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Entanglement in the nuclear low-lying collective motion

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Research Area: Nuclear Structure

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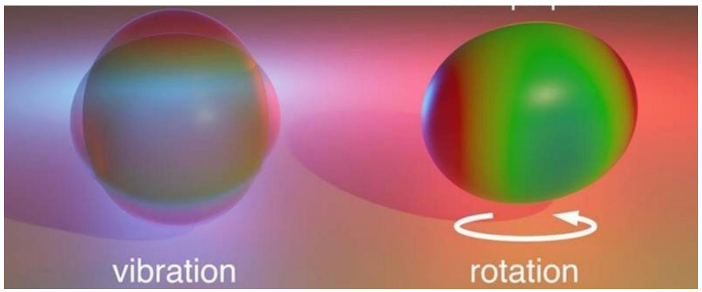
Outline

- Research Background
- Theoretical Framework
- Results and Discussion
- Summary

Nuclear Collective Motion

As a quantum many-body system, the low-lying excited states of a nucleus are dominated by collective degrees of freedom. Nucleons no longer move independently but form correlated collective modes.

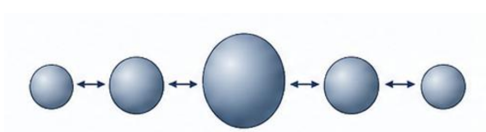


- **Vibration: Surface oscillation of spherical or weakly deformed nuclei**
- **Rotation: Rotational motion of a stably deformed nucleus about its symmetry axis**

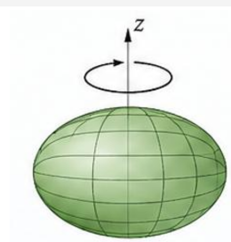
Within the Bohr-Mottelson framework, the low-lying collective motion of a nucleus is described by surface quadrupole deformation, introducing two intrinsic coordinates:

β: Deformation magnitude (degree of deviation from spherical shape)

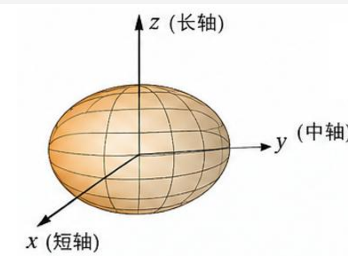
γ: Deformation type (axial symmetry vs. triaxiality)



Spherical vibration (β vibration)



Axial rotation(γ=0°)

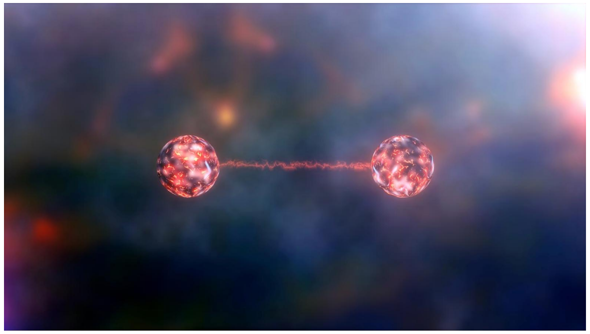


Triaxial deformation(γ≠0°)

Quantum Entanglement

Entanglement is the essential feature that distinguishes quantum physics from classical physics. It represents a nonlocal quantum correlation between two subsystems that cannot be described independently.

Subsystem A	Subsystem B
Shape degrees of freedom (β, γ)	Rotatiomal degrees of freedom Ω



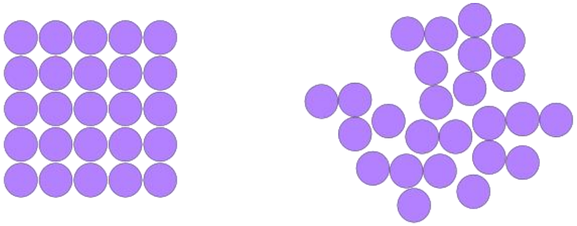
Shape and rotation are deeply coupled through collective motion, forming an inseparable quantum correlation.

