Shapes of neutron-rich $A \approx 190$ odd-odd nuclei

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The occurrence of oblate and prolate shapes is investigated theoretically for odd-odd neutron-rich nuclei with $A \approx 190$. Using the cranked Woods-Saxon-Strutinsky method, including configuration constraints, it is found that collective oblate rotation coexists with high-K prolate rotation, for tantalum and rhenium isotopes with $N = 115$ and 117.

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Following from the prediction by Hilton and Mang [1] of "giant backbending" in ^{180}Hf, caused by a collective oblate rotational band crossing the prolate ground-state band, there has been further theoretical investigation of this phenomenon [2–5]. The calculated shape change is understood to be induced by the effects of rotation alignment. It is related to the prediction of a ground-state shape transition from prolate to oblate with increasing neutron number [5–8] in the same mass region. An important consideration is the reinforcing effect of the protons and neutrons, both of which have their Fermi levels high in their respective shells. Thus high-K couplings for prolate shapes compete with low-K couplings for oblate shapes. It is the rotation alignment of the latter that, unusually, enables collective oblate rotation ($\gamma = -60^\circ$ in the Lund convention) to become yrast, i.e., to have the lowest excitation energy at a given angular momentum. Nevertheless, the experimental situation remains inconclusive [4,5,9].

The present work gives further theoretical insight by studying odd-odd nuclei in the neutron-rich $A \approx 190$ region. The initial supposition was that, since the proton and neutron shape-driving effects reinforce one another, it may be sufficient to have a single nucleon of each type in order to manifest the prolate-oblate shape coexistence. This is indeed found from the calculations, as shown below, and may lead to improved experimental opportunities to test the predictions.

Total Routhian surface (TRS) calculations have been performed for odd-odd $N = 115$ and 117 isotopes of tantalum ($Z = 73$), rhenium ($Z = 75$), and iridium ($Z = 77$), complementing our earlier study of even-even nuclides [5]. The single-particle energies are obtained from the deformed Woods-Saxon potential [10], with the Lipkin-Nogami (LN) treatment of pairing [11]. This avoids the spurious pairing phase transition encountered in the simpler BCS approach. The pairing strength, G, is determined by the average-gap method [12]. The total energy of a configuration consists of a macroscopic part which is obtained from the standard liquid-drop model [13] and a microscopic part resulting from the Strutinsky shell correction [14], $\delta E_{\rm shell} = E_{\rm LN} - \tilde{E}_{\rm Strut}$. Calculations are performed in the lattice of quadrupole (β_2, γ) deformations with hexadecapole (β_4) variation. For a given rotational frequency, pairing is treated self-consistently by solving the cranked LN equation at any given point of the deformation lattice and then the equilibrium deformation is determined by minimizing the obtained TRS (for details, see, e.g., Refs. [15,16]). Configuration-constrained calculations have been performed in the absence of rotation, as described by Xu *et al.* [17].

The critical neutron number for prolate-oblate shape coexistence is close to $N = 116$. This was discussed for even-even ^{190}W$_{116}$ [5], where, a $K^\pi = 10^-$ two-quasineutron (2ν) prolate excitation is predicted to be at similar energy to an $I^\pi \approx 10^+$, 2ν oblate excitation. The focus of the present work is on the neighboring odd-odd nuclides ^{188,190}Ta and ^{190,192}Re. Their TRS diagrams for negative parity are shown in Fig. 1 at low rotational frequency, $\hbar\omega = 0.1$ MeV. In each case the ground state, at $\hbar\omega = 0$, is prolate. Comparison can also be made with configuration-constrained calculations. The $K^\pi = 10^-\{\pi 9/2^-[514] \otimes \nu 11/2^+[615]\}$ Nilsson configuration is calculated to have prolate shape (see Table I) and is at low excitation energy. Indeed, it may form the ground state, though lower-K configurations cannot be ruled out. (There is experimental evidence for an $I^\pi = (2)^-$ ground state in ^{192}Re [18].) In contrast, at low rotational frequency, $\hbar\omega \approx 0.1$ MeV, the oblate, $\pi h_{11/2} \otimes \nu i_{13/2}$ configuration, with $I^\pi \approx 12^-$, becomes energetically favored, as shown in Fig. 1. Further details are given in Table I, and a schematic illustration of the competing prolate and oblate shapes is shown in Fig. 2.

