Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Isovector Giant Dipole Resonance in Hot Rotating Ruthenium Isotopes

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The isovector giant dipole resonances (IVGDR's) are extensively studied in certain rapidly rotating hot ruthenium isotopes using a rotating anisotropic harmonic oscillator potential and a separable dipole - dipole residual interaction. The shape and deformation of the above nuclei at high spins are determined by the cranked Nilsson – Strutinsky method extended for rotating medium mass nuclei. The influence of temperature on the isovector giant dipole resonance is assumed to occur through the change of deformation of the average field only. Calculations are performed for the considered ruthenium isotopes which have spherical ground state, to see how their shape transitions at higher excited states affect the isovector giant dipole resonance frequencies built on them. The results obtained show the general splitting of the frequencies of GDR at high spin and broadening of widths of frequencies in these nuclei increases on further increase of spin. It is seen that the width fluctuation present at T = 0, vanish at higher temperatures in these isotopes. Since this behaviour is found to be common in these isotopes, it may be noted that the role of temperature on shell effects do not affect the isovector giant dipole resonance widths in these isotopes at higher spins. Broadening of the giant dipole resonance as A as well as I increases is observed which is in good agreement with the experimental observations.
Keywords: High spin states of nuclei, Structural transitions, giant dipole resonance, cranked Nillsson - Strutinsky method

1. Introduction

Studies on giant dipole resonance play an important role in understanding nuclear structure especially at finite angular momentum and temperature. Isovector giant dipole resonance (IVGDR) is described as out-of-phase small-amplitude collective oscillation of neutron distribution against proton distribution, which is one of the strongly studied resonances in the past. Much progress has been made recently in the investigation of such resonances built on high spin states. These investigations open up the possibility of studying high spin states by just looking at the properties of giant resonances built on top of them. Recently Newton et al. [1] observed pronounced shoulders in the spectra of γ rays in E_γ >10 MeV following ^{40}Ar-induced reactions leading to the ^{122}Te, ^{150}Gd, and ^{164}Er systems. These shoulders were attributed to the isovector giant dipole resonances (IVGDR's), thus confirming experimentally the possibility of such resonances built on highly rotating states. Such experiments lead to a quite exciting new spectroscopy in which one can study the dynamical structure of high spin states just by looking at the properties of the IVGDR's built upon them. The centroid of GDR is related to the nuclear mass, the width is related to different damping mechanisms and the strength exhausts the major part of the Tomas-Reiche energy weighted sum rules for an electric dipole operator [2-4]. The possibility to build the IVGDR on excited states provides an excellent chance to obtain information on the nuclear structure under extreme conditions of high excitation energy, nuclear temperature and angular momentum [2, 5-6].

There are two types of calculations for the study of giant dipole resonance theoretically: (i) The harmonic oscillator model introduced by Brink [7] for the IVGDR built on the ground state which has been extended to the rotating case by several authors [8-10]; (ii) linear-response theory used by Egido and Ring [11] extended to finite temperatures [12]. In our previous investigation, we have used the first method to obtain the resonant energies and the corresponding peak cross sections for ^{152}Sm nuclei [13]; the shape and deformation of the above nuclei at high spin were determined by the cranked Nilsson - Strutinsky method for rotating heavy nuclei, and the allowed angular velocities for these deformations were obtained by the Fermi liquid drop model (FLDM). In this method, we have renormalized the single-particle level densities for the finite temperature [14].

The main feature that emerges from the experiments on the IVGDR's at high spins [15] is the broadening of the overall widths at higher angular momentum. The first observations of IVGDR's at high spins were made in the region of rare earth nuclei and it was found that the splitting due to nuclear rotation was small for the nuclei in this region. Since the splittings induced in heavy nuclei by nuclear rotation are small, they are difficult to observe. But, in light and medium mass nuclei, as first suggested by Hilton [9], one can expect a much stronger influence of nuclear rotation on the IVGDR's since the corresponding angular velocities in this region are greater. Measurement of the IVGDR's in medium mass nuclei at high spins would thus seem a worthwhile investigation which should manifest such effects most clearly. Further, the region of medium mass nuclei were not been studied much with such attention as the heavier nuclei. With this view, we have focused our attention on the study of the effect of spin and temperature on the IVGDR's in the isotopes of ruthenium nucleus wherein the bulk of the angular momentum is of an aligned nature.

In the present study, we have used the cranked Nilsson – Strutinsky method extended for rotating medium mass nuclei [16-18] to obtain the shape and deformation of ^{96,98,100,108}Ru as a function of temperature and spin. In this method, the single particle level densities are renormalized at finite temperature [14] for a particular angular momentum. The first step of our study is to determine the equilibrium deformations of nuclei at different spins and temperatures using the cranked Nilsson – Strutinsky method for hot rotating medium mass nuclei. The next step of our calculations is to find out the allowed angular velocities for these deformations. This was done in our previous work [13] using the Fermi liquid drop model [20]. But this model has some restrictions when one wants to consider prolate shapes and hence we have used the rotating liquid drop model (RLDM) [21] in this study. It is known [22] that the angular velocities determined by RLDM are the same as those obtained by the FLDM. The advantage which can be pointed out in the present method is the inclusion of the l.s and l^2 terms in the IVGDR frequency calculations. In order to compare with the experimental values, we need to transform the dipole motion to the laboratory frame, resulting in a much wider level splitting.

The first step of our study is to determine the equilibrium deformations of the nuclei considered at different spins. This is done by using the cranked Nilsson Strutinsky method extended to finite temperature. The main advantage of this method is that the changes of surface diffuseness with spin are automatically taken into account in this method. For the study of the IVGDR, which is mainly a surface effect [23], this method is thus more suitable. The next step in our calculations is to find out the allowed angular velocities for these deformations. This is done in this work by using the rotating liquid drop model. In this method, the angular velocity allowed for each equilibrium configuration is fixed by the balance of nuclear pressure, surface tension, and Coulomb energy. Once the angular velocities are known, the splitting of IVGDR energies can be studied by using the analytical microscopic method. Our results show the increasing widths of the IVGDR energies at higher angular momenta as being mainly due to dynamical deformation effects caused by rotation. To make the results more transparent, we calculate the IVGDR frequencies as a function of spin and temperature for the nuclei considered.

Section II describes the method used for obtaining the IVGDR frequencies and the required equilibrium deformations. The results obtained are discussed in Sec. III and the conclusions drawn from the study is given in Sec. IV.

2. The Method

2.1 Isovector Giant Dipole Resonances in Ruthenium Isotopes

In order to study the properties of the IVGDR's for the considered rapidly rotating warm ruthenium isotopes namely ^{96,98,100,102}Ru, we have used, for the average field of the nucleus, an oscillator potential with deformation parameters consistent with the angular momentum of the system. It is therefore essential to first track the rotation-induced changes of nuclear shapes. For this, one can use a simple parameterization [24] of the isoscalar component of the two particle interactions by quadrupole forces, but it permits only a qualitative analysis of the changes in the shapes of rapidly rotating nuclei. From the point of view of a quantitative description of the dependencies of the parameters of the deformation of the self-consistent mean field on the rotation frequency, this model is too primitive. In particular, the nuclear shape changes noticeably in this model at excessively larger angular momenta. More realistic from this point of view are estimates of the rotational deformability of the nuclei within the framework of the rotating liquid drop model [21]. But in this work we use the rotating Fermi liquid drop model for obtaining the allowed angular frequencies consistent with deformations at different spins, since this model has elements related not only to the liquid drop model but also to the random phase method.

