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Rotational co-existence in selenium isotopes

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Abstract. High spin states of ^{72,73,74}Se nuclei are discussed using calculations from the cranked Nilsson Strutinsky method with tuning to fixed spins. The low spin anomaly in the yrast bands of these nuclei is interpreted in a rotational co-existence picture. High K rotational isomers are proposed for I^{π} = 4^{+} in ^{72}Se and 6^{+} in ^{74}Se.

Keywords. Rotational co-existence; Se isotopes; CNSM; K-isomers.

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1. Introduction

Rotational co-existence can be defined as the situation in which a nucleus having the same spin and shape but with axis of rotation coinciding with or perpendicular to the axis of symmetry. Nuclei exhibiting such property may give rise to rotational isomers (or K-isomers). Large non-axial fluctuations can carry such nuclei from axially symmetric prolate or oblate shapes with $K = I$ to the same shapes with $K = 0$, penetrating a barrier in the $\beta - \gamma$ space [1]. Such a mechanism is referred to as γ-tunneling, which may give rise to high K-isomers. The main aim of this work is to construct the potential energy surfaces of the selenium isotopes, ^{72,73,74}Se at various spins to look for the occurrence of rotational co-existence. This is done using the cranked Nilsson Strutinsky method (CNSM) with tuning to fixed spins [2]. The effectiveness of the CNSM in interpreting the spectra of nuclei at high spins and in predicting the occurrence of such rotational isomers has been explicitly discussed in [1,3,4]. In this paper we will focus on the theoretical study of the competition between aligned and collective configurations and look at overall trends within the yrast bands of ^{72,73,74}Se. Irregularities observed along the yrast positive parity bands of ^{70,72,74}Se nuclei are well known and have been so far interpreted in a shape co-existence picture [5]. Besides a varying collectivity reflected by the $B(E2)$ values, they exhibit pronounced single-particle and shell effects [6]. Experimental studies have been recently pursued at the Nuclear Science Centre, New Delhi to obtain the high spin states of these nuclei [7].

2. Theoretical framework

The shell energy calculation for non-rotating case $(I = 0)$ assumes a triaxial Nilsson single particle field [2].

The Strutinsky shell correction method is adapted to $I \neq 0$ case by suitably tuning the angular velocities to yield fixed spins. For unsmoothened single particle level distribution we have

$$I = \int_{-\infty}^{\lambda} g_2 \mathrm{d}e^{\omega} = \sum_i \langle m_i \rangle \tag{1}$$

and

$$E_{\mathrm{sp}} = \int_{-\infty}^{\lambda} g_1 e^{\omega} \mathrm{d}e^{\omega} + \hbar\omega I = \sum_i e_i^{\omega} + \hbar\omega I, \tag{2}$$

where m_is are the spin projections and e_i^{ω}s are the single particle energies of the cranked Nilsson Hamiltonian.

For the Strutinsky smeared single particle level distribution, (1) and (2) transform into

$$\widetilde{I} = \int_{-\infty}^{\lambda} \widetilde{g_2} \mathrm{d}e^{\omega} = \sum_i \langle \widetilde{m_i} \rangle \tag{3}$$

and

$$\widetilde{E}_{\mathrm{SP}} = \int_{-\infty}^{\lambda} \widetilde{g_1} e^{\omega} \mathrm{d}e^{\omega} + \hbar\omega \widetilde{I} = \sum_i \widetilde{e_i^{\omega}} + \hbar\omega \widetilde{I}. \tag{4}$$

In the tuning method we have adapted [2], the total spin is calculated as

$$I = \widetilde{I}_z = \sum_{\nu=1}^{N} \left\langle \widetilde{j}_z \right\rangle_{\nu}^{\omega} + \sum_{\pi=1}^{Z} \left\langle \widetilde{j}_z \right\rangle_{\pi}^{\omega}. \tag{5}$$

The above relation allows us to select numerically the ω values that correspond to the chosen integer or half integer spins. Obviously the corresponding frequency values $\omega\,(I)$ change from one deformation point to another and the corresponding calculation have to be repeated accordingly.

The total energy is given by

$$E_{\mathrm{TOT}} = E_{\mathrm{RLDM}} + (E_{\mathrm{SP}} - \widetilde{E}_{\mathrm{SP}}) \tag{6}$$

where the rotating liquid drop energy at constant spin

$$E_{\mathrm{RLDM}} = E_{\mathrm{LDM}} - \frac{1}{2}\Im_{\mathrm{rig}}\omega^2 + \hbar\omega\widetilde{I}. \tag{7}$$

Here the liquid drop energy E_{LDM} is given by the sum of Coulomb and surface energies and $\Im_{\mathrm{rig}}$, the rigid body moment of inertia defined by β and γ including the surface diffuseness correction.

