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**Low-lying excited states in the neutron-deficient isotopes $^{163}$Os and $^{165}$Os**


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Excited states in the neutron-deficient isotopes $^{163}$Os and $^{165}$Os were identified using the JUROGAM and GREAT spectrometers in conjunction with the RITU gas-filled separator. The $^{163}$Os and $^{165}$Os nuclei were populated via the $^{106}$Cd($^{60}$Ni,3n) and $^{92}$Mo($^{78}$Kr,2n2p3n) reactions at bombarding energies of 270 MeV and 357 MeV, respectively. Gamma-ray emissions from these nuclei have been established unambiguously using the recoil-decay tagging technique and a coincidence analysis has allowed level schemes to be established. These results suggest that the yrast states are based upon negative-parity configurations originating from the $v_{f_{7/2}}$ orbitals.

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**I. INTRODUCTION**

The identification of excited states in atomic nuclei spanning complete shells is crucial to determining the evolution of nuclear structure from both empirical and theoretical perspectives. The osmium isotopes currently represent the best opportunity to probe the evolution of nuclear structure from both empirical and theoretical perspectives. The osmium isotopes currently represent the best opportunity to probe the evolution of nuclear structure from both empirical and theoretical perspectives.

The existence of the osmium isotopes in an uninterrupted sequence from $^{161}$Os to $^{203}$Os has been established [2], while excited states have been identified in these known nuclei below $^{200}$Os [4] with the exception of the odd-mass isotopes below $N = 89$. The excitation level schemes across the shell reveal the transitions between the single-particle and collective regimes as a function of neutron number.

The low-lying energy spectra in the osmium isotopes have been investigated from different theoretical perspectives. For example, the neutron-deficient osmium isotopes have been discussed in terms of general collective models [5], shape coexistence [6–8], and phase transitions between the limiting symmetries of the interacting boson approximation [9]. However, most theoretical investigations have focused on the even-$N$ isotopes above $^{170}$Os and little is known about the transition to single-particle structures as the $N = 82$ closed shell is approached.

II. EXPERIMENTAL DETAILS

Excited states in $^{163}$Os and $^{165}$Os were populated using the reactions listed in Table I. The beam species were accelerated by the K130 cyclotron at the University of Jyväskylä Accelerator Laboratory. Gamma rays emitted at the target position were detected by the JUROGAM spectrometer, comprising 43 escape-suppressed HPGe detectors [18]. Fusion-evaporation residues recoiling from the target were separated from scattered beam and transported to the focal plane by the RITU gas-filled separator [19–21]. At the focal plane fusion-evaporation residues were implanted into the double-sided silicon strip detectors (DSSDs) of the GREAT spectrometer [22]. The GREAT multiwire proportional counter provided energy loss and (in conjunction with the DSSDs) time-of-flight information, which allowed the recoils to be distinguished from the scattered beam and subsequent radioactive decays. All detector signals were time stamped and recorded by the total data readout data acquisition system [23], which allowed...
implanted nuclei to be identified through temporal and spatial correlations with their subsequent radioactive decays. These data were sorted offline and analyzed using the GRAIN [24] and ESCL8R [25] software analysis packages.

III. RESULTS

A. $^{163}$Os ($N = 87$)

The recoil-decay tagging (RDT) technique correlates $\gamma$ rays emitted promptly at the target position with the characteristic radioactive decays of the residual nucleus at the focal plane of a recoil separator [26–28]. The RDT technique provides high-confidence correlations under the optimum conditions of short decay half-lives and high decay branching ratios. The $\alpha$-emitting nucleus $^{163}$Os has decay properties well suited to RDT spectroscopy. The half-life of $^{163}$Os has been measured to be $5.5 \pm 0.6$ ms with an $\alpha$-decay branching ratio close to 100% [16]. A total of 10 656 full-energy ($E_\alpha = 6510$ keV) $\alpha$($^{163}$Os) decays was observed in Experiment 1 (see Table I).

Assuming a RITU separation efficiency of 50% [21] and an efficiency of 65% for full-energy $\alpha$-particle detection, this yield corresponds to a cross section of $\sim 0.5 \mu$b. Figure 1(a) shows $\gamma$ rays correlated with recoil implantations followed by the characteristic $\alpha$ decay of $^{163}$Os within the same DSSD pixel of the GREAT spectrometer. The recoil-decay correlation time was limited to 25 ms. The measured properties of $\gamma$ rays in $^{163}$Os are listed in Table II.