For oblate shape, the Fermi level is amongst the low-Ω $\pi h_{11/2}$ and $\nu i_{13/2}$ orbitals, and they undergo Coriolis-induced rotation alignment. Note that the TRS diagram in Fig. 1 for ^{190}Re shows a triaxial shape, but this becomes oblate at higher frequency ($\gamma = -72^\circ$ for $\hbar\omega = 0.2$ MeV). Also, for ^{188}Ta, the oblate minimum becomes yrast for $\hbar\omega > 0.1$ MeV. Moreover, in all four cases, oblate shapes dominate the high-spin behavior. It should be appreciated, however, that the oblate band heads are not well defined in the TRS calculations. This is due to the rotation alignment effects, with the calculations being performed in a frequency basis, rather than an angular-momentum basis. Full $\pi h_{11/2} \otimes \nu i_{13/2}$ alignment gives $I = 12$, but $I = 10$ band heads are also possible, i.e., with incomplete alignment, and this would be compatible with the oblate angular momenta at $\hbar\omega = 0.1$ MeV, as given in Table I. The decay of an oblate band head to its

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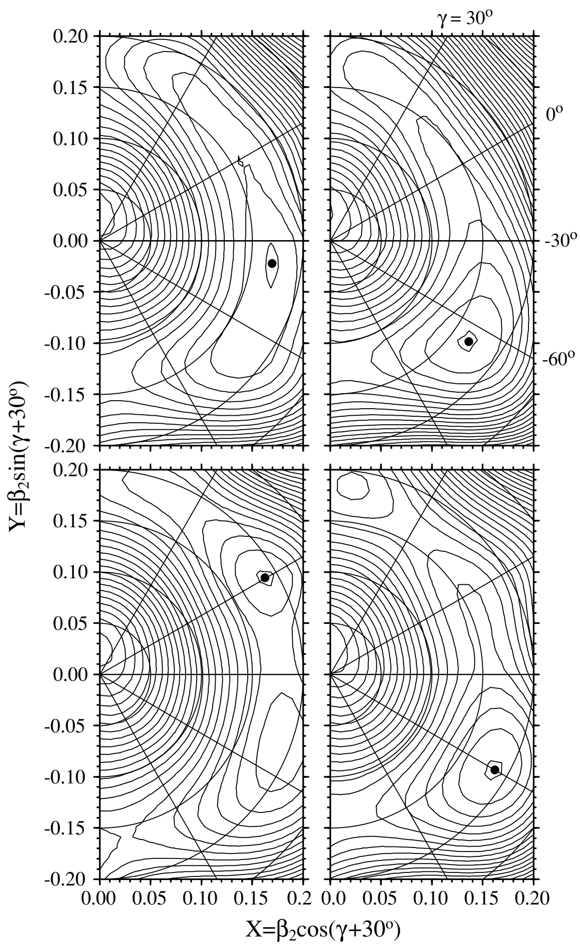

FIG. 1. TRS plots in the β_2, γ plane for ^{188,190}Ta (lower panels) and ^{190,192}Re (upper), all at $\hbar\omega = 0.1$ MeV. The $N = 115$ isotones are on the left-hand side, and the $N = 117$ isotones are on the right. The lowest energy in each diagram is indicated by a dot. The contours are at 200 keV intervals.

respective prolate ground state is likely to be associated with shape isomerism.

Included in Table I are calculated values for ^{192,194}Ir. Here, the high-K configuration is $\{\pi 11/2^-[505] \otimes \nu 11/2^+[615]\}_{11^-}$, but triaxiality becomes a crucial issue and considerably complicates the interpretation. In the present work, the focus is on the prolate—oblate competition in ^{188,190}Ta and ^{190,192}Re, where triaxiality plays a relatively minor role.

