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Yrast states in ^{194}Os: The prolate-oblate transition region

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Previously unidentified states in the neutron-rich nucleus ^{194}Os have been populated following a deep inelastic reaction using a 780 MeV ^{136}Xe beam on a thick ^{198}Pt target. γ-γ coincidence events were collected using the 8π detector array. The yrast band in ^{194}Os has been observed up to $I^{\pi}=(10^{+})$, for the first time. This represents the heaviest osmium nucleus where in-beam γ-ray spectroscopy has been performed to date. The excitation energies of the new levels are compared to the systematics of the lighter even-even osmium nuclei. The evidence for a transition from prolate to oblate-deformed ground states in the heavy osmium nuclei is discussed and total Routhian surface calculations are presented. An alignment analysis together with cranked shell model calculations, suggest that the yrast states have a prolate shape, in contrast to earlier interpretations. Predictions for the neighboring even-even tungsten isotopes are also described.

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Many nuclear structure phenomena are apparent in the $A\approx190$ osmium-platinum shape transition region, for example, K isomerism [1] and triaxiality [2,3]. Additionally, the possible existence of oblate-deformed ground states in the heavy osmium nuclei (for $A>192$) is predicted [4]. To date, very little spectroscopic information is known about ^{194}Os due to its neutron-rich nature. A previous study using a reactor based two-neutron capture reaction, ^{192}Os$(nn,\gamma)^{194}$Os, reported transitions from the excited 2_1^+ and 2_2^+ states lying at 218 keV and 657 keV, respectively [5]. A complementary (t,p) experiment [6] found evidence for an excited 4^+ state at 601 ± 5 keV. In the present work, we report on the use of deep inelastic reactions to populate medium spin, near yrast states in ^{194}Os.

A 780 MeV ^{136}Xe beam, provided by the 88 Inch Cyclotron at Lawrence Berkeley National Laboratory, was used to bombard a 7 mg cm^{-2} thick target of ^{198}Pt (enriched to 95.7%), backed with 50 mg cm^{-2} of $^{\mathrm{nat}}$Pb. This is the heaviest stable isotope of platinum and was used to enhance the production of neutron-rich products. The beam energy was chosen to be 15% above the Coulomb barrier consistent with previous deep inelastic reaction experiments [7–12]. The beam had a natural pulsing period of 180 ns. The residual nuclei were stopped at the target position at the focus of the 8π detector array, which consisted of 20 Compton suppressed germanium detectors and a BGO inner ball. The trigger condition for a ''good'' event required hits in at least two germanium detectors and two BGO elements within a 200 ns time window. Symmetrized γ-γ energy matrices were constructed with BGO conditions of >2 and >5 elements firing, respectively. This allowed the discrimination of low-multiplicity Coulomb excitation events. The nuclei identified in the target region range from $^{188}_{76}$Os up to $^{206}_{82}$Pb, although it is likely that some of the heavier products are populated via nucleon transfer and/or inelastic excitations on the lead backing rather than by reactions with the platinum. Discrete states up to $16\hbar$ have been observed, for example, in ^{198}Hg [13] as shown in Fig. 1. The ^{194}Os channel of interest contributed only $\sim0.1\%$ of the total reaction cross section, compared to $\sim5\%$ for the ^{198}Pt excitations.

Four previously unreported transitions have been assigned to ^{194}Os from states lying at excitation energies of 601, 1131, 1792, and 2541 keV, respectively. The energy of the 601 keV level is consistent with the energy of the 4^+ state at 601 ± 5 keV observed by Flynn *et al.* [6] (no evidence for the γ-ray decay to the 2^+ level was found in the previous study). Coincidence relations and relative intensities have been used to order the decays into a cascade. Figure 1 shows the coincidence spectrum gated by transitions in ^{194}Os. The propensity of deep inelastic reactions to populate near yrast states [14] and the earlier assignment of the nonyrast γ-vibrational bandhead at 657 keV [5] (which is very weakly populated here), suggests that the new levels form the yrast band. This, together with the rotational nature of the cascade, implies a sequence of stretched $E2$ transitions, extending the ground-state band to $I^{\pi}=(10^{+})$. It should be noted that weak coincidences between the 218 keV transition and decays in $^{140}_{56}$Ba [15], the binary partner of ^{194}Os, have been observed, providing further confirmation that the 218 keV γ ray has been correctly assigned to ^{194}Os. This also implies that ''cold'' transfer of nucleons is taking place at low spins, without the subsequent evaporation of neutrons. This effect is demonstrated in Fig. 2. The 218 keV decay at the bottom of the new band has a significantly lower sum energy (H) and multiplicity (K) distribution when compared to the 530 keV transition. The events with a low H and K component result from Coulomb excitation following cold transfer, populating low spin states.

