Isomeric states in neutron-rich Z = 76 isotopes and N = 116 isotones

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Outline

Abstract

Isomeric states in neutron-rich $Z = 76$ isotopes and $N = 116$ isotones

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We have employed both unpaired (cranked Nilsson-Strutinsky) and paired (cranked Nilsson-Strutinsky-Bogoliubov) cranked Nilsson-Strutinsky calculations to explore the properties of observed and potential isomers within the shape-transitional osmium ($Z = 76$) isotopes and $N = 116$ isotones. Our analyses reveal the prevalence of multiquasiparticle prolate and broken-pair triaxial structures in even-even osmium isotopes ($N = 112$–118) and $N = 116$ isotones ($Z = 72$–80). In addition, our exploration of $N = 116$ isotones identifies potential isomeric states, systematically, including noncollective 10^- and collective 12^+ states, constructed upon specific neutron configurations.

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Introduction: Nuclear Isomers

Definition

- A nuclear isomer is a metastable excited state of an atomic nucleus, with excitation energy in the MeV range and a lifetime from nanoseconds to 10^{15} years.
- Applications: Nuclear clocks, energy storage.

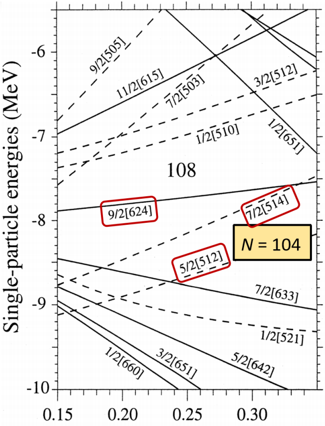
Theoretical Challenges

- Structural complexity: interplay of multiple shape minima, high-j intruder-orbital alignments, and multi-quasiparticle configuration mixing.
- Key models: the nuclear shell model , and mean-field approaches .

Introduction

Why do *K*-isomers exist:

- Dominant in deformed nuclei ($A \sim 130, 180$).
- Arise from **high-*j* intruder orbitals** crossing Fermi surface.
- **Hindered decays**: *K*-forbidden transitions .



Introduction

Why Focus on $A \approx 180$–190 Region?

- Shape transitions: In the $A \approx 180$–190 region, collective oblate or triaxial configurations have been predicted at high spin in Hf, W, Os, and Pt isotopes.
- Isomeric structures: Long-lived 12^+ isomers in even-A Pt isotopes originate from aligned $i_{13/2}$ neutron pairs.
- Unexplored isomers: Predicted oblate/triaxial states in Os need validation.

This Work's Goals:

- Map isomeric states in ^{192}Os and $N = 116$ isotones.
- Track collectivity evolution with neutron number.
- Analyze dominant MQP configurations in $N = 116$ isotones.

Theoretical framework:CNS

Hamiltonian:

$$H_\omega = H_{Nilsson} - \omega J_x \quad (1)$$

Total energy at spin *I*:

$$E_{\mathrm{tot}}(Z,N,I) = \min_{\varepsilon_i}\left[E_{\text{macro}}\,(Z,N,I,\varepsilon_i) + \delta E_{\text{shell}}\,(Z,N,I,\varepsilon_i)\right] \quad (2)$$

The shell correction part uses the Strutinsky shell correction method.

The rotating liquid drop energy

$$E_{\text{macro}} = E_{\mathrm{LD}}\,(Z,N,\varepsilon_i) + \frac{\hbar^2 I(I+1)}{2\mathcal{J}_{\text{rig}}\,(\varepsilon_i)} \quad (3)$$

No pairing interaction is included. The configuration is defined by blocked orbitals at given deformation and rotational frequency.

