High-$K$ isomers as probes of octupole collectivity in heavy nuclei

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Isomeric states in regions of octupole collectivity and in neutron-rich nuclei
1. Aim of the study

2. Theoretical framework
   - Reflection Asymmetric Deformed Shell Model
   - Pairing Interaction (BCS)
   - Two-quasiparticle configurations and magnetic moments

3. Numerical Results

4. Conclusion
Octupole deformation and isomeric states

- **Nuclear octupole degrees of freedom** → coupling of s.p. orbitals with different parity near the Fermi level ⇒ appearance of reflection asymmetric nuclear shapes ⇒ effects on nuclear excitations and electromagnetic transitions

- **High-$K$ isomeric states broken nucleon pairs** → two- or multi-quasiparticle excitations in even-even nuclei → coupled s.p. orbitals ⇒ appearance of isomeric states

- **Purpose:** Examine the influence of the quadrupole-octupole deformation on the forming and structure of high-$K$ isomeric states in even-even actinide nuclei; examine the effects on nuclear magnetic moments
Aim of the study

Theoretical framework

Numerical Results

Conclusion

Reflection Asymmetric Deformed Shell Model

Axially Deformed Woods-Saxon Potential

\[ H_{sp} = T + V_{ws} + V_{s.o.} + V_c \]

\[ V_{ws}(r, \hat{\beta}) = V_0 \left[ 1 + \exp \left( \frac{\text{dist}_\Sigma(r, \hat{\beta})}{a} \right) \right]^{-1} \]

\[ R(\theta, \hat{\beta}) = c(\hat{\beta}) R_0 \left[ 1 + \sum_{\lambda=2,3,\ldots} \beta_\lambda Y_{\lambda 0} (\cos \theta) \right], \quad \hat{\beta} \equiv (\beta_2, \beta_3, \beta_4, \beta_5, \beta_6) \]

[S. Cwiok et al., Comp. Phys. Comm. 46, 379 (1987)]
Reflection Asymmetric Deformed Shell Model

**Axially deformed harmonic-oscillator (ADHO) basis**

Diagonalization in axially deformed harmonic-oscillator (ADHO) basis $|N n_z \Lambda \Omega \rangle$

$$\Rightarrow \mathcal{F}_\Omega = \sum_{N n_z \Lambda} C_{N n_z} |N n_z \Lambda \Omega \rangle \quad (K = \Omega = \Lambda + \Sigma)$$

$$\hat{\pi}_{sp} |N n_z \Lambda \Omega \rangle = (-1)^N |N n_z \Lambda \Omega \rangle \quad \pi_{sp} = (-1)^N$$

$\beta_3 = 0 \Rightarrow N = \text{even} (\pi_{sp} = +)$ or $N = \text{odd} (\pi_{sp} = -)$

$\beta_3 \neq 0 \Rightarrow N = \text{even}$ and $N = \text{odd} \Rightarrow \text{parity mixed s.p. states}$

$\Rightarrow \text{expectation (average) value of the parity operator}$

$$\langle \hat{\pi}_{sp} \rangle = \langle \mathcal{F}_\Omega | \hat{\pi}_{sp} | \mathcal{F}_\Omega \rangle$$

$$= \sum_{N n_z \Lambda} (-1)^N |C_{N n_z \Lambda}^\Omega|^2$$
Gap equation

\[ \Delta = G \sum_k u_k v_k, \quad 2 \sum_k v_k^2 = N \]

\[ v_k^2 = \frac{1}{2} \left( 1 - \frac{\epsilon_k - \lambda}{\sqrt{\epsilon_k - \lambda}^2 + \Delta^2} \right), \quad u_k^2 = \frac{1}{2} \left( 1 + \frac{\epsilon_k - \lambda}{\sqrt{\epsilon_k - \lambda}^2 + \Delta^2} \right) \]

\[ \sum_k \frac{1}{\sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}} = \frac{2}{G}, \quad \sum_k \left( 1 - \frac{\epsilon_k - \lambda}{\sqrt{\epsilon_k - \lambda}^2 + \Delta^2} \right) = N \]

\[ G_{n/p} = \left( g_0 \mp g_1 \frac{N - Z}{A} \right) / A, \quad g_0 = 17.8 \text{ MeV}, \quad g_1 = 7.4 \text{ MeV} \]

included orbitals: \((15\, N)^{1/2}\) (neutrons), \((15\, Z)^{1/2}\) (protons) below and above the Fermi surface
Two-quasiparticle energies

