Structural properties of hot rotating \(^{40}\)Ca

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The yrast and yrare lines are obtained for \(^{40}\)Ca using a statistical method by assuming the nucleons to move in a triaxially deformed Nilsson harmonic oscillator potential. The backbending and yrast traps are observed in the case of \(^{40}\)Ca at certain spins. A shift in the first yrast minima towards higher angular momentum states with an increase in entropy is observed. A second backbending is found to occur at spin \(M = 17\hbar\) for all entropies. The excitation energy, the nuclear level density, the single-particle level density parameter, and the spin cutoff parameter are determined as functions of temperature and angular momentum by minimizing the free energy. The Strutinsky method is used to study the variation of the shell correction with angular momentum for equilibrium shapes. The Fermi energies obtained as a function of angular momentum are used for calculating this shell correction. The nucleus is found to be spherical up to \(M = 6\hbar\) and becomes oblate with a further increase in angular momentum. The shell correction is found to increase with the deformation having a minimum value for the spherical shape. [S0556-2813(97)05703-8]

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In spite of many realistic single-particle models being developed for the study of excited nuclei, there is a conceptual difficulty in treating an excited nucleus because of the possibility of the excited nucleus having different deformations. The effect of these deformations [1] on nuclear properties such as nuclear level density, single-particle level density parameter, spin cutoff parameter, and shell effects is to be investigated in detail. These thermodynamic properties can be best studied using the methods of statistical mechanics adopted by Moretto [2–4]. The statistical theory [5,6] involves the shell structure of the nucleus, and hence it is more suitable for studying the properties of the excited nucleus. The nucleus excited in the statistical region will have a very large energy dispersion compared to the level spacing, and for such a nucleus the definition of the deformation is more complicated. Further, there may be a coupling between collective and intrinsic degrees of freedom due to the overlapping of levels. There may be statistical equilibrium between all the degrees of freedom, and the nucleus is expected to explore all the deformations accessible to it based on the excitation energy [7].

In this work, an attempt has been made to study the high spin structure of \(^{40}\)Ca since the microscopic structure of this \(sd\)-shell nucleus is well-known. It exhibits rotational alignment and backbending effects as the heavy nuclei. The inputs for the statistical theory are the microscopic single-particle levels and single-particle spins corresponding to the triaxially deformed Nilsson harmonic oscillator potential [8]. Naturally, the results reflect the effect of the shell structure of the nucleus at different deformations. The \(K,\alpha\) pair used for generating the single-particle level scheme is as given in Ref. [9]. These parameters are appropriate since an agreement between Strutinsky's smoothed moment of inertia and the rigid rotor value [10] is obtained by Diebel et al. [9]. The deformation parameter \(\delta\) is varied from \(\delta = 0.0\) to 0.6 with \(\Delta\delta = 0.1\) for \(\theta = -180^\circ\) [11,12] corresponding to an oblate shape with the nucleus rotating around the symmetry axis. The levels generated up to \(N = 6\) are found to be sufficient for the range of temperatures used in this work. It is found that even for large deformations there are shell gaps in the nucleon level scheme. The cranking frequency \(\omega\) is taken to be zero, and the angular momentum is generated by means of the Lagrangian multiplier \(\gamma\) occurring in the statistical theory. This procedure is valid for rotation around the symmetry axis where the spin projection \(m_j\) is a good quantum number. Calculations are carried out by minimizing the free energy for equilibrium deformation. By solving the conservation equations for the proton number, the neutron number, and the total angular momentum \(M\) along the \(Z\) axis for a given temperature \(T = 1/\beta\), the Lagrangian multipliers \(\alpha_z\), \(\alpha_n\), and \(\gamma\) corresponding to these are determined.

The conservation equations [12] in terms of the single-particle energies are

\[
\langle Z \rangle = \sum n_i = \sum [1 + \exp(-\alpha_z + \beta \epsilon_i + \gamma m_i)]^{-1},
\]

\[
\langle N \rangle = \sum n_i^p = \sum [1 + \exp(-\alpha_n + \beta \epsilon_i^p + \gamma m_i^p)]^{-1},
\]

\[
\langle M \rangle = \sum n_i^p m_i^p + \sum n_i m_i^f,
\]

where \(n_i\) is the occupation probability of the \(i\)th shell.