A significant fraction of $\alpha$ particles escape from the DSSD without depositing their full energy. However, it is possible to utilize these decays if there is a distinct daughter $\alpha$ decay with appropriate decay properties. Figure 1(b) shows a $\gamma$-ray spectrum obtained by demanding correlations with escaping $\alpha$ particles that are followed by the distinct daughter $\alpha$ decay of $^{159}$W [29] within the same DSSD pixel. The $E_\alpha = 6292$ keV decay line in $^{159}$W has been measured previously to have a high $\alpha$-decay branching ratio (92%) and a half-life of $8.2 \pm 0.7$ ms [29], which is sufficiently short to give clean correlations with escaping $^{163}$Os $\alpha$ particles. In these data 2822 escaping $\alpha$ decays satisfied the criteria and were added to the statistics for the $\gamma$-$\gamma$ coincidence analysis. Figure 1(b) shows that the $\gamma$-ray counting statistics may be augmented through escape correlations without increasing the $\gamma$-ray background noticeably. Even so, a meaningful angular correlation analysis was not possible with these data due to the low level of statistics, which precluded unambiguous multipolarity assignments for the measured $\gamma$ rays.

A recoil-decay tagged $\gamma\gamma$-coincidence matrix correlated with the full-energy and escape $\alpha$($^{163}$Os) particles was produced from these data. This matrix demonstrated that the 238, 624, 669, and 700 keV $\gamma$ rays are in coincidence forming a cascade. Figure 1(c) shows a summed coincidence spectrum for these transitions. This cascade is assumed to be composed
TABLE II. Transition energies and relative intensities of γ rays assigned to 163Os and 165Os obtained from the pertinent α-correlated γ-ray singles spectrum. The error on the transition energies ranges from ≈ 0.5 keV to 1 keV. The angular intensity ratios $R_\theta$ for 165Os are listed (see text for details).

<table>
<thead>
<tr>
<th>163Os</th>
<th>165Os</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_\gamma$ (keV)</td>
<td>$I_\gamma$ (%)</td>
</tr>
<tr>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>112.0</td>
<td>23(3)</td>
</tr>
<tr>
<td>238.4</td>
<td>42(4)</td>
</tr>
<tr>
<td>521.4</td>
<td>31(4)</td>
</tr>
<tr>
<td>553.1</td>
<td>9(3)</td>
</tr>
<tr>
<td>556.0</td>
<td>6(3)</td>
</tr>
<tr>
<td>561.0</td>
<td>20(4)</td>
</tr>
<tr>
<td>623.7</td>
<td>100(7)</td>
</tr>
<tr>
<td>636.9</td>
<td>65(7)</td>
</tr>
<tr>
<td>651.4</td>
<td>26(6)</td>
</tr>
<tr>
<td>661.3</td>
<td>73(6)</td>
</tr>
<tr>
<td>668.5</td>
<td>39(4)</td>
</tr>
<tr>
<td>693.6</td>
<td>14(3)</td>
</tr>
<tr>
<td>700.0</td>
<td>43(5)</td>
</tr>
<tr>
<td>722.5</td>
<td>27(3)</td>
</tr>
</tbody>
</table>

of stretched $E2$ transitions feeding the ground state. The 624 keV peak is the most intense γ ray and is assumed to be the $(11/2^-) \to 7/2^-$ transition. The ordering of the 669, 700, and 238 keV transitions could not be unambiguously established from the intensity measurements and coincidence relationships, so the ordering is based on the systematics of excited states in the light Os nuclei. The excitation energy of the $(23/2^-)$ state is insensitive to the ordering of these γ rays. The 651 keV transition is observed to be in coincidence only with the 624 keV transition and is assigned to feed the $(11/2^-)$ state. The level scheme deduced for 163Os is presented in Fig. 2.

FIG. 2. Level scheme deduced for 163Os. The transition energies are in keV and their relative intensities are proportional to the width of the arrows. The white arrow components reflect the estimated internal conversion intensity.

B. 165Os ($N = 89$)

The neutron-deficient nucleus 165Os is an α-emitting nucleus with decay properties that are also ideally suited for recoil-decay tagging. The half-life of 165Os has been measured to be $72 \pm 3$ ms with a branching ratio close to 100% [29]. A total of 149 953 full-energy ($E_\alpha = 6188$ keV) α(165Os) decays was observed in Experiments 2 and 3 (see Table I), corresponding to a cross section of $\sim 5 \mu b$, assuming a RITU separation efficiency of 50% [21] and an efficiency of 65% for full-energy α-particle detection. Figure 3(a) shows γ rays correlated with recoil implantations followed by the characteristic α decay of 165Os within the same DSSD pixel.

