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RESEARCH ARTICLE

Structural changes of nuclei studied with high excitation energy and large angular momentum

V. Selvam[1*], D.R. Jayahar Devadhason[2]

[1]Department of Physics, Rani Anna Government College, Tirunelveli-627 008, Tamil Nadu, India
[2]Department of Physics, Marthandam College of Engineering and Technology, Kanyakumari-629 177, Tamil Nadu, India

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Abstract

The variation in nuclear deformation with angular momentum is considered in nuclei with A = 40 using the summation method extended to high spin. Pairing is not included in the formalism which is found to be of minor importance in light nuclei. Our results show that, the considered nuclei, undergo a shape transition from spherical to oblate and then to triaxial at high spin. For the extended calculations upto I = 60 ħ, Jacobi shape transitions are not obtained for the present candidates. Role of thermal fluctuations on the shape transitions of hot rotating nuclei is studied using Landau theory of shape transitions. With thermal fluctuations the averaged shape lead to triaxial at high excitation energy.

Keywords

Structural changes
Summation method
Jacobi shape transitions
Landau theory
Thermal fluctuations

Introduction

The shapes of nuclei arise from basic correlations in nuclear matter. It is important to study these correlations and find the limits where they break down. This is possible to do by subjecting the nucleus to extreme conditions, such as high rotation and internal excitation energy, and studying the shapes which then results. Nucleus on excitation gives rise to prolate and oblate shapes of varying degrees of deformation. In some cases, tri-axial shapes also occurs. A nucleus can be excited in two ways; either by internal excitation or rotational excitation. Internal excitation of the nucleus causes disturbance in the shell effects and thereby brings out shape transitions whereas rotational excitation brings in an interplay of collective and non-collective degrees of freedom. Fluctuations in nucleus arise due to rotations and vibrations.

In a collective rotation, the rotation axis is perpendicular to the symmetry axis. For a non-collective rotation, the rotation axis combines with the symmetry axis. The vibrations are relatively near the ground state at the beginning of the region of deformation. However they seem to go monotonically upward through the region of deformation, and downward at its end. On the other hand the non-axial γ vibrations are complex and show rather wide fluctuations. In ground state (E=0) or collective excitations there are no fluctuations whereas in non-collective excited states, there are fluctuations.

*Corresponding author, Tel: +91-9443581044
E-mail : vselvam_45@yahoo.com

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Nuclei at ground state are mostly spherical and prolate, oblate being less in number and ellipsoidal very scarce. But when they are excited to high angular momentum states one may come across fascinating shape transitions in them. Study of structural changes of nuclei at high excitation energy and large angular momentum has led us to a new phase in nuclear structure physics. The experimental analysis of giant dipole resonance built on excited states has started to yield information about the shape transitions that takes place in such nuclei. The combined effect of spin and temperature has created a variety of shape transition phenomena in nuclei. One such shape transition from non-collective oblate to highly deformed collective prolate or nearly prolate (triaxial) has been recently predicted and observed in case of light and medium mass nuclei [1-3]. This shape transition, which is similar to the Jacobi transition in gravitating rotating stars [4], has generated a lot of interest in recent times.

The aim of this work is to study the shape transitions in excited nuclei such as ^{40}Ca and ^{40}Ar as a function of spin and temperature. Cranked Nilsson summation method [5] extended to high spin is used in the calculations. In order to investigate shape evolutions in hot rotating ^{40}Ca and ^{40}Ar nuclei and to check whether the Jacobian instability is obtainable with thermal fluctuations, we have used the Landau theory of shape transition. Recently, lots of measurements have been performed to measure giant dipole resonance cross sections which may be used as a signature specifying the shapes of nuclei at high excitation. 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 Landau theory offers a natural frame work in which these fluctuations are introduced. All the complicated nuclear shapes and their transitions as a function of spin and temperature can be easily and effectively tackled by Landau's theory.

Finite temperature mean field calculations are found to yield sharp shape transitions in spite of the finite size of the nuclei. It was, however, recognized that the inclusion of statistical thermal fluctuations would modify these sharp shape transitions. By recognizing this fact, in the second phase of this work, we have obtained the shape evolutions in hot rotating ^{40}Ca and ^{40}Ar nuclei incorporating the most important thermal fluctuations using Landau theory.

The temperature dependent constants appearing in the Landau expression for the free energy are determined by using the free energy surfaces obtained by the cranked Nilsson Summation method [5]. **Fig 1** show the relation between shape of nuclei rotating around the Z – axis and various values of axial deformation parameter in collective and single particle phase.