For the considered ruthenium isotopes, we do not consider the deformation to be static, but to arise due to rotation, all the above nuclei are considered to be spherical in shape for zero rotation. Furthermore, a slight deviation from axial symmetry at higher spins of I > 20 in the case of ^{96}Ru is overlooked in our calculations. This enables us to treat all the above rotating nuclei as oblate spheroids rotating about their symmetry axes. The value of the deformation parameter δ at a particular spin is related to the allowed angular velocity Ω by the relation

$$\Omega^2 = \frac{2R^3}{\rho}\left[1-\frac{a_3^2}{a_1^2}\right]\left(\frac{15}{4}TA_{13}-\pi q^2 B_{13}\right) \quad (1)$$

where ρ is the matter density, q the charge density, and T the surface tension coefficient. The above equation (1) describes the balance of pressure of the surface, centrifugal, Coulomb, and nuclear forces, which uniquely relates the values of the semi axes a_i with angular velocity Ω. Here,

$$q^2 = 0.0665\,\frac{Z^2}{r_0^5 A^2}\ (\mathrm{MeV}) \quad (2)$$

where Z is the number of protons and T can be related to the corresponding Weiszacker parameter b =17 MeV. The two-index symbols A_{ij} and B_{ij} are given by Balbutsev et al. [25].

Let us consider the rotating nucleus to be an oblate spheroid. We shall express its semi axes a_i (i =1,2,3≡x,y, z) in terms of the deformation parameter δ:

$$a_1^2 = a_2^2 = a_0^2\left(1+\frac{2}{3}\delta\right)$$

$$a_3^2 = a_0^2\left(1-\frac{4}{3}\delta\right) \quad (3)$$

Here a_o is fixed by the condition of conservation of volume $a_1a_2a_3 = R^3 = r_0^3A$, where r_0=1.18 fm and A is the mass number. In order to obtain the shape and deformation of the rotating nucleus, we follow the cranked Nilsson Strutinsky method [18-19]. The IVGDR energies of the considered rotating nuclei is obtained using the analytical method [24,15]. In this method, the average field of the nucleus was taken to be an oscillator potential with deformation parameters consistent with the angular momentum of the system.

The shape changes of nuclei induced by rotation can be simulated by the average Hamiltonian of a triaxial harmonic oscillator given by

$$H_{av}(\Omega) = \sum_{v=1}^{A} h_v(\Omega) \quad (4)$$

where

$$h_v(\Omega) = \frac{p^2}{2m}+\frac{m}{2}\left(\omega_x^2x^2+\omega_y^2y^2+\omega_z^2z^2\right)-\Omega I_z \quad (5)$$

and $L_z = \sum_{v=1}^{A} l_z\,(v)$ is the operator for rotation about the z axis. The eigen functions and the eigenvalues of the Hamiltonian (4) can be conveniently determined from the equation

$$\left[H_{av}\,,a_\lambda^\dagger\right] = \omega_\lambda a_\lambda^\dagger \quad (6)$$

here $a_\lambda^\dagger$ are the oscillator-quantum creation operators that are linear combinations of the particle coordinates r_i and of the conjugate momenta p_i . In terms of the operators $a_\lambda^\dagger$ and a_λ, the Hamiltonian (4) can be expressed as

$$H_{av} = \sum_{\nu=1}^{A}\left\{\omega_z\left[\left(a_z^\dagger a_z\right)+\frac{1}{2}\right]+\omega_+\left[\left(a_+^\dagger a_+\right)+\frac{1}{2}\right]+\omega_-[\left(a_-^\dagger a_-\right)+\frac{1}{2}]\right\} \quad (7)$$

The normal frequencies are then obtained as

$$\omega_z = \omega_z\ ,$$

$$\omega_\pm = \left\{\frac{\omega_y^2+\omega_x^2}{2}+\Omega^2 \pm \frac{1}{2}\left[(\omega_y^2-\omega_x^2)^2+8\Omega^2(\omega_y^2+\omega_x^2)\right]^{1/2}\right\}^{1/2} \quad (8)$$

To generate the isovector dipole excitation mode, we add to the Hamiltonian (3) the effective dipole interaction

$$H_{int} = \eta\sum_{i=x,y,z}\frac{m\omega_i^2}{2A}\left[\sum_{\nu=1}^{A}\tau_3(\nu)x_i(\nu)\right]^2 \quad (9)$$

where $\tau_3(\nu)$ is the third projection of the Pauli isospin matrix,

$$\tau_3 = \begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix},$$

and η is a parameter that characterizes the isovector component of the neutron or proton average field and is represented by

$$V_{\substack{(n)\\(p)}}(\nu) = \frac{m}{2}\left[1 \mp \eta\frac{N-Z}{A}\right]\sum_{i=x,y,z}\omega_i^2\, x_i^2(\nu) \quad (10)$$

The value of η for an oscillator potential is found [24] to be 3 from the experimental data on the position of the giant resonance.

The giant dipole resonance frequencies of a rotating nucleus can be obtained by diagonalizing analytically the Hamiltonian (4) with the effective interaction (9) within the framework of the standard random phase approximation (RPA) procedure by using the similarity between the linear transformation corresponding to (4) and the RPA transformations.

The RPA equations for the isovector dipole modes can be written in a form similar to Eq. (6) as

$$\left[H + H_{int}, D_\lambda^\dagger\right] = \tilde{\omega}_\lambda D_\lambda^\dagger\ , \quad (11)$$

where $D_\lambda^\dagger$ is the dipole phonon-creation operator and is given by

$$D_\lambda^\dagger = \frac{1}{\sqrt{A}}\sum_{\nu=1}^{A}\tau_3(\nu)\tilde{a}_\lambda^\dagger(\nu)\ : \quad (12)$$

We obtain the components of the commutator (11) as

$$\left[\sum_{i=x,y,z}\frac{m\omega_i^2}{2}\sum_{\nu=1}^{A}x_i^2(\nu), D_\lambda^\dagger\right] = \sum_{i=x,y,z}m\omega_i^2\left[x_i,\tilde{a}_\lambda^\dagger\right]\frac{1}{\sqrt{A}}\sum_{\nu=1}^{A}\tau_3(\nu)x_i(\nu) \quad (13a)$$

$$\frac{1}{2}\eta\left[\sum_{i=x,y,z}\frac{m\omega_i^2}{2}\frac{1}{A}\left[\sum_{\nu=1}^{A}\tau_3(\nu)x_i(\nu)\right]^2, D_\lambda^\dagger\right] = \eta\sum_{i=x,y,z}m\omega_i^2\left[x_i,\tilde{a}_\lambda^\dagger\right]\frac{1}{\sqrt{A}}\sum_{\nu=1}^{A}\tau_3(\nu)x_i(\nu)$$

(13b)

The commutator of the phonon-creation operator $D_\lambda^\dagger$ with the Hamiltonian of the interaction in (13b) is thus proportional to the commutator of $D_\lambda^\dagger$ with the average field operator (13a), and consequently we can write

$$[H + H_{int}, D_\lambda^\dagger] = [\widetilde{H}_{av}, D_\lambda^\dagger] \qquad (14)$$

Where

$$\widetilde{H}_{av} = \sum_{v=1}^{A} \frac{p_v^2}{2m} + (1+\eta) \sum_{i=x,y,z} \omega_i^2 x_i^2(v) - \Omega L_z \qquad (15)$$

The expressions for the eigenvectors and the normal frequencies of Eq. (11) will be correspondingly determined by relations (9) in which we make the substitution $\omega_i = (1+\eta)^{1/2}\,\omega_i$.

By transforming this to the laboratory system, we get the frequencies of the giant dipole resonance as

$$\tilde{\omega}_z = (1+\eta)^{1/2}\,\omega_z$$

$$\tilde{\omega}_\pm = \left\{(1+\eta)\frac{\omega_y^2+\omega_x^2}{2} + \Omega^2 \pm \frac{1}{2}\left[(1+\eta)^2(\omega_y^2-\omega_x^2)^2 + 8\Omega^2(1+\eta)(\omega_y^2+\omega_x^2)\right]^{1/2}\right\}^{1/2} \mp \Omega \qquad (16)$$

In the case of rotating oblate nuclei, it is assumed by setting $\omega_x = \omega_y \neq \omega_z$. An advantage of this method is that with the rotation turned off ($\Omega=0$) one can get the frequencies of the isovector dipole modes of an axially deformed nucleus with static deformation.

