The Bioscan
AN INTERNATIONAL QUARTERLY JOURNAL OF LIFE SCIENCES
18(3): 227-232, 2023 www.thebioscan.com

ANALYSIS OF SHAPE-PHASE VARIATIONS AND FLUCTUATIONS IN HEATED FAST ROTATING EVEN-EVEN TRANSITIONAL NUCLEI WITH N~ 84

[1]SANTHANA PRIYA R and [2*]SELVAM V

[1](Reg. No: 19221172132018) Research Scholar, PG & Research Department of Physics, Rani Anna Government College for Women, Tirunelveli – 627 008, Affiliated to Manonmaniam Sundaranar University, Tirunelveli-627 012, Tamil Nadu, India.

[2*] PG & Research Department of Physics, Rani Anna Government College for Women, Tirunelveli – 627 008, Tamil Nadu, India.

[2*]Corresponding Author: **Selvam V**

E-mail: vselvamdr@gmail.com

DOI: 10.63001/tbs.2023.v18.i03.pp227-232

KEYWORDS
Structural transitions of nuclei, thermal fluctuations, Landau theory of phase transitions, cranked Nillsson - Strutinsky method.

Received on: 28-07-2023

Accepted on: 30-08-2023

Published on: 07-10-2023

ABSTRACT

Employing the Landau theory of phase transitions, which has been extended to encompass higher orders of deformation, we examine the shape evolution of Neodymium isotopes, specifically ^{144}Nd and ^{146}Nd, in relation to temperature and spin. The expansion of the free energy up to sixth power in β is used in these calculations. The spin dependence is introduced by additional constants which are obtained by fitting with the temperature-dependent moment of inertia. Thermal fluctuations are included in the usual way. Pairing is included in the study in an indirect way by solving the coupled equations. We show that in the presence of thermal fluctuations, the average shapes differ from the most probable shapes.

INTRODUCTION

The possibility of heating a nucleus to a finite temperature opens a new direction in the study of nuclear structure. The experimental analysis of giant dipole resonance (GDR) built on excited states have started to yield information about the shape transitions that takes place in such nuclei. This is also well known now that GDR cross section curves are not that clear as we expect in rotating nuclei, because in hot rotating nuclei, thermal fluctuations may make the GDR curves a little complicated to interpret. Due to the finite number of degrees of freedom it is necessary to include thermal shape fluctuations in order to obtain good fits to experimental observables such as the giant dipole resonance built on hot nuclei. The main theoretical methods used to describe hot nuclei are taken from statistical mechanics. The Landau theory [1] offers a natural frame work in which these fluctuations are introduced.

Many of the earlier calculations used the Landau theory in limited form with expansion of the free energy upto fourth power of β for the study of shape transitions in hot rotating light and medium mass nuclei [2,3]. The quality of Landau theory applied to medium and heavy mass nuclei when the free energy is expanded up to fourth power of β is not as good for lower temperatures and higher spins [4]. Hence in heavy nuclei, at medium temperatures (T ≤ 1.5 MeV), it is necessary to extend the Landau free energy upto sixth order of β and temperature and spin dependent moment of inertia must be used in the calculations. This is done by expanding the temperature dependent moment of inertia up to fourth power in β and extracting the constants involved by a least square fit procedure. In order to obtain the constants involved in the non-rotating component of the free energy expansion, the potential energy surface obtained by the cranked Nilsson - Strutinsky procedure is used. Pairing is used in the formalism through the gap parameters which determine the temperature-dependent moment of inertia. We have applied this extended form of Landau theory to study the shape evolutions of hot rotating transitional nuclei, especially for the isotopes of Neodymium such as ^{144}Nd and ^{146}Nd.

This paper is organized as follows. Section I is introductory.

Section II deals with the theoretical framework used in the study. The results of the present work are given in Sec. III. Finally the last section ends with a summary and conclusion.