The proposed decay scheme for ^{194}Os is shown in Fig. 3 along with the energy systematics for the lighter even-even

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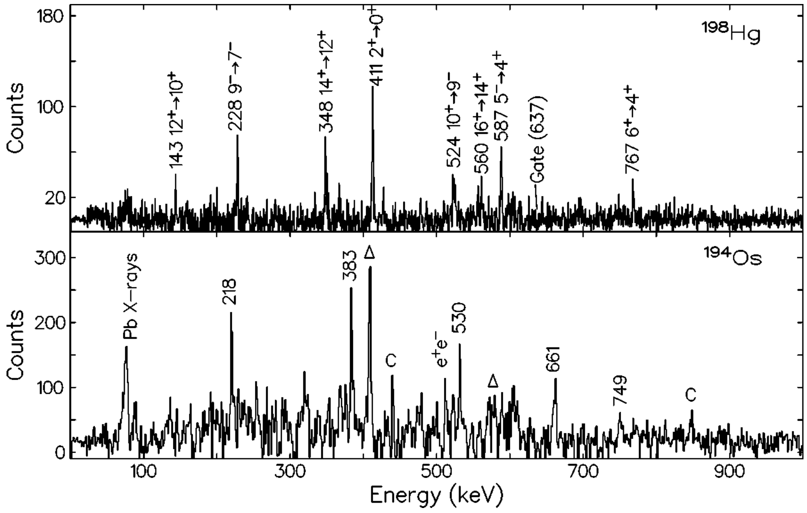

FIG. 1. The top panel shows a γ-ray coincidence spectrum gated by the 637 keV $4^+ \rightarrow 2^+$ transition in ^{198}Hg. Spin and parity assignments have been taken from Ref. [13]. The lower spectrum was produced by summing the ''logical and'' gates for pairs of transitions in the ^{194}Os band. (Each ''and'' spectrum is the minimum number of counts consistent with the two gating energies [16].) This was done to reduce contaminant lines. Only events for which >5 BGO elements fired are included. The peaks labeled with energies are in ^{194}Os and those marked by $\triangle$ are contaminants from ^{198}Pt (the target). Other contaminants are labeled by ''C.''

osmium isotopes. The energies of the ground-state band continue the trend of the lighter isotopes towards lower deformation as the $N=126$ closed shell is approached. However, it is the possibility of a deformed oblate ground state that makes this nucleus of particular interest. Hartree-Fock calculations with a Woods-Saxon single-particle potential, performed by Nazarewicz *et al.* [4], predict a ground-state oblate deformation for ^{194}Os with $\beta_2 = -0.14$.

The possibility of ^{194}Os having an oblate-deformed ground state was proposed earlier by Casten *et al.* [5]. The relative position of the γ-vibrational bandhead (2_2^+) was compared to the energies of the first excited 2^+ and 4^+ states. Zero or slightly negative values of $(E_{2_2^+} - E_{4_1^+})$ [17] point towards almost equal prolate and oblate minima, namely a γ-soft shape. In the osmium isotopes this is followed by an inversion in both this energy difference *and* the quantity $E_{2_2^+}/E_{2_1^+}$. This reemergence of a well defined deformation (i.e., reduced γ softness compared to ^{192}Os) was interpreted [5] to signify that the steady descent of the oblate minimum in the potential had culminated in an oblate deformed ground state for ^{194}Os. These energy systematics are shown in Fig. 4, with the tungsten isotopes included. Such a reversal in these quantities has so far only been observed in the $A \approx 190$ region for the $Z=76$ isotopic chain. The platinum nuclei across this region exhibit γ softness and an increasingly vibrational character, but no strong oblate polarization [5]. It should be noted that there is insufficient spectroscopic information known about the tungsten nuclei around $A \approx 190$ to rule out a similar change in the $Z=74$ isotopes (see Fig. 4). Some progress is now being made on the spectroscopy of neutron-rich tungsten isotopes by isomer spectroscopy studies following fragmentation reactions [18].