Entropy: A physical quantity that quantitatively measures the degree of quantum entanglement (disorder) between two subsystems.

von Neumann entropy

$$S = -Tr\,\rho\,ln\,\rho = -\sum_k p_k\,ln\,p_k$$

S=0, pure state **S>0, entangled**



J.von Neumann, Gott.Nach. 1927,273 (1927)

RDFT-5DCH

- **5DCH Hamiltonian**

$$\hat{T}_{\text{rot}} = \sum_{k=1}^{3} \frac{\hat{J}_k^2}{2\mathcal{J}_k}$$

$$\hat{H}_{\text{coll}}(\beta,\gamma) = \hat{T}_{\text{vib}}(\beta,\gamma) + \hat{T}_{\text{rot}}(\beta,\gamma,\Omega) + V_{\text{coll}}(\beta,\gamma)$$

$$\hat{T}_{\text{vib}} = -\frac{\hbar^2}{2\sqrt{wr}}\{\frac{1}{\beta^4}[\frac{\partial}{\partial\beta}\sqrt{\frac{r}{w}}\beta^4 B_{\gamma\gamma} - \frac{\partial}{\partial\beta}\sqrt{\frac{r}{w}}\beta^3 B_{\beta\gamma}\frac{\partial}{\partial\gamma}] + \frac{1}{\beta\sin 3\gamma}[-\frac{\partial}{\partial\gamma}\sqrt{\frac{r}{w}}\sin 3\gamma B_{\beta\gamma}\frac{\partial}{\partial\beta} + \frac{1}{\beta}\frac{\partial}{\partial\gamma}\sqrt{\frac{r}{w}}\sin 3\gamma B_{\beta\beta}\frac{\partial}{\partial\gamma}\Big]\}$$

7 inputs:

$\mathcal{J}_k\ (k=1,2,3),\ B_{\beta\beta},\ B_{\beta\gamma},\ B_{\gamma\gamma},\ V_{\text{coll}}(\beta,\gamma)$

provided by RDFT

- **Wave function**

$$\Psi_\alpha^{IM}(\beta,\gamma,\Omega) = \sum_{K\in\Delta I} \psi_{\alpha K}^{I}(\beta,\gamma)\Phi_{MK}^{I}(\Omega)$$

PRC79, 034303 (2009)

- **Density matrices**

$$\boxed{\rho_{K'K}^{(I\alpha)} = \int_0^\infty d\beta \int_0^{2\pi} d\gamma \psi_{\alpha K'}^{I*}(\beta,\gamma)\psi_{\alpha K}^{I}(\beta,\gamma)\beta^4|\sin 3\gamma|}$$

Y.M.Wang and Q.B. Chen, PLB 859, 139131 (2024)

- **Entanglement entropy**

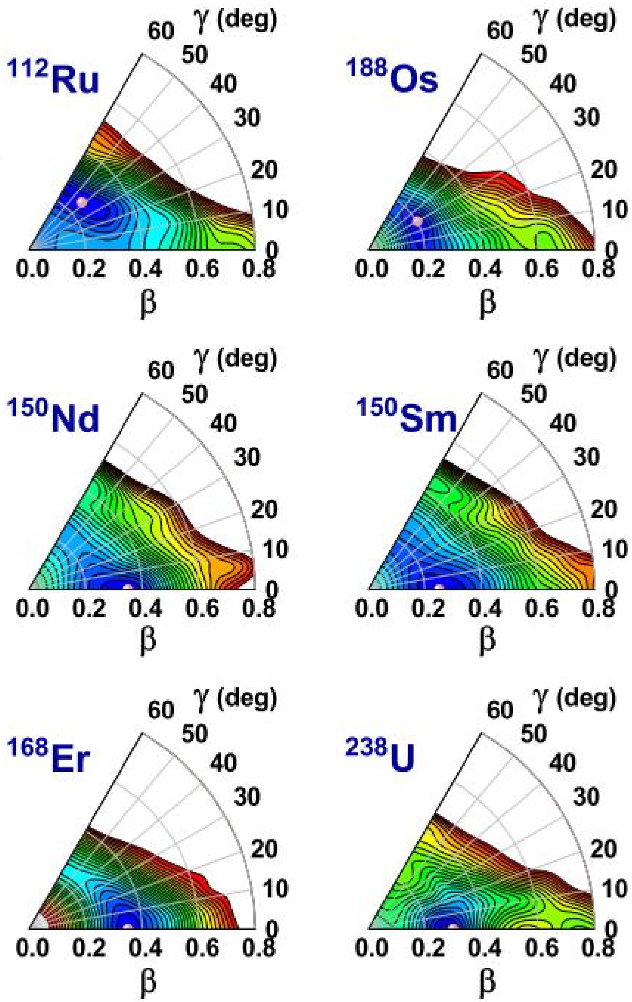
$$S = -Tr\,\rho\,ln\,\rho = -\sum_k p_k\,ln\,p_k$$