II. DETAILS OF CALCULATION

The free energy $F(T,\beta,\gamma)$ at a given temperature *T* and quadrupole deformation β and γ is expanded (up to sixth order in β) as [5,6]

$$F(T,\beta,\gamma)=F_0+F_2\beta^2+F_3\beta^3\cos 3\gamma+F_4\beta^4+F_5\beta^5\cos 3\gamma+F_6^{(1)}\beta^6+F_6^{(2)}\beta^6\cos^2 3\gamma+....(1)$$

Here F_0, F_2,… are the temperature dependent Landau parameters. These expansion coefficients are determined by least square fit to the Strutinsky calculation results in the considered nuclei. Then the angular momentum is brought in within the cranking approach. Up to second order in cranking frequency ω the free energy is given by.,

$$F(T,\omega;\beta,\gamma)=F(T,\omega=0;\beta,\gamma)-\frac{1}{2}J_{zz}(T,\beta,\gamma)\omega^2 \qquad (2)$$

where the temperature dependent moment of inertia with respect to the body fixed z axis is given by [4]

$$J_{zz}(T,\beta,\gamma)=J_0+J_1\beta\cos\gamma+J_2^{(1)}\beta^2+J_2^{(3)}\beta^2\sin^2\gamma+J_3^{(1)}\beta^3\cos 3\gamma+J_3^{(2)}\beta^3\cos\gamma+J_4^{(1)}\beta^4+J_4^{(2)}\beta^4\cos 3\gamma\cos\gamma+J_4^{(3)}\beta^4\sin^2\gamma \qquad (3)$$

The parameters J_0, J_1,… are also determined by a fitting procedure. Expression (2) above gives the free energy for fixed ω. For fixed spin this can be Legendre transformed [9] as

$$F(T,I;\beta,\gamma)=F(T,I=0;\beta,\gamma)+\frac{I^2}{[2J_{zz}(T,\beta,\gamma)]} \qquad (4)$$

To include thermal fluctuations in our calculations we proceed as follows. The probability for a given shape to occur is [7]

$$P(\beta,\gamma,I,T)\propto\exp[-\frac{F(\beta,\gamma,I,T)}{T}] \qquad (5)$$

For a given spin and temperature, consider an ensemble of nuclei with this distribution of deformations. The ensemble average of β and γ are

$$\bar\beta=\langle\beta\rangle=\frac{\int\beta P(\beta,\gamma)\beta^4\,|\sin 3\gamma|\,d\beta d\gamma}{\int P(\beta,\gamma)\beta^4\,|\sin 3\gamma|\,d\beta d\gamma} \qquad (6)$$

Similarly, the ensemble average of γ is,

$$\bar\gamma=\langle\gamma\rangle=\frac{\int\gamma P(\beta,\gamma)\beta^4\,|\sin 3\gamma|\,d\beta d\gamma}{\int P(\beta,\gamma)\beta^4\,|\sin 3\gamma|\,d\beta d\gamma} \qquad (7)$$

where $\beta^4\,|\sin 3\gamma|\,d\beta d\gamma$ is the volume element as given in the Bohr rotation-vibration model.

Equation (5) shows that when the temperature is zero, there are no thermal shape fluctuations. Then the averaged shape is identical to the most probable shape. But at finite temperature, the averaged shape may be different from the most probable shape.

For extracting the constants in the nonrotating component of the free energy we used the Strutinsky expression,

$$F(T,I;\beta,\gamma)=E(T,I;\beta,\gamma)-TS-\tilde{E}(T=0,I;\beta,\gamma)+E_{RLDM} \qquad (8)$$

Where E_S is the Strutinsky smoothed energy for extracting shell correction and E_{RLDM} is the rotating liquid drop energy given by

$$E_{RLDM}=E_{LDM}-\frac{1}{2}J_{rig}\omega^2+\hbar\omega\tilde{I} \qquad (9)$$

Here the liquid drop energy E_{LDM} is given by the sum of Coulomb and surface energies, J_{rig} the rigid body moment of inertia defined by β and γ including the surface diffuseness correction, and $\tilde{I}$ is the Strutinsky smoothed spin. In the above expression the calculation of Strutinsky smoothed energy can be extended to finite temperature [8], but it is a good approximation to take the ground state Strutinsky smoothed energy for extracting the shell correction in the formalism.

In order to obtain the temperature-dependent moment of inertia we follow the following approximate procedure [9,10]. The temperature dependent moment of inertia is given by

$$J(A,\beta;T)=J_{rig}(A,\beta)\left[1-g\left(\frac{\beta\hbar\omega_0}{2\Delta(T,I)}\right)\right](10)$$

where., $$g(x)=\frac{\ln\left[x\sqrt{1+x^2}\right]}{x\sqrt{1+x^2}}$$

The above expression has to be considered for neutrons and protons separately. The gap parameter $\Delta(T,I)$ occurring in the expression is obtained by solving the temperature dependent coupled equations within the BCS formalism [11]. The quasiparticle energies E_μ and the occupation numbers u_μ and v_μ are defined as usual in the BCS theory as

