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Discovery of ^{157}W and ^{161}Os

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ABSTRACT

The nuclides ^{157}W and ^{161}Os have been discovered in reactions of ^{58}Ni ion beams with a ^{106}Cd target. The ^{161}Os α-decay energy and half-life were 6890 ± 12 keV and 640 ± 60 µs. The daughter ^{157}W nuclei β-decayed with a half-life of 275 ± 40 ms, populating both low-lying α-decaying states in ^{157}Ta, which is consistent with a $7/2^-$ ground state in ^{157}W. Fine structure observed in the α decay of ^{161}Os places the lowest excited state in ^{157}W with $I^\pi = 9/2^-$ at 318 ± 30 keV. The branching ratio of $5.5^{+3.1}_{-2.2}\%$ indicates that ^{161}Os also has a $7/2^-$ ground state. Shell-model calculations analysing the effects of monopole shifts and a tensor force on the relative energies of $2f_{7/2}$ and $1h_{9/2}$ neutron states in $N = 83$ isotones are presented.

The study of nuclei far from the line of β stability has revealed significant modifications of single-particle energies. It has been shown that the presence of a tensor component in the nucleon–nucleon effective interaction is important for understanding the shell structure of neutron-rich nuclei. This gives rise to particular shifts in the relative energies of specific orbitals, depending on their occupancy [1,2]. This tensor term most probably plays a significant role in determining the structure of much heavier nuclei [3,4], as revealed through the evolution of the relative energies of single-particle levels in isotopic or isotonic chains of nuclei at closed shells [5]. In this work, focusing on the region at the proton drip line above $N = 82$, the structure of nuclei is governed at low spin and excitation energy by valence neutrons in the $2f_{7/2}$ and $1h_{9/2}$ orbitals and protons in the $3s_{1/2}$, $2d_{3/2}$ and $1h_{11/2}$

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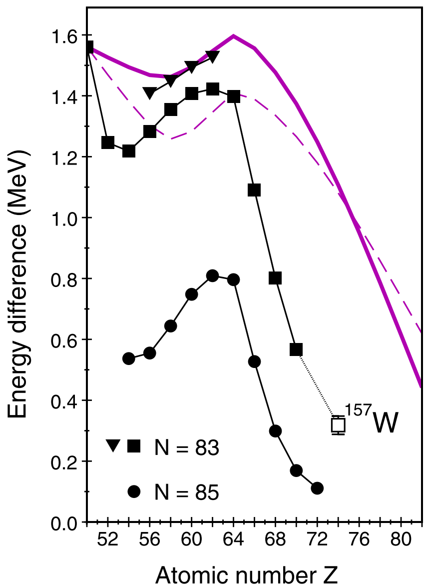

Fig. 1. (Colour online.) The triangles show energy differences measured from transfer reactions on stable nuclei of the centroid energies determined for the $2f_{7/2}$ and $1h_{9/2}$ neutron single-particle orbitals for N = 83 isotones, while energy differences between the lowest-lying $7/2^-$ and $9/2^-$ states for N = 83 and N = 85 isotones are shown by the squares and circles, respectively. The open square shows the value for ^{157}W from this work. Data are taken from [7,9]. Comparison of data for N = 83 isotones with shell model calculations of the $\nu 1h_{9/2}$–$\nu 2f_{7/2}$ energy difference with (thick line) and without (dashed line) the added tensor force. The calculations are normalized to the value for $^{133}_{50}Sn_{83}$.

orbitals [6]. In particular, one expects the proton–neutron tensor force component acting between protons filling the $1h_{11/2}$ orbital and a single neutron in the $1h_{9/2}$ or $2f_{7/2}$ orbitals to modify their relative single-particle energies in a specific way that differs from the changes arising only from a central force.