The dipole photo absorption cross section as a function of angular momentum plays a crucial role in the study of the spectra of γ quanta emitted from rapidly rotating nuclei. By using the semi-classical theory of the interaction of photons with nuclei, the shape of a fundamental resonance in the absorption cross section is that of the Lorentz curve

$$\sigma(E) = \frac{\sigma_m}{1+(E^2-E_m^2)^2/E^2\Gamma^2} \qquad (17)$$

where the Lorentz parameters E_m, σ_m, and Γ are the resonance energy, peak cross section, and full width at half maximum, respectively. For deformed spheroidal nuclei, the giant resonance consists of two such Lorentz lines corresponding to the absorption of photons which induce oscillations of the neutron and proton fluids in the nucleus against each other. In such cases,

$$\sigma(E) = \sum_{i=1}^{2} \frac{\sigma_{mi}}{[1+(E^2-E_{mi}^2)^2/E^2\Gamma_i^2]} \qquad (18)$$

where i=1,2 correspond to the lower and high energy lines. The lower energy line corresponds to oscillations along the longer axis and the high energy line corresponds to oscillations along the shorter axis. It is to be noted that these Lorentz lines are noninterfering, but Γ_i is assumed here to depend on energy.

J.R. Nix et al., [26], using a surface plus window dissipation model, could get resonance widths comparable to experimental values, but only for giant quadrupole and octupole resonances. As in ref. [27], the energy dependence on the GDR width can be well approximated by the relation

$$\Gamma_\lambda \approx 0.026 E_\lambda^{1.9} \quad (19)$$

This expression is useful, also for the parameterization of the IVGDR width in a rotating nucleus, with due allowance for the corresponding changes of the energies of the resonances, and is used in our calculations.

2.2 Cranked – Nilsson Strutinsky method

To obtain the potential energy surfaces as a function of spin and temperature for ruthenium isotopes, the cranked Nilsson - Strutinsky method in cylindrical representation is used. The theoretical framework for obtaining for by is as follows:

In this method the nucleons move in a cranked Nilsson potential with the deformation determined by β and γ. The cranking is performed around one of the principal axes, the z- axis and the cranking frequency is given by ω. The triaxial Nilsson model in the rotating frame is used in the calculations. The shell energy calculations for non-rotating case (I=0) assumes a single particle field

$$H^0 = \sum_i h^0$$

(20)

where h^0 is the triaxial Nilsson Hamiltonian given by [28]

$$h_i^0 = \frac{p^2}{2m} + \frac{1}{2} m \sum_{k=1}^{3} \omega_k^2 x_k^2 - \kappa\hbar \overset{0}{\omega_0} [2l.s + \mu(l^2 - 2\langle l^2 \rangle)]$$

(21)

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

$$\omega_x = \omega_0 \exp\left[-\sqrt{\frac{5}{4\pi}}\beta \cos\left(\gamma - \frac{2}{3}\pi\right)\right]$$

(22a)

$$\omega_y = \omega_0 \exp\left[-\sqrt{\frac{5}{4\pi}}\beta \cos\left(\gamma - \frac{4}{3}\pi\right)\right]$$

(22b)

$$\omega_z = \omega_0 \exp\left[-\sqrt{\frac{5}{4\pi}}\beta \cos\gamma\right]$$

(22c)

with the constraint of constant volume for equipotentials

$$\omega_x \omega_y \omega_z = \overset{0}{\omega_0}{}^3 = \text{constant}$$

(23)

For the Nilsson parameters κ and μ, the following values are chosen [20] separately for protons and neutrons:

Protons		Neutrons	
κ	μ	κ	μ
0.070	0.390	0.073	0.290

where the oscillator frequency $\hbar\overset{0}{\omega_0}$ is chosen as

$$\hbar\overset{0}{\omega_0} = \frac{45.3}{(A^{1/3}+0.77)} MeV$$

(24)

In the expression for h_i^0 (Eqn. 21), the term $\left\langle l^2 \right\rangle$ has been doubled 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 re-determined with the help of single-particle levels in the given mass region. The Hamiltonian (21) is diagonalized in cylindrical representation up to N=11 major shells.

For the rotating case $(I \neq 0)$, the Hamiltonian becomes

$$H^{\omega} = \sum_i h_i^{\omega} ,$$

(25)

where

$$h_i^{\omega} = h_i^0 - \omega j_z ,$$

(26)

if it is assumed that the rotation takes place around the Z-axis.

The single particle energy e_i^{ω} and the wave function ϕ_i^{ω} are given by

$$h_i^{\omega}\phi_i^{\omega} = e_i^{\omega}\phi_i^{\omega}$$

(27)

The spin projections are obtained as

$$\left\langle m_i \right\rangle = \left\langle \phi_i^{\omega} \left| j_z \right| \phi_i^{\omega} \right\rangle$$

(28)

The total shell energy is given by

$$E_{sp} = \sum_i \left\langle \phi_i^\omega \middle| h_i^0 \middle| \phi_i^\omega \right\rangle = \sum_i \left\langle e_i \right\rangle, \quad (29)$$

where

$$e_i^\omega = \left\langle e_i \right\rangle - \hbar\omega \left\langle m_i \right\rangle \quad (30)$$

Thus the total spin and shell energy for the unsmoothened single particle level distribution is given by

$$I = \sum_i \left\langle m_i \right\rangle \quad (31)$$

$$E_{sp} = \sum_i e_i^\omega + \hbar\omega I \quad (32)$$

Since the difficulties encountered in the evaluation of total energy for large deformations through the summation of single particle energies for I=0 case may be present for I≠0 case also [18], we use the Strutinsky shell correction method adopted to I≠0 case by suitably tuning the angular velocities to yield fixed spins.

For the Strutinsky smeared single particle level distribution [19], Eqs. (31) and (32) transform into

$$\tilde{I} = \sum_i \left\langle \tilde{m}_i \right\rangle \quad (33)$$

and

$$\tilde{E}_{sp} = \sum_i^N \tilde{e}_i^\omega + \hbar\omega \tilde{I} \quad (34)$$

In the tuning method, first the energy values are evaluated with different degrees of freedom and different angular velocities. Then the obtained spin is treated under standard interpolation with the given angular velocity to obtain the exact angular velocities for the actual spin sequence for the nuclei considered.

The energy expression can have the form with specified N, Z & spin I and also deformation β as.,

$$E_{total}^{\omega(I)}(N, Z, \beta) = R_{total}^{\omega(I)} + \omega(I) I \quad (35)$$

and the total spin,

$$I = \tilde{I}_Z = \sum_{\nu=1}^{N} \left\langle \tilde{j}_Z \right\rangle_{\nu}^{\omega} + \sum_{\pi=1}^{Z} \left\langle \tilde{j}_Z \right\rangle_{\pi}^{\omega}$$

(36)

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 calculations have to be repeated accordingly. The energy values are thus calculated for the exact spin sequence.

The total energy is now given by

$$E_T = E_{RLDM} - (E - \tilde{E}_{sp})$$

(37)

where the rotating liquid drop energy at constant spin

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

(38)

the second term on the right hand side being the rotational energy. Here the liquid drop energy E_{LDM} is given by the sum of Coulomb and surface energies and J_{rig}, the rigid body moment of inertia defined by β and γ including the surface diffuseness correction.