A study of the corresponding quantities in the $N=76$ isotonic chain yields a gradual decrease in the ratio $E_{2_2^+}/E_{2_1^+}$ as A decreases towards the $Z=50$ closed shell, whereas the value of $(E_{2_2^+} - E_{4_1^+})$ increases along the chain as $^{126}_{50}\mathrm{Sn}_{76}$ is

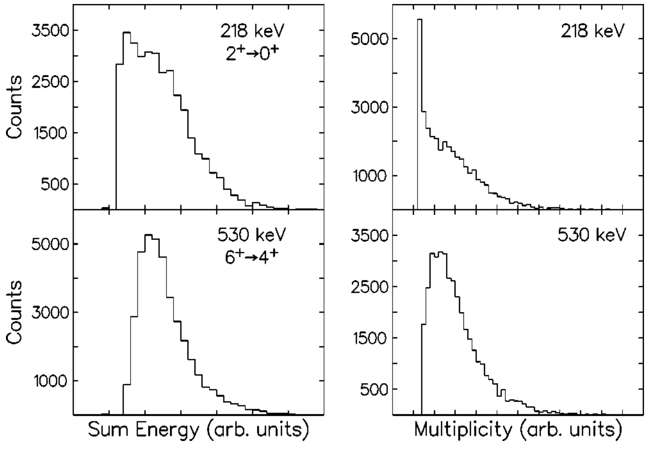

FIG. 2. Sum energy and multiplicity spectra gated by the 218 keV $2^+ \rightarrow 0^+$ transition and the 530 keV $6^+ \rightarrow 4^+$ transition in ^{194}Os. (Note that the 530 keV transition is contaminated by the $6^+ \rightarrow 4^+$ and $4^+ \rightarrow 2^+$ energy doublet in ^{140}Ba [15], the binary partner nucleus of ^{194}Os.)

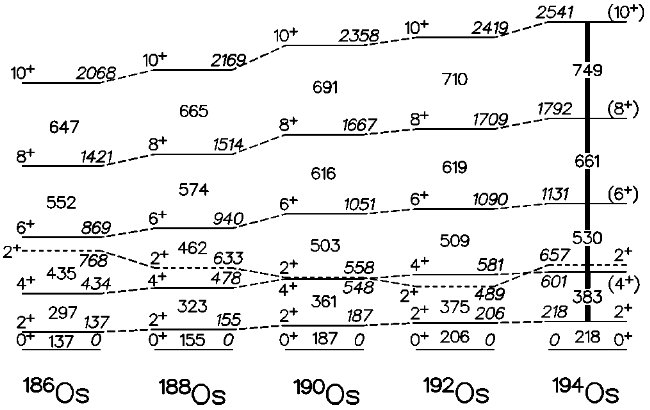

FIG. 3. Partial level scheme for ^{194}Os observed in the present work and the energy systematics of the ground-state bands for the even-even osmium isotopes $A=186$–192 [2]. The $E2$ γ-ray energies for the ground-state bands are quoted between the levels and new transitions are represented by solid vertical lines. The dashed levels correspond to the second excited 2^+ states. The osmium isotopes $A=188$–194 have been identified in the present experiment. The spin and parity assignment for the first three excited states in ^{194}Os are taken from Ref. [5].