$$E_\mu=\left[\left(\varepsilon_\mu-\lambda\right)^2+\Delta^2\right]^{1/2},$$

$$u_\mu=\left\{\frac{1}{2}\left[1+\left(\varepsilon_\mu-\lambda\right)/E_\mu\right]\right\}^{1/2} \qquad (11)$$

and

$$v_\mu^{\,2}=1-u_\mu^{\,2}$$

The temperature-dependent gap equation is

$$2/G=\sum_\mu\frac{\tanh\left(E_\mu/2T\right)}{E_\mu} \qquad (12)$$

and the conservation condition for the particle number N is given by

$$N=\sum_\mu\left\{\left[1-\left(\varepsilon_\mu-\lambda\right)/E_\mu\right]\tanh\left(E_\mu/2T\right)\right\} \qquad (13)$$

The values used for the pairing strengths G_p and G_n in our calculations are

$G_p = 17/A$ and $G_n = 23/A$

The spin dependence of the moment of inertia comes through $\Delta(T,I)$ evaluated using the cranked single particle energies. We have used the complete form of the Landau theory to study the shape-phase variations including thermal fluctuations.

III. RESULTS AND DISCUSSION

In this study, we have endeavored to investigate the shape evolutions of hot rotating Neodymium isotopes by employing the extended Landau model that incorporates thermal fluctuations. The Landau constants are determined through least square fitting of the free energy surfaces derived from the finite temperature variant of the cranked Nilsson Strutinsky method. The results illustrating shape transitions as a function of spin at temperatures of 0.25, 0.5, 1.0, 2.0, and 2.5 MeV, respectively, with thermal fluctuations using the extended Landau model for the isotopes ^{144}Nd and ^{146}Nd are presented in the figures. It is observed from the figures that for ^{144}Nd nuclei at T = 0.25 MeV, a shape transition occurs from a triaxial nearly prolate configuration to a nearly oblate one as the spin increases, subsequently transitioning to a more triaxial shape at higher spins. During this transition, the deformation intensifies with increasing spin. A similar trend, albeit with greater deformations, is noted as a function of spin at the other temperatures for the same isotopes. For the ^{146}Nd nuclei at T = 0.25 MeV and at I = 20 ħ, a triaxial shape that is closer to prolate becomes distinctly triaxial at higher spins. This trend, characterized by elongated deformations, is also observed at higher temperatures. It is noteworthy from these figures that sharp shape transitions are not evident in the presence of thermal fluctuations, thereby substantiating the notion that averaging over all possible shapes consistently results in a triaxial configuration.

IV. SUMMARY AND CONCLUSION

Any research that involves hot rotating nuclei must take thermal fluctuations into account. In this context, we have applied the Landau theory of phase transitions to investigate the shape evolution of hot rotating Neodymium isotopes while considering thermal fluctuations. The free energy is expanded to the sixth order in β, and the temperature-dependent moment of inertia is expanded to the fourth power in β. All constants involved are determined through least square fitting, and these constants allow us to derive the resulting shape transitions in the nuclei under consideration. We demonstrate that the distinct shape transitions evolve into a triaxial configuration as a function of spin influenced by thermal fluctuations. At lower spin values, a nearly prolate shape is observed, which is particularly significant in this study. This study thus provides extensive information regarding the shape transitions and fluctuations of Neodymium isotopes as a function of rotation and internal excitation. In conclusion, it should be noted that the Landau theory of phase transitions is highly effective for examining shape changes in hot rotating nuclei with N approximately equal to 84.

