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Author(s): Joss, D.T.; Page, R.D.; Herzan, A.; Donosa, L.; Uusitalo, Juha; Carroll, R.J.; Darby, I.G.; Andgren, K.; Cederwall, B.; Eeckhaudt, Sarah; Grah, Tuomas; Greenlees, Paul; Hadinia, B.; Jakobsson, Ulrika; Jones, P. M.; Julin, Rauno; Juutinen, Sakari; Leino, Matti; Leppänen, Ari-Pekka; Nyman, May; O'Donnell, D.; Pakarinen, Janne; Rahkila, Panu; Sandzelius, Mikael; Sarén, Jan; Scholey, Catherine; Seweryniak, D.; Simpson, J.; Sorri, J.
Title: Spectroscopy at the two-proton drip line: Excited states in 158W

Year: 2017

Version:

Please cite the original version:

Joss, D.T., Page, R.D., Herzan, A., Donosa, L., Uusitalo, J., Carroll, R.J., Darby, I.G., Andgren, K., Cederwall, B., Eeckhaudt, S., Grah, T., Greenlees, P., Hadinia, B., Jakobsson, U., Jones, P. M., Julin, R., Juutinen, S., Leino, M., Leppänen, A.-P., . . . Sorri, J. (2017). Spectroscopy at the two-proton drip line: Excited states in 158W. *Physics Letters B*, 772, 703-707. <https://doi.org/10.1016/j.physletb.2017.07.031>

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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. Rähkila^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 Jyväskylä, PO Box 35 FI-40014, Jyväskylä, 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.

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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).

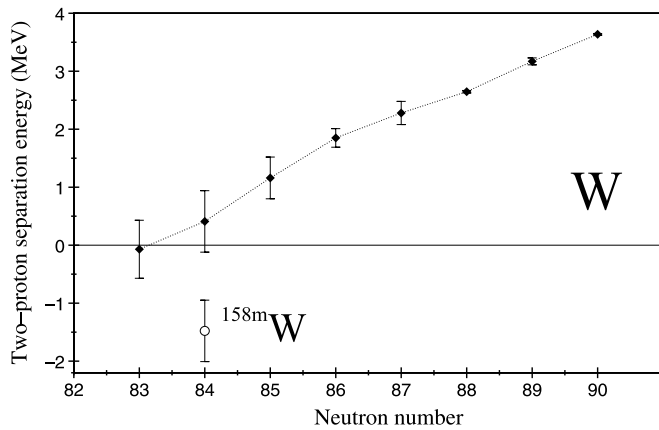


Fig. 1. Two-proton separation energies for the neutron-deficient W isotopes. The solid diamonds denote ground-state two-proton separations energies taken from the atomic masses table [11]. The unfilled circle denotes the two-proton separation energy of the 8^+ isomer in ^{158m}W deduced using references [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 ^2He 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 Jyväskylä 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 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 $\sim 0.5 \mu\text{s}$ 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

