Study of shape evolution and isovector dipole strength distribution of thorium isotopes

E. Ummukulsu [1],[2]* and Antony Joseph[1]
[1] *Department of Physics, University of Calicut, Thenhipalam, 673636 and*
[2] *Department of Physics, Farook College, Kozhikode*

Introduction

An atomic nucleus is primarily characterized by its shape, with the most commonly encountered ones being spherical, prolate, and oblate. Investigating nuclear rotations and the occurrence of shape phase transitions in nuclei has proven to be a highly sensitive approach for exploring nuclear structure. The collective motion of nucleons leads to various phenomena, including nuclear deformation, rotational and vibrational motions, giant resonances etc. It yields extensive information on nuclear structure, nuclear reactions and features of nuclear matter.

Giant resonance is the prime example of collective oscillation of nucleons. If protons and neutrons are oscillating out of phase it is termed as the isovector mode. In Giant dipole resonance, the collective oscillation of protons is relative to the oscillation of neutrons and creates the dipole mode. To study the GDR of nuclei, the most commonly used one is the quasiparticle random phase approximation (QRPA) technique.

Theoretical formalism

The self-consistent mean-field theory is a powerful approach that allows us to trace the development of quadrupole shapes within nuclei. The energy density functional provides precise details of the structural characteristics of nuclei, ranging from light to heavy, extending from the proton drip line to the neutron drip line. The deformations of quadrupole shapes can be described by using the polar coordinates β_2 and γ, which are connected to the quadrupole moments Q_{20} and Q_{22} as,

$$\beta_2 = \sqrt{\frac{5\pi}{9}}\frac{Q_{20}}{AR_0^2} \tag{1}$$

and

$$\gamma = arctan(\frac{Q_{22}}{Q_{20}}) \tag{2}$$

The transition strength function $S(f,\omega)$ is defined as,

$$S(f,\omega) = \sum_{\mu<\nu} F^{20*}_{\mu\nu}(\omega)X_{\mu\nu}(\omega)+F^{02*}_{\mu\nu}(\omega)Y_{\mu\nu}(\omega) \tag{3}$$

and the response function is,

$$\frac{dB}{d\omega} = -\frac{1}{\pi}ImS(f,\omega) \tag{4}$$

where B is strength distribution.

Results and Discussion

We have studied the shape evolution and isovector dipole strength distribution of thorium isotopes, spanning from ^{204}Th to ^{240}Th. We performed calculations to determine the total binding energy of thorium nuclei, varying with the deformation parameter β_2 . In the present calculation, we have employed the relativistic density dependent point-coupling (DD-PC1) functional [2].

The resulting binding energy curves are presented in FIG 1. These energies were scaled or normalized with respect to the binding energy of the lowest-energy state. The binding energy curve spans a range of β_2 values from -0.4 to 0.4. The minima observed in the binding energy curves for each isotope offer valuable insights into the shapes of the corresponding isotope [1].

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*Electronic address: `ummukulsu.e@uoc.ac.in`

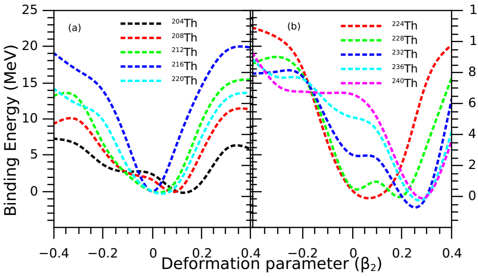

FIG. 1: The binding energy of thorium nuclei $^{204-240}Th$, varying with the deformation parameter β_2

Notably, ^{204}Th exhibits higher deformation compared to ^{208}Th, as evidenced by the binding energy minimum being considerably distant from zero. For ^{212}Th and ^{220}Th, the binding energy curves show broad minima around zero, suggesting a transitional shape that lies between prolate and spherical configurations. The distribution of binding energy for ^{216}Th is centered around zero, indicating a shape closer to being spherical. Likewise, ^{224}Th displays wide minima around zero in its binding energy curve, suggesting a potential transitional shape. This observation implies that ^{224}Th may be in a transitional state between different nuclear shapes.

The isovector dipole strength distribution of thorium isotopes also estimated and plotted in FIG 2. Here, the finite amplitude method for the relativistic quasiparticle random phase approximation is incorporated into the stationary relativistic Hartree-Bogoliubov equation. The quasiparticle random phase approximation technique is used here to study the collective vibrations of thorium nuclei. In GDR, a dual component structure is observed in deformed nuclei, and this splitting arise from the distinct frequencies of oscillation along the major and minor axes of deformation. In axially deformed thorium nuclei, the isovector giant dipole resonance display two components with K=0,1, where K is the projection of total angular momentum J=1 on the symmetry axis. There is no energy separation between the two modes of oscillation in ^{216}Th due to their spherical symmetry.

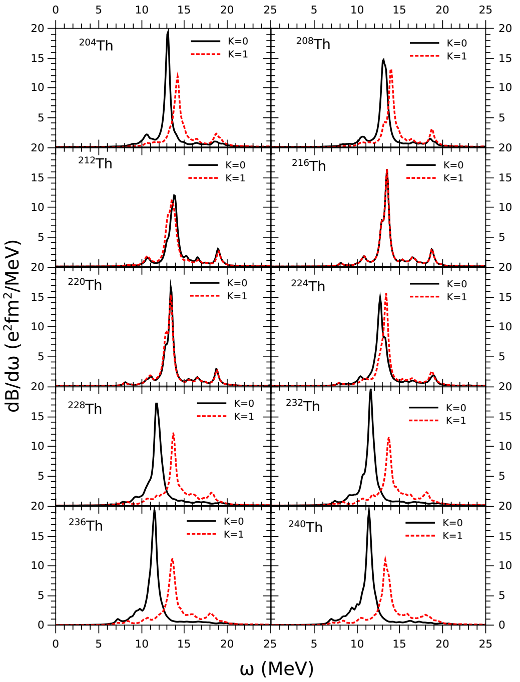

FIG. 2: The isovector dipole strength distribution of thorium isotopes, two components with K=0,1.

Conclusion

There is no energy separation between the two modes of oscillation in ^{216}Th due to their spherical symmetry. This study confirm the possibility of having shell closure and extra stability of nuclei. The dual component structure is observed in deformed nuclei, and this splitting arise from the distinct frequencies of oscillation along the major and minor axes of deformation.

References

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