The Lagrangian multipliers \(\alpha_z\) and \(\alpha_n\) determine the Fermi energies for the protons and neutrons, respectively.
These Fermi energies are very important for the calculation of the shell correction since the shell correction is very sensitive to the density of the single particle levels near the Fermi energy. The shell level density near the Fermi energy oscillates periodically as a function of deformation, and this is highly pronounced in magic and midshell nuclei [13]. The Fermi energies determined as a function of spin are used in the calculation of the shell correction as a function of spin using the Strutinsky prescription [13,14].

The Strutinsky shell correction [2,13] is given as

$$\delta U = U - \overline{U},$$

where the sum of the single-particle energies is

$$U = \sum_i 2\varepsilon_i,$$

with the sum over all occupied states. The smoothed shell model energy is

$$U = 2\int_{-\infty}^{\lambda} g(\varepsilon) d\varepsilon.$$  

The Gaussian smoothed single-particle level density is

$$g(\varepsilon) = \frac{1}{\sqrt{\pi} \gamma} \sum_i f_k \exp\left[-\left(\varepsilon - \varepsilon_k\right)^2/\gamma^2\right],$$

where $\varepsilon_k$ are the single-particle levels and $\gamma$ is the width of the smoothing function. The function $f_k$ is chosen to retain the variations up to the fixed order $\delta$ as in Ref. [2]. The quantity $\lambda$ is the Fermi energy which is determined as a function of angular momentum from the conservation equations for the number of particles using statistical theory.

The variation of the excitation energy of the yrast levels as a function of angular momentum and the associated backbending features [11] are investigated for $^{40}$Ca. The excitation energy is determined using the expression

$$E^*(M,T) = \left[\sum n_i^2\varepsilon_i - \sum_{i<j}^2 \varepsilon_i \varepsilon_j\right] + \left[\sum n_i^2\varepsilon_i^2 - \sum_{i<j}^n \varepsilon_i^2 \varepsilon_j\right]$$

for equilibrium deformation where the summations in the first and third terms is carried over all the levels generated up to $N=6$ for the triaxial Nilsson potential.

The entropy is obtained as

$$S = -\sum [n_i \ln n_i + (1-n_i) \ln(1-n_i)].$$

The spin-dependent rotational frequency $\omega_\delta$ is obtained using the expression [15,16].

$$M = \delta E_{\text{rot}} / \delta \sqrt{M(M+1)} = \left[E(M) - E(M-2)/2\right]$$

for various angular momenta. The rotational frequencies as a function of angular momentum are calculated by keeping the entropies to be constant and by minimizing the free energy for equilibrium shapes. The rotational frequencies for various angular momenta are also calculated for fixed temperatures.

The nuclear level density [17] is

$$\rho(M,E^*) = \beta \exp S(M,E^*),$$

where $S$ is the dimensionality of the phase space, which is the number of eigenstates used [18]. The single-particle level density parameter is calculated using the relation

$$a = S^2/4E^*.$$  

The spin cutoff parameter is estimated from the rotational energy for various temperatures from the expression

$$\sigma^2 = T(\omega_\delta^2),$$  

where the moment of inertia is given by the relation

$$J = h^2 M(\partial E_{\text{rot}}/\partial M).$$

The rotational energies are calculated using the relation

$$E_{\text{rot}} = E(M,T) - E(0,T)$$

for different angular momenta at a given temperature for minimized deformation parameter $\delta$.

The change in Fermi energy, $\Delta \varepsilon$, as a function of temperature and angular momentum is displayed in Fig. 1. No distinction has been made between the protons and neutrons since the same level scheme is used for both. The calculated Fermi energies correspond to equilibrium shapes of $^{40}$Ca at a given temperature and angular momentum. It is found that initially the Fermi energy increases with temperature, reaches a maximum, and with a further increase in temperature this increase in Fermi energy is reduced for a given angular momentum. It is also evident that as the angular momentum increases, the Fermi energy is lowered at a given temperature. However, in the temperature range 0.7-1.3 MeV for a very high spin of $M=24h$ the fluctuation in the
Fermi energy is due to the oscillations in the oblate shape of $^{40}$Ca between $\delta=0.3$ and $\delta=0.5$. For spins above $M=6\hbar$, the nucleus is oblate, while it is spherical up to $M=6\hbar$. The maximum change in Fermi energy occurs at zero spin for low temperatures. This maximum change in Fermi energy takes place up to the midvalue 2.5 MeV of the energy gap $=5\text{ MeV}$ between the last filled level $d_{3/2}$ and the next higher level $f_{7/2}$ [9].