The calculations are carried out by varying ω values in steps of $0.025\omega_0$ from $\omega = 0.0$ to $\omega = 0.3\omega_0$, ω_0 being the oscillator frequency for tuning to fixed spins. γ is varied from -180^0 to -120^0 in steps of -10^0 wherein $\gamma=-180^0$ and β values are varied from 0.0 to 1.2 in steps of 0.1.

3. Results and Discussion

In this work the isovector giant dipole resonances (IVGDR's) are extensively studied in certain rapidly rotating hot ruthenium isotopes using a rotating anisotropic harmonic oscillator potential and a separable dipole - dipole residual interaction. The shape and deformation of the above nuclei at high spins are determined by the cranked Nilsson – Strutinsky method extended for rotating medium mass nuclei. Calculations are performed for the considered ruthenium isotopes which have spherical ground state, to see how their shape transitions at higher excited states affect the isovector giant dipole resonance frequencies built on them. In the first step, we have determined the equilibrium deformations of the considered nuclei at different spins. This is done by using the cranked Nilsson - Strutinsky method extended to finite temperature. The main advantage of this method is that the changes of surface diffuseness with spin are automatically taken into account in this method. The next step in our calculations is to find out the allowed angular velocities for these deformations. This is done in this work by using the rotating liquid drop model. In this method, the angular velocity allowed for each equilibrium configuration is fixed by the balance of nuclear pressure, surface tension, and Coulomb energy. Once the angular velocities are known, the IVGDR frequencies as a function of spin and temperature were studied for the considered ruthenium isotopes.

3.1 Shape evolutions in Ruthenium isotopes

In the present work, the shape evolutions in $^{96\text{-}102}$Ru isotopes are first studied as a function of spin using cranked Nilsson Strutinsky method. The potential energy surfaces for these isotopes have been obtained by tuned spin Strutinsky procedure. In the calculations performed here the spin is varied from I= 0 to 60 ħ in steps of 2 ħ at various temperatures starting from zero. The equilibrium deformations are displayed in the (□-□) plane. Figures 1-4 show the equilibrium shape evolution of ^{96}Ru, ^{98}Ru, ^{100}Ru and ^{102}Ru isotopes respectively at different spins and temperatures performed with the tuned spin cranked Nilsson Strutinsky method. We see from Fig.1 that at T=0.0 MeV, the ^{96}Ru has spherical shape at its ground state (I=0 ħ) with deformation β=0.0 and which remains in