Theoretical framework: CNSB

Hamiltonian:

$$H_\omega = \sum_{q=p,n} \left[h_q^{\mathrm{MO}}(\bar{\varepsilon}) - \omega_x (j_x)_q - \Delta_q \left(P_q^\dagger + P_q \right) - \lambda_q \hat{N}_q \right]. \tag{4}$$

- h^{MO}: Modified Oscillator potential, including deformation effects.
- $P_q^\dagger = \sum_k a_k^\dagger a_{\bar{k}}^\dagger$: pair generation operator.
- $\Delta_q = G_q \sum_k u_k v_k$: BCS pair gap definition.

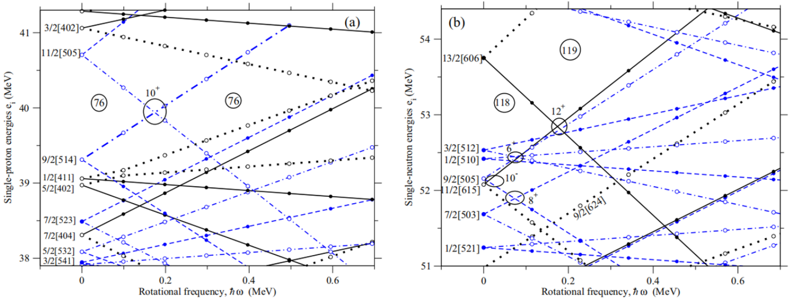
Total energy:

$$E_{\text{tot}}(Z,N,I) = \min_{\varepsilon_i,\Delta,\lambda} \left[E_{\text{macro}}(Z,N,I,\varepsilon_i) + \delta E_{\text{shell + pair}}(Z,N,I,\varepsilon_i,\Delta,\lambda) \right] \tag{5}$$

Pairing strength G is reduced by 2–5% to approximately simulate particle-number projection effects.

Result:Favored noncollective MQP states in Z=76 isotopes

In Fig. 1, we have drawn the neutron and proton single particle energies。



- Unpaired CNS single-particle Routhians for (a) protons and (b) neutrons for the deformation $\varepsilon_2 = 0.143$, $\varepsilon_4 = 0.041$, $\gamma = -120^\circ$
- CNSB pairing results agree with unpaired ones; the 8^+ state is closer to the Fermi surface, favoring the $18^+/20^+$ states.

Result:Favored noncollective MQP states in Z=76 isotopes

Favored states in ^{192}Os

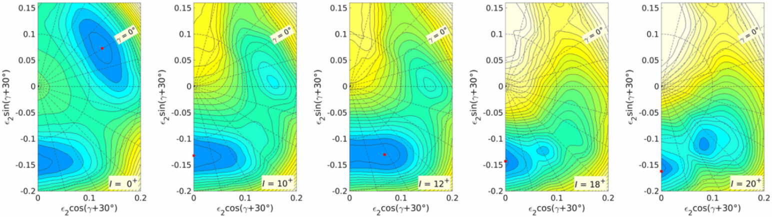
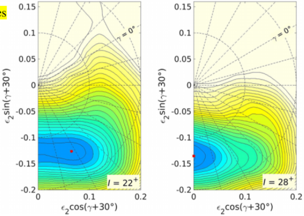


FIG. 2. Calculated CNSB potential-energy surfaces



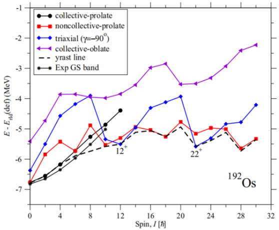


FIG. 3. The CNSB $(+,0)(+,0)$ yrast line in ^{192}Os compared with the energy at different fixed deformations governed by the minima shown in Fig. 2. The collective prolate state energy is obtained

Result:Favored noncollective MQP states in Z=76 isotopes

Favored states in ^{192}Os

TABLE I. The calculated energy and structure of prolate noncollective MQP states in ^{192}Os. The energies are minimized with respect to the deformation and pairing parameters. The last column shows if the state is favored or unfavored by the Gallagher-Moszkowski rules. Energies are in MeV.