Figure 2 shows the dependence of the shell correction on deformation and angular momentum for $^{40}$Ca calculated using Strutinsky's prescription. The shell corrections calculated for spherical and oblate deformations are displayed in the figure. It is found that the shell correction fluctuates around 0 MeV for $\delta=0.0$ (spherical), around 21 MeV for $\delta=0.1$, and around 8 MeV for $\delta=0.2$. For a higher oblate deformation $\delta=0.4$, the shell correction fluctuates around $-8\text{ MeV}$ below $M=12\hbar$, reaches a very high value at $M=12\hbar$, and fluctuates around $+12\text{ MeV}$ above $M=12\hbar$. This sudden increase in the shell correction at $M=12\hbar$ for $\delta=0.4$ is due to the chemical potential reaching the midvalue of the energy gap between the last filled level $d_{3/2}$ and the next higher level $f_{7/2}$. It is to be noted that Fig. 2 does not correspond to equilibrium deformations. These curves are drawn to investigate the dependence of the shell correction on deformation. The value of the smoothing parameter for this calculation is chosen to be 1.3 $\hbar\omega$. It is evident that the shell nonuniformities in the energy distribution of the nucleons do not disappear in the deformed nucleus [14].

The shell correction calculated for $^{40}$Ca as a function of angular momentum for realistic equilibrium deformations is depicted in Fig. 3. The dashed lines in the figure correspond to the spherical shape, whereas the solid lines correspond to the equilibrium shape for the smoothing parameter $\gamma=1.6\hbar\omega$. It is found that the spherical shape gives rise to fluctuations in the shell correction, oscillating around 0 MeV for all spins. However, as a result of the shape transition from spherical ($\delta=0.0$) to oblate ($\delta=0.1$) at $M=7\hbar$, the shell correction shoots up and starts oscillating around 6 MeV up to $M=18\hbar$. For higher spins above $M=18\hbar$, the nucleus becomes highly deformed, corresponding to the oblate deformation $\delta=0.4$, and the shell correction for these spins oscillates around 7.5 MeV. This leads us to conclude that the shell correction increases with an increase in deformation and it is minimum for a spherical shape.

Figures 4 and 5 represent the excitation energy $E^*$ for the hot rotating $^{40}$Ca plotted against the Z projection of the angular momentum for constant entropies and constant temperatures, respectively. These lines for the various values of the entropies show systematic dips at specific spin values.
indicating structural changes in the rotating nucleus which may be associated with the shape transitions of the nucleus. It is predicted that the nucleus may well be trapped in these pockets in the process of deexcitation along the constant-entropy lines. Consequently, a sudden change in the moment of inertia of the nucleus occurs around these values of $M$, leading to the backbending phenomenon. The lowest entropy line corresponds to the yrast line; and the higher entropy lines are the yrare lines. The striking observation is that the pockets of minima of the excitation energy shift from $M=7\hbar$ to $M=9\hbar$ for various excitations of the nucleus as the energy increases from $S=6$ to $S=24$. This type of peculiar behavior has not been hitherto reported for $^{40}\text{Ca}$. As the excitation energy and consequently the entropy increase, the energy minimum in the deformation plane shifts towards larger values, causing the minima to occur at higher angular momentum states. This reflects the interplay between the effects of temperature, spin, and deformation. This interplay between the different degrees of freedom causes the particles to occupy higher levels $\varepsilon_f > \varepsilon_F$, at the same time increasing the spin of the nucleus. This interplay is reflected through the Lagrangian multipliers $\alpha$ and $\gamma$. The excitation energy $E^*$ when $M=0$ is the excitation energy for the nonrotating nucleus and is purely due to the temperature of the nucleus. Comparing the present set of curves with those of or et al. [19], we conclude that for cold $^{40}\text{Ca}$ there is no yrast line limitation of fusion formed from the fusion reaction $^{16}\text{O}+^{24}\text{Mg}$. But for a hot nucleus, there is a yrast line limitation of fusion at a given entropy since the phase space available for the hot nucleus is determined by the entropy. These curves help us in determining the yrast line limiting value of entropy at which the fusion of $^{16}\text{O}+^{24}\text{Mg}$ may occur to form $^{40}\text{Ca}$. In a recent series of experiments at Seattle [20], statistical giant dipole resonance decays in a wide range of excited nuclei from $A=24$ to 66 have been studied. In these experiments most of the compound nuclei were found at initial excitation energies $E^*$ between 35 and 52 MeV and spins in the range of $0\hbar$–$25\hbar$. Thus it is better to consider not only the yrast line for comparing with empirical fusion bands, but also the yrare lines at different temperatures. The entropy line at $S=21$ roughly corresponds to the experimental observation [19], and it is expected that the $^{40}\text{Ca}$ formed from fusion should finally end up with an excitation energy $E^*=30$ MeV at $M=0\hbar$. It is found that the constant-entropy lines are roughly at constant energy above the yrast line of the cold nucleus, in agreement with the observation of Newton [21].