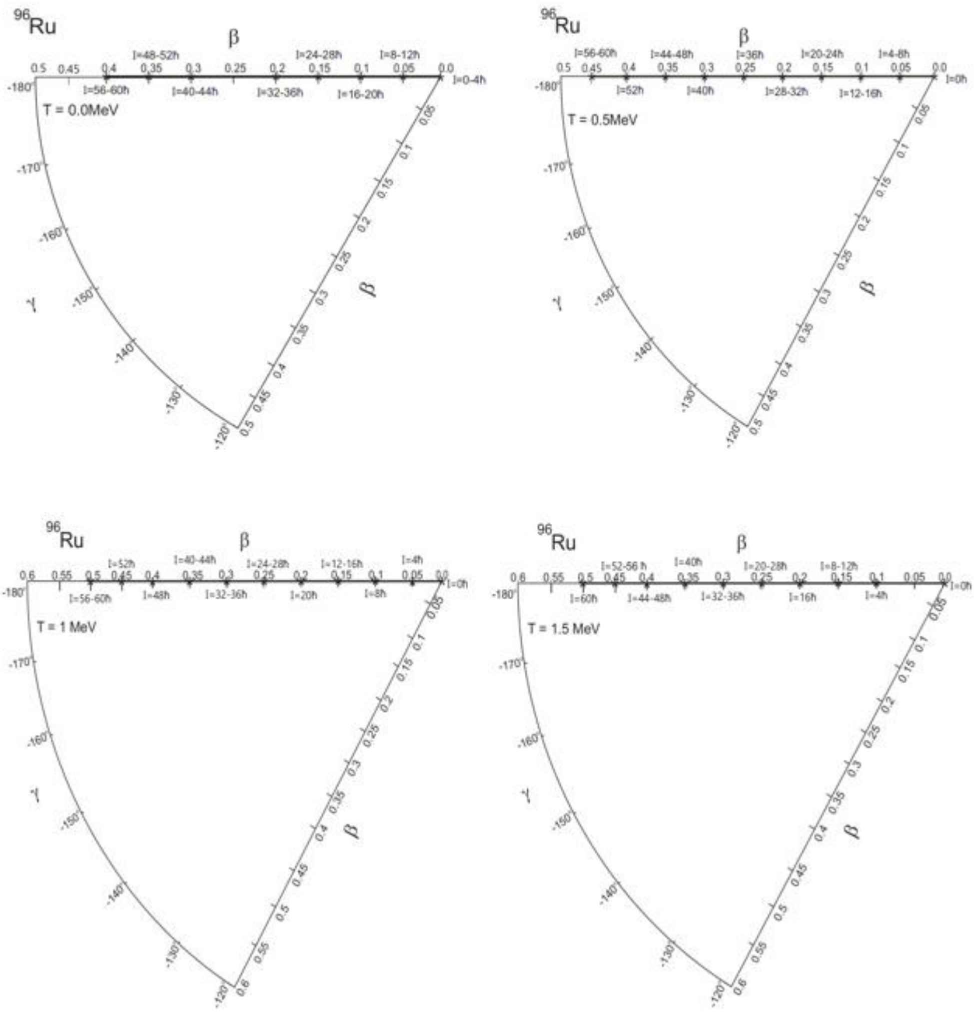

Fig. 1. Shapes of 96Ru isotope as a function of spin at different temperatures

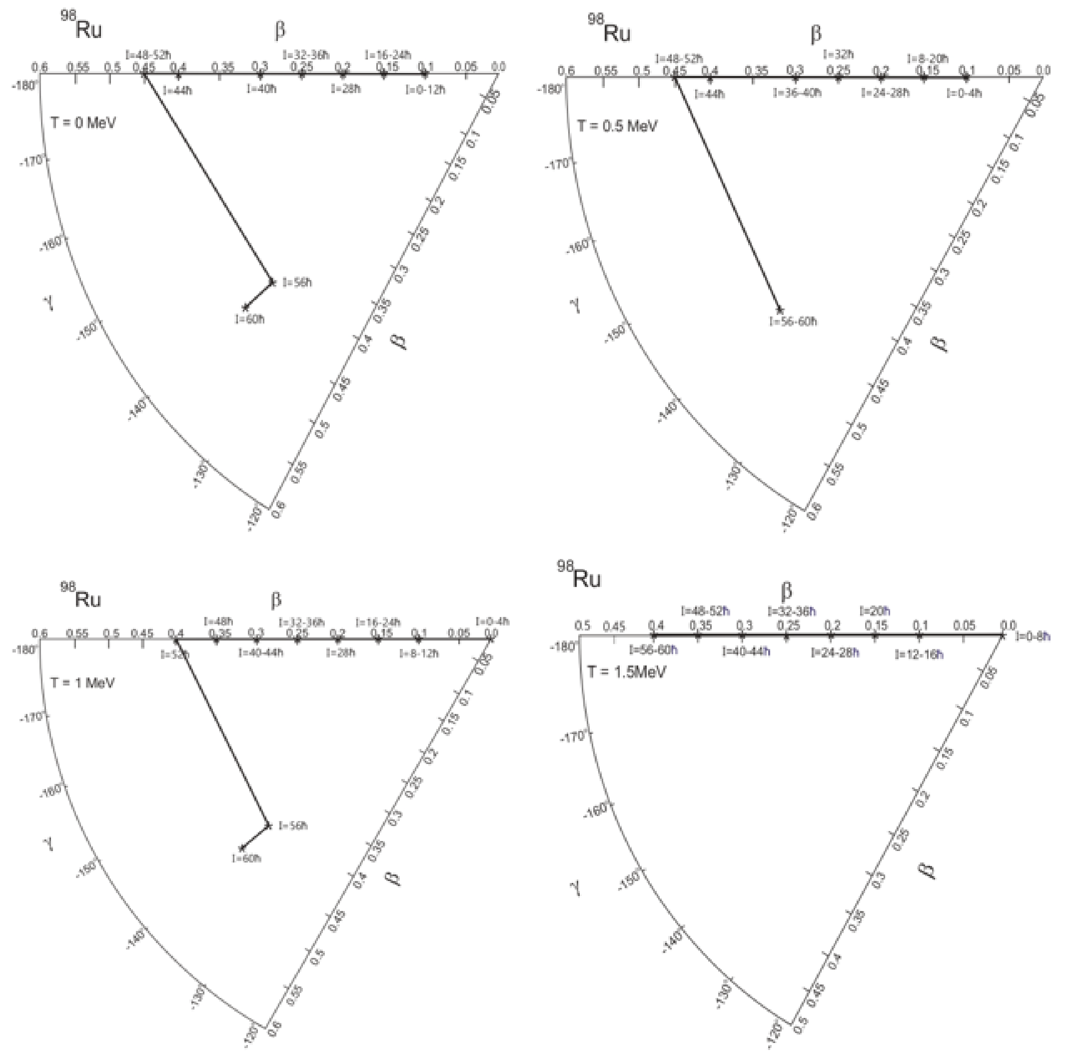

Fig. 2. Shapes of 98Ru isotope as a function of spin at different temperatures

spherical up to I=4 ħ. As spin increases there is a shape transition to oblate shape at I=8 ħ and which persists in the same shape with increased deformation for the further increase of spin up to I=60 ħ. When temperature is included, that is at T=0.5-1.5MeV, the ^{96}Ru nucleus initially in spherical shape with I=0 ħ become oblate at high spin but the transition occurs at I=4 ħ.

It is noted from Fig. 2 that the ^{98}Ru nuclei is oblate at its ground state with T=0.0 MeV, I=0 ħ and β=0.0, which persists in the same shape up to I=52 ħ with increased deformation. As spin increases it undergoes triaxial shape (γ=-140^0) and stays in triaxial with little elongation of increased deformation. Almost the same trend is obtained for ^{98}Ru at T=0.5 MeV with elongation occurs at earlier spin values leading to triaxial (γ=-140^0) finally. For the case of ^{98}Ru at T=1.0 MeV, the shape at spin I=0 ħ is spherical and then transition occurs to oblate and then triaxial at higher spins. At T=1.5 MeV spherical to oblate transition occurs as a function of spin and transition to triaxiality vanishes.

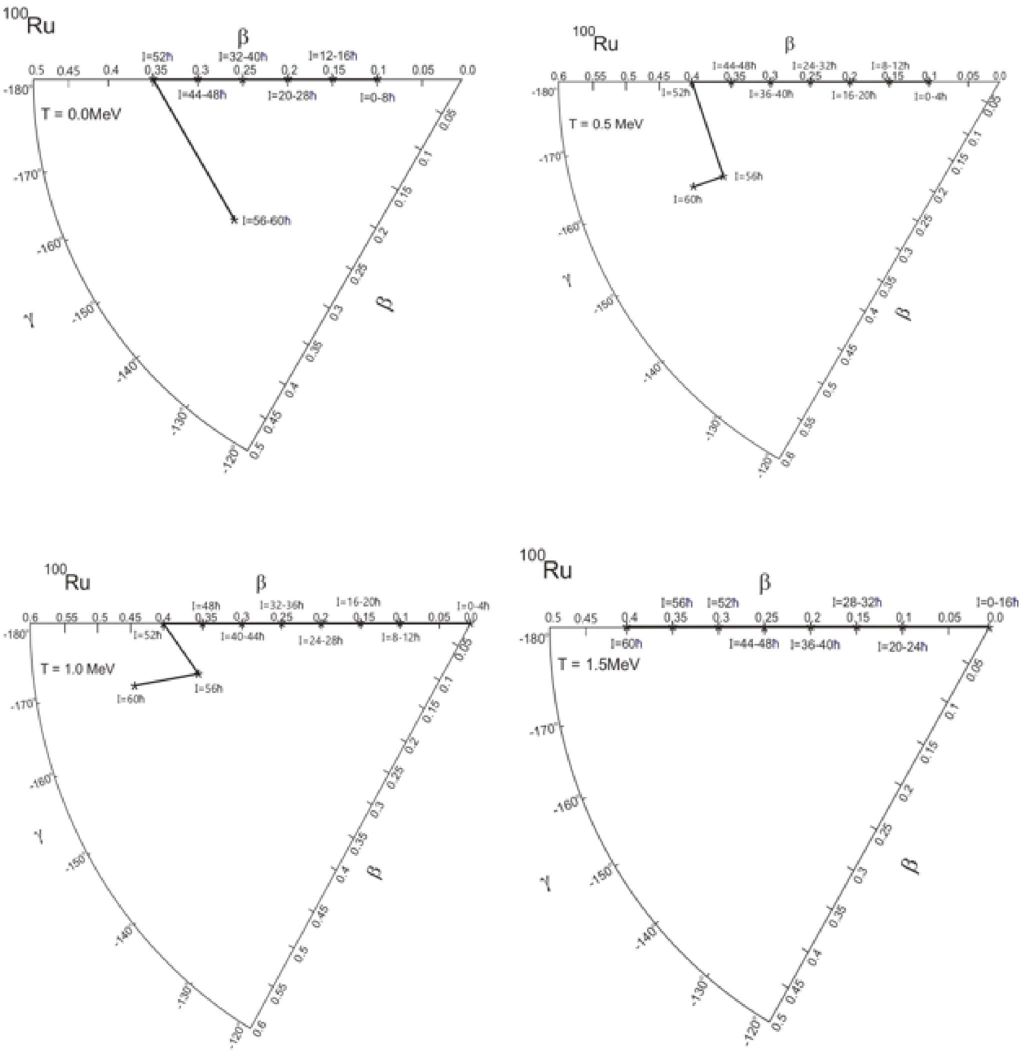

Fig. 3. Shapes of 100Ru isotope as a function of spin at different temperatures

From Fig. 3 it is noted that the ^{100}Ru nuclei is oblate at its ground state with T=0.0 MeV, I=0 ħ and β=0.0, which persists in the same shape up to I=52 ħ with increased deformation. As spin increases it undergoes triaxial shape (γ=-150^0) and stays in triaxial. Almost the same trend is obtained for ^{100}Ru at T=0.5 MeV with elongation occurs at earlier spin values leading to triaxial (γ=-160^0) finally. For the case of ^{100}Ru at T=1.0 MeV, the shape at spin I=0 ħ is spherical and then transition occurs to oblate and triaxial (γ=-170^0) at higher spins. At T=1.5 MeV spherical to oblate transition occurs as a function of spin and transition to triaxial vanishes.