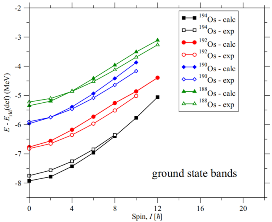
K^π	E_{calc}	Proton conf.	Neutron conf.	Coupling
6^+	1.132	GS	9/2[505]3/2[512]	Unfavored
7^-	1.417	GS	11/2[615]3/2[512]	Favored
10^-	1.538	GS	11/2[615]9/2[505]	Favored
10^+	1.814	11/2[505]9/2[514]	GS	Unfavored
12^+	2.350	GS	13/2[606]11/2[615]	Unfavored
17^-	3.396	11/2[505]9/2[514]	11/2[615]3/2[512]	Unfavored
18^+	3.426	GS	13/2[606]11/2[615]9/2[505]3/2[512]	Favored
20^+	4.176	GS	13/2[606]11/2[615]9/2[505]7/2[503]	
22^+	4.426	11/2[505]9/2[514]	13/2[606]11/2[615]	Favored
28^+	5.525	11/2[505]9/2[514]	13/2[606]11/2[615]9/2[505]3/2[512]	

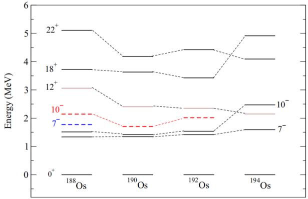
- Only the $\pi 11/2[505] \otimes 9/2[514]$ excitation is considered, as other proton excitations are energetically unfavorable.
- Residual interactions are not included in the calculation; energy ordering is interpreted based on the GM rule.
- The 20^+ and 28^+ states involve both favored and unfavored pairs, making classification ambiguous.

Result:Favored noncollective MQP states in Z=76 isotopes

Favored states in Os isotopes with N = 112-118

- The left panel: CNSB results show prolate ground-state shapes in Os isotopes and well reproduce the observed excitation energies.

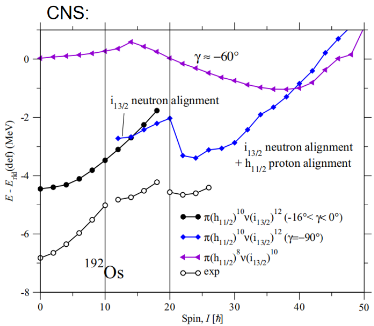


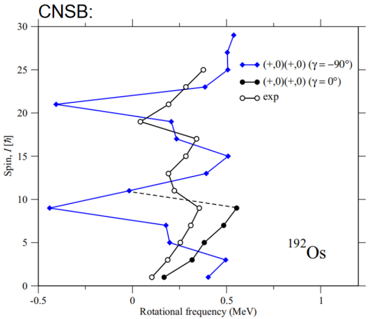


- The right panel shows favoured MQP states and the 12^+ state. Very low-lying high-K isomers are predicted in $^{194}\mathrm{Os}$, though not yet observed. The most favourable 22^+ state is likely to be experimentally accessible.

Result:Favored noncollective MQP states in Z=76 isotopes

Favored collective states in ^{192}Os





I=12: neutron alignment
I=22: proton alignment

but, experimental: 12^+, 20^+

angular momentum. These increments occur at approximately $I \approx 12^+$ and $I \approx 20^+$ states, corresponding to alignment gains of approximately $12\hbar$ and $8\hbar$, respectively, mentioned in

The I=20^+ state may involve a core spin contribution in the opposite direction (negative rotational frequency), explaining its lower energy.