The excitation energies and spectroscopic factors of $9/2^-$ states in the stable N = 83 isotones $^{139}_{56}$Ba, $^{141}_{58}$Ce, $^{143}_{60}$Nd and $^{145}_{62}$Sm were recently measured using transfer reactions [7]. This allowed the centroid energy of the $\nu 1h_{9/2}$ orbital relative to the $\nu 2f_{7/2}$ orbital to be deduced in these nuclei, see Fig. 1. Above Z = 64, the occupation probability of the $\pi 1h_{11/2}$ orbital increases with increasing Z and the energy difference between the $\nu 2f_{7/2}$ and $\nu 1h_{9/2}$ orbitals is expected to drop rapidly. Unfortunately, the heavier isotones required to extend these systematics above Z = 64 are all unstable, rendering the measurement of spectrosopic factors and thus of the single-particle content for these states impossible at present. However, the measured energy differences between the lowest-lying $9/2^-$ and $7/2^-$ states for the N = 83 and N = 85 isotones plotted in Fig. 1 do indeed show a rapid drop above Z = 64. Although caution should be exercised in case there is significant fragmentation of single-particle strength in nuclei when moving away from stability, the measured spectroscopic factors for both $7/2^-$ and $9/2^-$ levels for $Z \leqslant 64$ [7,8] suggest this drop is reflecting the gradual approach in energy of the $1h_{9/2}$ and $2f_{7/2}$ neutron single-particle orbitals. The steep slope for these heavy N = 83 isotones suggests that the energies of the neutron single-particle orbitals may even become inverted for high Z. New experimental data for nuclei above Z = 70 are necessary to provide a definitive answer on this possibility.

In this Letter we present the discoveries of $^{161}_{76}Os_{85}$ and $^{157}_{74}W_{83}$, which have 23 fewer neutrons than their lightest stable isotopes. The experiment was performed at the Accelerator Laboratory of the University of Jyväskylä. The ^{161}Os nuclei were populated in the ^{106}Cd(^{58}Ni, 3n) reaction. The target was a 1.1 mg/cm^2 thick,

