α-spectroscopy studies of the new nuclides ^{165}Pt and ^{170}Hg

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The new nuclides ^{165}Pt and ^{170}Hg were produced in the reactions ^{92}Mo(^{78}Kr,5n) and ^{96}Ru(^{78}Kr,4n) at bombarding energies of 418 MeV and 390 MeV, respectively. For ^{170}Hg an α-decay energy of E_α=7590(30) keV and half-life of $T_{1/2} = 0.08^{+0.40}_{-0.04}$ ms were deduced, while for ^{165}Pt the corresponding values were 7273(14) keV and $0.24^{+0.24}_{-0.08}$ ms. Comparison of the reduced α-decay widths with systematics indicates that both α decays are unhindered. Although combining the measured α-decay Q values with extrapolated masses suggests that both new nuclides are unbound to two-proton emission by more than 1 MeV, their α-decay half-lives are too short for this decay mode to compete. Improved data were also obtained for ^{166,167}Pt, produced via αxn evaporation channels in reactions with the ^{96}Ru target at ^{78}Kr bombarding energies of 390 MeV and 418 MeV.

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I. INTRODUCTION

Investigating exotic nuclei at the proton drip line is a very challenging process. The lightest isotopes of heavy elements often have extremely small production cross sections and in order to study them it is essential to employ efficient and selective techniques. The main challenge then arises from the short half-lives, which drop dramatically for exotic nuclei close to the proton drip line [1]. One common solution used to study such nuclei is the combination of an in-flight separator with a fast and efficient decay spectroscopy system capable of resolving the proton and α-particle energies of different reaction products. By transporting short-lived nuclei to a focal plane equipped accordingly in only a few hundred ns, decay spectroscopy can be undertaken on nuclei with lifetimes as short as a few μs.

Measurement of the α-particle energy and half-life allows calculation of the reduced α-decay width, which can assist in assignments of the spins and parities of the states involved. Decay Q values also allow testing and potential refinement of theoretical mass models. Systematic studies of these properties can give insights into how magic numbers and other shell effects evolve far from β stability.

In this work, the new MARA vacuum mode recoil mass separator [2, 3] was used to investigate neutron-deficient isotopes of Pt and Hg. Until now, the lightest known isotopes of platinum were ^{166,167}Pt, with measured α-particle energies of $E_\alpha = 7110(15)$ keV, 6988(10) keV and half-lives of $t_{1/2} = 0.3(1)$ ms, 0.7(2) ms for ^{166}Pt and ^{167}Pt, respectively [4]. The previous lightest known isotope of mercury was ^{171}Hg, for which values of $E_\alpha = 7488(12)$ keV and $t_{1/2} = 59^{+36}_{-16}$ μs were reported [5]. The present work improves upon the previous Pt results with more precise measurements of both energy and half-life in addition to presenting the identification and measurements of the α-decay properties of the new nuclides ^{165}Pt and ^{170}Hg.

II. EXPERIMENTAL DETAILS

This work uses data from separate experiments conducted using the MARA in-flight vacuum mode mass separator at the University of Jyväskylä, Finland. The K130 cyclotron was used to produce a beam of ^{78}Kr^{15+} ions that bombarded targets in three different data sets shown in table I.

The ^{96}Ru target was a foil of 96.5% isotopic enrich-

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TABLE I: Information about the beam energies, targets and irradiation times for the data sets used in this work. In all cases, the incident beam was ^{78}Kr and the specified beam energy is the value upstream of the target. The target thicknesses provided are the nominal values from when the target foils were manufactured.

Energy (MeV)	Target	Target thickness (μg/cm^2)	Irradiation Time (h)	Data set
418(4)	^{92}Mo	500	67	A
418(4)	^{96}Ru	170	257	B
390(4)	^{96}Ru	170	179	C

ment supported by a 60 μg/cm^2 thick layer of carbon. The target was mounted so that the carbon layer was upstream of the ^{96}Ru material. The ^{92}Mo target was a self-supporting foil of ~97% isotopic enrichment. The average beam intensity was 12 pnA for data sets A and B, and 5 pnA for data set C. The electric and magnetic fields of MARA for data sets A, B and C were chosen to optimise the transmission of ^{165}Pt, ^{169}Au and ^{170}Hg ions, respectively. In this experiment the flight time of ions through MARA was estimated to be ~600 ns.