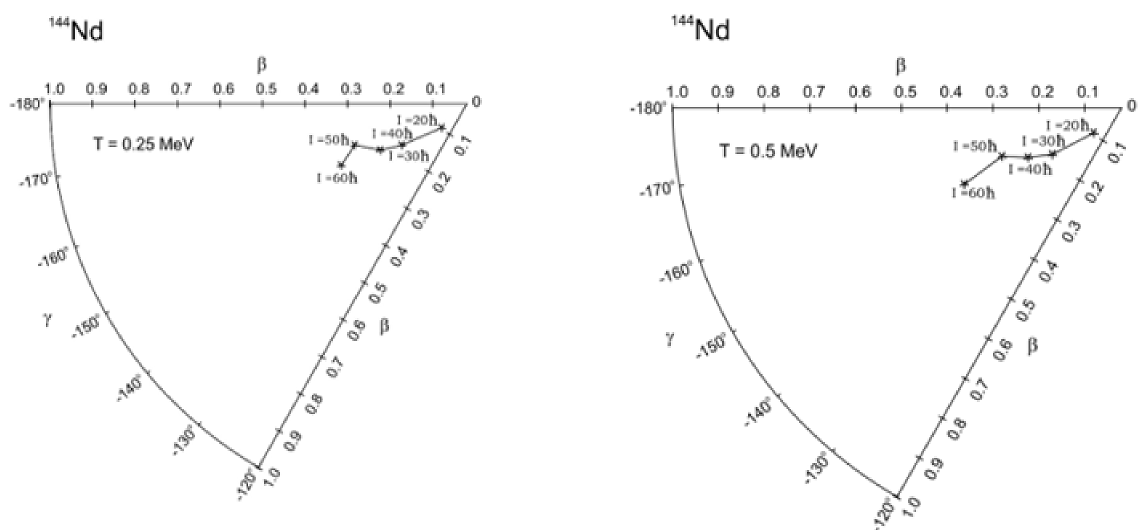

Fig. 3.1 Shape variations in ^{144}Nd as a function of spin for temperatures T=0.25 MeV and T=0.5 MeV

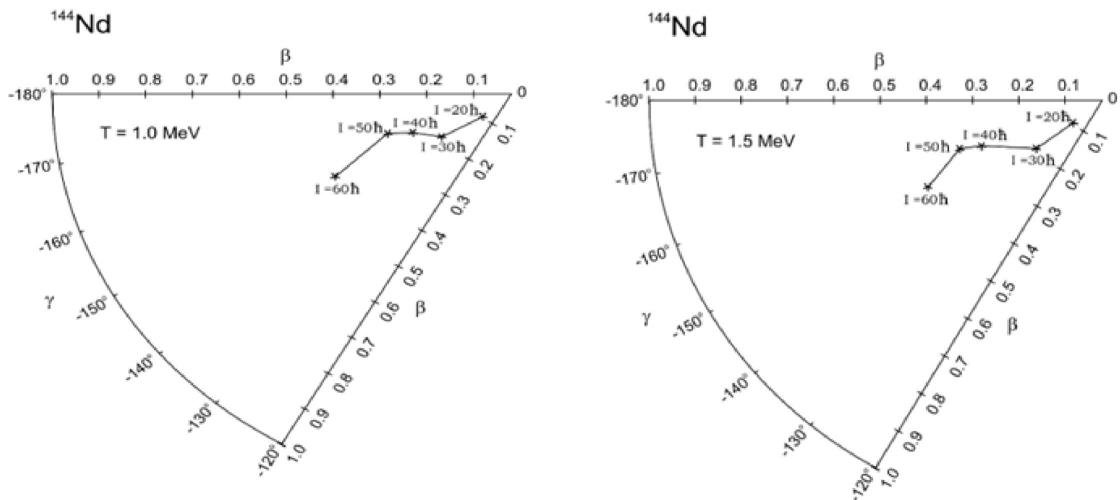

Fig. 3.2 Shape variations in ^{144}Nd as a function of spin for temperatures T=1.0 MeV and T=1.5 MeV

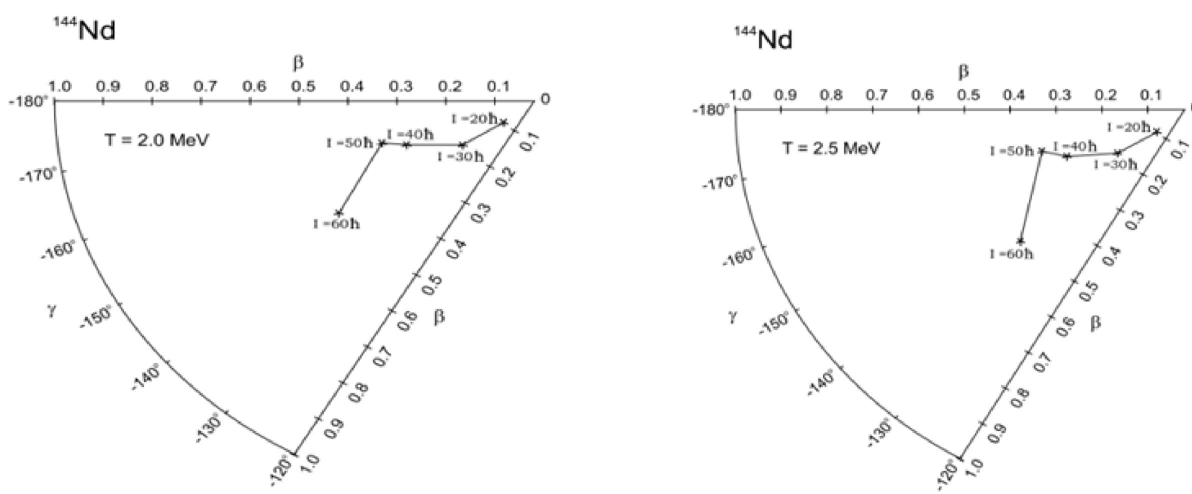

Fig. 3.3 Shape variations in ^{144}Nd as a function of spin for temperatures T=2.0 MeV and T=2.5 MeV