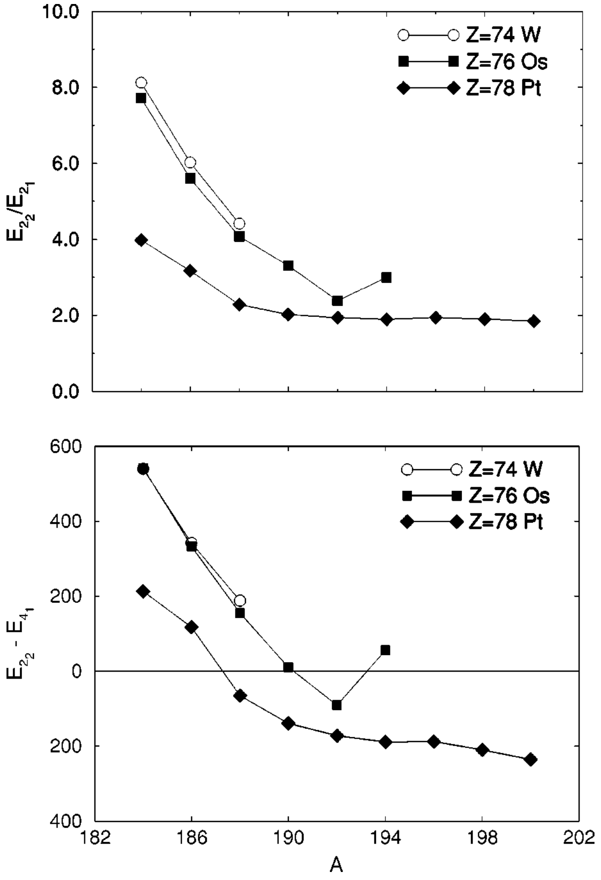

FIG. 4. A plot of mass number vs relative energy systematics for the even-even tungsten, osmium, and platinum isotopes in the $A\approx 190$ region [5,20]. Top: the ratio $E_{2_2^+}/E_{2_1^+}$; bottom: the quantity $(E_{2_2^+}-E_{4_1^+})$. The points for ^{188}W are tentative. The second 2^+ state in ^{188}W state was assumed to be the third excited state [21], but no spin and parity assignment has previously been made.

approached. (The energies $E_{2_1^+}$, $E_{2_2^+}$, and $E_{4_1^+}$ are all increasing.) This indicates a reduction in deformation and γ softness with the steady onset of vibrational character. The absence of an energy inversion in the $A\approx 130$ systematics is not surprising given the different single-particle structure and the known influence of the strong neutron-proton interaction between high-j orbitals in generating deformation [19]. For $Z=76$, $N\approx 116-120$, the last protons are filling the high-Ω $h_{11/2}$ Nilsson orbitals while the neutrons are in the high-Ω components of the $i_{13/2}$ state. The result is a high degree of spatial overlap between neutrons and protons in orbitals which are both oblate driving and hence the development of a strong oblate minimum in the potential. In the $A\approx 130$ region, the protons are in the low-Ω $g_{7/2}$ orbitals while the neutrons are filling the high-Ω $h_{11/2}$ states as well as the $d_{3/2}$ states. However, it might be interesting to study the $N=76$ nuclei below the $Z=50$ proton shell where both protons and neutrons will again occupy high-Ω, high-j orbitals ($g_{9/2}$ and $h_{11/2}$, respectively) with the possibility of an oblate minimum again developing in the potential.

From the alignment systematics shown in Fig. 5, the new band seems to be just starting to up-bend at $I=(10)\hbar$. This is consistent with the lighter even-even isotopes, although ^{186}Os is the heaviest osmium to be studied through the backbend [3]. Comparisons with cranked shell model (CSM) calculations, of the type described in Refs. [22,23], suggest that this is due to a prolate structure, because an oblate configuration would enter the first band crossing at a much lower frequency, $\hbar\omega\approx 0.2$, compared to $\hbar\omega\approx 0.40$ from Fig. 5. Deformation parameters $|\beta_2|=0.16$, $\beta_4=-0.072$, $\gamma=0°$ (prolate) and $|\beta_2|=0.15$, $\beta_4=-0.023$, $\gamma=-60°$ (oblate) have been used, and were obtained from the total Routhian surface (TRS) calculations described below. The absence of evidence for the onset of alignment in ^{194}Os in Fig. 5 suggests that no change in structure takes place up to spin 10. This is (model dependent) evidence that the yrast states in ^{194}Os occupy a prolate potential minimum. However, in order to unambiguously distinguish between prolate and oblate shapes in the osmium isotopes, additional data are needed from the odd-N osmium isotopes to establish the single-particle orbits that reside close to the Fermi surface and the evolution of the yrast structure with spin. To date only low-spin states (up to $7/2\hbar$) have been identified in ^{193}Os [24]. Unfortunately, no evidence for transitions in ^{193}Os and ^{195}Os was found in the present study.