Fusion-evaporation reaction products ("recoils") transported to the focal plane of MARA passed through a Multi-Wire Proportional Counter (MWPC) before being implanted into a Double-sided Silicon Strip Detector (DSSD). Two different designs of DSSD were used in this work, both with a nominal thickness of 300 μm. The DSSD used for data sets A and B had 128 strips on one face and 48 on the other. The strip pitch was 1 mm on both faces and the full width half maximum (FWHM) measured for the ^{169}Pt α-decay line was 40 keV. The DSSD used for data set C had a strip pitch of 0.67 mm, with 192 and 72 strips on its 2 faces. Using this DSSD a FWHM of 33 keV was measured for the ^{155}Lu^m α-decay peak.

The MWPC comprised a grid of 20 μm diameter gold-coated tungsten wires with 1 mm spacing in low-pressure flowing isobutane gas and provided spatial information on the recoils, which were dispersed across the MARA focal plane according to the ratio of their mass number (A) and charge (Q). This can be seen in figure 1, which shows two-dimensional spectra of the A/Q ratio of the recoils versus the energy of subsequent α decays in the same DSSD pixel. Combining information on the time of flight of the recoils between the MWPC and the DSSD with the energy measured in the DSSD allowed evaporation residues to be distinguished from other implanted ions. Two 500 μm thick silicon detectors were mounted adjacently behind the DSSD to identify light ions that punched through the DSSD. Signals observed in the DSSD without a coincident signal in these silicon detectors or in the MWPC were assumed to be from radioactive decays of implanted nuclei.

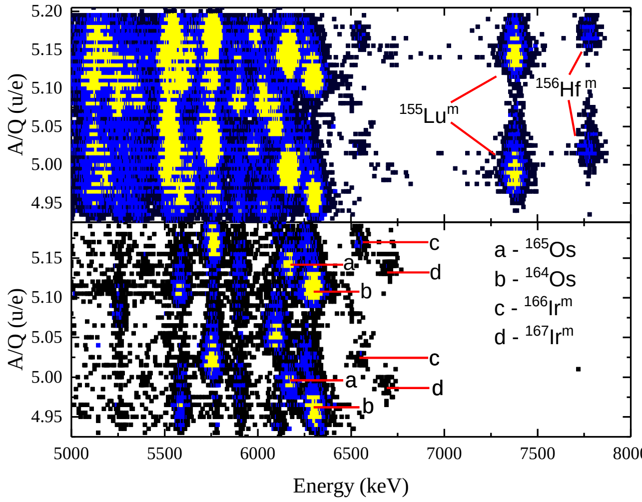

FIG. 1: (Colour online) The upper panel shows the distribution of the energies of α-particles occurring withing 10 ms of a recoil being implanted into the same DSSD pixel plotted against the ratio of the mass number to charge state ratio (A/Q) of the recoil at the MWPC. The lower panel shows the α-particle energy spectrum of the same decays occurring within 10 ms of the recoil, but only those followed within 50 ms by another α decay, versus the A/Q of the recoil. The plots present the part of data set A that was used to calibrate the A/Q distribution for the experiment and show that two charge states were collected for each labelled nuclide. The colour scale in both panels is set such that black points represent 2-4 events, blue points 5-24 events and yellow points ≥25 events.

All detector signals were time stamped by a global 100 MHz clock to allow both temporal and positional correlations to be made between recoils and subsequent radioactive decays within the full detector array [6]. The data were analysed with the GRAIN software package [7] and with analysis code written in the Python programming language.

