In-beam γ-ray spectroscopy of the $N = 85$ isotones ^{159}W and ^{160}Re

P. J. Sapple, R. D. Page, D. T. Joss, L. Bianco,* T. Grahn,† J. Pakarinen,‡ and J. Thomson
Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom

J. Simpson and D. O'Donnell§
STFC Daresbury Laboratory, Daresbury, Warrington WA4 4AD, United Kingdom

S. Ertürk
Niğde Üniversitesi, Fen Edebiyat Fakültesi, Fizik Bölümü, TR-51100 Nigde, Turkey

P. T. Greenlees, U. Jakobsson, P. M. Jones, R. Julin, S. Juutinen, S. Ketelhut, M. Leino, M. Nyman, P. Peura, A. Puurunen, P. Rahkila, P. Ruotsalainen, J. Sarén, C. Scholey, and J. Uusitalo
Department of Physics, University of Jyväskylä, FI-40014 Jyväskylä, Finland

(Received 25 July 2011; published 3 November 2011)

Excited states have been identified in the isotones $^{159}_{74}$W and $^{160}_{75}$Re, which were produced in fusion-evaporation reactions of a beam of 310-MeV ^{58}Ni ions with an isotopically enriched ^{106}Cd target. The strongest γ-ray transitions in ^{159}W and ^{160}Re are interpreted as continuing the regular sequence of states identified in lighter $N =$ 85 isotones that are built upon $9/2^-$ and 10^+ states, respectively. The half-life of ^{155}Hf, the β-decaying daughter of the α decay of ^{159}W, was measured with improved precision to be 840 ± 30 ms.

DOI: 10.1103/PhysRevC.84.054303 PACS number(s): 23.20.Lv, 23.40.−s, 23.60.+e, 27.70.+q

I. INTRODUCTION

The properties of proton-rich $N = 85$ isotones have received considerable attention recently with the discoveries of the α decay of ^{161}Os [1] and a γ-decaying isomer in ^{160}Re [2]. The structure of low-lying states in these nuclei is governed by protons in the $s_{1/2}$, $d_{3/2}$, and $h_{11/2}$ orbitals, which are nearly degenerate in energy [3], and neutrons in the $f_{7/2}$ and $h_{9/2}$ orbitals. Much of the focus of these studies has concentrated on the decreasing energy of states involving the $\nu h_{9/2}$ orbital relative to those from the $\nu f_{7/2}$ orbital as the occupancy of the $\pi h_{11/2}$ orbital increases.

Excited states in the $N = 85$ isotones ^{155}Yb and ^{156}Lu were studied by Ding *et al.* [4], who discussed the regular sequence of excited states built upon the $(\nu f_{7/2})^2(\nu h_{9/2})_{9/2^-}$ states (even-Z isotones) or $(\pi h_{11/2})(\nu f_{7/2})^2(\nu h_{9/2})_{10^+}$ states (odd-Z isotones). The excitation energy of these states above the lowest-lying $(\nu f_{7/2})^3{}_{7/2^-}$ or $(\pi h_{11/2})(\nu f_{7/2})^3{}_{9^+}$ states was found to decrease with increasing Z. In the present work, excited states have been identified in ^{159}W and ^{160}Re through in-beam γ-ray spectroscopy.

II. EXPERIMENTAL DETAILS

The experiment was performed at the Accelerator Laboratory of the University of Jyväskylä. The ^{159}W and ^{160}Re nuclei were produced in fusion-evaporation reactions induced by ^{58}Ni ions impinging on a 1.1-mg/cm^2-thick, self-supporting ^{106}Cd target foil of 96.5% isotopic enrichment. An average beam current of 3 pnA was delivered for 100 hours at a beam energy of 310 MeV. The average cross sections for producing ^{159}W and ^{160}Re nuclei under these conditions were estimated from the measured yields of their radioactive decays to be ∼10 and ∼1 μb, respectively.