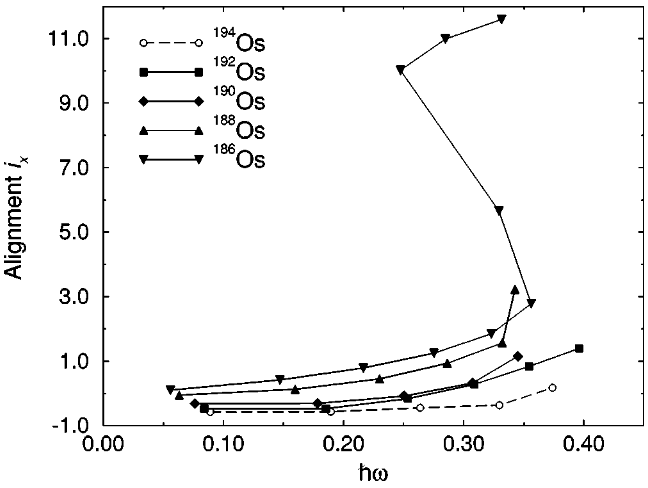

FIG. 5. A plot of rotational frequency, $\hbar\omega$, vs the intrinsic alignment, i_x, for $^{186-194}$Os. Harris parameters $\mathfrak{I}_0^{(1)}=20\hbar^2$ MeV^{-1} and $\mathfrak{I}_1^{(2)}=35\hbar^2$ MeV^{-3} have been used.

States in the $N=120$ osmium isotope ^{196}Os could not be established from the current data. Two level energies (with uncertainties of ±20 keV) have been assigned to ^{196}Os from a two-proton transfer reaction study [25], but no cross coincidences with the binary partner nucleus $^{138}_{56}$Ba could be identified here. A probable explanation for this is the strong Q-value dependence for two-nucleon transfers [12] favoring the two-proton stripping reaction, leading to the strong population of $^{200}_{80}$Hg.

Total Routhian surface (TRS) calculations, as described in Refs. [26–28], have been performed for the nuclei $^{190-196}$Os, corresponding to neutron numbers $N=114-120$. These calculations show the adiabatic structure as a function of deformation in the $\beta-\gamma$ plane. Axially symmetric prolate shapes correspond to $\gamma=0°$ and axially sym-