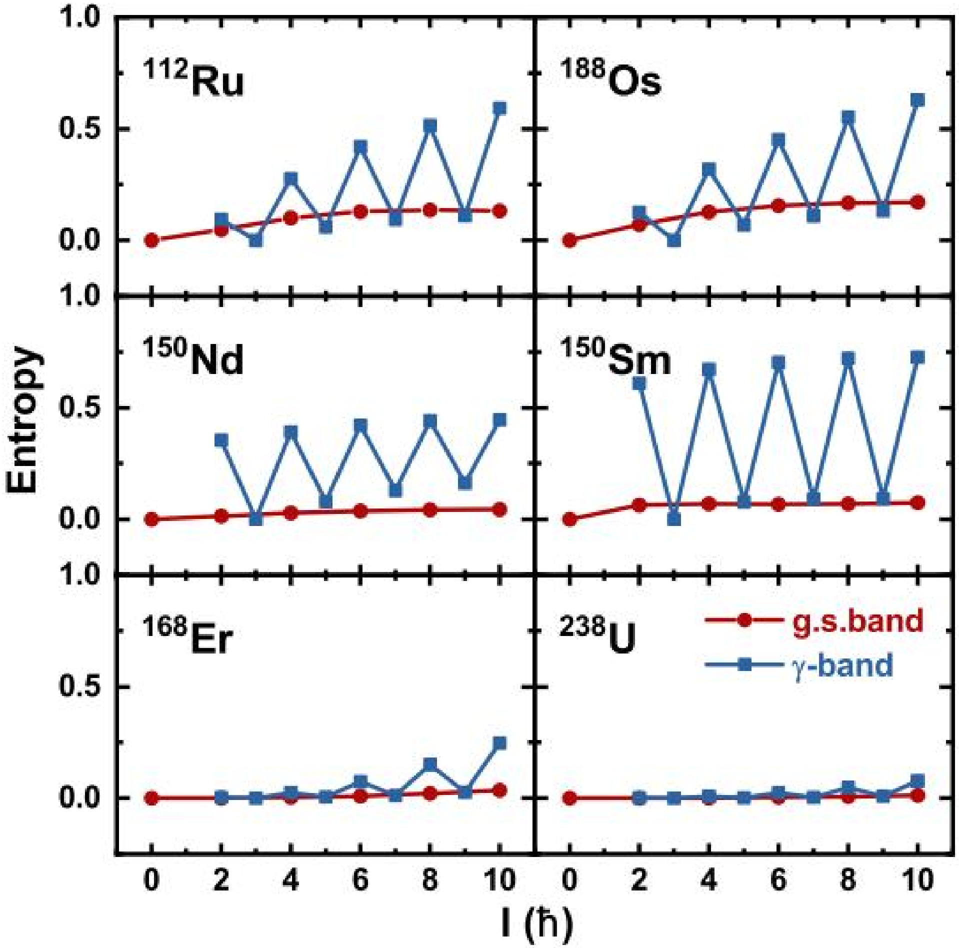
J.von Neumann, Gott.Nach. 1927,273 (1927)