Prompt γ rays were detected at the target position using the JUROGAM γ-ray spectrometer [5] consisting of 43 EUROGAM Phase I escape-suppressed germanium spectrometers [6]. Fusion reaction products were separated in flight from other reaction products and scattered beam particles by the recoil ion transport unit (RITU) gas-filled separator [7], then implanted into the double-sided silicon strip detectors (DSSDs) of the Gamma Recoil Electron Alpha Tagging (GREAT) spectrometer [8]. Each of the DSSDs had an active area of 60 mm × 40 mm, a thickness of 300 μm, and a strip pitch of 1 mm on both faces, giving a total of 4800 independent pixels. A multiwire proportional counter provided discrimination between evaporation residues, scattered beam, and decay particles. An array of twenty-eight 500-μm-thick Si PIN diodes was mounted in a box arrangement around the perimeter of the DSSDs in order to measure the residual energies of α particles escaping from the DSSDs in the backward direction. These allowed the full energy of the α particles to be reconstructed, thereby increasing the prompt γ-ray tagging efficiency. A planar double-sided germanium-strip detector was mounted inside the vacuum enclosure a few millimeters behind the DSSDs to measure the energies of low-energy γ rays.

Detector signals were passed to the GREAT triggerless Total Data Readout data acquisition system [9], where they were time stamped with a precision of 10 ns to allow flexible offline

*Present address: Department of Physics, University of Guelph, Guelph, Ontario, Canada N1G 2W1.
†Present address: Department of Physics, University of Jyväskylä, FI-40014 Jyväskylä, Finland.
‡Present address: ISOLDE, CERN, Geneva, Switzerland.
§Present address: Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom.

data analysis using the GRAIN software package [10]. Sixteen of the JUROGAM detectors were read out using TNT2 digital electronics modules [11] and incorporated into the data stream.

III. RESULTS

Gamma-ray transitions in ^{159}W were identified using the recoil-decay tagging technique [12,13]. The α-particle emitter ^{159}W has a short half-life and an α-decay branching ratio close to 100% and would therefore appear to be ideally suited for this method; see Fig. 1. However, the α-decay energy and half-life are similar to those of the $11/2^-$ state in ^{161}Re and the corresponding state in its daughter ^{157}Ta that were also produced in this reaction; see Fig. 2(a). Correlations were therefore also required with the α decays of its daughter ^{155}Lu in order to identify γ rays from ^{159}W unambiguously. The resulting γ-ray energy spectrum is shown in Fig. 3(a), in which a number of peaks can be identified that are assigned to ^{159}W. Although this spectrum does not appear to have significant levels of background from ^{161}Re or ^{157}Ta γ rays, the level of statistics is rather low. This is a consequence of the α-decay branching ratios of the states in ^{155}Lu [14], the comparatively long half-life of the intervening β decay of ^{155}Hf [15], and the average ion implantation rate of 840 Hz in the DSSDs.

In order to increase the level of statistics in the ^{159}W γ-ray energy spectrum while suppressing the background from ^{161}Re, ^{159}W α decays were selected with the requirement that no subsequent decay was observed in the following 20 ms. This is equivalent to 4.6 ^{157}Ta half-lives. The resulting spectrum is shown in Fig. 3(b), in which it can be seen that the peaks assigned to ^{159}W are significantly more intense. The energies and intensities of these γ rays are summarized in Table I. The γ-ray transitions previously assigned to feed the $11/2^-$ state in ^{161}Re [16] have been suppressed by this procedure, although some peaks are still visible. As can be seen in Fig. 2(a), this procedure also affects the intensity

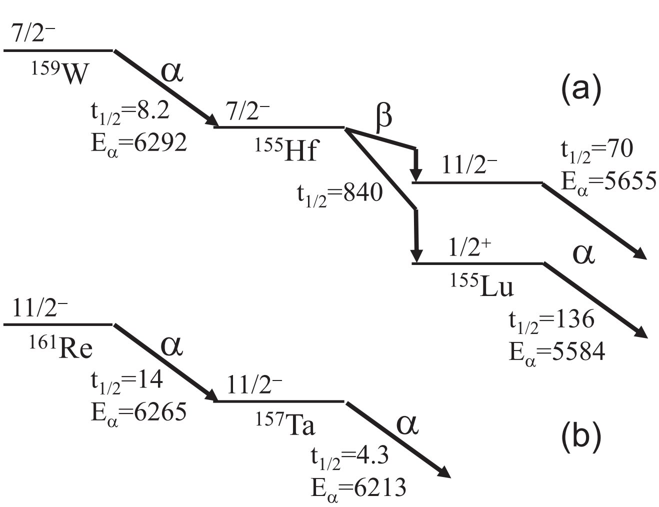

FIG. 1. Schematic decay chains of (a) ^{159}W and (b) the $\pi h_{11/2}$ isomer in ^{161}Re. Note that the β decays of ^{155}Hf may populate the $1/2^+$ and $11/2^-$ α-decaying isomers in ^{155}Lu via intermediate states. Half-lives (in ms) and α-decay energies (in keV) are taken from [14] except for the β-decay half-life of ^{155}Hf, which is from the present work.