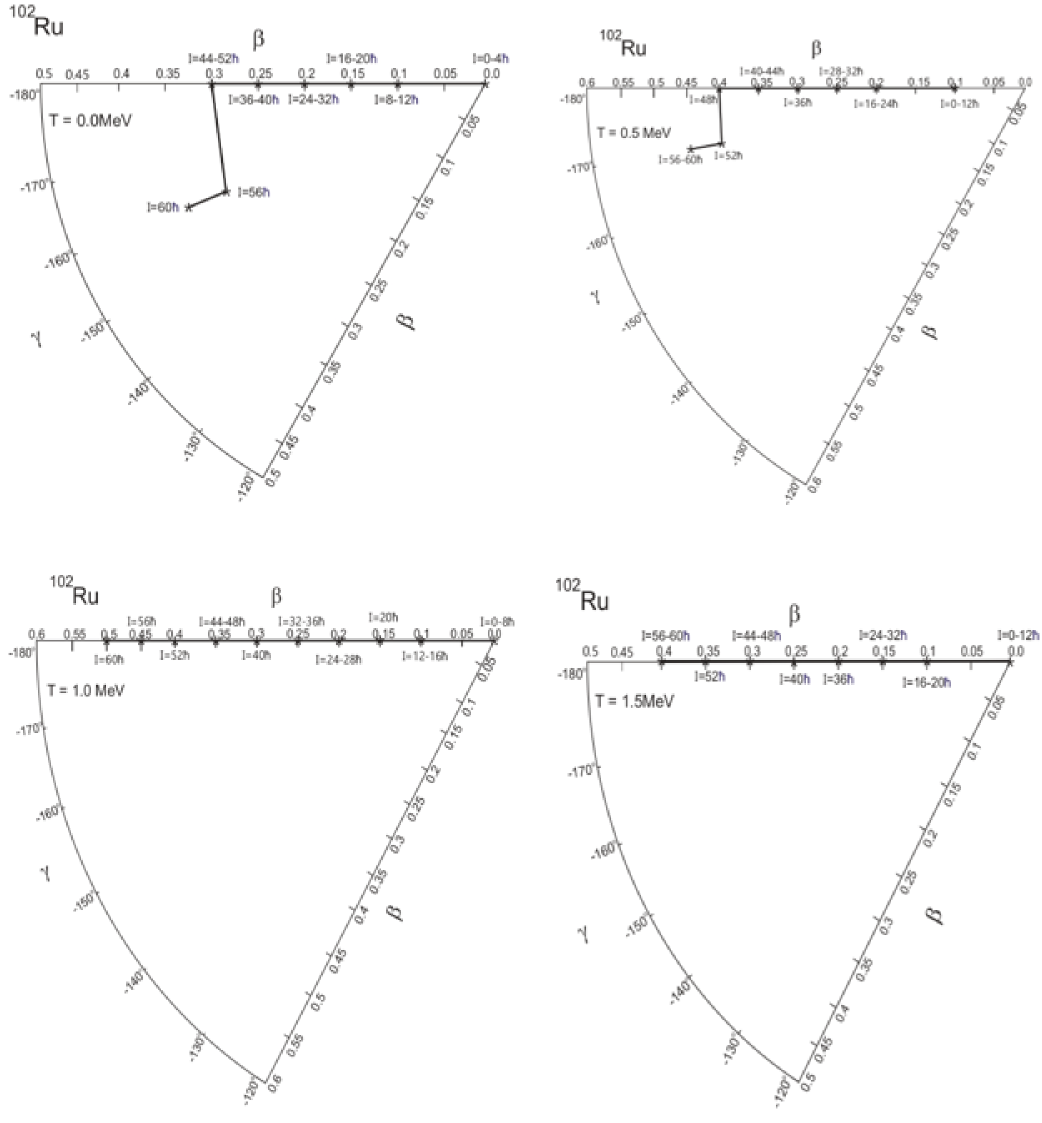

Fig. 4. Shapes of 102Ru isotope as a function of spin at different temperatures

If we look at Fig.4, at T=0.0 MeV, the ^{102}Ru nuclei has spherical shape at its ground state (I=0 ħ) with deformation β=0.0 and which remains in spherical up to I=4 ħ. As spin increases there is a shape transition to oblate shape at I=8 ħ and which persists in the same shape with increased deformation for the further increase of spin up to I=52 ħ. As spin increases it undergoes triaxial shape (γ=-160^0) and stays in triaxial with little elongation of increased deformation. When temperature is included, that is at T=0.5 MeV, the ^{102}Ru nucleus initially in oblate shape with I=0 ħ become triaxial (γ=-170^0) at I=52 ħ and stays in triaxial with elongation on further increase of spin. But at high temperatures T=1.0-1.5 MeV, a spherical to oblate transition as a function of spin is obtained. Thus it is to be noted from the above discussion that the ruthenium nuclei starting from spherical or oblate shape becomes oblate or triaxial as a function of spin and temperature which is in conformity with the experimental and theoretical results [3,4,30].

3.2 Giant Dipole Resonance in Ruthenium isotopes

We present our results of GDR calculations for the case of ^{96}Ru, ^{98}Ru, ^{100}Ru and ^{102}Ru isotopes in Figs. 5-8 respectively. For spherical shape of a nucleus, there is only one Isovector Giant Dipole Resonance (IVGDR) frequency in the intrinsic or the laboratory frame. But for prolate and oblate shapes, we have two frequencies in the nonrotating case, the splitting being caused by static deformation. When such nuclei start rotating, the two frequencies will divide into three in the intrinsic frame. These three modes observed in the intrinsic system divide, in the laboratory frame, into five frequencies for the prolate case while the transformation to the laboratory frame just brings the frequencies back to coincide with their original values at zero rotation for oblate system rotating about the symmetry axis. This expected behavior is clearly brought out in Figs. 5-8. In ^{96}Ru, (see Fig. 5) the frequency splitting has only one component for its spherical shape and which has two components when it undergo oblate shape rotating about the symmetry axis. But this behavior changes in ^{98}Ru (see Fig. 6). For this nucleus, the splitting has five, one as well as two components depending upon the spherical or oblate shapes rotating about the symmetry axis at different spins and temperature. If we consider the effect of temperature alone, we see that the width fluctuations vanish at T=1.5 MeV itself in the case of ^{98}Ru. The same trend of frequency splitting reflecting the shape transitions in ^{100}Ru and ^{102}Ru as a function of spin and temperature is clearly seen in figures 7-8. The general broadening of IVGDR widths with excitation is clearly seen in all the cases considered.

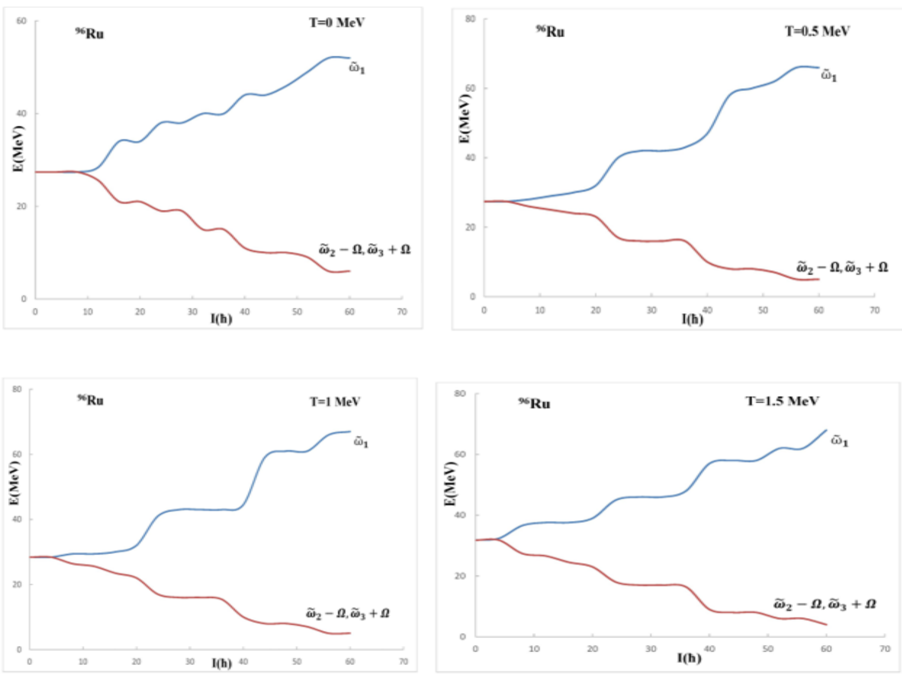

Fig. 5. Dependence of the isovector giant dipole energy E on the angular momentum I for

96Ru isotope at different temperatures.