Result:Collective and noncollective states in N = 116 isotones

Nucleus	K^π	E_{expt}	E_{theor}	ε_2	γ	ε_4	Proton conf.
Noncollective 11/2[615]9/2[505] neutron state							
$^{188}_{72}$Hf$_{116}$	10^-		1.304	0.18	$-120°$	0.055	GS
$^{189}_{73}$Ta$_{116}$	$25/2^-$		1.335	0.17	$-120°$	0.053	5/2[402]
$^{189}_{73}$Ta$_{116}$	$29/2^+$		1.439	0.17	$-120°$	0.056	9/2[514]
$^{190}_{74}$W$_{116}$	10^-	1.839	1.435	0.17	$-120°$	0.055	GS
$^{191}_{75}$Re$_{116}$	$25/2^-$	1.601	1.362	0.17	$-120°$	0.058	5/2[402]
$^{191}_{75}$Re$_{116}$	$29/2^+$		1.427	0.17	$-120°$	0.054	9/2[514]
$^{192}_{76}$Os$_{116}$	10^-	2.015	1.538	0.16	$-120°$	0.059	GS
$^{193}_{77}$Ir$_{116}$	$31/2^+$	2.277	1.684	0.15	$-120°$	0.052	11/2[505]
$^{194}_{78}$Pt$_{116}$	10^-		2.019	0.15	$-120°$	0.050	GS
$^{195}_{79}$Au$_{116}$	$31/2^+$	2.461+X	2.843	0.12	$-80°$	0.019	11/2[505]
Collective 13/2[606]11/2[615] neutron state							
$^{188}_{72}$Hf$_{116}$	12^+		1.822	0.16	$-87°$	0.023	GS
$^{189}_{73}$Ta$_{116}$	$25/2^+$		1.873	0.16	$-89°$	0.024	1/2[411]
$^{189}_{73}$Ta$_{116}$	$33/2^-$		2.039	0.16	$-88°$	0.023	9/2[514]
$^{190}_{74}$W$_{116}$	12^+	2.655	2.002	0.15	$-89°$	0.026	GS
$^{191}_{75}$Re$_{116}$	$25/2^+$		1.855	0.15	$-88°$	0.026	1/2[411]
$^{191}_{75}$Re$_{116}$	$33/2^-$		2.178	0.15	$-94°$	0.028	9/2[514]
$^{192}_{76}$Os$_{116}$	12^+	2.865	2.151	0.15	$-92°$	0.026	GS
$^{193}_{77}$Ir$_{116}$	$35/2^-$		1.875	0.14	$-94°$	0.024	11/2[505]
$^{193}_{77}$Ir$_{116}$	$27/2^+$		2.025	0.14	$-90°$	0.028	3/2[402]
$^{193}_{77}$Ir$_{116}$	$33/2^-$		2.471	0.14	$-88°$	0.020	9/2[514]
$^{194}_{78}$Pt$_{116}$	12^+	2.451	1.733	0.13	$-88°$	0.021	GS
$^{195}_{79}$Au$_{116}$	$27/2^+$		1.879	0.13	$-86°$	0.019	3/2[402]
$^{195}_{79}$Au$_{116}$	$25/2^+$	1.980	1.953	0.13	$-84°$	0.019	1/2[411]
$^{195}_{79}$Au$_{116}$	$35/2^-$		2.056	0.13	$-84°$	0.024	11/2[505]
$^{196}_{80}$Hg$_{116}$	12^+	2.439	1.902	0.12	$-80°$	0.017	GS

Summary

- This work systematically studies isomeric states in neutron-rich $Z = 76$ isotopes and $N = 116$ isotones using the cranked Nilsson-Strutinsky (CNS) and blocked-CNS (CNSB) models.
- By mapping deformation energy surfaces and analyzing high-K multi-quasiparticle configurations, it provides consistent interpretations for observed 10^-, 7^-, 12^+, and 22^+ isomers across this mass region.
- The calculations reveal pronounced shape coexistence phenomena (prolate–triaxial–oblate) and demonstrate that isomer stability is sensitive to orbital occupations, particularly at $N = 118$ and in $N = 116$ isotones.
- The model also predicts several unobserved isomers with long half-lives or low transition energies, highlighting experimental detection challenges.
- These findings reinforce the CNS/CNSB model's predictive power for transitional nuclei and emphasize the interplay between single-particle structure, deformation, and isomerism in the $A \sim 190$ region.