Prediction and possible observation of an oblate shape isomer in ^{190}W

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Energy-surface calculations for nuclides in the neutron-rich $^{190}_{74}$W$_{116}$ region show consistently that the collective rotation of a deformed oblate shape is an energetically favoured mode, especially for angular momenta $I > 12\hbar$. By comparing the calculations with existing experimental data, it is concluded that the reported $t_{1/2} \sim 1$ ms isomer in ^{190}W may be an oblate shape isomer.

The small number of oblate-shaped nuclei found in nature, compared with the many prolate nuclei, is a surprising feature of nuclear structure, which seems to be related to the strength of the nuclear spin-orbit interaction [1]. Furthermore, with increasing angular momentum, the collective rotation of an oblate shape, about an axis perpendicular to its axis of symmetry, is disadvantaged relative to prolate rotation, on account of the mass distribution leading to a larger moment of inertia for the latter. Therefore, the prediction that there would be "giant backbending" in the well deformed nuclide ^{180}Hf at $I \approx 26\hbar$, made by Hilton and Mang in 1979 [2], was remarkable. They performed HFB calculations to show that collective oblate rotation, incorporating rotation-aligned nucleons, could take place at a lower energy than prolate rotation. The transition from one shape to the other would represent a striking and sudden structural change, quite unlike anything yet observed. Nevertheless, despite experimental and theoretical advances [3–5], experimental evidence for the oblate mode in the mass-180 region has been inconclusive. For example, it has not proved possible to reach high enough angular momentum in ^{180}Hf [6], though some evidence for oblate rotation has been found in ^{175}Hf at $I \approx 40\hbar$ [5]. However, it has been shown, on the basis of Total Routhian Surface (TRS) calculations [3], that the angular momentum at which oblate rotation becomes favoured decreases with increasing neutron number. Therefore, more detailed investigation of neutron-rich nuclei may give the best chance of finding the oblate rotational mode in this mass region. Indeed, it can be argued [3] that this region is optimal on account of reinforcing proton and neutron shell structures, with both Fermi levels being high (but not too high) in their respective shells. While a similar effect occurs for neutrons in the mass-130 region [7], with associated oblate states, the protons then favour prolate shapes at high angular momentum. The competing proton and neutron contributions lead to triaxiality, which itself has interesting consequences [8, 9].

In the present work, we investigate the neutron-rich mass-190 region theoretically, with particular attention to ^{190}W, where a $t_{1/2} \sim 1$ ms isomer was found in a projectile-fragmentation experiment [10]. Rather than the then proposed prolate, high-K interpretation (where K is the angular momentum projection on the symmetry axis) we now argue that the isomer may be an oblate, $(i_{13/2})^2$ rotational-aligned state. This lays the foundation for the "giant backbending" predicted by Hilton and Mang [2].

TRS calculations have been performed for even-even nuclides in the mass-190 region, including $^{186-190}$Yb, $^{188-192}$Hf, $^{186-196}$W, $^{190-200}$Os and $^{192-200}$Pt. The single-particle energies are obtained from the deformed Woods-Saxon potential [11], with the Lipkin-Nogami (LN) treatment of pairing [12]. This avoids the spurious pairing phase transition encountered in the simpler BCS approach. The pairing stength, G, is determined firstly by the average-gap method [13] and then adjusted by fitting experimental odd-even mass differences [14], which gives an enhancement of about 10% in the G values for both neutrons and protons. The increased pairing strengths lead to consistent moments of inertia and multi-quasiparticle energies [14, 15]. The total energy of a configuration consists of a macroscopic part which is obtained from the stardard liquid-drop model [16] and a microscopic part resulting from the Strutinsky shell correction [17], $\delta E_{shell} = E_{LN} - \tilde{E}_{Strut}$. 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 [18, 19]). Quadrupole pairing in doubly stretched coordinate space [20] has a negligible effect on energies, but is included because it has an important influence on collective angular momenta [19].

The results of the present calculations of ground-state shapes are broadly consistent with previous work [21, 22] where it has been noted that there is a predicted transition from prolate to oblate shapes with increasing neutron number. However, the inclusion of the axially asymmetric γ degree of freedom in the present work adds considerable clarity to the nature of the shape transition. For example, in the ytterbium isotopes, the TRS calculations predict the ground-state shape change to occur between ^{186}Yb$_{116}$ ($\beta_2 = 0.205$, $\gamma = -1°$) and ^{188}Yb$_{118}$ ($\beta_2 = 0.188$, $\gamma = 60°$) with clear prolate and oblate