III. RESULTS AND DISCUSSION

A. Decay of ^{165}Pt

The dominant radioactive decay mode of the ground state of ^{165}Pt is expected to be α-particle emission [8]. As shown in Fig. 2, the daughter of the α decay of ^{165}Pt is ^{161}Os, which was first identified by Bianco *et al.* who reported an α-decay energy of 6890(12) keV and half-life of 0.64(6) ms [9]. They found that the ^{161}Os α decay populates ^{157}W, which in turn undergoes β decay with a half-life of 275(40) ms. These β decays indirectly feed both low-lying states in ^{157}Ta that decay by α-particle emission with energies and half-lives of 6117(4) keV and 10.1(4) ms, and 6213(4) keV and 4.3(1) ms [10].

Data set A was searched for α decays of ^{165}Pt followed in the same DSSD pixel by event sequences consistent with the decay chain of its daughter ^{161}Os. Fig 3(a) shows the correlation plot of parent decays that occurred within 10 ms of recoil implantation plotted against the energies of daughter decays that occurred within a further 50 ms. Three correlated event chains can be seen where the daughter energy is consistent with that reported for ^{161}Os. The mean lifetime for the daughter decays is consistent within errors with that of ^{161}Os.

Analysis of the granddaughter decays for these event chains presented in Table II reveals that for the first two the energy is consistent with it being an α decay of ^{157}Ta, while the third is much lower. The probability of an α particle escaping from the DSSD without depositing its full energy was measured to be $\sim$30 % in this experiment and it is assumed that this is what happened to the ^{157}Ta α particle in this decay chain. In the correlation analysis, DSSD signals with recorded energies below 0.5 MeV were excluded, which means that the decays of ^{157}W were not considered because β particles generally deposited lower energies than this in the DSSD. The time intervals between the daughter and granddaughter decays in all three cases are compatible with the reported half-lives of ^{157}W and states in ^{157}Ta. On the basis of this evidence, these decay chains are assigned as the α decays of the new nuclide ^{165}Pt. A further decay chain was assigned as a decay of ^{165}Pt and is presented in Table II. The daughter energy is interpreted as a ^{161}Os α particle that deposited only part of its energy, while the granddaughter decay energy matches that of the ground state of ^{157}Ta. The triple-correlated α decays of all 4 ^{165}Pt decay chains are shown in Fig. 4(a).

An α-decay energy of 7272(14) keV was deduced for ^{165}Pt from the data for the 4 decay chains, based on the energy calibration for data set A that was derived from the α decays of the nuclei ^{149}Tb, ^{151}Dy, ^{150,151}Dy, ^{151}Ho, ^{152,153}Er [11]; and ^{155}Lu^{m}, ^{156}Hf^{m} [10] that were implanted into the DSSD. It is interesting to note that the time interval between the recoil implantation and the ^{165}Pt α decay for the fourth decay chain is much shorter at 22 μs than the other 3, which are between 400 μs and 500 μs. This might suggest that there are 2 distinct α-decaying states, although such a short half-life for the fourth decay chain would be difficult to reconcile with half-lives expected from the measured α-decay energy. However, analysis of the distribution of the decay times using the method of ref. [12] indicates that they are in fact consistent with emanating from the same state. A half-life of $0.24^{+0.30}_{-0.08}$ ms was determined for ^{165}Pt from the 4 decay chains using the method of maximum likelihood [13]. This is much shorter than the predicted half-life for the β decay of ^{165}Pt [8], so it assumed that the α-decay branching ratio is $\approx$100 %.

TABLE II: Alpha-decay energies (E_α) and time intervals (τ) of all events observed in the candidate ^{165}Pt decay chains, compared with literature values where available. Note that because the present experiment was not sensitive to β particles, the time interval between a given ^{161}Os α decay and its associated subsequent ^{157}Ta α decay represents the sum of the time interval between the ^{161}Os α decay and the ^{157}W β decay, and the time interval between this ^{157}W β decay and the ^{157}Ta α decay.