The relatively strong 661, 637, and 521 keV transitions that are associated with 165Os, see Fig. 1(a) and Table II, do not appear to be in prompt coincidence with the main cascade and could not be placed in the level scheme.

FIG. 3. (a) Gamma rays correlated with recoil implantations followed by the characteristic α decay of 165Os within the same DSSD pixel of the GREAT spectrometer. (b) Summed γ-ray spectrum in coincidence with the 490, 633, 700, or 692 keV transitions generated from an α(165Os)-correlated γγ-coincidence matrix. (c) Summed γ-ray spectrum in coincidence with the 499, 597, 559, or 593 keV transitions generated from an α(165Os)-correlated γγ-coincidence matrix. The recoil-α correlation time was limited to 280 ms in each case.

The neutron-deficient nucleus 165Os is an α-emitting nucleus with decay properties that are also ideally suited for recoil-decay tagging. The half-life of 165Os has been measured to be $72 \pm 3$ ms with a branching ratio close to 100% [29]. A total of 149 953 full-energy ($E_\alpha = 6188$ keV) α(165Os) decays was observed in Experiments 2 and 3 (see Table I), corresponding to a cross section of $\sim 5 \mu b$, assuming a RITU separation efficiency of 50% [21] and an efficiency of 65% for full-energy α-particle detection. Figure 3(a) shows γ rays correlated with recoil implantations followed by the characteristic α decay of 165Os within the same DSSD pixel.
of the GREAT spectrometer. The recoil-decay correlation time was limited to 280 ms. The measured properties of γ rays in 165 Os are listed in Table II.

The γ-ray spectrum in Fig. 3(a) shows the same transitions discovered by Appelbe et al. in an earlier RDT experiment probing 165 Os [12]. In that experiment there were insufficient coincidence data to determine an excitation level scheme. Given the complex character of the spectra in nuclei approaching the single-particle regime, γ-ray coincidence analyses are crucial for ordering the excitation level schemes. Figures 3(b) and 3(c) show summed γ-ray coincidences obtained from an α(165 Os)-correlated γγ-coincidence matrix. Correlations with the escaping α(165 Os) decays were not included due to the γ-ray background generated by correlations with the daughter, 161 W (t1/2 = 409 ± 18 ms, bγ = 73 ± 3%) [29], which is significantly longer lived than the 163 Os daughter, 159 W. Multipolarity assignments for the strongest γ-ray transitions in 165 Os were obtained from angular intensity ratios, Rθ. In this method a ratio of α(165 Os)-correlated γ-ray intensities detected at the θ = (158° and 134°) and θ = (94° and 86°) spectrometer angles was extracted. The method employed discriminated between different multipolarities in 166 W yielding typical Rθ values of approximately 1 and 0.6 for stretched quadrupole and stretched dipole transitions, respectively [30]. The angular intensity ratios extracted for 165 Os are listed in Table II. Figure 4 shows the level scheme deduced on the basis of γ-ray coincidences, relative intensities and angular intensity ratios.

While the level of counts is very low, these summed coincidence spectra suggest that there are two distinct low-spin structures in 165 Os. Figure 3(b) shows γ rays in coincidence with the 490, 633, 700, or 692 keV γ rays, which form the left-hand side of Fig. 4. It is assumed that the 95 keV transition, which is not apparent in Fig. 3(c), is a stretched magnetic dipole transition connecting a stretched E2 cascade to the 7/2− ground state as observed in 167 Os [13]. Allowing for the total conversion coefficient of 6.5 for a 95 keV M1 transition [31], the intensity of this transition is greater than that of the 490 keV E2 transition feeding the 9/2− state. A parallel sequence of γ rays comprising the 499, 597, 559, and 593 keV transitions (shown on the right-hand side of Fig. 4) is also assumed to feed the ground state based on comparisons with the structure of 167 Os [13]. The energy spectrum of these summed γ-ray coincidences is shown in Fig. 3(c).