Shape-Rotation Coupling

Y. M. Wang and Q.B. Chen, PRC111, L051306 (2025)

- **Triaxial**
- **Axial γ-soft**
- **Axial γ-rigid**



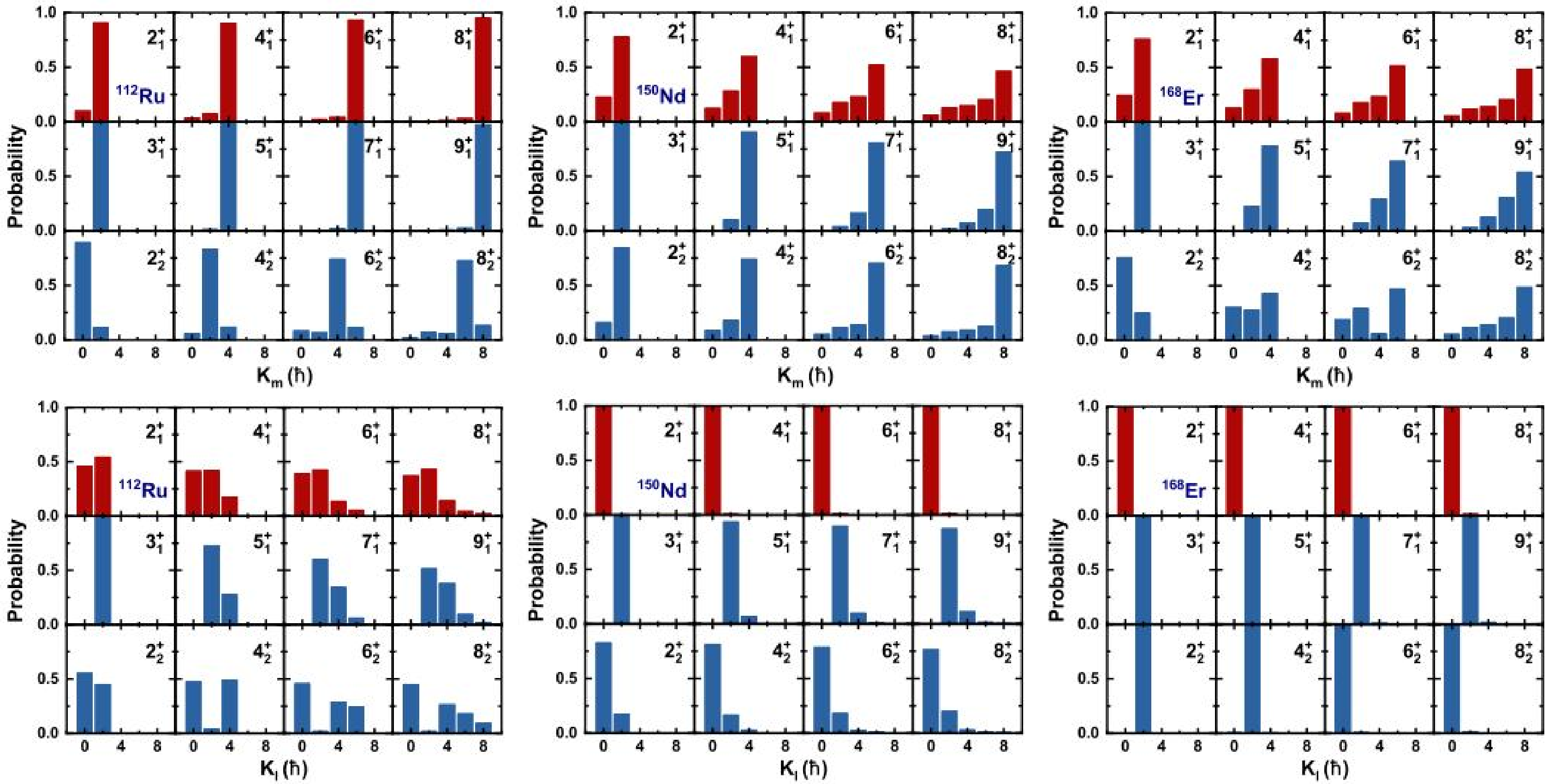


The entanglement entropy exhibits diverse trends across different deformed nuclei.