Nuclide	E_α^1	E_α^2	E_α^3	E_α^4	E_α^{ref} (keV)
^{165}Pt	7267	7267	7286	7265	—
^{161}Os	6941	6872	6891	2612	6890(12) [9]
^{157}Ta	6158	6187	2963	6110	6117(4) [14] 6213(4) [10]
Nuclide	τ^1	τ^2	τ^3	τ^4	$t_{1/2}^{\text{ref}}$ (ms)
^{165}Pt	0.45	0.55	0.50	0.022	—
^{161}Os	2.2	1.35	1.0	1.4	0.64(0.06) [9]
^{157}W					275(40) [9]
^{157}Ta	288	186	490	91	10.1(4) [14] 4.3(1) [10]

B. Decays of ^{166,167}Pt

The isotopes ^{166,177}Pt were first identified by Bingham *et al.*, who used beams of 357 MeV and 384 MeV ^{78}Kr ions to bombard a ^{92}Mo target [4]. Data set A in the present work was obtained using the same beam and target species, but at a significantly higher beam energy of 418 MeV. The fact that no decay chains of ^{166,167}Pt could be identified in data set A is probably a consequence of their production cross sections being much lower at this higher beam energy. However, decays of both these isotopes were identified in data sets B and C using the ^{96}Ru target, in which they were produced via αxn evaporation channels (see Fig. 2). In total, 11 decay chains of ^{166}Pt and 35 decay chains of ^{167}Pt were identified and their triple-correlated α decays are shown in Figs. 4(b) and (c), respectively. As can be seen in Fig. 3(b), correlations with daughter decays were not sufficient to distinguish the decay chains of interest from other interfering activities, but the granddaughter correlations did allow clean separations to be made. For ^{166}Pt, an α-decay energy of 7118(8) keV and a half-life of $0.26^{+0.10}_{-0.06}$ ms were deduced from these decay chains, while the corresponding values for ^{167}Pt were 6985(8) keV and $1.1^{+0.3}_{-0.2}$ ms, respectively. All values are in good agreement with those previously reported. The energy calibration for data sets B and C was based on the α decays of ^{155}Lu [15]; ^{161}Ta, ^{162,163}W, ^{167,168}Os, ^{169}Ir [11]; ^{158}Hf, ^{160}W, ^{166}Os, ^{168}Ir^{m} [10]; and