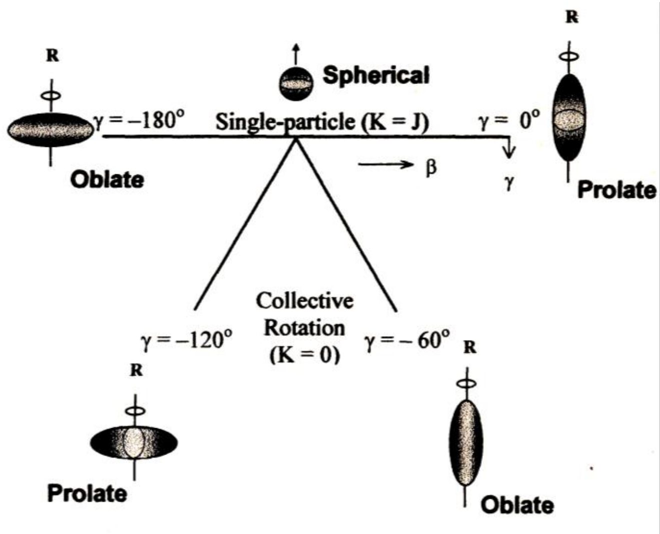


Fig 1 The relation between shape of nuclei rotating around the z-axis and various values of deformation parameter γ

The summation method for the study of rotating nuclei

Nilsson model is a deformed shell model. It deals with the independent particle motion of the nucleons in a deformed nuclear potential. The potential is assumed to be anisotropic. The deformations of the nuclear field have great influence on the individual motion of the nucleons. The Mottelson – Nilsson summation method for the rotating light nuclei can be described as follows. In the case of rotating nucleus without internal excitation, the nucleons move in a cranked Nilsson. potential with the deformation described by β and γ [5].

The cranking is performed around one of the principal axes, the z – axis and the cranking frequency is given by ω_c. In these calculations, the triaxial Nilsson model in the rotating frame is used. If h^0 is the tri – axial Nilsson Hamiltonian then, in this system of reference, the total Hamiltonian is given by,

$$h^{\omega_c} = h^o - \omega j_z \quad (1)$$

where

$$h^o = \frac{p^2}{2m} + \frac{1}{2} m \sum_{i=1}^{3} \omega_i^2 x_i^2 + Cl.s + D[l^2 - 2 < l^2 >] \quad (2)$$

The three oscillator frequencies ω_i are given by the Hill - Wheeler parameterization as

$$\omega_x = \omega_o \exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos\left(\gamma - \frac{2}{3}\pi\right)\right] \quad (3a)$$

$$\omega_y = \omega_o \exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos\left(\gamma - \frac{4}{3}\pi\right)\right] \quad (3b)$$

and $$\omega_z = \omega_o \exp\left[-\sqrt{\frac{5}{4\pi}}\beta\cos\gamma\right] \quad (3c)$$

With the constraint of constant volume for equipotentials

$$\omega_x.\omega_y.\omega_z = \omega_o^{o3} = \text{constant.} \quad (4)$$

For the Nilsson parameter κ, μ and $\hbar\omega_o^o$ the following values are chosen [6] for the considered mass region around A ~ 46.

κ = 0.093

μ = 0.15

$$\hbar\omega_0^0 = 45.3MeV \Big/ \left(A^{1/3} + 0.77\right) \quad (5)$$

Since the considered nuclei fall equal or very close to N = Z regime, same values are used for protons as well as neutrons. It may be noted that in h^0 (eqn. 2) the factor in front of $<l^2>$ has been doubled, following ref. [7], from the conventional value of 0.5 [8] to obtain better agreement between the Strutinsky smoothed moment of inertia and the rigid rotor value (here within 10%). Accordingly the parameter D has been redetermined with the help of single – particle levels in the mass region indicated. The Hamiltonian (1) is diagonalized in cylindrical representation [9] upto N = 8 shells using the matrix elements given in ref. [10]. This is in contrast to the Strutinsky method wherein the diagonalization upto about N = 11 shells is required. Thus there is an enormous reduction in computation time in the present method.

The calculations have been performed in the range β = 0.0 to 0.6, $\gamma = -180^o$ to -120^o in steps of Δβ = 0.1 and $\Delta\gamma = -2^o$ respectively for the first calculations. The cranking frequency ω_c is varied from 0.0 ω_o^o upto 0.3 ω_o^o in steps of Δω = 0.03 ω_o^o. Scaling ω with the oscillator constant ω_o^o has now the advantage that all terms in $h^{\omega c}$ (eqn. 1) are proportional to $\hbar\omega_o^o$ so that all calculations of single-particle states and energies have to be performed only once in a given mass range.