According to the calculations, the rotation alignment of one proton and one neutron is sufficient to enable the oblate shape to become yrast, and additional alignments at higher rotational frequency maintain the oblate yrast status. It seems, therefore, that these odd-odd nuclides are very favourable for experimental investigation of the oblate-rotor behavior. While these are neutron-rich nuclides, making them difficult to access experimentally, advances with radioactive-beam facilities may soon open up the possibilities. It is notable, for example, that an $I^\pi = (6^-)$ isomer is already known in ^{190}Re [18], and isomeric decays have recently been identified in ^{188}Ta and ^{192}Re [19] using the projectile-fragmentation technique with delayed

TABLE I. Calculated spins and deformation parameters for $N = 115$ and 117 negative-parity, near-prolate high-K energy minima at $\hbar\omega = 0$ (left-hand columns), and near-oblate energy minima at $\hbar\omega = 0.1$ MeV (right-hand columns, including energies relative to the high-K minima). The values of β_4 are in the range -0.02 to -0.07.

	$\hbar\omega = 0$			$\hbar\omega = 0.1$ MeV[a]			
	$I(\hbar)$	β_2	γ	E (MeV)	$I(\hbar)$	β_2	γ
^{188}Ta	10	0.18	0°	1.12	11.6	0.19	−52°
^{190}Ta	10	0.16	0°	0.18	11.5	0.19	−60°
^{190}Re	10	0.16	0°	0.71	10.6	0.17	−37°
^{192}Re	10	0.14	±9°	1.31	12.7	0.17	−66°
^{192}Ir	11	0.15	±30°	0.49	12.3	0.15	−77°
^{194}Ir	11	0.13	±30°	0.05	12.5	0.14	−75°

[a]The ^{188}Ta near-oblate minimum at $\hbar\omega = 0.1$ MeV is a local minimum (see Fig. 1).

γ-ray detection. Half-lives of, respectively, 5 and 120μs were found. However, there is insufficient information to associate these isomers with the predicted prolate-oblate coexistence, and further data are needed. A key observation would be the rotational bands built on the different shapes, since these are expected to be in the form of strongly coupled $\Delta I = 1$ sequences for high-K prolate shapes, and rotation-aligned $\Delta I = 2$ sequences for oblate shapes.

The $N = 117$ and 119 iridium isotopes, ^{192,194}Ir, are close to stability (^{193}Ir is stable) and easier to access experimentally. It is interesting to note that high-spin isomers are known in these isotopes [18]: $I^\pi = (11^-)$, $T_{1/2} = 241$ years, $E = 168$ keV in ^{192}Ir; and $(10^-, 11^-)$, 171 days, 370 keV in ^{194}Ir. A similar $(11)^-$ isomer is also known in ^{190}Ir [18]. Indeed, Jain *et al.* [20] specifically mention the possibility of prolate-oblate shape coexistence in the vicinity of ^{192}Ir. However, in view of the predicted triaxiality of the iridium isotopes (see above) it is likely that their eventual interpretation will be complex.

In summary, TRS calculations show that oblate shape is induced in the odd-odd nuclides ^{188,190}Ta and ^{190,192}Re by the rotation alignment of the $\pi h_{11/2} \otimes \nu i_{13/2}$ pair of nucleons,

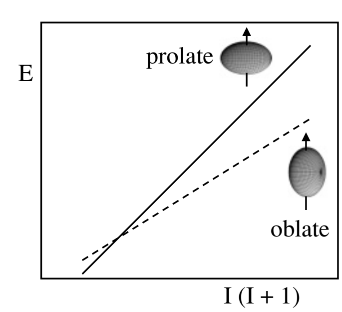

FIG. 2. Schematic energy-versus-spin representation of $\pi h_{11/2} \otimes \nu i_{13/2}$ prolate-oblate competition, in odd-odd nuclides adjacent to ^{190}W. The apparently high moment of inertia (low gradient of dashed line) for the oblate shape comes from rotation alignment of the unpaired proton and neutron.

and the oblate shape remains yrast over a large range of angular momentum. The experimental verification of yrast oblate rotation remains a challenge.

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