IV. DISCUSSION

The low-lying states in the neutron-deficient osmium isotopes are based on single quasiparticle configurations formed when the odd neutron occupies one of the available f7/2, h9/2, or i13/2 states near the Fermi surface [32–36]. Figure 5 compares selected low-lying excited states in 163 Os and 165 Os with the ground-state bands in their lighter even-N neighbors. The low-lying states in 163 Os and 165 Os fit in with the systematic trend of the light Os isotopes of increasing excitation energy in nuclei closer to N = 82. This indicates a change in structure from collective rotations in the N > 90 Os isotopes towards a single-particle regime. Indeed, in 163 Os a low-lying 8+ state was identified and interpreted as the (f7/2, h9/2)4+ or (h9/2)6+ configuration [10]. The low-lying 23/2− state in 163 Os lies between the 8+ states in the neighboring even-N isotopes. Therefore, the 23/2− states is interpreted as the maximally aligned (f7/2, h9/2)23/2− state.

There is evidence in this mass region for the existence of a low-lying 13/2+ isomer based on a configuration where the odd neutron occupies the i13/2 orbital. The relative ordering of the single-quasiparticle excitations in nearby nuclei has been deduced from the electromagnetic decay paths of the 13/2− isomeric state. For example, Scholey et al. measured the half-lives of the 13/2+ isomers in 166 W and 167 Os to be 154 ± 3 ns and 672 ± 7 ns, respectively, and deduced that the decay path comprises an M2 transition to the 9/2− state followed by an M1 transition to the 7/2− ground state, see Fig. 6. Thus, the first excited structure is interpreted as a single quasineutron

![FIG. 4. Level scheme deduced for 165 Os. The transition energies are in keV and their relative intensities are proportional to the width of the arrows. The white arrow components reflect the estimated internal conversion intensity.](image)

![FIG. 5. Comparison of energy levels in 163 Os and 165 Os with the ground state bands in their lighter even-N neighbors. All levels are placed relative to the ground state. All level spin assignments are tentative. The dashed lines connect states with similar structure.](image)
FIG. 6. Comparison of energy levels in \(^{165}\text{Os}\) with its heavier odd-\(N\) isotope \(^{167}\text{Os}\) and its lower-\(Z\) isotope \(^{163}\text{W}\). All levels are placed relative to the ground state. All level spin assignments are tentative. The dashed lines connect states with similar structure.

configuration based upon the \(h_{9/2}\) orbital. Figure 6 compares the excited states based upon the \((9/2^+)\) state in \(^{165}\text{Os}\) with the structures based on the \(h_{9/2}\) configuration in the lighter even-\(Z\) (\(N = 89\)) isotope \(^{163}\text{W}\) [37] and the heavier odd-\(N\) isotope \(^{167}\text{Os}\) [13]. This structure in \(^{163}\text{Os}\) shows a marked similarity with these neighboring nuclei and is also assumed to be based on the \(h_{9/2}\) state. The \(vi_{13/2}\) band built on the \(13/2^+\) isomer is the most intense structure in the yrast spectra of nearby odd-\(N\) nuclei, such as the \(vi_{13/2}\) bands in \(^{163}\text{W}\) and \(^{167}\text{Os}\) shown in Fig. 6. However, in \(^{165}\text{Os}\) only excited states built upon the \(vi_{7/2}\) and \(vfh_{9/2}\) configurations have been observed. The absence of this structure in \(^{165}\text{Os}\) is consistent with the trend of increasing excitation energy of the \(i_{13/2}\) state with decreasing neutron number in the Os [13,32], W [37,38], and Ta [39] isotopes when approaching the \(N = 82\) shell closure.

**V. CONCLUSIONS**

Gamma-ray transitions have been observed for the first time in the highly neutron-deficient nucleus \(^{163}\text{Os}\). The low-lying yrast structure has been established to a tentative spin and parity \(23/2^+\) corresponding to the maximally aligned \((f_{7/2}, h_{9/2})_{23/2^-}\) state. A level scheme for the heavier odd-\(N\) isotope \(^{165}\text{Os}\) has also been established for the first time. The level structures in both nuclei are interpreted in terms of configurations involving the negative-parity \(f_{7/2}\) and \(h_{9/2}\) neutron orbitals and reflect the transition from \(\gamma\)-soft shapes observed in the heavier isotopes to near-spherical shapes near the closed \(N = 82\) shell. The observation of excited states in \(^{163}\text{Os}\) and \(^{165}\text{Os}\) completes the knowledge of excited states in the osmium nuclei spanning an uninterrupted isotopic chain from \(^{162}\text{Os}\) to \(^{199}\text{Os}\).

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