Figure 5 shows the excitation energy as a function of angular momentum for various constant temperatures. It is seen that for $^{40}\text{Ca}$ only the yrare lines up to $T=2.4$ MeV are relevant for considering fusion limitation of $^{16}\text{O}+^{24}\text{Mg}$.

Figure 6 shows the angular momentum $\sqrt{M(M+1)}$ versus the spin-dependent rotational frequency $\omega_M$ for temperatures $T=1, 2,$ and $3$ MeV for $^{40}\text{Ca}$. The spin cutoff parameter determined from the rotational frequency is plotted in Fig. 7 as a function of angular momentum at different temperatures. The spin cutoff parameter for different temperatures shows deviations at spin values in the range $M=8\hbar$–$12\hbar$, which may be suggestive of the dis-
FIG. 7. Variation of spin cutoff parameter with angular momentum for different temperatures in the case of $^{40}$Ca.

FIG. 8. Single-particle level density parameter as a function of temperature and angular momentum for $^{40}$Ca.

FIG. 9. Dependence of the nuclear level density on excitation energy for various angular momenta in $^{40}$Ca.

tortions caused by the oblate noncollective states.

The single-particle level density parameter as a function of temperature and angular momentum is presented in Fig. 8 for $^{40}$Ca. It is evident that at low temperatures the single-particle level density parameter increases sharply and at higher temperatures of about $T=4$ MeV it reaches the constant value $=\Lambda/10$, predicted experimentally [22,23].

Assuming that all states with the excitation energy $E^*$ are equally populated, the nuclear level density can be expressed as a function of excitation energy. Figure 9 shows the logarithm of the nuclear level density as a function of $E^*$ for various spins.

It is found that the nuclear level density increases with excitation energy for all spins. For building up higher spins at a given nuclear level density, a higher excitation energy is needed.

In this paper we have studied the high spin properties of $^{40}$Ca under extreme conditions of temperature and deformation. The interplay between the various degrees of freedom has been investigated. The pairing correlations are not included in this work since pairing effects are generally absent and the deformation behavior of a rotating nucleus is quite insensitive to the presence of pairing in magic nuclei.

Comparison of our calculations here with the experimental fusion data helps us to predict the valid limits of temperature and entropy for forming $^{40}$Ca by the fusion of $^{16}$O+$^{24}$Mg. It is to be mentioned that entrance channel effects are not included here. This is because of the fact that though the entrance channel properties are important for heavy-ion-induced fusion reactions [24], the situation is not so dear in light nuclei.
SURFACE TENSION CONSTANT AS A FUNCTION OF SURFACE DIFFUSENESS IN $^{16}$O

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The nuclear matter is an infinite system of nucleons with uniform distribution in the interior. However with the density falling enormously near the surface the bulk properties of the nuclei are altered. Various approaches [1-3] had been made to investigate the effect of surface diffuseness on the bulk properties of nuclei. In this work the dependence of surface tension constant on nuclear surface thickness is presented in the case of $^{16}$O.