The single-particle energies in the rotating system $e_i^{\omega_c}$ and the wave functions $\chi_i^{\omega_c}$ are obtained.
From the diagonalization,

$$h^{\omega_c}\chi_i^{\omega_c} = e_i^{\omega_c}\chi_i^{\omega_c} \quad (6)$$

The single-particle energies in the laboratory system e_i and the single-particle spin contributions m_i are calculated as expectation values. The calculations have been extended to have large spin values with deformation upto 1.0.

$$e_i = < x_i^{\omega_c} \left| h^o \right| x_i^{\omega_c} > \quad (7)$$

and

$$m_i = < x_i^{\omega_c} \left| J_z \right| x_i^{\omega_c} > \quad (8)$$

The total energy is then obtained as

$$E = E\left(\beta,\gamma,\omega_c\right) = \sum_i e_i + E_c \quad (9)$$

where $$e_i = \sum_i e_i^{\omega_c} + h\omega_c \sum_i m_i$$

with the total spin given by

$$I = I\left(\beta,\gamma,\omega\right) = \sum_i m_i \quad (10)$$

The summation should be carried out over the occupied states where the occupation is determined from the order of the quantities $e_i^{w_c}$. The factor E_c in eqn. (9) is the nuclear Coulomb energy which depends on deformation. For fixed spin I, one can construct an energy surface from equation (9) and (10) and the minima in these surfaces then determine the shape and deformation of the given nucleus.

The nuclear Coulomb energy, should, in principle, be treated as a residual force for the particles moving in the single – particle potential (1). The most accurate procedure is, however, very cumbersome, and one, therefore determines the Coulomb energy of a homogenous proton distribution with an ellipsoidal shape. The exact expression for the Coulomb energy of an ellipsoid E_c in units of Coulomb energy of a sphere $E_c^{(0)}$ was derived by Pal [11], Gotz *et. al* [12] and Leander [13]. The Leander's expression for the ratio B_c is used in the present calculations.

$$B_c = \frac{E_c}{E_c^{(0)}} \frac{R_0^0}{\left(b^2 - c^2\right)^{\frac{1}{2}}} F_c \quad (11)$$

Where a, b, c denote the semi axes of the ellipsoid, arranged so that c < a < b; R_0^o is the radius of the equivalent sphere given by 1.16 $A^{1/3}$ fm.

F_c is the elliptic integral of the first kind given by,

$$F_c = F(\varphi, k_c) \quad (12)$$

$$\text{where } \varphi = \arc\sin \frac{(b^2 - c^2)^{\frac{1}{2}}}{b} \quad (13)$$

$$\text{and} \quad k_c^2 = \frac{(b^2 - a^2)}{(b^2 - c^2)} \quad (14)$$

For numerical calculations of the elliptic integral, the method of arithmatico – geometric mean together with Leander's transformation [14] is used. For spheroidal shapes, these integrals reduce to particularly simple forms [15]. The diffuseness correction to the Coulomb energy is omitted since it is shown that [7, 11] it is independent of deformation and hence cancels out when the total energy is normalized such that E (β = 0, γ = 0) = 0. One can construct an energy surface for fixed I from eqns. (9) and (10). The minima in these surfaces then give the equilibrium deformations of the considered light nuclei. An important feature of light nuclei is that the pairing correlations appear to be of minor importance and hence they have been neglected in the present study.

It is to be noted that the above method is not only economical, but also it automatically accounts for the change of diffuseness with spin which is very important for light nuclei.

Landau theory of shape transitions

For finite temperatures, one should also consider the thermal fluctuations which create shapes different from the most probable shape obtained by minimizing the free energy F = E - TS. These shape fluctuations can significantly alter the properties of hot rotating nuclei. According to Landau theory [16,17], the free energy at $\omega = 0$ can be written to fourth order in β as

$$F(T,\omega=0,\beta,\gamma) = Fo(T) + A(T)\beta^2 - B(T)\beta^3\cos 3\gamma + C(T)\beta^4 \quad (15)$$