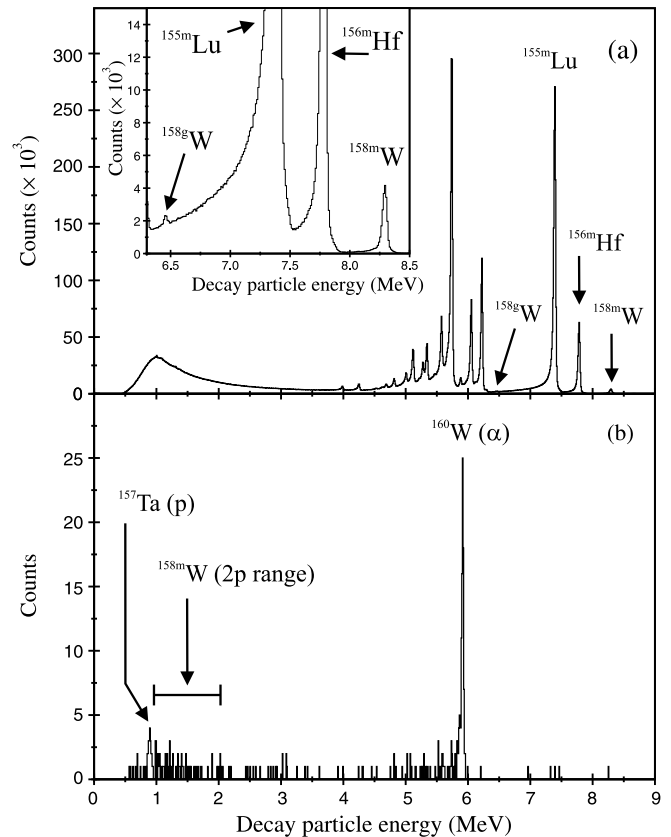


Fig. 2. (a) Decay particle energy spectrum of decays detected within 5 ms of an ion implantation in the same DSSD pixel of the GREAT spectrometer. The α decay from the 8^+ isomer in ^{158}W is seen at 8286 keV in addition to other α decay peaks that are labelled by their emitting nucleus. The inset shows 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.

counter and were implanted into the adjacently mounted double-sided silicon strip detectors (DSSDs). Each DSSD had an active area of $60 \times 40 \text{ mm}$ 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.

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 $\sim 1 \mu\text{b}$ for this nucleus assuming a transmission efficiency of $\sim 30\%$. The high α -decay branching ratios, decay energies and short half-lives of the 0^+ ground state [$E_\alpha = 6433(3) \text{ keV}$, $t_{1/2} = 1.25(21) \text{ ms}$] and 8^+ isomer decays [$E_\alpha = 8286(7) \text{ keV}$, $t_{1/2} = 0.143(19) \text{ ms}$] [24,26,35] are well suited to experiments that

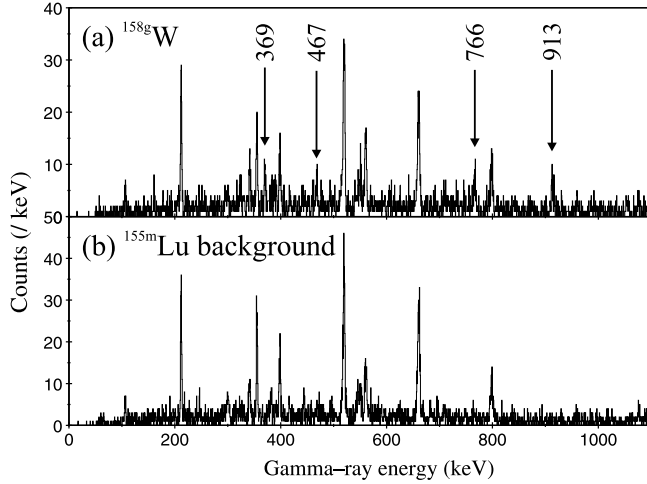


Fig. 3. Gamma-ray energy spectra measured with the Jurogam spectrometer. (a) Spectrum showing all γ rays correlated with ion implantations followed by the characteristic ground-state α decay of ^{158}W in the same DSSD pixel of the GREAT spectrometer within 5 ms. Gamma rays assigned to ^{158}W are labelled by their transition energies. The remaining γ rays belong to ^{155}Lu and appear due to correlations with the $\alpha(^{155}\text{Lu})$ background. (b) Spectra showing all γ rays correlated with ion implantations followed by background from ^{155m}Lu α decays selected above the ^{158g}W α -decay peak. The energy interval used to select recoil-decay correlations was the same as used in (a) and the recoil- α correlation time was limited to 5 ms. The 369 keV, 467 keV, 766 keV and 913 keV γ rays assigned to ^{158}W are not present.

allow the identification of γ -ray transitions in specific nuclides using temporal and spatial decay correlations [36–38].

The ground-state α decay of ^{158}W sits upon a low-energy tail from the α -decay peak of the $25/2^-$ isomer in ^{155}Lu [$E_\alpha = 7390(5)$ keV] [26], see Fig. 2(a). The tail is part of an extended α -particle background caused by ^{155}Lu α particles that escape from the surface of the DSSD, depositing only a fraction of their full energy, and charge trapping due to radiation damage of the DSSD. It is expected that γ -ray spectra generated from recoil-decay correlations with the ^{158}W ground-state α decay will be contaminated by γ -ray emissions from ^{155}Lu ($t_{1/2} = 2.71(2)$ ms [26]) due to this underlying background.