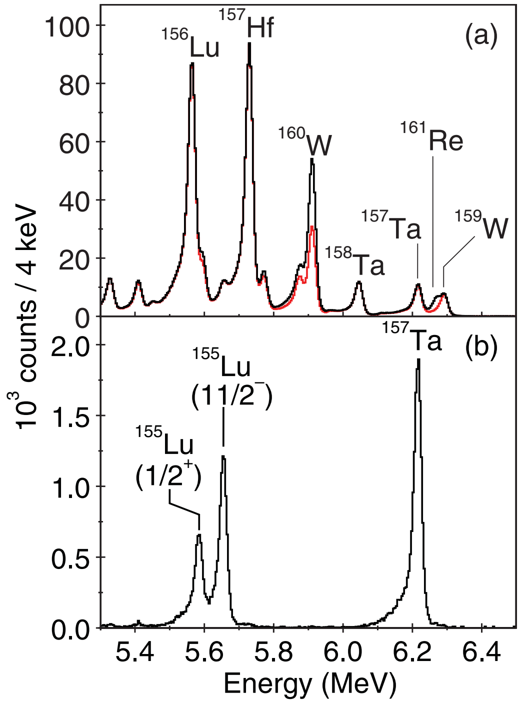

FIG. 2. (Color online) (a) Energy spectrum of α decays observed within 40 ms of the implantation of an ion into the same DSSD pixel. The peak between 6.2 and 6.3 MeV is an unresolved mixture of ^{159}W and ^{161}Re α decays, with a contribution from the high-energy tail of the ^{157}Ta α-decay peak. The energy spectrum of these decays that were not followed within a further 20 ms by any other signal in the same DSSD pixel is shown in red (gray). This requirement suppresses ^{161}Re α decays. (b) Energy spectrum of α decays that follow the ^{159}W α decays in the same DSSD pixel between 20 ms and 4 s later. Both of the low-energy α-decay lines of ^{155}Lu [14] are visible, as well as ^{157}Ta α decays that occur more than 20 ms after a ^{161}Re α decay.

of the ^{160}W α-decay peak, which is followed by the α decay of its daughter ^{156}Hf ($t_{1/2} = 23$ ms [14]). However, α decays of ^{157}Ta nuclei that are produced directly in the reaction cannot be eliminated in this way, and the γ-ray transitions previously assigned to this nuclide [17] are also visible in Fig. 3(b).

A γ-γ coincidence matrix was constructed for ^{159}W. In order to increase the statistics still further in this matrix, α particles that escaped from the DSSDs and were detected in the PIN diodes were included in the analysis. Figure 3(c) shows the energy spectrum of γ rays observed in prompt coincidence with the 885-keV γ-ray transition in ^{159}W. From this spectrum it is clear that this transition is in coincidence with many of the γ rays that are assigned to ^{159}W. Analysis of the γ-γ coincidence matrix established that the 196-, 662-, and 885-keV γ rays were mutually coincident. As will be discussed in Sec. IV, these γ rays are interpreted as the cascade of stretched $E2$ transitions built on the lowest $9/2^-$ state in ^{159}W.

From the γ-ray spectra it is not possible to establish whether the $9/2^-$ state is the ground state or whether ^{159}W has a $7/2^-$ ground state like its lighter even-Z $N = 85$ isotones. However, the radioactive decay properties of ^{159}W and its daughter ^{155}Hf can shed light on this question. Figure 2(b) shows the energy spectrum of α decays that follow the ^{159}W α