Where the coefficients F_o, A, B and C depend on the temperature T and β and γ are the usual intrinsic deformation parameters. The free energy which depends on β and γ will also depend on the orientation angles relative to the rotation axis ω for the rotating case $\omega \neq 0$. Extending Eqn. (15) to the rotating case with ω parallel to Z axis,

$$F(T,\omega,\beta,\gamma) = F(T,\omega=0;\beta,\gamma) - \frac{1}{2}J_{zz}(\beta,\gamma,T)\omega^2 \quad (16)$$

For fixed spin this can be Legendre transformed as

$$F(T,I;\beta,\gamma) = F(T,I=0;\beta,\gamma) + \frac{I^2}{2J_{zz}(\beta,\gamma,T)} \quad (17)$$

where

$$J_{zz} = J_0(T) - 2R(T)\beta\cos\gamma + 2J_1(T)\beta^2 + 2D(T)\beta^2\sin^2\gamma \quad (18)$$

with J, R and D suitably defined to absorb various numerical constants. The R term has the leading shape dependence of the rigid-body moment of inertia, while the D term alone would represent the leading shape dependence of the irrotational moment of inertia. For ω dependent terms in eqn. (17), as in reference [16], the rigid-body moment of inertia is assumed, setting

$$J_0 = \frac{2}{5}mAR_0^2, \quad R = \left[\frac{5}{16\pi}\right]^{1/2} J_0 \quad \text{and} \quad D = J_1 = 0 \quad (19)$$

In this study, the Landau constants A(T), B(T) and C(T) are evaluated by least square fitting with the ω = 0 free energy surfaces obtained by Summation method. This method has the advantage that the accuracy of the fitting can be checked by the resulting error bars. In the Summation method, the free energy is computed as,

$$F(T,I;\beta,\gamma) = E(T,I;\beta,\gamma) - TS(T,I;\beta,\gamma) \quad (20)$$

Here, S is the total entropy of the fermion gas and is given by

$$S = -\sum_{i=1}^{\infty}[f_i \ln f_i + (1-f_i)\ln(1-f_i)] \quad (21)$$

Expressed in terms of Fermi-Dirac occupation numbers

$$f_i = \frac{1}{1+\exp[\frac{(e_i^\omega - \lambda)}{T}]} \quad (22)$$

The chemical potential λ is obtained with the constraint $\sum_{i=1}^{\infty} f_i = N$, where N is the total number of particles. It is to be noted that, in this method there is no need to renormalize the single-particle level density at finite temperature.

Thermal fluctuations and their effect on the shape parameters

For a nucleus with finite number of particles and at moderately high temperatures, thermal fluctuations produce an average shape, which is qualitatively different from equilibrium shapes predicted by mean field theories [18-22]. Thermal fluctuations in the collective parameters were first considered by Moretto [23] (for the pairing gap parameter) and later on for the shape parameters by several authors [24,25]. These shape fluctuations can significantly alter the properties of hot rotating nuclei. The probability of finding the nucleus in a state with deformation $\alpha_{2\mu}$ is characterized by the free energy $F(\alpha_{2\mu}; I,T)$ is,

$$P(\alpha_{2\mu}; I,T) \propto e^{-F(\alpha_{2\mu};I,T)/T} \quad (23)$$

with $$F(\alpha_{2\mu}; I,T) = E(\alpha_{2\mu}; I,T) - TS$$

Using classical statistics, therefore, the ensemble average of an observable X which is deformation – dependent, is given by an average over all possible shapes.

$$\overline{X}(I,T) = \frac{\int X(\alpha_{2\mu}; I,T) e^{-F(\alpha_{2\mu};I,T)/T} D[\alpha_{2\mu}]}{\int D[\alpha_{2\mu}] e^{-F(\alpha_{2\mu};I,T)/T}} \quad (24)$$

where $D[\alpha_{2\mu}]$ is the volume element in the deformation space. Using equation (24), the ensemble average of β is, $$\overline{\beta} = \langle \beta \rangle = \frac{\int \beta P(\beta,\gamma) \beta^4 |\sin 3\gamma| \, d\beta d\gamma}{\int P(\beta,\gamma) \beta^4 |\sin 3\gamma| \, d\beta d\gamma} \quad (25)$$

Similarly the ensemble average of γ is

$$\overline{\gamma} = \langle \gamma \rangle = \frac{\int \gamma P(\beta,\gamma) \beta^4 |\sin 3\gamma| \, d\beta d\gamma}{\int P(\beta,\gamma) \beta^4 |\sin 3\gamma| \, d\beta d\gamma} \quad (26)$$

where $\beta^4 |\sin 3\gamma| \, d\beta d\gamma$ is the volume element as given in the Bohr rotation – vibration model. Equation (23) 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 [18-25].