Fig. 3(a) shows γ rays detected in the Jurogam spectrometer and correlated with recoil implantations followed by a ground-state α decay of ^{158}W in the same GREAT DSSD pixel. The spectrum is dominated by γ rays feeding the high-spin $25/2^-$ isomer in ^{155}Lu [39] although new γ rays at 369 keV, 467 keV, 766 keV and 913 keV are also observed. The level of contamination from ^{155}Lu can be assessed by demanding recoil-decay correlations with the background. Fig. 3(b) shows a γ -ray spectrum generated using the same spatial and temporal correlation conditions but sampling the higher-energy background close to the ^{158}W α -decay peak. The γ -ray transitions from ^{155}Lu dominate the spectrum but the new γ rays identified in Fig. 3(a) are absent from this spectrum. Thus, the 369 keV, 467 keV, 766 keV and 913 keV γ rays are assigned as transitions above the ground state of ^{158}W . The three most intense of these γ rays are assumed on the basis of systematics to be stretched E2 transitions and are ordered on the basis of their relative intensities, see Fig. 4. In the isotope ^{156}Hf , side transitions are assigned feeding the yrast 2^+ , 4^+ and 6^+ states [27]. It is possible that the 467 keV transition might be such a γ ray but it was not possible to place it unambiguously in the level scheme of ^{158}W .

The identification of γ rays above the 8^+ isomer can be made through correlations with the $E_\alpha = 8286(7)$ keV α decay [24]. This high-energy α decay is well separated from other peaks and in a region of low background. Fig. 5(a) shows γ rays detected in the Jurogam spectrometer and correlated with all recoil implanta-

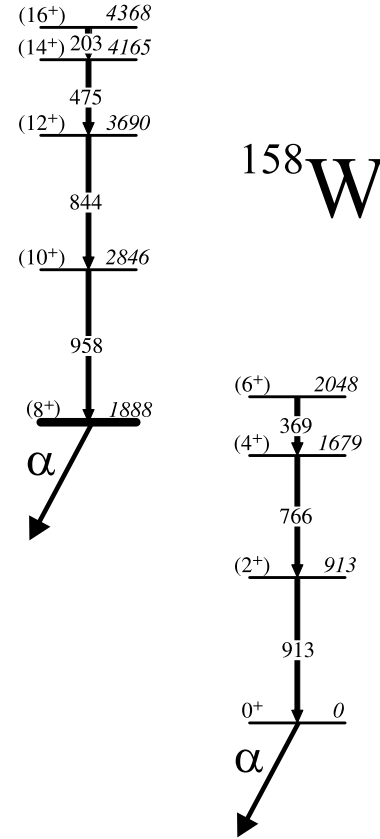


Fig. 4. Level scheme deduced for ^{158}W . The level and transition energies are given in keV. Parentheses denote tentative assignments.

tions subsequently followed by an α decay from the 8^+ isomer in the same DSSD pixel. A previous study identified three γ rays at 203 keV, 475 keV and 1074 keV in a recoil- $\alpha(^{158m}\text{W})$ correlated γ -ray singles spectrum [27]. Fig. 5(a) confirms the assignment of the 203 keV and 475 keV transitions to ^{158}W . A coincidence analysis was permitted by the increase in statistics over the previous work, although there were insufficient data to allow angular distribution measurements. Typical $\alpha(^{158m}\text{W})$ -correlated γ -ray coincidence spectra are shown in Fig. 5(b)–(d). The spectra provide evidence that the 203 keV, 475 keV and 844 keV transitions are mutually coincident and that the latter two are in coincidence with the 958 keV transition. The transitions are ordered in terms of their relative intensities and guided by systematic trends, assuming they form a cascade of stretched E2 transitions (see Fig. 4).