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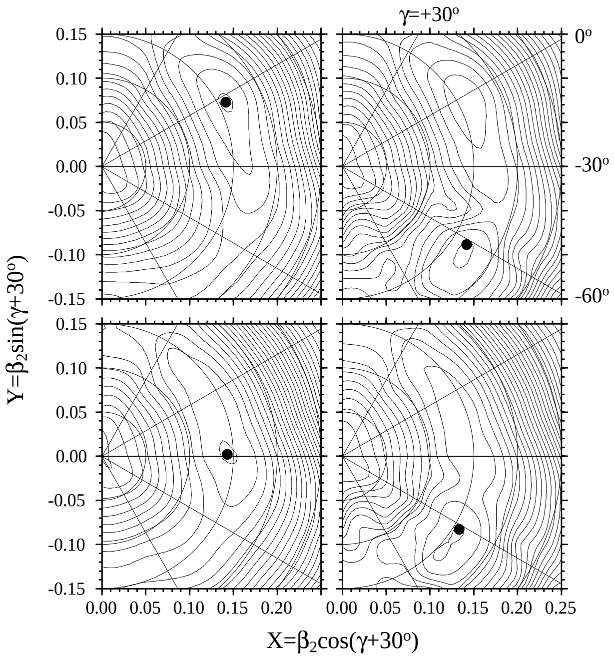

FIG. 1: TRS plots in the β_2, γ plane for ^{190}W (upper panels) and ^{192}Os (lower). Rotational frequencies are $\hbar\omega = 0.20$ MeV (left) and 0.22 MeV (right).

minima, respectively. However, the corresponding shape change is less distinct for osmium isotopes, and takes place between $N = 118$ and 120. The calculated triaxiality of the platinum isotopes is in accord with other work [23].

Here we focus on the angular momentum degree of freedom for the $N = 116$ isotones ^{188}Hf, ^{190}W and ^{192}Os, which all have calculated prolate ground-state shapes. In each case, at low rotational frequency, $\hbar\omega \approx 0.22$ MeV, there is a sudden transition to oblate rotation as the lowest-energy collective mode. This can be associated with the rotation alignment, at oblate shape, of a pair of $i_{13/2}$ neutrons, contributing 12 units of angular momentum. It is the same process as has been proposed previously [2, 3], but now, at higher neutron number, the prolate−oblate change occurs at lower angular momentum. Indeed, it seems to occur at the lowest possible angular momentum, $12\hbar$, for the full alignment of an $i_{13/2}$-neutron pair. Furthermore, with increasing rotational frequency, the oblate shape remains energetically favoured, as proton alignments contribute to neutron alignments in building the angular momentum. TRS plots, in the critical shape-changing region of rotational frequency, are shown in Figure 1 for ^{190}W and ^{192}Os. In both cases, the angular momentum jumps by $12\hbar$, $I = 4$ to 16, over a small rotational-frequency interval, $\hbar\omega = 0.20$ to 0.22 MeV, due to the rotation alignment of an $i_{13/2}$-neutron pair. In ^{190}W the associated shape change is from prolate ($\gamma = -3°$) to oblate ($\gamma = -62°$), while in ^{192}Os the shape change is from triaxial ($\gamma = -29°$) to oblate ($\gamma = -62°$).

The ^{190}W situation is now considered in the context of existing experimental data [10, 24]. The $t_{1/2} \sim 1$ ms isomer, which feeds into the ground-state rotational band at $I^\pi = (10^+)$, was tentatively assigned a $K^\pi = 10^-$ 2-quasiparticle Nilsson configuration, $\nu 11/2^+[615] \otimes \nu 9/2^-[514]$, based on the similar energies of known $K^\pi = 10^-$ isomers in ^{190,192}Os [25], and supported, at least qualitatively, by multi-quasiparticle calculations [10]. However, as part of the present work, configuration-constrained calculations [15] have been carried out to compare the excitation energies in detail. Energies and shape parameters are given in Table I. It is now found that, while the experimental ^{190,192}Os $K^\pi = 10^-$ energies are well reproduced by the calculations, as illustrated in Figure 2, there is a significant discrepancy for the corresponding state in ^{190}W. If, in fact, there is another isomer at lower energy, matching the theoretical prediction for ^{190}W, then its non-observation experimentally would not be surprising. Its lower energy would lead to a significantly longer lifetime, with loss of the time correlations that are needed for association of the γ-ray events with the arrival of ^{190}W ions following fragmentation reactions.

TABLE I: Calculated $K^\pi = 10^-$ energies and deformation parameters, including experimental energies for comparison.