Shape-Rotation Coupling

- **K-distributions → Visualization of diagonal elements of ρ**

Single peak → Pure
Multiple peaks → Mixed



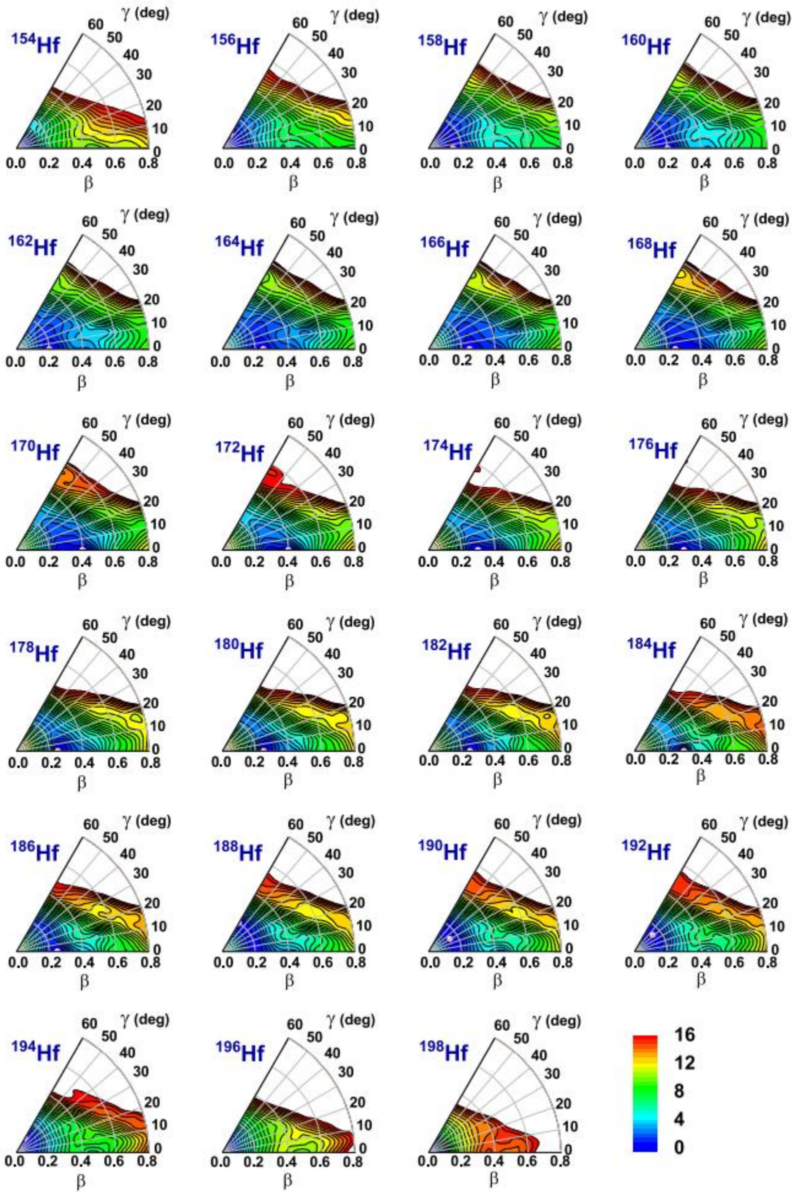
Odd →single value→S≈0
Even→multiple values→S↑