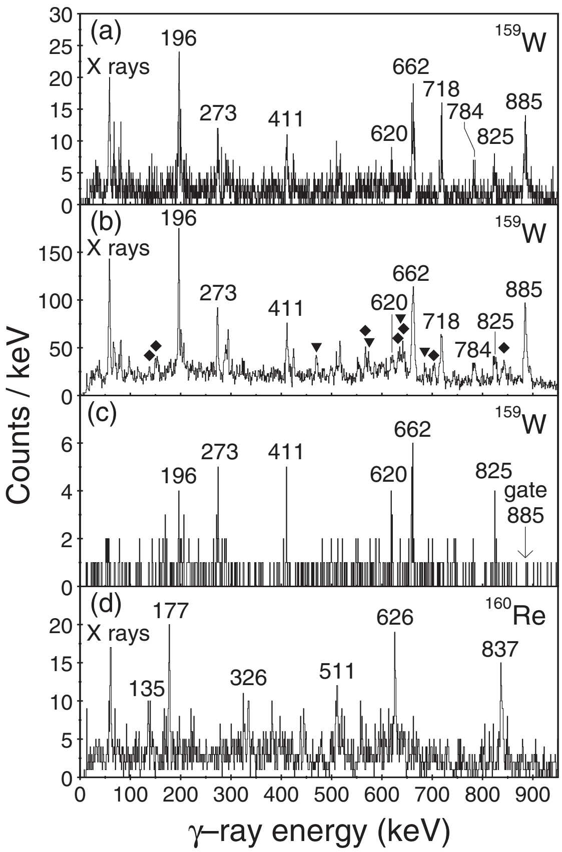

FIG. 3. (a) Energy spectrum of γ rays obtained by tagging on ^{159}W α decays occurring within 40 ms of an ion implantation and followed within 4 s by an α decay from either decay peak of ^{155}Lu shown in Fig. 2(b). (b) Energy spectrum of γ rays obtained by tagging on ^{159}W α decays that are not followed within 20 ms by any other decay in the same DSSD pixel. Transitions previously assigned to ^{161}Re and ^{157}Ta are indicated by the solid triangles and diamonds, respectively. (c) Energy spectrum of prompt γ rays observed in coincidence with the 885-keV γ-ray transition in ^{159}W. (d) Energy spectrum of prompt γ rays obtained when tagging on the proton- and α-decay branches of ^{160}Re. The ^{160}Re decays were required to occur within 4 ms of an ion being implanted into the same DSSD pixel, while the proton decays were required to be followed within a further 40 ms by a ^{159}W α decay. The strongest γ-ray transitions assigned to ^{159}W and ^{160}Re are labeled with their energies in keV.

decays between 20 ms and 4 s later. A peak arising from ^{157}Ta α decays that occur beyond 20 ms is visible. The daughter of ^{159}W α decays is ^{155}Hf, which β decays to ^{155}Lu; see Fig. 1. The observation of the α decays from both low-lying states in ^{155}Lu in Fig. 2(c) confirms that ^{155}Hf has a $7/2^-$ ground state: if the ^{155}Hf ground state were instead $9/2^-$, then the β decay would preferentially populate the $11/2^-$ state in ^{155}Lu through a favored Gamow-Teller decay [18], and only the 5655 keV α-decay peak of ^{155}Lu would have been observed. The reduced α-decay width of ^{159}W is compatible with an s-wave decay [1], indicating that the ground state of ^{159}W is also a $7/2^-$ state. The time differences between the α decays of ^{159}W and those of the 5655-keV line in ^{155}Lu were used to deduce the half-life of the unobserved β decay of ^{155}Hf. The resulting value of 840 $\pm$ 30 ms is consistent with the value of 890 $\pm$ 120 ms from Ref. [15] but is more precise.

TABLE I. Properties of γ-ray transitions measured using JUROGAM and assigned to ^{159}W. Intensities have been corrected for the JUROGAM detection efficiency and normalized to the intensity of the 885-keV transition.

γ-ray energy (keV)	Intensity (%)
77.0(3)	9(3)
81.1(2)	19(3)
98.0(4)	9(2)
196.2(1)	44(4)
201.0(2)	13(2)
205.8(4)	8(2)
212.6(7)	3(2)
273.2(1)	22(2)
293.9(3)[a]	18(2)
411.1(3)	26(3)
416.6(1)	6(2)
424.4(4)	12(3)
509.6(6)	11(3)
517.5(4)	19(3)
567.2(4)	16(3)
573.5(5)	12(3)
620.1(7)	10(3)
661.8(2)[a]	86(6)
718.1(3)[a]	48(6)
783.6(6)	28(4)
824.5(6)	29(3)
885.2(2)	100(5)

[a]These peaks are very close in energy to published ^{157}Ta and ^{161}Re transitions. The corresponding intensity measurements in this table are corrected for contamination.