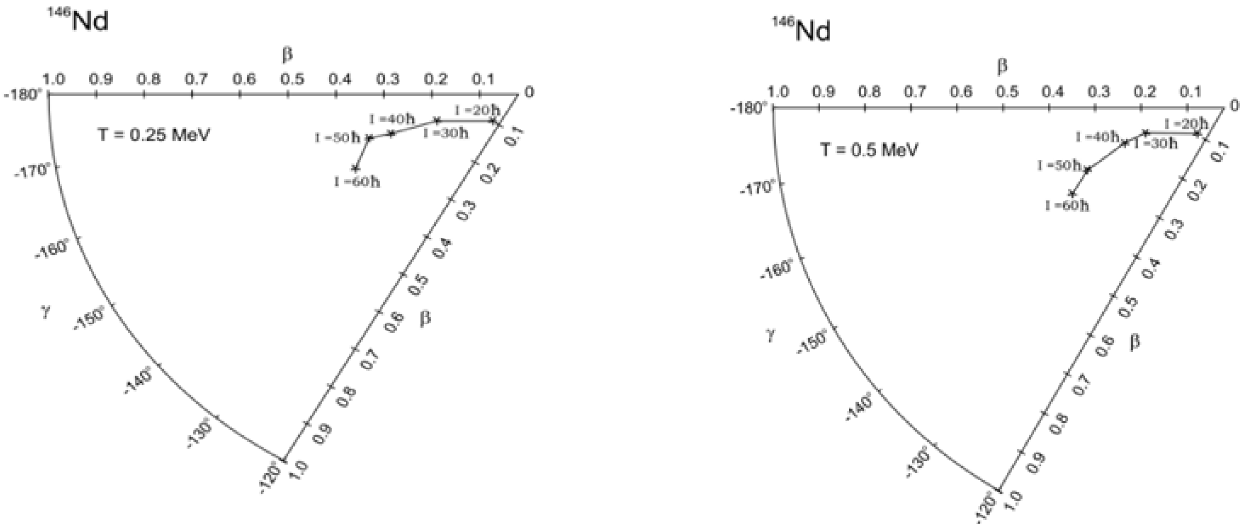

Fig. 3.4 Shape variations in ^{146}Nd as a function of spin for temperatures T=0.25 MeV and T=0.5 MeV