The free energy of the nucleus in terms of the shell energies $\varepsilon_k$ at zero temperature is

$$\Omega = \sum \varepsilon_k + 4\pi R^2 S$$

Where $S$ is called the surface tension constant in analogy with classical consideration. The surface term which has been neglected in the generation of single particle states arises due to the two body interaction. This acts as the restoring force against the internal pressure of the system. The single particle energies and wavefunctions are obtained by numerically solving the Schroedinger equation for the bound states of $^{16}$O using the phenomenological Saxon – Woods potential form and parameters fitted to experimental elastic scattering cross-section by Elton and Swift [4]. The surface tension constant is determined using the equilibrium condition at finite nuclear saturation density at equilibrium radius $R_o$ as

$$\left. \frac{\partial \Omega}{\partial R} \right|_{R = R_o} = 0$$

The surface tension constant then becomes

$$\dot{S} = - 1/8\pi R_o \sum \varepsilon_k \left. \frac{\partial \varepsilon_k}{\partial R} \right|_{R = R_o}$$
The factor $\frac{\partial \varepsilon_k}{\partial R}$ is calculated from the numerically generated derivative of the potential and the wavefunctions using the Hellman - Feynmann theorem as

$$\sum \frac{\partial \varepsilon_k}{\partial R} = \sum \int \psi_k^* \frac{\partial V}{\partial R} \psi_k \, d\vec{r}$$

We have used the potential parameters of Elton and Swift [4].

Surface tension constant as a function of surface diffuseness is depicted in Table

Variation of Surface Tension Constant with surface diffuseness in $^{16}O$

<table>
<thead>
<tr>
<th>Diffuseness parameter in fm</th>
<th>$\sum \frac{\partial \varepsilon_k}{\partial R}$ MeV/fm</th>
<th>Surface Tension Constant in MeV/fm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>163.06</td>
<td>1.866</td>
</tr>
<tr>
<td>0.3</td>
<td>169.47</td>
<td>1.939</td>
</tr>
<tr>
<td>0.4</td>
<td>173.66</td>
<td>1.976</td>
</tr>
<tr>
<td>0.45</td>
<td>174.58</td>
<td>1.985</td>
</tr>
<tr>
<td>0.55</td>
<td>174.32</td>
<td>1.978</td>
</tr>
<tr>
<td>0.65</td>
<td>171.53</td>
<td>1.943</td>
</tr>
<tr>
<td>0.75</td>
<td>166.95</td>
<td>1.887</td>
</tr>
<tr>
<td>0.85</td>
<td>161.18</td>
<td>1.817</td>
</tr>
<tr>
<td>0.95</td>
<td>154.73</td>
<td>1.740</td>
</tr>
</tbody>
</table>

It is evident that surface tension constant increases with increase in the diffuseness parameter ‘a’ and almost remains a maximum around the experimentally fitted value of the diffuseness parameter, thereafter decreasing with increase of the diffuseness parameter.

References


DEFORMATION DEPENDENCE OF EXCITATION ENERGY FOR HOT ROTATING $^{40}$Ca

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In this work, the variation of excitation energy with angular momentum in hot rotating $^{40}$Ca is investigated for various deformations using Statistical theory [1]. The nucleons are assumed to move in a triaxially deformed Nilsson potential [2]. The single particle energies and the single particle spins are generated by diagonalizing the triaxial Nilsson Hamiltonian in cylindrical representation using the parameters $K$ and $\mu$ given in [3].

By solving the conservation equations for particle number and spin, the occupation probabilities for the various single particle levels are calculated. The total energy of the system in calculated using the expression

$$E_{\text{tot}} = \sum_i n_i \epsilon_i$$

The excitation energy of the system is given by,

$$E_{\text{tot}}(M,T) = E_{\text{tot}}(M,T) - E_0$$

Where the ground state energy is,

$$E_0 = \sum_i \epsilon_i$$

The figure shows the variation of excitation energy with angular momentum for various deformations. $\epsilon=0.2$, 0.4 and 0.6. The value of the deformation parameter $\epsilon$ is chosen to be -180' corresponding to the oblate deformation. The cranking frequency $\omega$ is taken to be zero. The $Z$ - projection of the angular momentum is generated using a spin conserving Lagrangian multiplier.

Figure shows the excitation energy as a function of angular momentum for various deformations. The solid lines correspond to a low
temperature of $T = 0.5 \text{ MeV}$ while the dashed lines correspond to $T = 2 \text{ MeV}$.