The matrix was searched for evidence of a γ-ray transition from the $9/2^-$ state to the ground state, but no statistically significant peak could be identified. This is consistent with the systematics [4,19] that indicate that this $M1$ transition is likely to be of low energy and therefore highly converted. Figure 4(a) shows the low-energy part of the γ-ray energy spectrum obtained by selecting only α decays with full energy deposition in the DSSDs and the veto to suppress ^{161}Re γ rays applied. In addition to the K x-ray peaks, there are possible peaks at energies of 77, 81, and 98 keV. Since these transitions are observed at the target position, their short lifetimes are only compatible with an $E1$ or $M1$ multipolarity assignment. After allowing for the γ-ray detection efficiency and internal conversion assuming an $M1$ transition [20], only the 77- and 81-keV transitions have sufficient intensity to be consistent with that of the 885-keV γ ray that would feed it. The 98-keV transition is therefore excluded as a candidate for the lowest transition in the prompt level scheme. However, the possibility that the $9/2^-$ to $7/2^-$ transition is of even lower energy and that the 77- and 81-keV transitions should be placed higher in the level scheme cannot be excluded on the basis of the present data.

The isotone ^{160}Re is known to decay by both proton- and α-particle emission from its $\pi d_{3/2}$ ground state [2,14,21,22]. The energy spectrum of prompt γ rays obtained by tagging on both of these decay branches is shown in Fig. 3(d). The

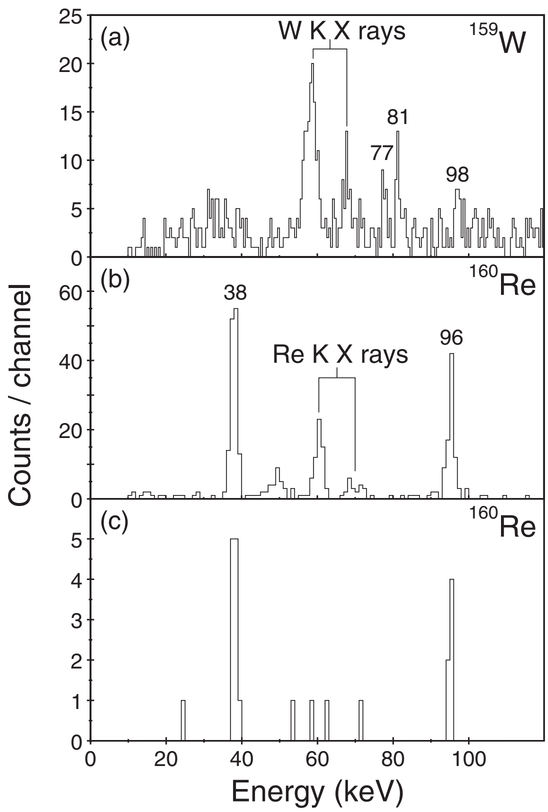

FIG. 4. (a) The low-energy part of the energy spectrum of ^{159}W γ rays measured using JUROGAM and shown in Fig. 3(a). (b) Energy spectrum of γ rays emitted in the decay of the microsecond isomer in ^{160}Re [2] measured in the planar Ge strip detector of GREAT. (c) Energy spectrum of γ rays from (b) observed in coincidence with the 177-, 626-, or 837-keV prompt γ-ray transitions measured in JUROGAM.

same γ-ray transitions are seen when gating on each of the decay branches individually, supporting their assignment as decays from the same state in ^{160}Re. The energies and relative intensities of the strongest transitions in ^{160}Re are presented in Table II. The level of statistics was insufficient to allow a prompt γ-γ coincidence analysis to be performed.

Recently, Darby *et al.* reported the discovery of a γ-decaying microsecond isomer in ^{160}Re [2]. Figure 4(b) shows the energy spectrum of delayed γ rays measured in the planar Ge detector within 15 μs of an ion being implanted into one of the GREAT DSSDs, with the requirement that the ion is followed by either the proton or α decay of ^{160}Re. The observation of the γ-ray peaks at 38 and 96 keV, as well as Re K x rays, confirms the findings of Ref. [2]. Figure 4(c) shows the energy spectrum of delayed γ rays that were observed also to be in delayed coincidence with the 177-, 626-, or 837-keV prompt γ-ray transitions. Coincidences with the 38- and 96-keV peaks can clearly be seen, indicating that the 837-keV transition populates the isomeric state in ^{160}Re.