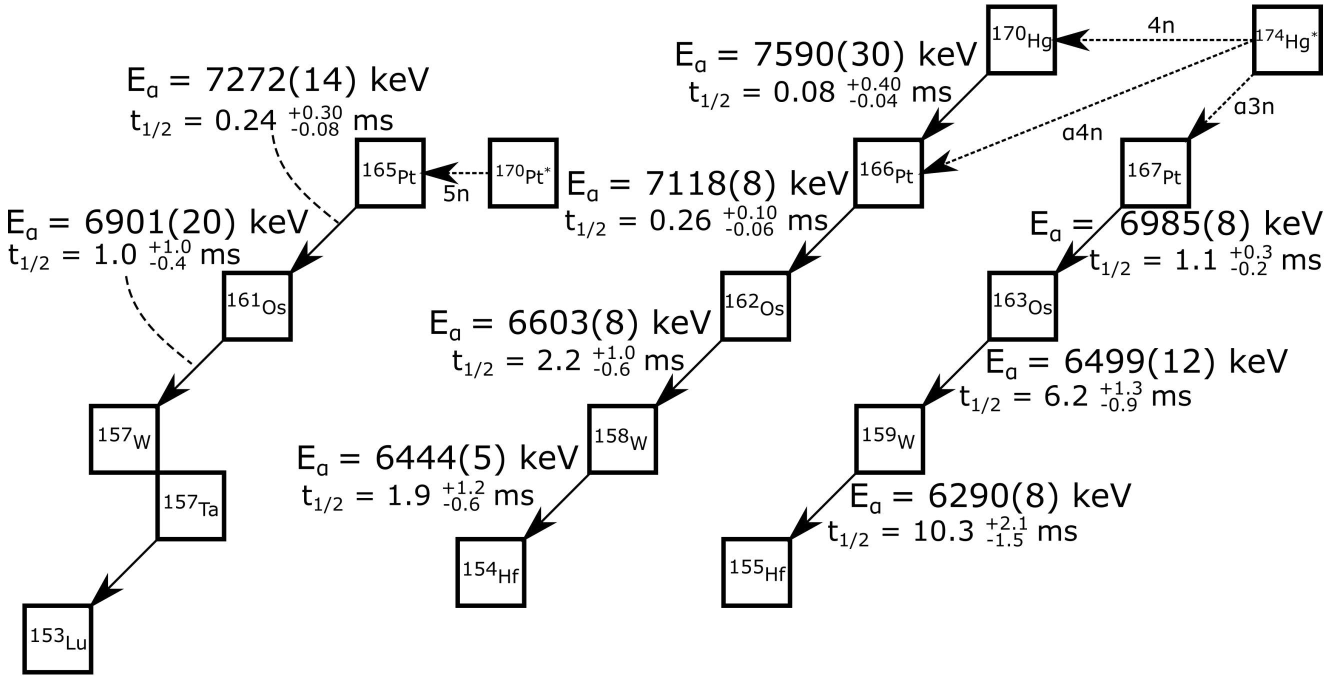

FIG. 2: The decay chains of the nuclides of interest labelled with the α-particle energies (E_α) and half-lives ($t_{1/2}$) measured in this work. The dashed arrows denote fusion-evaporation channels, while the solid arrows indicate α-decays.

^{169}Pt [16] nuclei that were implanted into the DSSD.

C. Decay of ^{170}Hg

Data sets B and C were searched for evidence of the expected α decay of ^{170}Hg [8]. A single candidate event chain was identified and is indicated in Fig. 3(b). The candidate ^{170}Hg α-decay event of energy 7590 keV occurred 0.12 ms after the implantation of a recoil into the same DSSD pixel and was followed by a sequence of decay events with energies of 7065 keV, 1840 keV and 6430 keV. This decay sequence is interpreted as the α decays of ^{166}Pt, ^{162}Os, and ^{158}W, where the ^{162}Os α particle did not deposit its full energy in the DSSD (see Fig. 2). The time intervals between successive decays were 0.23 ms, 1.50 ms, and 3.35 ms, respectively, and are compatible with the reported half-lives of these α emitters [4, 17]. Fig. 4(d) shows decay energies of members of this quadruple-correlated decay chain. Using the method of maximum likelihood [13], a half-life of $0.08^{+0.40}_{-0.04}$ ms was deduced for the ^{170}Hg candidate event. As in the case of ^{165}Pt, this is much shorter than the predicted half-life for the β-decay branch [8], so it assumed that the α-decay branching ratio is ≈100 %.

D. Cross sections

Production cross sections were estimated from the measured yields of the nuclides of interest. The transport efficiency was simulated for each of the ions according to the different settings of MARA used during the experiment. The cross section for producing ^{170}Hg was estimated to be ∼0.5 nb in data set C, for which the beam energy was 390 MeV. This can be compared with the cross section of 4 nb reported by Bingham *et al.* for ^{166}Pt [4], which like ^{170}Hg in the present work, was produced via the 4n evaporation channel. The lower value found for ^{170}Hg could be a consequence of increased competition from fission in the de-excitation of the compound nucleus ^{174}Hg compared with ^{170}Pt.

The estimated cross section for the production of ^{165}Pt via the 5n evaporation channel was ∼0.7 nb. This continues the trend of decreasing cross sections with the increasing number of evaporated neutrons needed to produce isotopes that lie further from the line of β stability. The present cross section is consistent with the previously reported upper limit of 1 nb, albeit at a different beam energy [4]. The ^{166,167}Pt nuclei were produced via αxn evaporation channels in this work with cross sections at 390 MeV of 3.4 nb and 13.8 nb, and at 418 MeV (data set B) of 0.7 nb and 1.0 nb, respectively. The value for ^{166}Pt at 390 MeV is similar to that reported by Bingham *et al.* for production via the 4n evaporation channel, but the cross sections for ^{167}Pt at the beam energies used in the present work are lower than their value of 65 nb for the