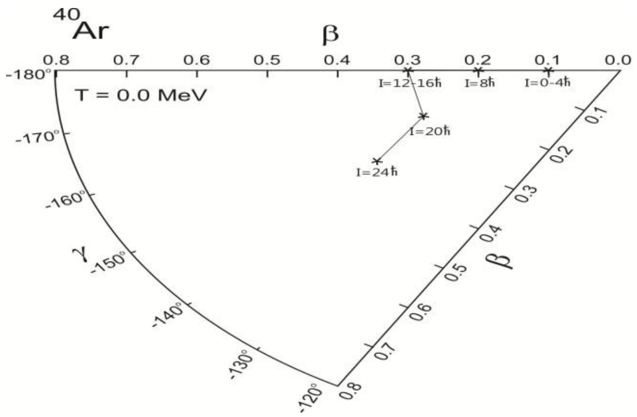
Results and discussion

The investigation of structural changes of nuclei at high excitation energy is a topic of current interest in nuclear structure studies. To detect the shape transitions theoretically we have chosen two nuclei namely in ^{40}Ar and ^{40}Ca. In the calculations performed in this work, the cranked Nilsson Summation method is used to obtain the shape and deformation of the considered nuclei as a function of spin. The Nilsson Hamiltonian is diagonalized in cylindrical representation up to N = 8 shells using the appropriate constants which are applicable for the nuclear region considered.

Shape transitions studied as a function of spin

The Hill – Wheeler expressions for frequencies have been used in the cranked Nilsson model in order to take care of large deformations involved in the calculations. Change of surface diffuseness with spin is included in the calculations which are very important for the considered in light nuclei.

The energy eigen values are generated for γ ranging from -180^o to -120^o in steps of -10^o and β ranging from 0.0 to 0.6 in steps of 0.1 for the first calculations. The cranking frequency ω_c is varied from 0.0 to 0.3 in steps of 0.03. The single particle routhians are generated with spin values I = 0 ħ to 24 ħ in steps of 2 ħ. **Figs 2** and **3** show the shape transitions as a function of spin for ^{40}Ar and ^{40}Ca respectively.



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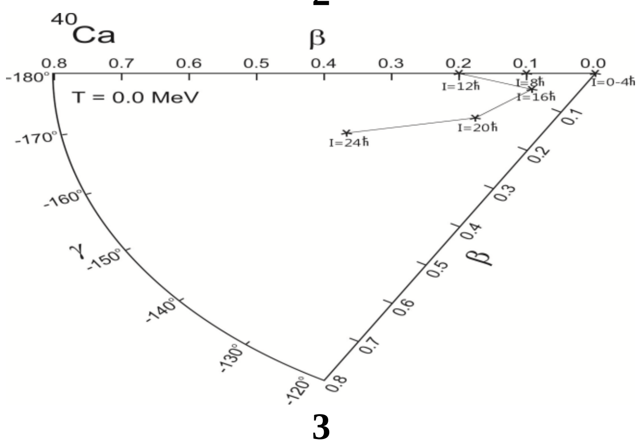

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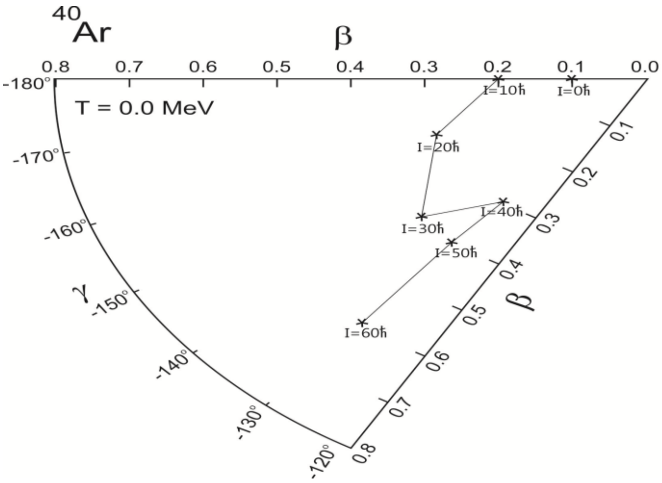
Figs 2,3 Shape transitions as a function of spin upto 24 ħ for ^{40}Ar and ^{40}Ca respectively.