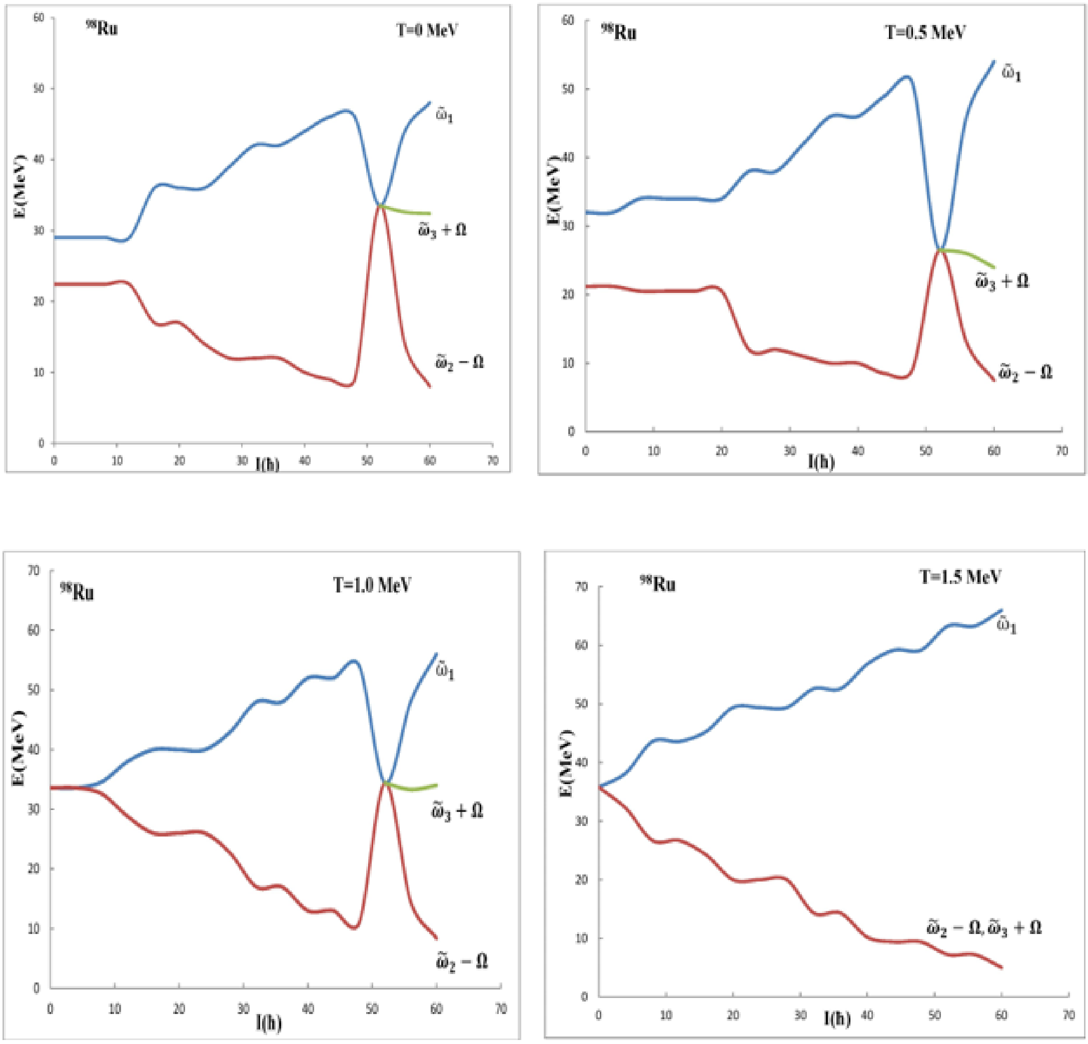

Fig. 6. Dependence of the isovector giant dipole energy E on the angular momentum I for 98Ru isotope at different temperatures.

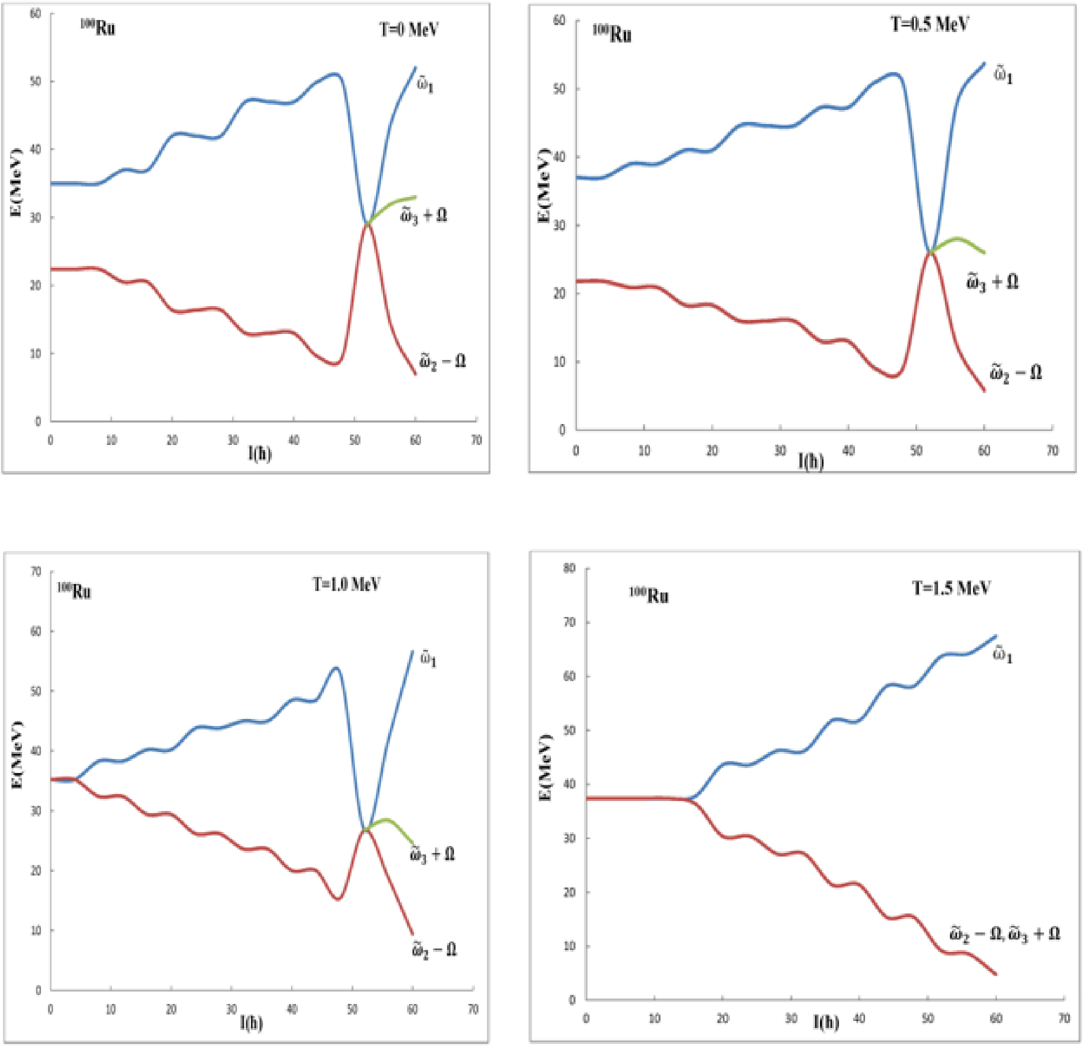

Fig. 7. Dependence of the isovector giant dipole energy E on the angular momentum I for 100Ru isotope at different temperatures.