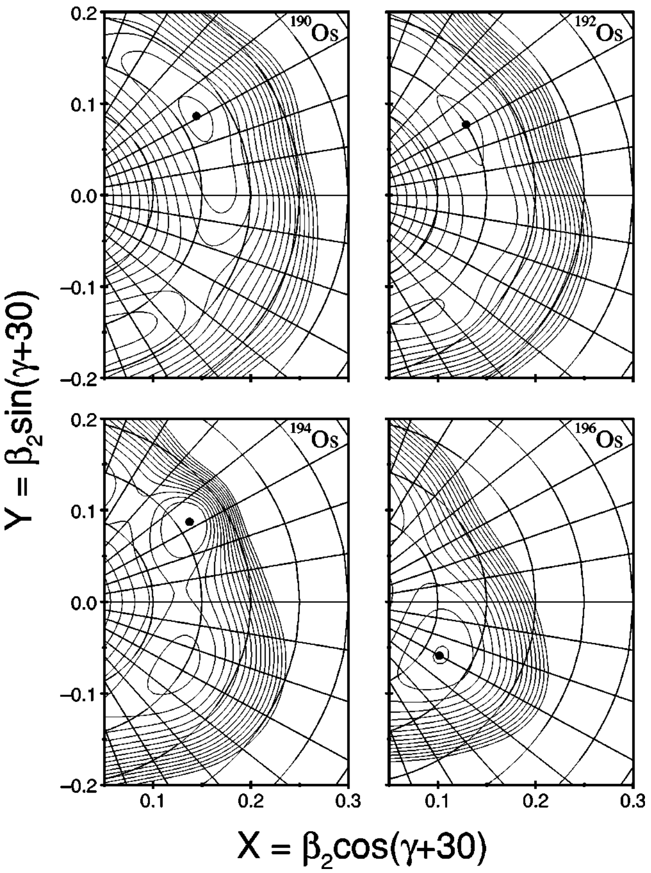

FIG. 6. Total Routhian surface calculations for the ground states of (a): ^{190}Os with $|\beta_2|=0.17$ and $\gamma \leqslant 2°$; (b): ^{192}Os with $|\beta_2|=0.15$ and $\gamma \leqslant 2°$; (c): ^{194}Os with $|\beta_2|=0.16$ and $\gamma \leqslant 2°$; (d): ^{196}Os with $|\beta_2|=0.12$ and $\gamma=-60°$. The contour lines represent energy increments of 200 keV.

metric oblate shapes have $\gamma=-60°$ for collective rotation. The resulting calculations for the ground-state configurations are shown in Fig. 6. These predict a progression from a γ-soft prolate minima at ^{190}Os to a well-defined oblate shape for ^{196}Os. For ^{194}Os there are both oblate and prolate γ-soft minima, with the prolate minimum being slightly deeper, whereas in the calculations by Nazarewicz *et al.* [4], the oblate potential is more favored. This is consistent with competing oblate and prolate shapes and the small differences in the specific details of the two calculations. The overall shape is very γ soft, but the potential for ^{196}Os is more defined and centered on an oblate deformation. The same calculations show the dominance of the prolate minimum in ^{194}Os up to $10\hbar$, which agrees with the alignment analysis. In addition, a similar prolate-oblate shape transition is predicted to occur in the tungsten isotopes. γ-soft potentials are predicted for ^{188}W and ^{190}W, and ^{192}W is calculated to have competing oblate and prolate minima. A well-defined energetically favored oblate shape is predicted for ^{194}W, with $|\beta_2|=0.14$ and $\gamma=-62°$. A hint of this γ softness can be seen in the reduced E_{4^+}/E_{2^+} ratio ($=2.7$) for ^{190}W [18] (compared to 3.33 for a good rotor), and is supported by recent potential-energy-surface calculations [18]. Extending the systematics of the neutron-rich osmium isotopic chain and the observation of the low-lying yrast and near-yrast states in the heavy tungsten nuclei provides an experimental challenge in order to elucidate how these two elements behave across the transition region approaching the $N=126$ magic number.

The analysis of these new results for ^{194}Os suggests that, while there may be a low-lying oblate-deformed minimum, up to $I=(10)$, the prolate minimum is yrast. This is in contrast to the earlier interpretation of the γ-bandhead energy systematics, discussed here and in Ref. [5], thought to show a change to oblate deformation in ^{194}Os. This suggests that the reemergence of rotational structure (indicated by the inversion of the E_{2^+} characteristics) is associated with the prolate deformed minimum, and that the trend of a steady decrease in the energy of the oblate potential minimum, observed for $A<192$, *reverses* at $A=194$.

In summary, the yrast states in ^{194}Os have been observed up to $(10)\hbar$ for the first time, using deep inelastic reactions on a thick ^{198}Pt target, extending the systematics of the heavy even-even osmium isotopes to $N=118$. Comparisons with CSM calculations imply that the prolate minimum dominates in the yrast states, in contrast to the earlier interpretation of the energy systematics which suggested a transition to an oblate shape in ^{194}Os. In fact, the TRS calculations discussed here suggest that this transition may take place at ^{196}Os ($N=120$). Predictions have also been made for the tungsten nuclei in this region which are becoming accessible through the application of novel spectroscopic techniques such as the fragmentation of relativistic heavy-ion beams.

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