One-quasiparticle energy:

\[ E_{1qp}^{\Omega \pi} = \sqrt{(E_{sp}^{\Omega \pi} - \lambda)^2 + \Delta^2} \]

Two-quasiparticle energy:

\[ E_{2qp}^{K \pi} = E_{1qp}^{\Omega_1 \pi_1} + E_{1qp}^{\Omega_2 \pi_2} \]

\[ K = \Omega_1 + \Omega_2 \]

\[ \pi = \pi_1 \cdot \pi_2, \text{ for } \beta_3 = 0 \]

\[ \pi = \text{sign}\langle \pi_1 \rangle \cdot \text{sign}\langle \pi_2 \rangle, \text{ for } \beta_3 \neq 0 \]
Two-quasiparticle configurations and magnetic moments

**Magnetic moment in the two-quasiparticle configuration**

\[
\mu = \mu_N \left[ g_R \frac{I(I+1) - K^2}{I+1} + g_K \frac{K^2}{I+1} \right]
\]

\[
\mu_N = \frac{e\hbar}{2mc}, \quad g_R = \frac{Z}{A}
\]

\[
g_K = \frac{1}{K} \sum_{n=1,2} \langle F_{\Omega_n} | g_s \cdot \Sigma + g_l \cdot \Lambda | F_{\Omega_n} \rangle
\]

\[
\Sigma = \Omega \mp \Lambda \rightarrow \text{the intrinsic spin projection}
\]

\[
g_l, g_s \rightarrow \text{gyromagnetic ratios} \quad (g_s = 0.6g_s^{\text{free}})
\]
Application of the Deformed Shell Model (DSM) + BCS approach

- **Test of the approach** → reproduction of a well known two-quasiparticle isomeric state through the quadrupole-octupole deformation → $K^\pi = 6^-$

  \[ \{ \nu 5/2[633] \otimes \nu 7/2[743] \} \text{ in } ^{234}\text{U} \]

- **Identification of new isomeric states** by examining the quadrupole and octupole deformations in the DSM+BCS approach; application of extended calculations on a $(\beta_2, \beta_3)$ net → $K^\pi = 8^-$ \[ \{ \nu 7/2[624] \otimes \nu 9/2[734] \} \text{ state in } ^{244}\text{Pu} \]

- **Further examples**: $K^\pi = 8^-$ \[ \{ \nu 7/2[624] \otimes \nu 9/2[734] \} \text{ state in } ^{252}\text{No}; \]

$K^\pi = 6^+, \{ \nu 5/2[622] \otimes \nu 7/2[624] \} \text{ configuration in } ^{244}\text{Cm}$
Neutron s.p. levels in $^{234}$U ($\{\nu5/2[633] \otimes \nu7/2[743]\}$ configuration)
Neutron s.p. levels in $^{244}\text{Pu}$ ($\{\nu 7/2[624] \otimes \nu 9/2[734]\}$ configuration)

$\beta_2 = 0.293$

$\beta_3$

s.p. energy (MeV)
Two-quasiparticle energy of the $K^\pi = 8^-$, $\nu7/2[624] \otimes \nu9/2[734]$, state in $^{244}Pu$
Magnetic moment in the $K^\pi = 8^-$, $\{\nu 7/2[624] \otimes \nu 9/2[734]\}$, state of $^{244}Pu$
Magnetic moment in the $K^\pi = 8^-$, $\{\nu 7/2[624] \otimes \nu 9/2[734]\}$, state of $^{244}\text{Pu}$
Magnetic moments in the $K^\pi = 6^+$ state of $^{244}\text{Cm}$ and $K^\pi = 6^-$ state in $^{234}\text{U}$
The octupole deformation plays a considerable role in the forming of two-quasiparticle high-K isomeric states in heavy actinide nuclei.

A pronounced sensitivity of the magnetic moments to the octupole deformation is found, future measurements of the dipole moments would provide useful constraints on the degree of octupole deformation (a variety of experimental techniques would appear to be open to exploitation).

An extended study of a wider range of heavy deformed nuclei would provide a systematic information about the influence of the quadrupole-octupole deformations on the formation of high-K isomeric states, further realistic estimations of the two-quasiparticle energies and the electromagnetic de-excitation probabilities.