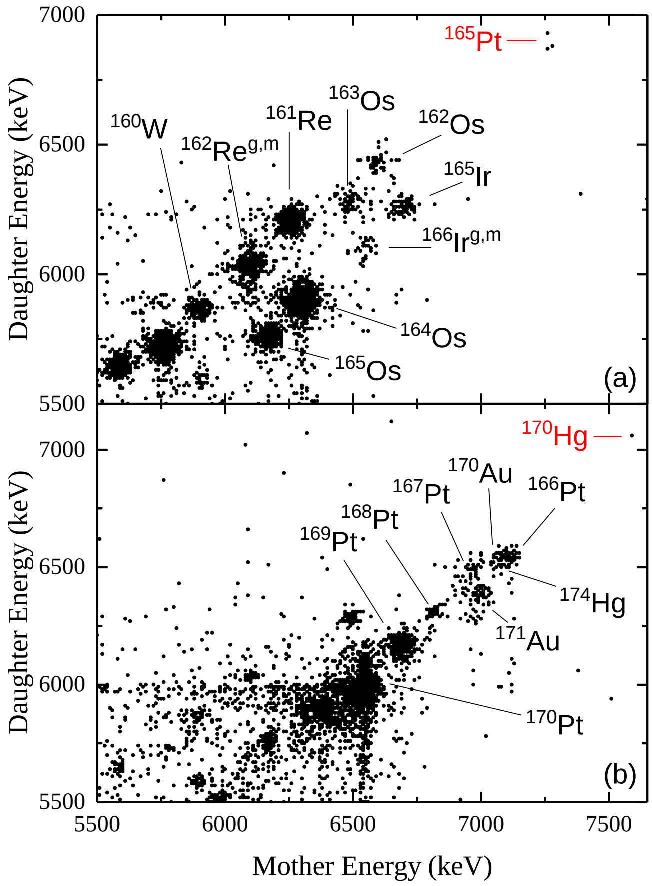

FIG. 3: Two-dimensional spectra of α-particle energies of parent decays occurring within 10 ms of a recoil being implanted into the same DSSD pixel plotted against those of subsequent daughter α decays occurring (a) within 50 ms from data set A, and (b) within 100 ms from data set C. Selected correlated parent α decays are labelled, with newly identified nuclides highlighted in red.

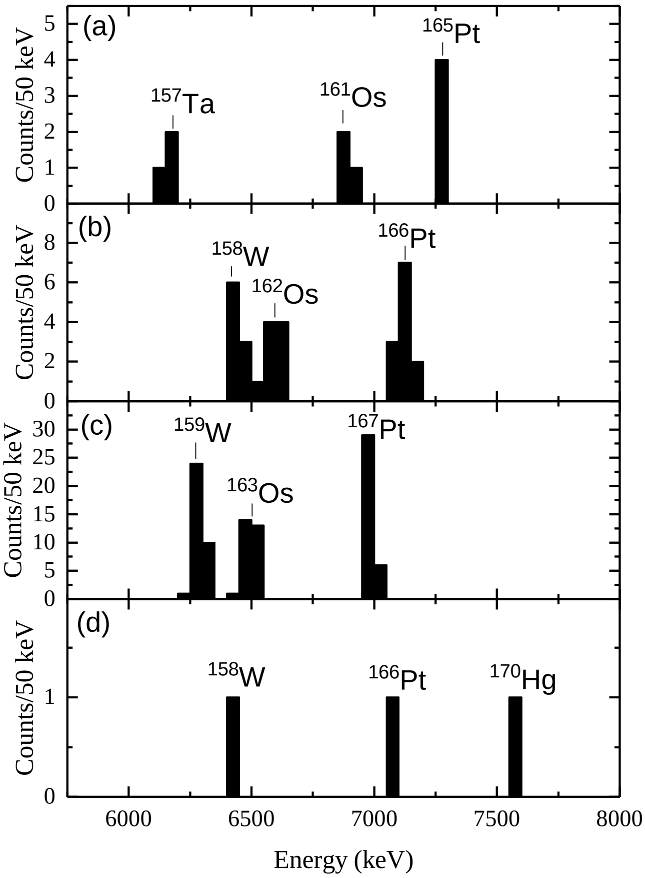

FIG. 4: Energy spectra of multiply correlated α decays for the decay chains of (a) ^{165}Pt, (b) ^{166}Pt, (c) ^{167}Pt, and (d) ^{170}Hg. The individual decay energies and time intervals for events in the ^{165}Pt chains are summarised in Table II.