It is noted from **Fig 2** that, the ^{40}Ar nucleus is oblate in shape at its ground state with deformation β = 0.1. It exists in the same shape and deformation as the angular momentum increases to 4 ħ. The same oblate configuration persists with spin upto 16 ħ. At a spin of 20 ħ, there occurs a shape transition from oblate (γ=-180^o, β=0.3) to triaxial (γ=-160^o, β=0.3). On further increase of spin to 24 ħ, the nucleus stays in the triaxial shape with axilality changes to -150^o. This indicates that the ^{40}Ar nuclei, starting from oblate in its ground state, undergo a shape transition to triaxial at high excitation energy. The result is also presented in table 1. **Fig 3** represents the shape transition in ^{40}Ca as a function of angular momentum. ^{40}Ca is known as a doubly magic nuclei and it should be spherical in shape at its ground state. Our calculation clearly reproduces the same behavior and it happens upto a spin of 4 ħ. At 8 ħ, the shape of the nucleus changes from spherical to oblate. It stays in the oblate shape upto I = 12 ħ and then turns into triaxial shape at high spin. More elongated triaxial shape is obtained at I = 24 ħ. The equilibrium shape and deformation is also given in table 2. In order to check whether the Jacobi shape transitions occur in the considered nuclei, we have extended our calculations with spin up to 60 ħ. Figures 4 and 5 represents the shape transitions as a function of spin in ^{40}Ar and ^{40}Ca respectively with extended spin upto 60 ħ.It is noted that, in the case of ^{40}Ar, starting from the oblate ground state the nucleus turn into triaxial at I=20 ħ (γ=-60^o). At I=40 ħ, the shape changes to nearly prolate (γ=-130^o) with β=0.4. It stays in the same phase up to I=60 ħ with elongation β=0.6. The Jacobi shape transition from non-collective



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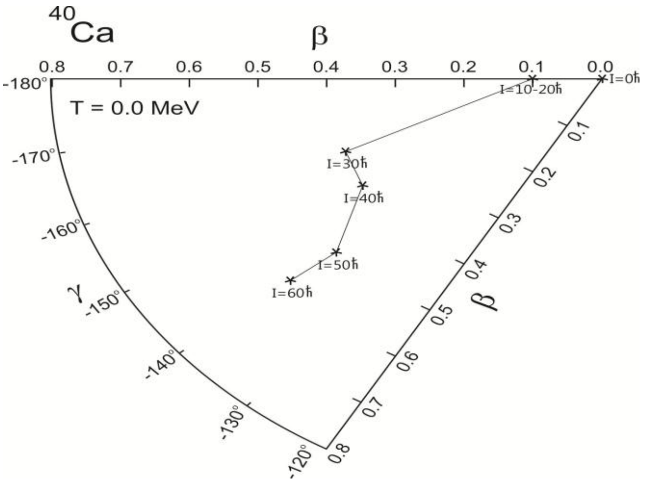

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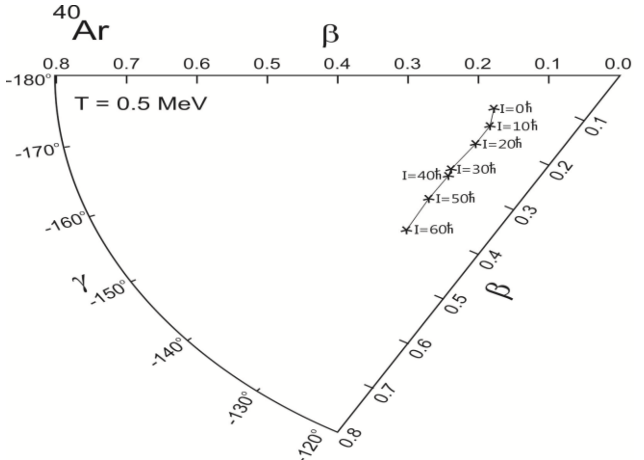
Fig 4,5 Shape transitions as a function of spin upto 60 ħ for ^{40}Ar and ^{40}Ca respectively.

oblate to collective prolate (or nearly prolate) with large deformation is not obtained in this nucleus but instead the transition is obtained via triaxial. In the case of ^{40}Ca also, the transition leads to triaxial and the clear Jacobi transition is not obtained. These results are also given in the tables 3 and 4. This indicates that the considered light nuclei is not fertile to harvest the Jacobi shape transitions.