	E_{exp} (keV)	E_{calc} (keV)	β_2	β_4	$\gamma°$
^{190}Os	1705	1700	0.157	−0.053	−1
^{192}Os	2015	1920	0.147	−0.053	0
^{190}W	2360±25	1633	0.162	−0.057	−1

We have searched in detail, through TRS and configuration-constrained calculations, for alternative configurations which might account for the observed isomer in ^{190}W. The only reasonable solution is to identify the bandhead of the oblate rotation-aligned structure as the probable explanation. The energy is approximately correct, but in these calculations the energy of the bandhead itself is not well defined, due to the calculations being performed in a rotational-frequency basis, rather than an angular-momentum basis. Extrapolation of the theoretical spin-projected energies gives an estimate of 2250 keV for the $I^\pi = 12^+$ state, with an uncertainty from the extrapolation of about 150 keV. This compares well with the experimental isomer energy of 2360±25 keV [10, 24]. Also, inspection of comparable rotation-aligned $(i_{13/2})^2$ structures known to exist in neighbouring nuclides is valuable. Figure 3 shows data for $N = 116$ isotones, based the recent interpretation of Levon et al. [26] for ^{194}Pt and ^{196}Hg. It is seen that the 12^+ $(i_{13/2})^2$ isomers in ^{194}Pt and ^{196}Hg are at similar energies to the isomer in ^{190}W. The corresponding isomer energy for ^{192}Os

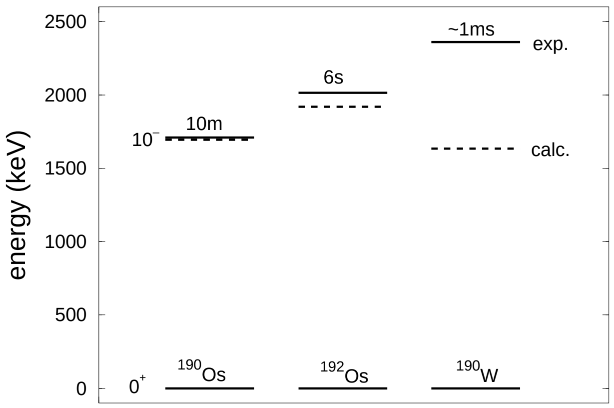

FIG. 2: Comparison of experimental (full line) and calculated (dashed line) isomer energies for ^{190}Os, ^{192}Os and ^{190}W. Experimental half-lives are indicated.

is unknown experimentally, though it is notable that, in addition to the 6 s, $K^\pi = 10^-$ isomer, a $t_{1/2} \sim 200$ ns isomer has also been identified, feeding into the ground-state band at high spin [27]. From the calculations, an oblate $I^\pi = 12^+$ isomer is expected at about 2100 keV in ^{192}Os. This stable nuclide needs further experimental investigation.

The implications of Figure 3 are striking. We propose that the observed $t_{1/2} \sim 1$ ms isomer in ^{190}W may be an oblate rotation-aligned state, with its long half-life deriving from the substantial shape change required for its decay to the prolate ground-state band. The much shorter (few ns) half-lives of the comparable isomers in ^{194}Pt and ^{196}Hg can then be due to the much less dramatic shape changes involved, as their ground-state bands are weakly deformed and triaxial (see also ref. [28]). Note that for low-energy $E2$ decays in $Z \approx 80$ nuclei, the strong variation of the electron conversion coefficient with γ-ray energy [25] leads to little dependence of half-life on transition energy. Hence the large half-life difference between the ^{194}Pt and ^{190}W isomers could not be ascribed solely to the energies of their $E2$ ($12^+ \rightarrow 10^+$) decays, which are uncertain in both cases.

Confirmation of the oblate shapes requires additional experimental data. The combination of quadrupole moments, g-factors, and transition-rate hindrance factors [29], should be able to give firm information for both ^{190}W and ^{192}Os. The isomerism is a key feature in giving access to these observables. Also, according to the calculations, the rotational bands above the oblate isomers should be decoupled and have high rotational alignments, contrasting with the strongly coupled bands associated with the alternative prolate, high-K interpretation. The ^{190}W structure is a candidate for a classic case of "giant backbending", of the type originally described by Hilton and Mang [2].

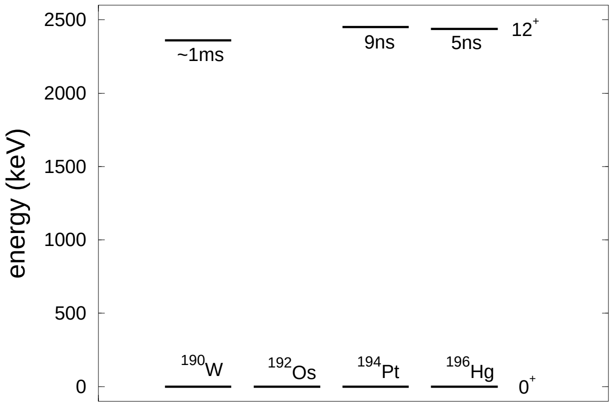

FIG. 3: Comparison of experimental isomer energies and half-lives for $N = 116$ isotones.

In summary, the need to understand better the excitation energy and structure of an isomer in ^{190}W has led to detailed energy-surface calculations and comparisons with neighbouring nuclides. It is concluded that the $t_{1/2} \sim 1$ ms isomer in ^{190}W could correspond to a predicted oblate shape isomer.

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