IV. DISCUSSION

Even-Z $N = 85$ isotones above $Z = 64$ have been found to exhibit a regular sequence of $9/2^-$, $13/2^-$, $17/2^-$, and $21/2^-$ excited states interpreted as having $(\nu f_{7/2})^2(\nu h_{9/2})$ configurations, while in odd-Z isotones the corresponding 10^+, 12^+, 14^+, and 16^+ states are formed by coupling an $h_{11/2}$ proton to these states. These systematics are presented in Fig. 5, together with the three strongest transitions observed in this work for ^{159}W (196, 662, and 885 keV) and for ^{160}Re (177, 626, and 837 keV). The data from this study fit with the established trends and are therefore tentatively assigned as the corresponding structures in these heavier isotones.

The energies of the $7/2^-$ states and 9^+ states relative to the $9/2^-$ and 10^+ states are also plotted in Fig. 5. This suggests that the corresponding transition in ^{160}Re is too low in energy to have been observed in this work. However, the assignment of

TABLE II. Properties of γ-ray transitions measured using JUROGAM and assigned to ^{160}Re. Intensities have been corrected for the JUROGAM detection efficiency and normalized to the intensity of the 837-keV transition.

γ-ray energy (keV)	Intensity (%)
135.1(4)	17(6)
177.2(2)	37(7)
325.9(8)	16(5)
334.1(5)	20(6)
381.9(7)	18(5)
437.7(4)	10(4)
444.6(5)	17(7)
448.7(8)	9(5)
510.5(4)	39(8)
519.8(6)	20(6)
557.1(2)	9(1)
560.6(2)	8(1)
626.1(5)	62(11)
837.4(3)	100(11)

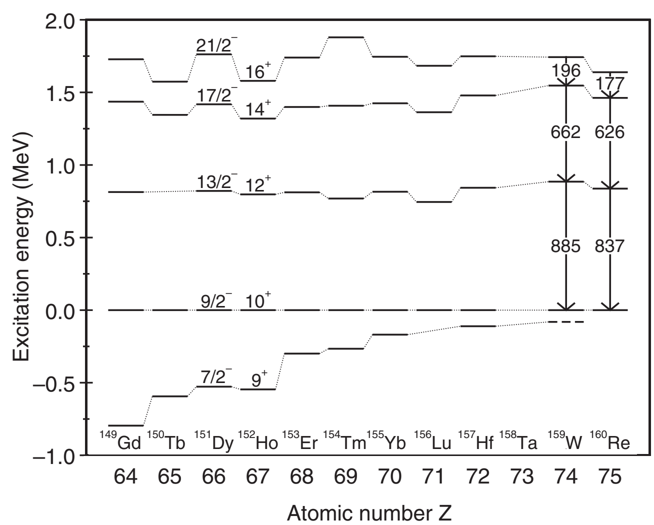

FIG. 5. Systematics of energy levels built upon $9/2^-$ and 10^+ states in $N = 85$ isotones. The energies of the $7/2^-$ and 9^+ states below these states, respectively, are also shown. The $7/2^-$ level in ^{159}W is shown by the dashed line at 81 keV, but this should be regarded as a lower limit; see text for details. Data are taken from Refs. [4,19,23–27] and the present work.

transitions to the sequence of states built upon the 10^+ state in ^{160}Re is very interesting, especially given that the γ-ray energy spectrum was obtained by tagging on the decays of the $\pi d_{3/2}$ ground state. This interpretation is consistent with the scenario proposed in Ref. [2] in which the isomer decays represent part of a γ-decay path from $\pi h_{11/2}$ states to the ground state.

Whether the 77- or 81-keV γ rays in ^{159}W represent the transition between the $9/2^-$ and $7/2^-$ states or a transition of even lower energy is responsible, the systematics suggest that the transition energy is lower than the value of 111 keV in ^{157}Hf [19]. Determining the energy of the lowest transition in the intermediate isotone ^{158}Ta would clearly be of interest. In the recent discovery of the heaviest known $N = 85$ isotone, ^{161}Os, it was argued that the ground state was also a $7/2^-$ state [1], but these systematics suggest that the $9/2^-$ state in this exotic isotone is probably located very close in excitation energy. One possible way to establish this could be to measure fine structure in the α decay of the as yet unknown nuclide ^{165}Pt.