Role of thermal fluctuations

For finite temperature, one should also consider thermal fluctuations which create shapes different from the most probable shape obtained by



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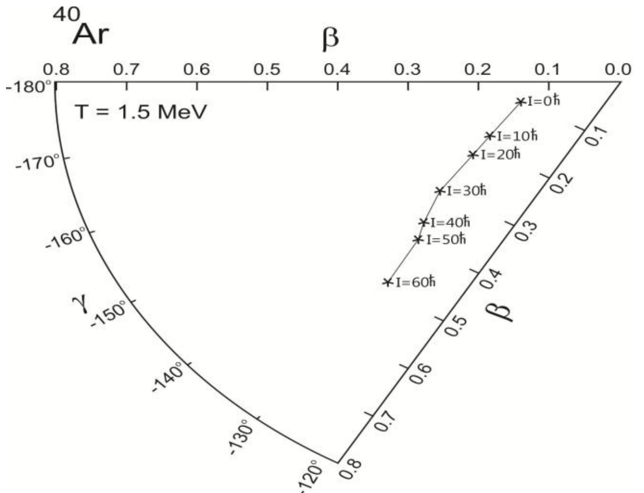

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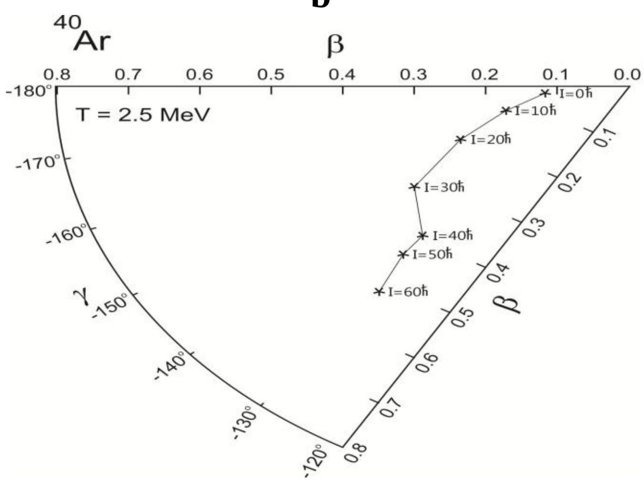

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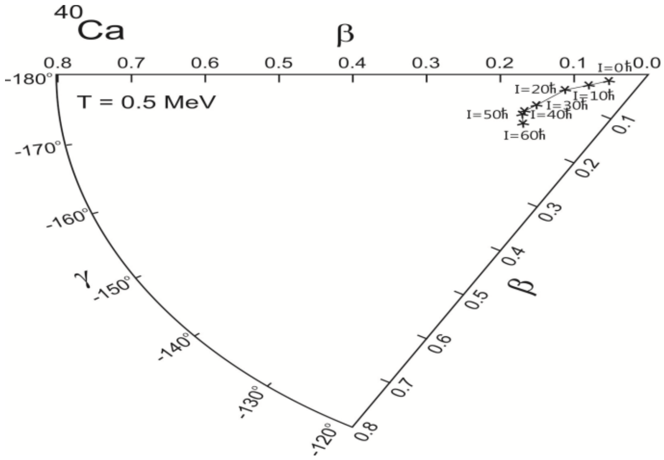
Fig 6 (a-c) Shape evolutions of ^{40}Ar as a function of spin and temperature with thermal fluctuations for temperatures T = 0.5, 1.5 and 2.5 MeV respectively.

minimizing the free energy. The nuclei considered here lie in the lighter region wherein the thermal fluctuations are expected to be more pronounced because of the fewer number of nucleons involved. In the second phase of this work, we have used the Landau theory of shape transitions to obtain the shape evolutions in hot rotating ^{40}Ar and ^{40}Ca nuclei. In this case the expansion of the Landau free energy is done upto fourth power of β.



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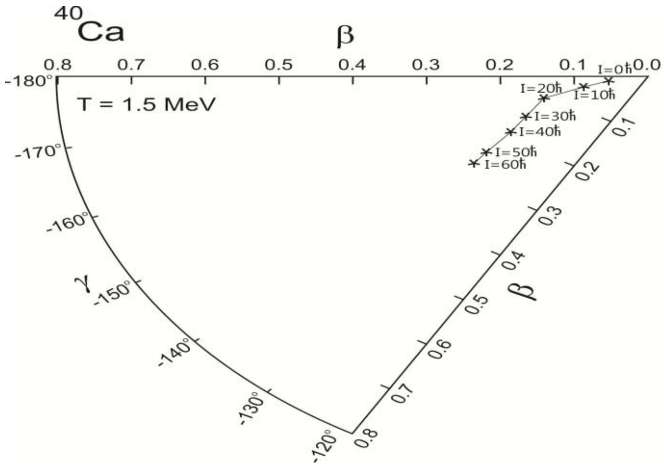