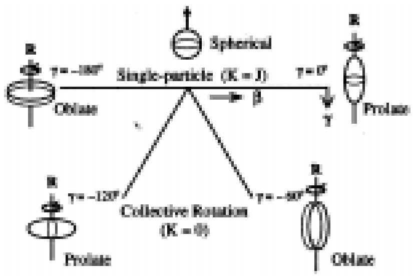

Figure 1. The relation between shape of nuclei rotating around the z-axis and various values of deformation parameter γ.

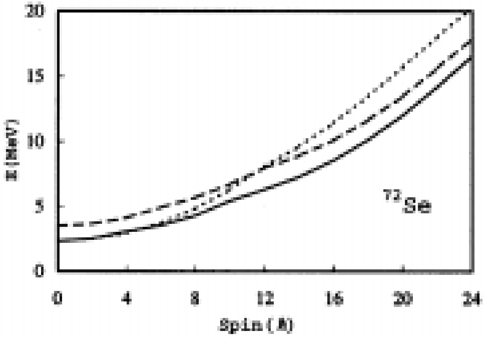

Figure 2.

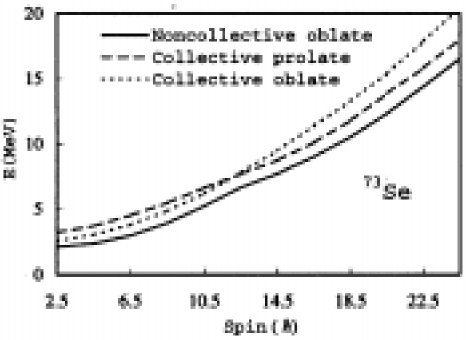

Figure 3.

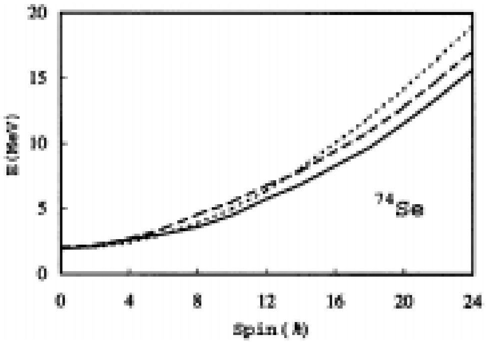

Figure 4.

Figures 2–4. Energy vs. spin plots for the nuclei ^{72,73,74}Se.

The resulting energies are normalized according to the Strutinsky prescription and then the minimum at fixed spin over different deformations is searched for.

3. Details of calculations

The calculations are carried out by varying ω values in steps of 0.02 ω_0 from $\omega = 0$ to $\omega = 0.16\omega_0$, ω_0 being the oscillator frequency. Since we are interested in non-collective oblate ($\gamma = -180°$), collective prolate ($\gamma = -120°$) and collective oblate ($\gamma = -60°$)

shapes, γ is varied from -180° to -60° in steps of 10°. The β values are varied from β = 0.0 to β = 1 in steps of 0.1. The κ and μ values are taken as the same for all the shells and are given below as

κ(P) = 0.068, μ(P) = 0.48
κ(N) = 0.071, μ(N) = 0.36.

In these first calculations pairing has been omitted.

4. Rotational co-existence in ^{72,73,74}Se nuclei

Within a given axially deformed nucleus, we define the term ‘rotational isomers’ as two (or more) states of the same spin and similar gross shape but with the spin vector in different directions [3]. In this work, only oblate isomers have been proposed. These correspond to collective rotation with the spin vector perpendicular to the symmetry axis and to aligned coupling along the symmetry axis. The aligned isomers, often referred to as ‘rotating around the symmetry axis’ need not possess a long lifetime (e.g., nano-seconds or longer). The γ-tunneling framework provides a natural explanation for the rotational co-existence. The γ-tunneling path is assumed to be the path of steepest ascent to the saddle point and steepest descent from the saddle point. In order to detect the rotational co-existence and to pin point the spins at which it occurs, energy vs. spin plots are constructed for the nuclei ^{72,73,74}Se, which are shown in figures 2, 3 and 4 respectively. The potential energy surfaces for all the three nuclei are found to be looking very similar at fixed spins. The ground state shapes of these nuclei are clearly oblate with $\beta \approx 0.2$, which is preserved to high spins up to 24$\hbar$. The yrast state is found to be non-collective oblate. The γ-softness of these nuclei is clearly observed. Competing minima are found to occur along non-collective oblate, collective oblate and collective prolate lines. At lower spins, the competition between the non-collective oblate and collective oblate states is significant which may cause rotational isomers. In the case of ^{72,74}Se nuclei, one interesting feature we observe is that at a spin of 4$\hbar$ and 6$\hbar$ respectively, the collective oblate and non-collective shapes coexist. This can be clearly seen in figures 2 and 4. Thus there is a strong indication of the existence of rotational isomers at the spin of 4$\hbar$ where the competition between the collective and single particle states occurs. Such a crossing-over of non-collective and collective oblate lines is not observed in the case of ^{73}Se, which has an odd number of neutrons.

5. Conclusion

It is thus to be concluded that the ^{72,74}Se isotopes are good candidates to look for rotational coexistence and K-isomers.

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