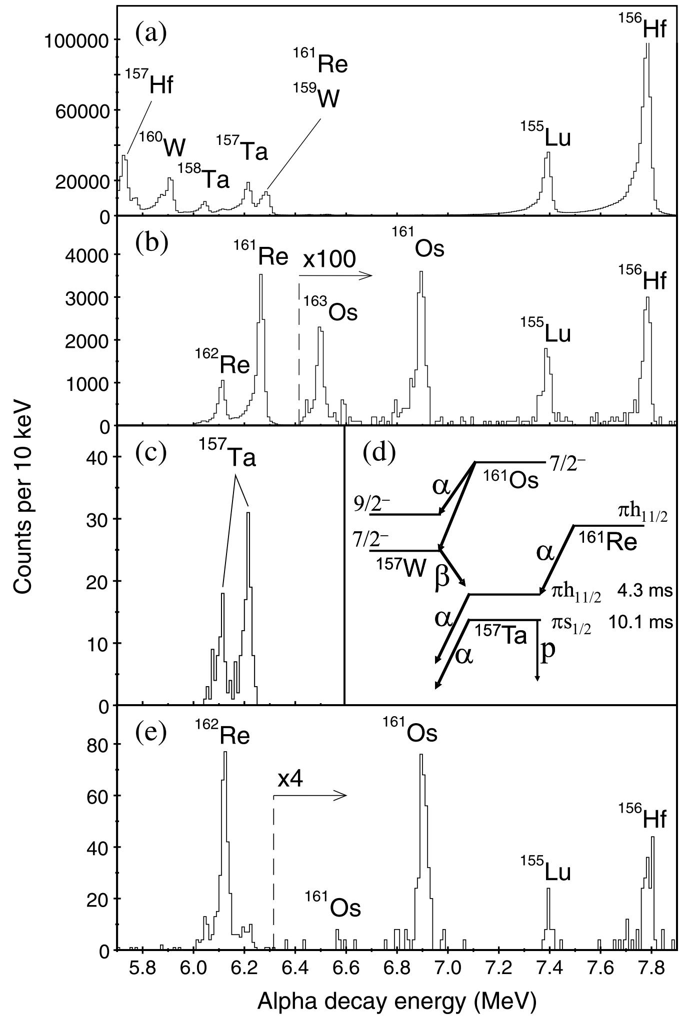

Fig. 2. (a) Spectrum of α decays occurring within 4 ms of an ion implantation into the same DSSD pixel. (b) As (a), but with the additional requirement that the α decay is followed within 4 s by either of the α-decay branches of ^{157}Ta [15]. (c) Spectrum of ^{157}Ta α decays following α decays in the ^{161}Os peak. (d) Decay scheme of ^{161}Os and related nuclei. The spin and parity assignments for the states in ^{161}Os and ^{157}W are from the present work. (e) Spectrum of α decays occurring between 250 μs and 1.5 ms after an ion implantation into the same DSSD pixel that are followed between 70 ms and 1.5 s later by either of the α-decay branches of ^{157}Ta.

self-supporting ^{106}Cd foil of 96.5% isotopic enrichment. Average beam currents were 2.3 particle nA for 104 hours at 290 MeV, 4.7 particle nA for 75 hours at 300 MeV and 3.0 particle nA for 96 hours at 310 MeV. The gas-filled separator RITU [10] transported the reaction products to the GREAT spectrometer [11]. α-decay spectroscopy was facilitated by two adjacent double-sided silicon strip detectors (DSSDs) into which the reaction products were implanted. The DSSDs had an active area of 60 mm × 40 mm and a thickness of 300 μm. The strip pitch of 1 mm gave a total of 4800 independent pixels, which made it possible to correlate decays occurring within a few seconds of each other. All detector signals were passed to the triggerless data acquisition system [12], which time stamped them with a precision of 10 ns, allowing temporal correlations to be analysed using the GRAIN software package [13].

The lightest known osmium isotopes are short-lived nuclei and decay predominantly by α-particle emission [14]. In order to isolate α decays of ^{161}Os from the large number of counts in the α-decay energy spectrum of Fig. 2(a), correlations were sought with the α decays of ^{157}Ta, populated via the β decay of ^{157}W, see

Fig. 2(d). Two low-lying α-decaying states are known in ^{157}Ta: the $\pi 1h_{11/2}$ state decays by emitting 6213 keV α particles with a half-life of 4.3 ms [14], while the $\pi 3s_{1/2}$ ground state has a half-life of 10.1 ms and emits 927 keV protons, with a branching ratio of 3.4%, and 6117 keV α particles [15]. Fig. 2(b) shows the energy spectrum of the decays in Fig. 2(a) that are followed within 4 s by either ^{157}Ta α decay. The strongest peak in this spectrum is the 6.27 MeV α decay of the $\pi 1h_{11/2}$ state in ^{161}Re, which populates the corresponding state in ^{157}Ta [14,15]. The peak at 6.5 MeV is from ^{163}Os α decays correlated with those of ^{159}W [14,16], the low-energy tail of whose 6.3 MeV α-decay line extends into the ^{157}Ta energy gate, while the peak at 6.1 MeV arises from ^{162}Re α decays correlated with the 6.05 MeV α decays of ^{158}Ta [17], which also falls within the ^{157}Ta energy gate. The ^{155m}Lu and ^{156m}Hf peaks [14] arise from random correlations. The clear peak comprising ∼200 counts at 6890 ± 12 keV is a new activity that we assign as the α decay of ^{161}Os. The energy fits in well with the systematic variation of α-decay Q-values with neutron number, while the yield corresponds to a cross section of ∼10 nb, or one ^{161}Os nucleus in every 5 million evaporation residues.

The half-life of this activity was determined as 640 ± 60 μs using the method of maximum likelihood [18]. A reduced α-decay width of 37 ± 5 keV for ^{161}Os was calculated from the measured α-decay energy and half-life, assuming s-wave emission [19]. This is compatible with the value of 45 ± 4 keV for its odd-A isotone ^{159}W.

If the ground state of ^{157}W were a $\nu 1h_{9/2}$ state, its β decay would proceed mainly to the $\pi 1h_{11/2}$ state in ^{157}Ta through a favoured Gamow–Teller transition [20], but if the ground state were a $\nu 2f_{7/2}$ state, then neither ^{157}Ta state could be fed directly by an allowed decay. Instead, the β decays would feed intermediate states that γ decay and one could expect both ^{157}Ta states to be populated. Fig. 2(c) shows the energy spectrum of ^{157}Ta α decays that follow the ^{161}Os α decays within 4 s. From this spectrum it is evident that both α-decaying states in ^{157}Ta are fed by the β decay of ^{157}W, confirming that a $\nu 2f_{7/2}$ state represents its ground state. The half-life of ^{157}W was deduced to be 275 ± 40 ms from the time differences between the ^{161}Os and ^{157}Ta α decays.