3n channel [4]. There was no evidence in the present data for ^{165}Pt decay chains produced via the α5n evaporation channel in data sets B or C.

IV. DISCUSSION

The measured α-decay energy for ^{165}Pt appears to continue the smooth systematic trend exhibited by its heavier isotopes, as can be seen in Fig. 5(a). Only a single decay chain for ^{170}Hg was identified, so there is some uncertainty as to whether the emitted α-particle deposited its full energy in the DSSD. However, the value deduced for ^{170}Hg from this decay chain would also fit in well the systematics of α-decay Q values for the ground states of Hg isotopes. Assuming that the full ^{170}Hg α-particle energy was registered, the reduced α-decay width determined using the method of Rasmussen [20] is 63^{+79}_{-53} keV. This value is compatible with those for α decays of other even-even nuclei in this region, see Fig. 6(a).

The corresponding value for ^{165}Pt is 33^{+23}_{-18} keV, while reduced decay widths of 90^{+23}_{-17} keV and 73^{+15}_{-12} keV were deduced for ^{166,167}Pt, respectively, from the averages of the α-decay energies and half-lives measured in the present work and those reported by Bingham *et al.* [21]. These values are shown in shown in Fig. 6(b). The value for ^{165}Pt is slightly lower than values determined for its heavier odd-A isotopes but appears to follow the trends of reducing decay widths with decreasing neutron number observed in lighter elements [22]. A similar trend has been identified above the $N = 126$ neutron shell closure and the $Z = 82$ shell closure and been attributed to reducing α-particle preformation probabilities [23, 24]. When approaching shell closures, the α-particle preformation probability reduces due to there being fewer valence protons and neutrons, while further away from the shell closures nuclei are more deformed and α decays may therefore be faster. When comparing the reduced α-decay width for ^{165}Pt with that of its nearest even-even neighbour, ^{166}Pt, yields a hindrance factor of 2.9, which is consistent with it being unhindered. This would

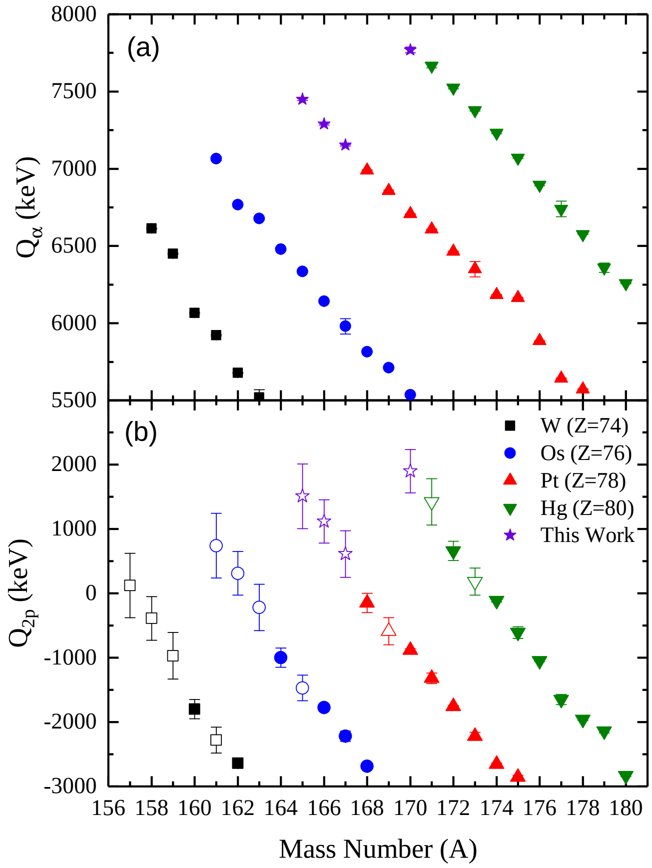

FIG. 5: The Q values for (a) α-decay and (b) 2-proton decay plotted as a function of mass number for isotopes of W, Os, Pt, and Hg [18, 19]. Values that required a predicted mass to be used in the calculation are denoted by hollow markers, whereas values that use only directly measured masses have solid markers. In (a) the error bars are smaller than the plotted symbols.