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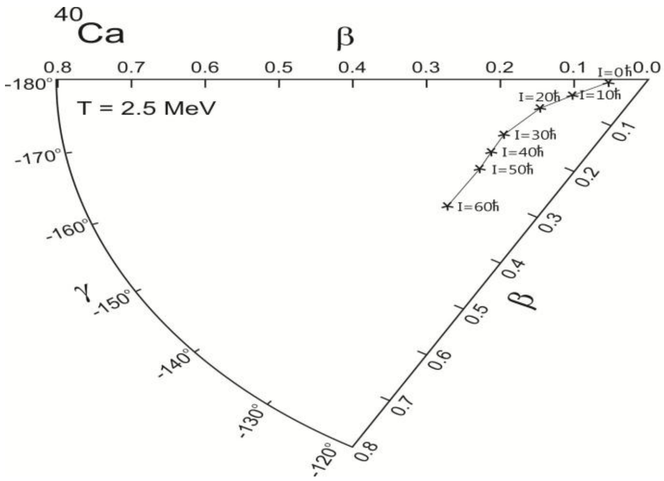

c

Fig 7 (a-c) Shape evolutions of ^{40}Ca as a function of spin and temperature with thermal fluctuations for temperatures T = 0.5, 1.5 and 2.5 MeV respectively.

The temperature dependent constants are evaluated by cranked Nilsson Sumation method. **Figs 6(a-c)** shows the shape evolutions in hot rotating ^{40}Ar nucleus at temperatures T=0.5, 1.5 and 2.5 MeV respectively. It is noted from these figures that when thermal fluctuations are included the shapes turn into triaxial and the deformation increases as a function of spin. Almost the same behaviour is obtained for ^{40}Ca which are given in **Figs 7(a-c)**. Thus it is clear that, the thermal fluctuations create mostly triaxial averaged shapes.

Conclusions

In this paper we have presented the results of shape evolutions in light nuclei such as ^{40}Ar and ^{40}Ca as a function of spin. Cranked Nilsson Summation method is used in the calculations with limited spin in the first calculations. The considered nuclei undergo a shape transition from oblate to triaxial at high spin. In order to look for the Jacobi type shape transition in these nuclei, we have extended our calculations upto a spin of 60 ħ. The sharp Jacobi shape transitions are not obtained in the considered nuclei in the present calculations. The role of thermal fluctuations on the shape transitions of hot rotating nuclei is studied by using the Landau theory of shape transitions. It is seen that thermal fluctuations create mostly triaxial averaged shapes unlike the most probable prolate, oblate or spherical shapes usually obtained without considering thermal fluctuations.

Table 1 Shape and deformation of even nuclei such as ^{40}Ar considered at different spins upto 24 ħ.

I (ħ)	β	γ
0	0.1	-180^0
2	0.1	-180^0
4	0.1	-180^0
6	0.1	-180^0
8	0.2	-180^0
10	0.2	-180^0
12	0.3	-180^0
14	0.3	-180^0
16	0.3	-180^0
18	0.3	-180^0
20	0.3	-160^0
22	0.4	-160^0
24	0.4	-150^0

Table 2 Shape and deformation of even nuclei such as ^{40}Ca considered at different spins upto 24 ħ.

I (ħ)	β	γ
0	0.0	-180^0
2	0.0	-180^0
4	0.0	-180^0
6	0.0	-180^0
8	0.1	-180^0
10	0.1	-180^0
12	0.2	-180^0
14	0.1	-160^0
16	0.1	-180^0
18	0.2	-160^0
20	0.1	-180^0
22	0.2	-1700
24	0.4	-1600

Table 3 Shape transitions in ^{40}Ar with extended spins upto 60 ħ.

I (ħ)	β	γ
0	0.1	-180^0
10	0.2	-180^0
20	0.3	-160^0
30	0.4	-140^0
40	0.3	-130^0
50	0.4	-130^0
60	0.6	-130^0

Table 4 Shape transitions in ^{40}Ca with extended spins upto 60 ħ.

I (ħ)	β	γ
0	0.0	-180^0
10	0.1	-180^0
20	0.1	-180^0
30	0.4	-160^0
40	0.4	-150^0
50	0.5	-140^0
60	0.6	-140^0

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