Observing fine structure in the α decay of ^{161}Os could reveal its ground-state configuration, see Fig. 3. One difficulty is that in the excitation energy region of ∼300 keV expected from the systematics, there is potentially interference from α decays of ^{163}Os to ^{159}W, see Fig. 2(b). To eliminate this source of background, only decays appearing in Fig. 2(b) that were followed more than 70 ms later by a ^{157}Ta α decay were considered. In addition, when decays occur shortly after the implantation of an ion, the measured peak widths are broader owing to variations in the shaping amplifier baseline. Decays occurring less than 250 μs after ion implantation were therefore also excluded. The resulting spectrum is shown in Fig. 2(e), in which a group of counts at 6580 ± 30 keV can be seen. The time distribution of these counts is compatible with the half-life measured for the main ^{161}Os α-decay line. The possibilities that these counts arise from decays of ^{163}Os or from a fluctuation in background levels can both can be excluded with 99% confidence, while the possibility that the counts could be part of the low-energy tail of the main ^{161}Os α-decay line can be excluded with a confidence of 90% [21]. These counts are therefore tentatively assigned as α-decay fine structure of ^{161}Os.

The branching ratio for this activity is $5.5^{+3.1}_{-2.2}$% and the excitation energy in ^{157}W is 318 ± 30 keV. These values are consistent with a $7/2^-$ ground state in ^{161}Os that decays to an excited $9/2^-$ state in ^{157}W as well as its ground state (see Fig. 3). Note that if the ground state of ^{161}Os were $9/2^-$ rather than $7/2^-$, the branching ratio should be much larger than is observed, as indicated by the dashed line in Fig. 3. This is because with a $9/2^-$ ground-state spin assignment for ^{161}Os the α decay to the excited state in ^{157}W could then proceed by s-wave emission, while the decay to the ground state would proceed by d-wave emission, which is relatively hindered by the additional centrifugal component to the potential barrier. The measured excitation energy of the $9/2^-$ state above the $7/2^-$ ground state in ^{157}W is plotted in Fig. 1.

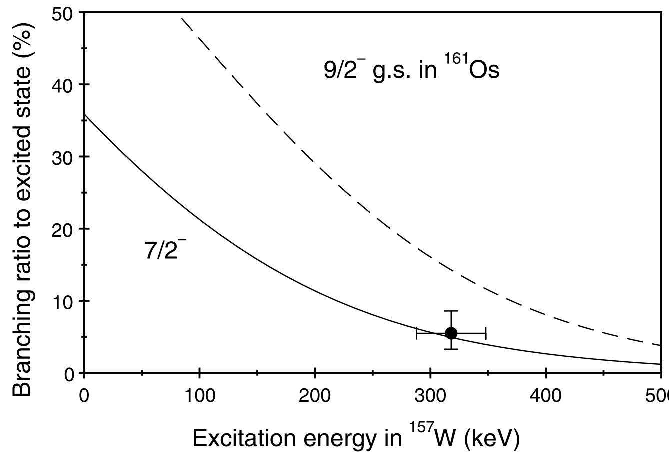

Fig. 3. Branching ratios for ^{161}Os α decay to the first excited $9/2^-$ state in ^{157}W as a function of its excitation energy calculated using the method of Rasmussen, in which the penetration of an α particle through the real part of an optical model potential barrier is computed using the WKB approximation [19]. The dashed curve is the branching ratio to the excited state in ^{157}W that would be expected for a $9/2^-$ ground state in ^{161}Os, while the solid line is for a $7/2^-$ ground state. The same reduced width has been assumed in all calculations. The data point indicates the measured values from the present work.