Even spins in γ-band
spread uniformly→S>0

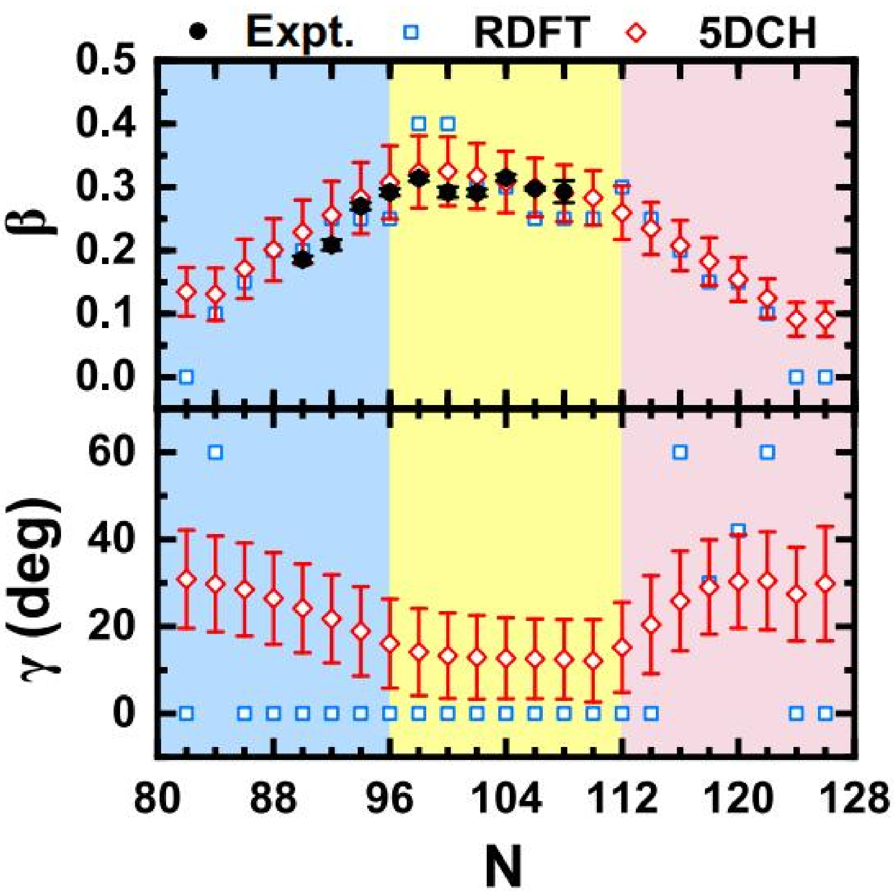
Focus on a single value→S≈0

Y. M. Wang and Q.B. Chen, PRC111, L051306 (2025)

Shape and Entropy Evolution in the Hf Isotopic Chain



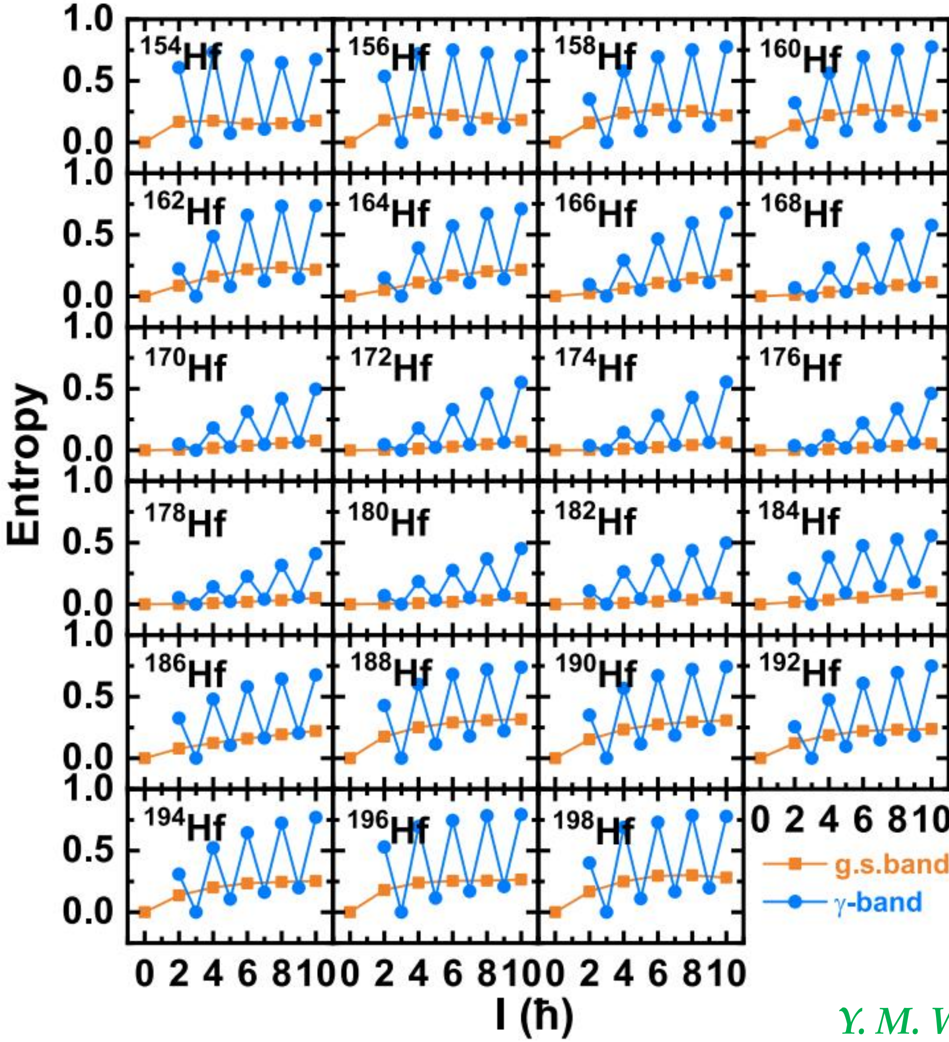
- **Shape evolution:**
  spherical → prolate → triaxial