ACKNOWLEDGMENTS

The authors thank the technical staff at the University of Jyväskylä for their excellent support and Paul Morrall for making the targets. This work has been supported by the UK Science and Technology Facilities Council; by the EU 6th Framework Programme "Integrating Infrastructure Initiative Transnational Access," Contract No. RII3-CT-2004-506065 (EURONS); and by the Academy of Finland under the Finnish Centre of Excellence Programme 2006-2011 (Nuclear and Accelerator Based Physics Programme at JYFL), Contract No. 213503. C.S. (Contract No. 209430) and P.T.G. (Contract No. 111965) acknowledge the support of the Academy of Finland. We thank the GAMMAPOOL European Spectroscopy Resource for the loan of germanium detectors for JUROGAM, and we thank the French CNRS/IN2P3 for the use of the TNT2 digital electronics.

[1] L. Bianco *et al.*, Phys. Lett. B **690**, 15 (2010).
[2] I. G. Darby *et al.*, Phys. Lett. B **695**, 78 (2011).
[3] C. N. Davids *et al.*, Phys. Rev. C **55**, 2255 (1997).
[4] K. Y. Ding *et al.*, Phys. Rev. C **64**, 034315 (2001).
[5] C. W. Beausang and J. Simpson, J. Phys. G **22**, 527 (1996).
[6] C. W. Beausang *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **313**, 37 (1992).
[7] M. Leino, Nucl. Instrum. Methods Phys. Res., Sect. B **126**, 320 (1997).
[8] R. D. Page, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 634 (2003).
[9] I. H. Lazarus *et al.*, IEEE Trans. Nucl. Sci. **48**, 567 (2001).
[10] P. Rahkila, Nucl. Instrum. Methods Phys. Res., Sect. A **595**, 637 (2008).
[11] L. Arnold *et al.*, IEEE Trans. Nucl. Sci. **53**, 723 (2006).
[12] R. S. Simon, K.-H. Schmidt, F. P. Heßberger, S. Hlavac, M. Honusek, G. Münzenberg, H.-G. Clerc, U. Gollerthan, and W. Schwab, Z. Phys. A **325**, 197 (1986).
[13] E. S. Paul *et al.*, Phys. Rev. C **51**, 78 (1995).
[14] R. D. Page, P. J. Woods, R. A. Cunningham, T. Davinson, N. J. Davis, A. N. James, K. Livingston, P. J. Sellin, and A. C. Shotter, Phys. Rev. C **53**, 660 (1996).
[15] S. Hofmann, G. Münzenberg, F. Heßburger, W. Reisdorf, P. Armbruster, and B. Thuma, Z. Phys. A **299**, 281 (1981).
[16] K. Lagergren *et al.*, Phys. Rev. C **74**, 024316 (2006).
[17] D. Seweryniak *et al.*, Phys. Rev. C **71**, 054319 (2005).
[18] E. Nolte, G. Korschinek, and Ch. Setzensack, Z. Phys. A **309**, 33 (1982).
[19] A. F. Saad *et al.*, Z. Phys. A **351**, 247 (1995).
[20] T. Kibédi, T. W. Burrows, M. B. Trzhaskovskaya, P. M. Davidson, and C. W. Nestor Jr., Nucl. Instrum. Methods Phys. Res., Sect. A **589**, 202 (2008).
[21] R. D. Page, P. J. Woods, R. A. Cunningham, T. Davinson, N. J. Davis, S. Hofmann, A. N. James, K. Livingston, P. J. Sellin, and A. C. Shotter, Phys. Rev. Lett. **68**, 1287 (1992).
[22] I. G. Darby *et al.*, Phys. Rev. C **83**, 064320 (2011).
[23] M. Piiperinen *et al.*, Z. Phys. A **300**, 133 (1981).
[24] G. Duchêne *et al.*, Z. Phys. A **350**, 39 (1994).
[25] M. Piiperinen, S. Lunardi, P. Kleinheinz, H. Backe, and J. Blomqvist, Z. Phys. A **290**, 337 (1979).
[26] S. André, C. Foin, D. Santos, D. Barnéoud, J. Genevey, Ch. Vieu, J. S. Dionisio, M. Pautrat, C. Schück, and Z. Méliani, Nucl. Phys. A **575**, 155 (1994).
[27] C. Foin, S. André, D. Barnéoud, G. Bastin, A. Peghaire, and J. P. Thibaud, Z. Phys. A **305**, 81 (1982).