The monopole shifts for single-particle states in the N = 82–126 shell-model space were calculated using a spin–isospin exchange part of the central Yukawa-type force with a strength of 10 MeV (see Ref. [22] for more details). The results agree reasonably well with the measured centroid energies [7]: the behaviour up to Z = 64–66 is to a large extent due to the radial overlap of the proton orbitals, when filling the $1g_{7/2}$ and $2d_{5/2}$ orbitals, with the neutron $1h_{9/2}$ and $2f_{7/2}$ orbitals, respectively. This causes an initial small drop and subsequent upsloping behaviour of the latter two neutron orbitals, as observed experimentally in the energy centroids. Once the proton $1h_{11/2}$ orbital starts to fill, the neutron $1h_{9/2}$ state decreases quickly in energy, relative to the $2f_{7/2}$ orbital. Therefore with solely a central force one expects approaching $\nu 1h_{9/2}$ and $\nu 2f_{7/2}$ orbitals beyond Z = 64, see Fig. 1. This effect is primarily due to the greater spatial overlap of the $\nu 1h_{9/2}$ orbital with the $\pi 1h_{11/2}$ orbital, mainly filling beyond Z = 64, as compared with the $\nu 2f_{7/2}$ orbital.

Adding a tensor force with a strength of 20 MeV [23,24] to the Yukawa force describes well the observed systematics of the $\nu 1h_{9/2}$ and $\nu 1i_{13/2}$ [7] single-particle energy difference in the region $56 \leqslant Z \leqslant 62$ and also slightly improves the relative energy shift of the $\nu 1h_{9/2}$ versus the $\nu 2f_{7/2}$ orbital, already starting at Z = 52. However, doubling the strength of the tensor term does not lead to any significant further improvement, but rather worsens the agreement with measurements for the $\nu 1i_{13/2}$ orbital in N = 83 isotones. This gives an indication of the constraints on the strength of the tensor force component.

When filling the proton $1h_{11/2}$ orbital (orbital angular momentum parallel to the spin orientation), the typical signature of the presence of a tensor force in relative single-particle energy changes with generalized spin–orbit partners is a strong decrease in energy of the antiparallel oriented orbital (here the neutron $1h_{9/2}$ orbital) relative to the energy of the parallel oriented orbital (here the neutron $2f_{7/2}$ orbital). This effect is much less pronounced in the present $N = 83$ nuclei because of the difference in the radial quantum number n and the subsequent strongly reduced radial overlap between the 2f and 1h orbitals. A similar effect has been observed for the $N = 28$ nuclei and the changing neutron $1f_{7/2}$ to $2p_{3/2}$ energy gap with decreasing proton number, starting at ^{48}Ca, down to ^{44}S, ^{42}Si (removing protons from the $2d_{3/2}$ orbital) and further down to ^{36}O (removing protons from the $2d_{5/2}$ orbital) [25]. It is important to stress the fact that for the $N = 20$ and $N = 28$ mass region, these conclusions follow from an effective interaction describing the full sd-pf shell-model space [26] and carrying out a decomposition in its central, vector and tensor components. In the paper by Smirnova et al. [25], and, independently by Otsuka et al. [27], it was shown that one needs the cooperative effect of both a central and a tensor force in order to describe the observed changing shell structure in light and medium-heavy nuclei. It would be instructive in the future to construct a realistic effective interaction in the model space spanning the $Z = 50$–82 proton orbitals as well as neutrons filling the $N = 82$–126 neutron orbitals to overcome the limitation of using a more phenomenological approach of considering the combined effect of a central and tensor force.

The discoveries of ^{161}Os and ^{157}W mark them among the most distant known nuclides from the line of maximum β stability. Our measurements show that a $7/2^-$ state forms their ground states and that the excitation energy of the $9/2^-$ state in ^{157}W continues the trend of decreasing values with increasing occupation of the $\pi 1h_{11/2}$ orbital. The presence of a tensor component in the nucleon–nucleon effective interaction, in addition to the central component, appears to be important in order to improve agreement with the measured data for $N = 83$ isotones, although interactions with tensor terms fitted globally to a range of data need to be developed before definitive conclusions can be drawn [5].

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