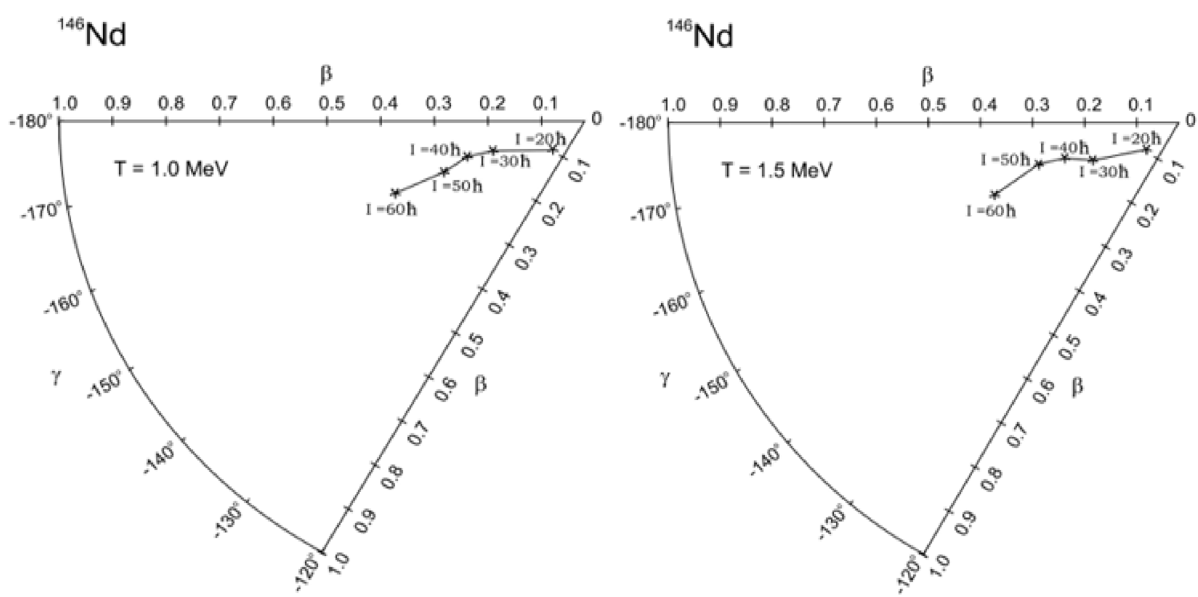

Fig. 3.5 Shape variations in ^{146}Nd as a function of spin for temperatures T=1.0 MeV and T=1.5 MeV

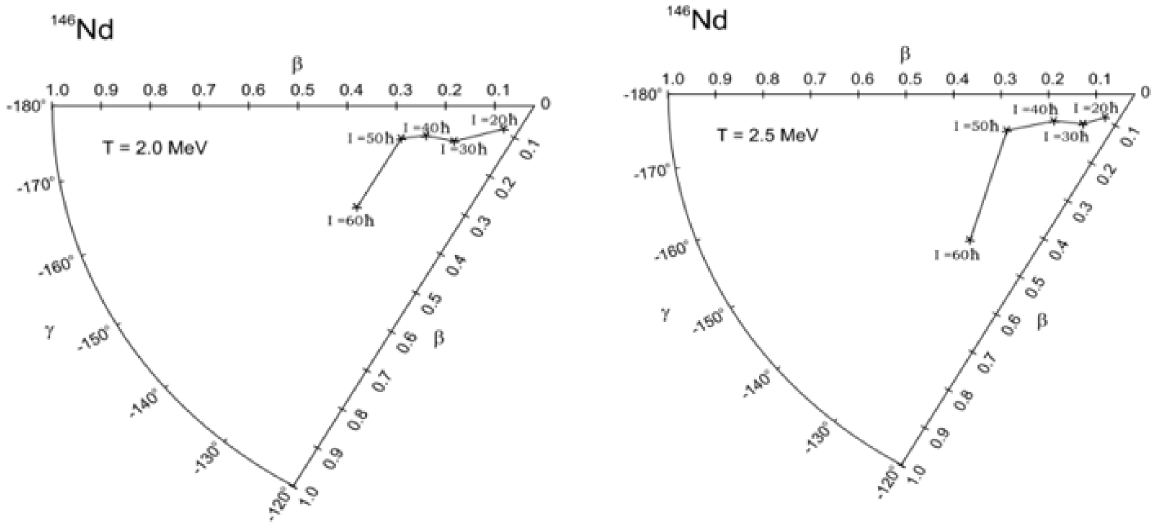

Fig. 3.6 Shape variations in ^{146}Nd as a function of spin for temperatures T=2.0 MeV and T=2.5 MeV

REFERENCES

- [1] Y. Alhassid, J. Zingman, and S. Levit, Nucl. Phys **A469**, 205
- (1987)
- [2] G. Shanmugam, Kalpana Sankar, and K. Ramamurthi, Phys.
- Rev. **C52**, 1443 (1995)
- [3] G. Shanmugam, Kalpana Sankar and V. Selvam, Proc. of the
- Int. WNP(1995)
- [4] Y. Alhassid and B. Bush, Nucl. Phys. **A549**, 12 (1992)
- [5] G. Shanmugam and V. Selvam, Phys. Rev. **C62**, 014302(2000)
- [6] Y. Alhassid and N. Whelan, Nucl. Phys. **A565**, 427 (1993)
- [7] V. Selvam, D.R. Jaahar Devadhason and J.M. Beula, Braz. J.
- Phys. 44, 7652(2014)
- [8] A.K. Ignatiuk, I. N. Mikhailov, L.H. Molina, R.G. Nazmitdinov,
- and K. Pomorsky, Nucl. Phys. **A346**, 191 (1980)
- [9] R. Bengtsson and S. Aberg, Phys. Lett. B **172**, 277 (1986)
- [10] L. Golttig and W. Nazarewicz, J. Phys. G **16**, L 51 (1990)
- [11] M. Brack, Jens Damagaard, A. S. Jensen, H. C. Pauli, V.M.
- Strutinsky, and C.V. Wong, Rev. Mod. Phys. **44**,320 (1972).