separator RITU [29,30] to the GREAT spectrometer [31] located at its focal plane. The ions passed through a multiwire proportional counter and were implanted into the adjacently mounted double-sided silicon strip detectors (DSSDs). Each DSSD had an active area of 60 × 40 mm and was 300 μm thick. The strips on their front and back surfaces were orthogonal and the strip pitch of 1 mm on both faces provided 4800 independent pixels. All detector signals were passed to the triggerless data acquisition system [32], where they were time stamped with a precision of 10 ns. The data were analysed by using the GRAIN [33] and RADWARE [34] software packages.

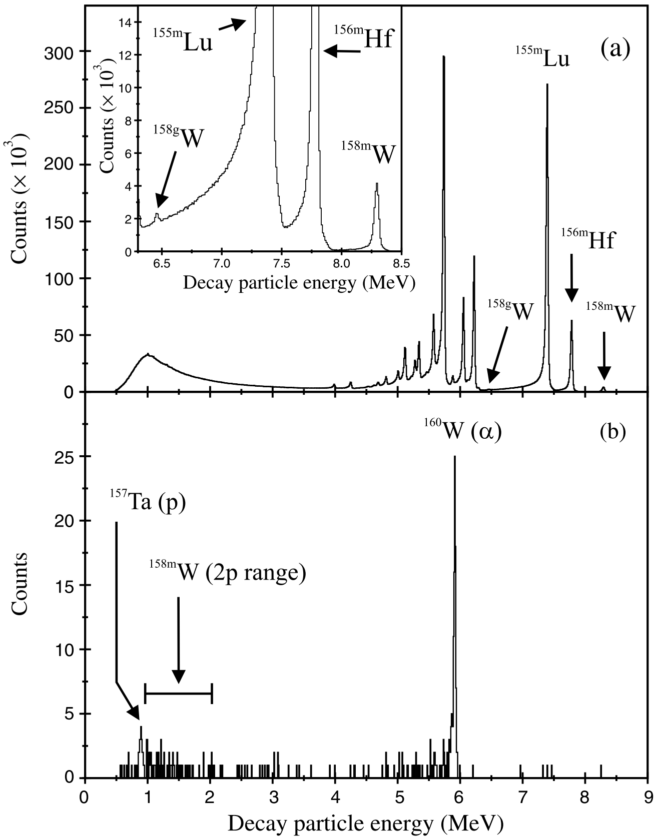

Fig. 2. (a) Decay particle energy spectrum of decays detected within 5 ms of an ion implantation in the same DSSD pixel of the GREAT spectrometer. The α decay from the 8^+ isomer in ^{158}W is seen at 8286 keV in addition to other α decay peaks that are labelled by their emitting nucleus. The inset shows an expanded region near the α decay from the $25/2^-$ isomer in ^{155}Lu. The ground-state α decay of ^{158}W can be seen on the low-energy tail of the ^{155m}Lu peak. The superscripts g and m denote α decays from ground and isomeric states, respectively. (b) Energy spectrum observed in GREAT and showing radioactive decays following a recoil implantation within 750 μs in the same pixel of the detector. An additional requirement that the decay was followed by a ground-state α decay of ^{156}Hf in the same pixel within 100 ms was applied. The proton decay from ^{157}Ta and α decay of ^{160}W are indicated. The nucleus ^{160}W was produced in reactions with traces of $A > 102$ Pd isotopes present in the target.

3. Results

Prior to this work, radioactive-decay spectroscopy experiments identified α decays from both the 0^+ ground state and the 8^+ isomer in ^{158}W [24,26,35]. In the present experiment a total of 1750 and 18000 α decays were measured from the ground state and 8^+ isomer in ^{158}W, respectively. This corresponds to an estimated cross section of ~1 μb for this nucleus assuming a transmission efficiency of ~30%. The high α-decay branching ratios, decay energies and short half-lives of the 0^+ ground state [$E_\alpha = 6433(3)$ keV, $t_{1/2} = 1.25(21)$ ms] and 8^+ isomer decays [$E_\alpha = 8286(7)$ keV, $t_{1/2} = 0.143(19)$ ms] [24,26,35] are well suited to experiments that