These data were probed for evidence of two-proton emission from the 8^+ isomer in ^{158}W . For ^{158}W this was achieved by searching for correlations with the α decay from the ground state of its two-proton-decay daughter, ^{156}Hf [$E_\alpha = 5873(4)$ keV, $t_{1/2} = 23(1)$ ms] [26]. Fig. 2(b) shows the intervening decays following a recoil implantation and preceding a ^{156}Hf α decay. The time correlation criteria demanded that the first radioactive decay occurred up to 750 μs after a recoil implantation in the same DSSD pixel and the subsequent ^{156}Hf ground state α decays followed up to 100 ms later. Fig. 2(b) shows peaks arising from the proton decay of ^{157}Ta [22] and the ground-state α decay of ^{160}W [26], which are both populated directly in the fusion evaporation reactions and have ^{156}Hf as their daughter. There is no peak in the correlation spectra indicating direct two-proton emission from the 8^+ isomer in ^{158}W . An upper limit for this decay branch was been deduced as $b_{2p} \leq 0.17\%$ at the 90% confidence level using the method out-

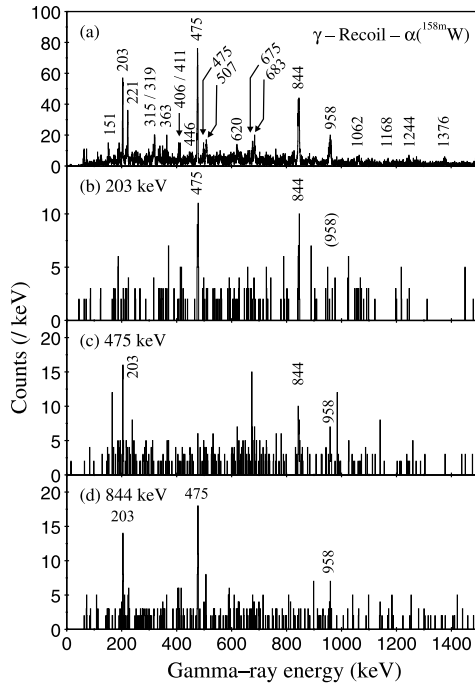


Fig. 5. Gamma-ray energy spectra measured with the Jurogam spectrometer. (a) Spectrum showing all γ rays correlated with ion implantations followed by the α decay from the 8^+ isomer in ^{158}W in the same DSSD pixel of the GREAT spectrometer. The recoil- α correlation time was limited to 0.75 ms. Gamma rays assigned to ^{158}W are labelled by their transition energies. Gamma-ray coincidence spectra generated from an $\alpha(^{158m}\text{W})$ -correlated γ - γ matrix. The recoil- α correlation time was limited to 0.75 ms. Gamma rays in coincidence with the (b) 203 keV transition; (c) 475 keV transition; and (d) 844 keV transition are shown. No background has been subtracted from these spectra due to low statistics.

lined in ref. [40], which corresponds to a lower limit for the partial half-life of $t_{1/2} \geq 85$ ms for this decay mode.

4. Discussion

The low-lying excited states up to the first 6^+ state in the even- Z $N = 84$ isotones are formed by aligning the spins of the two valence neutrons in the $f_{7/2}$ state [42]. Fig. 6 shows the variation of the low-lying yrast states in the $N = 84$ isotones as a function of atomic number. The 2^+ , 4^+ and 6^+ states show a smooth monotonic increase in excitation energy with increasing proton number reflecting the lower average deformation of nuclides closer to the $Z = 82$ closed shell [20].

Fig. 6 also shows that the excitation energy of the lowest-lying 8^+ state falls smoothly above $Z = 64$ and drops below the 6^+ state at ^{156}Hf ($Z = 72$). In this work, the identification of excited states feeding the ground state in ^{158}W confirms the character of the α -decaying 8^+ state as an yrast trap isomer. The structure of the 8^+ isomer is interpreted in terms of neutron excitations involving the $\nu(f_{7/2} \otimes h_{9/2})$ configuration as observed in ^{156}Hf [27] and the lighter $N = 84$ isotones [42–45]. The inversion of the 6^+ and 8^+ states is due to an increasingly attractive proton–neutron interaction between the spin-orbit partner $\pi h_{11/2}$ and $\nu h_{9/2}$ orbitals as the former subshell is filled [46]. A similar isomer has been observed in the odd- Z isotope ^{155}Lu in which this configuration is coupled with an odd $h_{11/2}$ proton to give a $25/2^-$ state [35,47]. States above the 8^+ isomer were interpreted on the basis of comparisons with shell model calculations as $\pi h_{11/2}^2$ configurations coupled with excitations of the valence neutron pair [27].