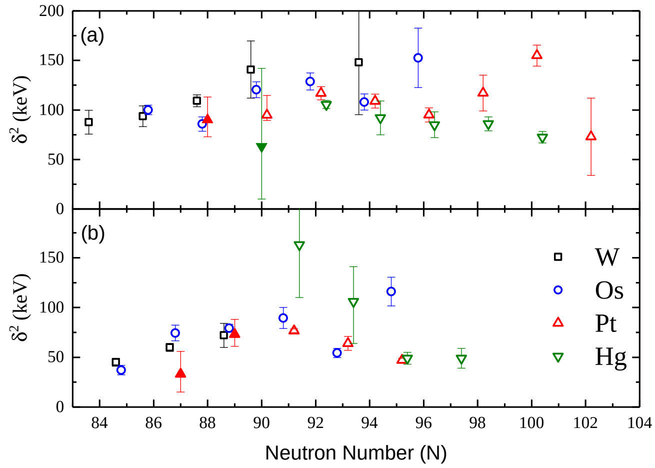

FIG. 6: Reduced α-decay widths of W, Os, Pt, and Hg nuclei calculated using the method of Rasmussen [20]. Panel (a) shows values for even-A nuclei plotted as a function of neutron number, while panel (b) shows values for odd-A nuclei. The values for ^{170}Hg and ^{165,166,167}Pt are denoted by the solid symbols. Literature values for the other nuclides were taken from [11, 15, 21, 26–33].

suggest its ground state has the same spin and parity $(\frac{7}{2}^-)$ as was proposed for the ground state of ^{161}Os [9].

Although both ^{165}Pt and ^{170}Hg are predicted to be unbound to the emission of 2 protons [8], values for their atomic masses, separation energies, etc. are not included in the 2016 Atomic Mass Evaluation [18, 19]. However, it is possible to estimate their Q_{2p} values using the α-decay Q values determined in the present work combined with the evaluated 2-proton separation energies of ^{161}Os and ^{166}Pt. The resulting values are shown in Fig. 5(b), from which it can be seen that these values continue the smooth trend of increasing Q_{2p} values with decreasing mass number for a given isotopic chain. Both new nuclides are two-proton unbound by more than 1 MeV, but both still decay primarily via α decay. The data were searched for evidence of 2-proton decay candidate events, but none were found. The non-observation is perhaps not surprising as in the work of Olsen *et al.* [25] it is predicted that two-proton decay will only begin to compete with α decay in ^{155}Pt and ^{159}Hg.

It seems improbable that such exotic nuclei could be observed using the same experimental methods as in the present work, because the cross sections are likely to be far too low. However, the cross sections may not be prohibitively small for the next nuclides beyond ^{165}Pt and ^{170}Hg. The smooth variation of α-decay Q values with mass number evident in Fig. 5(a) can be used to estimate how much further from stability one could probe before the half-lives drop below $\sim$1 μs, the typical time of flight through a recoil separator. If the trend continues, this lifetime threshold is likely to be crossed for Hg isotopes somewhere around ^{166}Hg. Similarly, for the Pt isotopes, $^{162-164}$Pt are probably all sufficiently long-lived to be observed although there was no evidence of α decays of ^{164}Pt in the present data. One could expect that the α-decay Q value departs from the smooth trend at the $N = 83$ nuclide ^{161}Pt so that, like its heaviest known isotone ^{157}W, it mainly undergoes β decay and identifying these β decays will present additional experimental challenges.

V. ACKNOWLEDGEMENTS

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