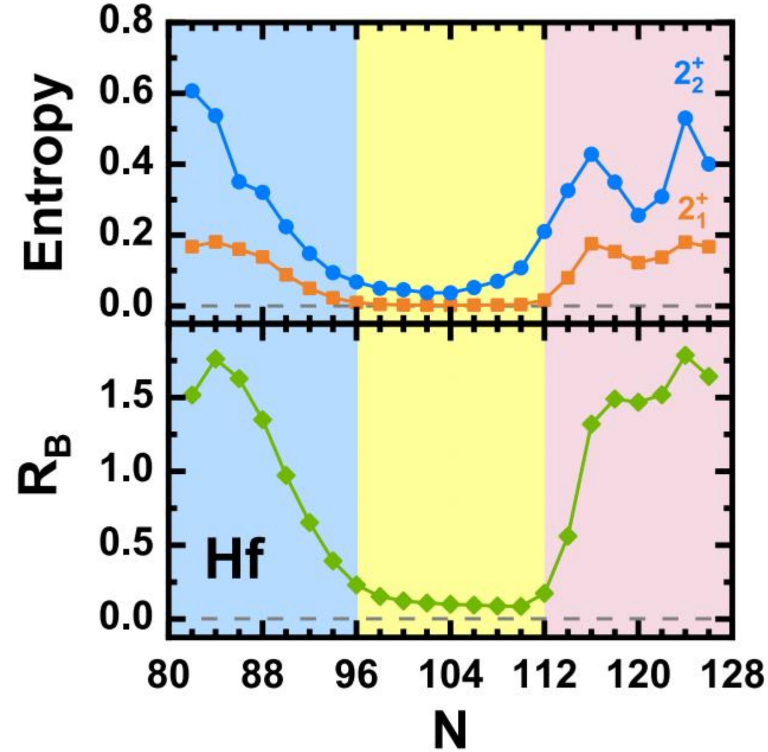
Y. M. Wang, J. Y. Lin, and Q. B. Chen, PRC 113, 044305 (2026)

Shape and Entropy Evolution in the Hf Isotopic Chain

- **Entropy response:**
  decreasing → vanishing → resurgence



- **R_B serves as an experimental probe of entropy-encoded structure**



R_B=B(E2,2_2 to 2_1)/B(E2, 2_1 to 0_1):
=0, rigid axially symmetric rotor;
=10/7, γ-soft rotor;
=2, spherical vibrator.

Y. M. Wang, J. Y. Lin, and Q. B. Chen, PRC 113, 044305 (2026)

Summary

- ✓ Reveal the deformation-type dependence of shape-rotation entanglement in low-lying states
- ✓ Propose entanglement entropy as a novel signature of shape evolution and establish its connection with experimental observables

Thank you!