The absence of any discernible signal of two-proton emission from the 8^+ state is indicative of the sensitivity of the barrier

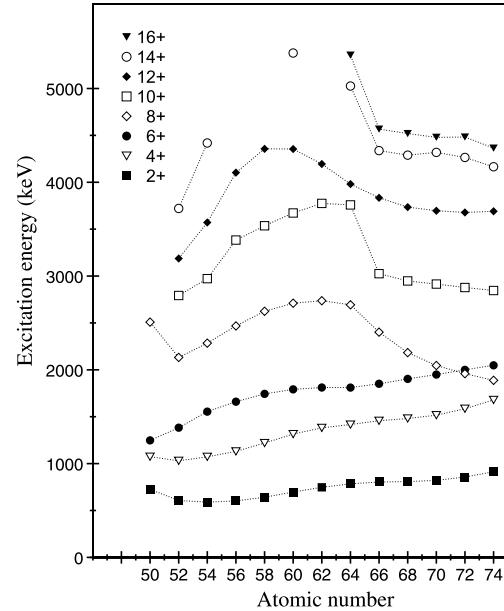


Fig. 6. Energy level systematics for the $N = 84$ isotones above $Z = 50$. Even-spin, positive-parity states up to 16^+ are plotted relative to the ground state. Data are taken from references [27,41].

penetration probability to the level excitation energy and the angular momentum change between initial and final states. At the excitation energy of the 8^+ isomer in ^{158}W it appears that the Q value for two-proton emission is too low for this decay mode to compete effectively with α -particle emission. Moreover, it has recently been demonstrated that large spin changes can promote enhanced stability against proton emission even in cases where large Q_p values exist. For example, the 19^- isomer in ^{158}Ta has $Q_p = 3261(14)$ keV yet the large spin change to the $7/2^-$ ground state in the ^{157}Hf daughter hinders this decay mode [48].

If the smooth trends for the 6^+ and 8^+ states up to ^{158}W continue for ^{160}Os one can estimate the excitation energies of these states relative to the ground state to be approximately 2100 and 1950 keV, respectively. Therefore another spin trap isomer is expected and would be a candidate for two-proton emission, since ^{160}Os is predicted to be less bound to two-proton emission than ^{158}W by 1.5 MeV [20]. The main competing decay mode would be α decay, for which a half-life of approximately 13 μs is estimated by extrapolating the Q_α value and assuming an angular momentum change of $\Delta I = 8\hbar$. This half-life is feasible for study at the focal plane of a recoil separator, although any experiment would be challenging since the production cross section is expected to be at the nanobarn level.

5. Conclusions

Excited states in the exotic nucleus ^{158}W , which lies near the two-proton drip line, have been identified using recoil-decay correlations. The excited states built upon the ground state have been identified up to the 6^+ state. The 6^+ state has a higher excitation energy than the α -decaying 8^+ state and confirms that this long-lived state is a spin-trap isomer. All excited states in ^{158}W are expected to be unbound to two-proton emission but no evidence for two-proton decays of the 8^+ isomer has been found. An upper limit for the two-proton decay branch has been deduced as $b_{2p} \leq 0.17\%$ at the 90% confidence level, corresponding to a partial half-life of $t_{1/2,2p} \geq 85$ ms. Although no two-proton emission was observed from this isomer, it is possible that isomers expected in more exotic neighbouring nuclei could exhibit two-proton radioac-

tivity. These isomers should be more accessible for experimental study than those nuclei predicted to undergo two-proton emission from their ground state and could therefore be a unique source of data on this rare decay mode in heavy nuclei.

Acknowledgements

This work has been supported through the United Kingdom Science and Technology Facilities Council, EURONS (European Commission contract no. RII3-CT-2004-506065), the Academy of Finland under the Finnish Centre of Excellence Programme 2006–2011 (Nuclear and Accelerator Based Physics contract 213503) and the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract no. DE-AC02-06CH11357 (ANL). The UK/France (STFC/IN2P3) Loan Pool and GAMMAPOOL network are acknowledged for the EURO GAM detectors of JUROGAM. TG, PTG and CS acknowledge the support of the Academy of Finland, contract numbers 131665, 111965 and 209430, respectively.

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