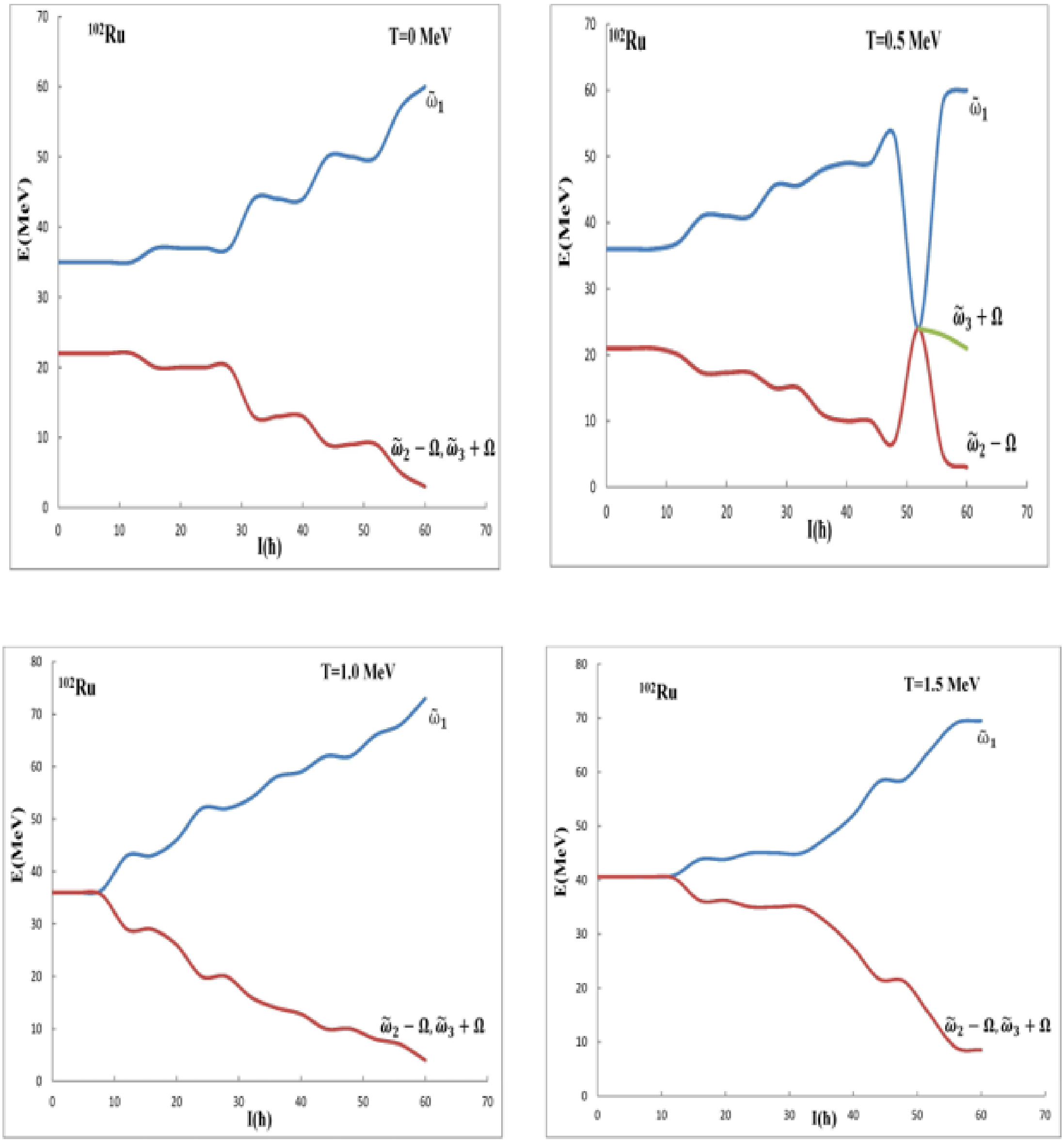

Fig. 8. Dependence of the isovector giant dipole energy E on the angular momentum I for 102Ru isotope at different temperatures

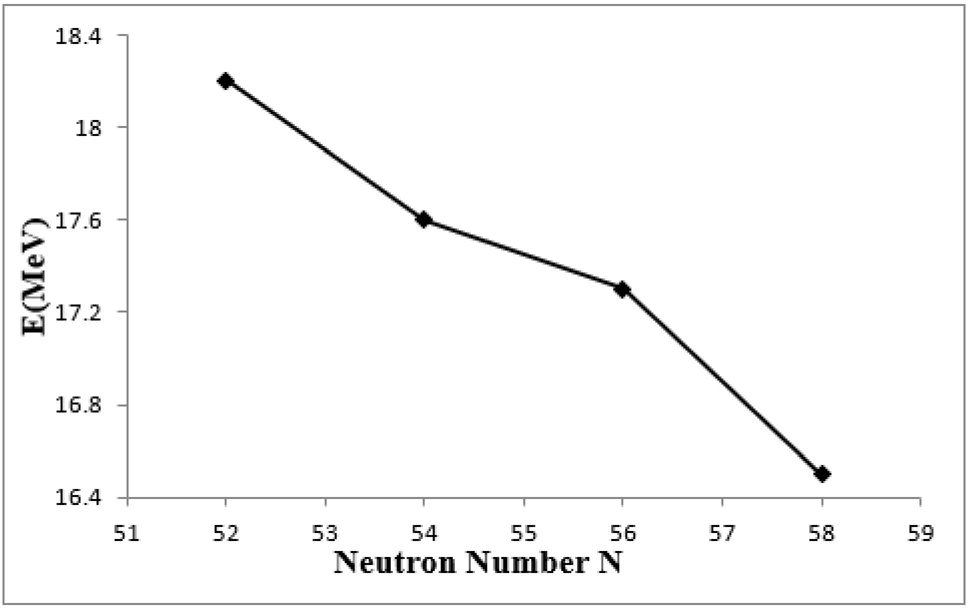

Fig. 9. IVGDR energies as a function of neutron number for 96-102Ru

Fig.9 shows the Isovector Giant Dipole Resonance (IVGDR) energies as a function of neutron number for the case of ^{96}Ru, ^{98}Ru, ^{100}Ru and ^{102}Ru isotopes. It is seen that the deformation energy decreases as function of neutron number.

4. Conclusion

In this work the isovector giant dipole resonances (IVGDR's) are extensively studied in rapidly rotating hot ruthenium isotopes using a rotating anisotropic harmonic oscillator potential and a separable dipole - dipole residual interaction. The shape and deformation of the above nuclei at high spins are determined by the cranked Nilsson – Strutinsky method extended for rotating medium mass nuclei. The results obtained show the general splitting of the frequencies of GDR at high spin and broadening of widths of frequencies in these nuclei increases on further increase of spin. The influence of temperature on the isovector giant dipole resonance is assumed to occur through the change of deformation of the average field only. The deformation energy is found to decrease as function of neutron number. The results obtained show the general splitting of the frequencies of GDR at high spin and broadening of widths of frequencies in these nuclei increases on further increase of spin. It is seen that the width fluctuation present at T = 0, vanish at higher temperatures in these isotopes. Since this behaviour is found to be common in these isotopes, it may be noted that the role of temperature on shell effects do not affect the isovector giant dipole resonance widths in these isotopes at higher spins. Broadening of the giant dipole resonance as A as well as I increases is observed which is in good agreement with the experimental observations [30]. Our results show the increasing widths of the IVGDR's at higher angular momenta as being mainly due to dynamical deformation effects caused by rotation.

To sum up, in this work we have chosen four ruthenium isotopes which are spherical, oblate at the ground state stays in oblate for some cases and becomes triaxial in some other cases as a function of spin and temperature. The IVGDR frequencies clearly reflect the shape transitions. Thus it can be noted that the GDR is ascribed as a signature for the shape transitions in the considered ruthenium nuclear isotopes.

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