It is found that at both these temperatures, the excitation energy increases with angular momentum. For a given spin and deformation the excitation energy is naturally greater for higher temperatures. For spins greater than $M = 12h$, the excitation energy shows a decrease with increasing deformation. But for spins less than $12h$ and for higher temperature, a very high deformation $\epsilon = 0.6$ leads to a lower excitation.

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FERMI ENERGY DEPENDENCE ON TEMPERATURE AND ANGULAR MOMENTUM IN $^{40}$Ca.

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The variation of Fermi energy $E_F$ as a function of temperature and angular momentum is studied using Statistical Theory [2] in $^{40}$Ca nucleus. The nucleons are assumed to move in a triaxially deformed Nilsson harmonic oscillator potential [3]. The calculated Fermi energies correspond to the equilibrium shapes for a given temperature and angular momentum.

The conservation equations for particle number and total angular momentum are solved and the Lagrangian multipliers are determined for each temperature and angular momentum. These Lagrange multipliers fix the Fermi energy and angular momentum.

Figure shows the change in Fermi energy as a function of temperature and angular momentum. It is found that the Fermi energy increases with temperature initially, reaches a maximum and with further increase in temperature this increase in Fermi energy is reduced for a given angular momentum. It is also evident that with increase in angular momentum the Fermi energy is lowered at a given temperature. However for a very high spin of $M=24\hbar$, the observed change in Fermi energy in the temperature range 0.7 MeV to 1.3 MeV is due to the changes in the shape of $^{40}$Ca which is spherical up to $M=7\hbar$ and is oblate with increasing spin.

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SHELL CORRECTION IN $^{40}$Ca AS A FUNCTION OF DEFORMATION AND ROTATION USING STRUTINSKY'S PRESCRIPTION.

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The dependence of shell correction on deformation is one of the oldest in nuclear theory. In this work, an attempt is made to determine the shell correction as a function of deformation and rotation using Strutinsky's prescription[1]. The conservation equations for particle number and spin are solved using Statistical Theory[2] and the chemical potential $\Lambda$ is calculated from the Lagrangian multipliers. Calculations are carried out for various oblate deformations.

The shell correction[1] is given by $\delta U = U - \bar{U}$ where $U$ is the sum of the single particle energies calculated using Nilsson potential[3] for a given deformation, $\bar{U}$ is the uniform single particle energies.

The uniform level distribution function is found using Gaussian distribution involving the smoothing parameter $\gamma$.

The shell correction as a function of angular momentum for spherical and prolate deformations are displayed in the figure. It is found that the shell correction fluctuates about zero Mev for $\epsilon = 0.0$ (spherical), about 2 MeV for $\epsilon = 0.1$, about 8 MeV for $\epsilon = 0.2$ for spin greater than $4\hbar$.

For a higher deformation $\epsilon = 0.4$, below $M=12\hbar$, the shell correction fluctuates about -8 MeV, at $M=12\hbar$, it reaches a very high value and above $M=12\hbar$ it fluctuates about +12 MeV. This sudden increase at $M=12\hbar$ is due to the chemical potential reaching the midvalue of the energy gap between the last filled level and the next higher level. This means that the shell non-uniformities in the energy distribution of the nucleons do not disappear in the deformed nucleus.

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SHELL CORRECTION AND NUCLEAR LEVEL DENSITY IN $^{124}$Ba:
THEIR DEPENDENCE ON ANGULAR MOMENTUM

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The $^{124}$Ba nucleus is investigated using statistical theory\cite{1} for studying the dependence of shell correction and nuclear level density on angular momentum. The nucleons are assumed to move in a triaxially deformed Nilsson potential and the free energy is minimised for equilibrium deformation. The shell correction for Ba is calculated by extending the thermodynamical method of Ramamurthy et al.\cite{2} to rotating nuclei. The excitation energy without rotational energy is calculated\cite{3} from

$$E_{\text{exc}}(M, T) = E(M, T) - E(M, 0)$$

for each angular momentum $M$ at various temperatures. By plotting $S^2$ versus $E_{\text{exc}}$ for each $M$ the shell correction $\Delta E_{\text{shell}}$ is calculated using the relation

$$S^2 = 4\alpha(E_{\text{exc}}(M, T) + \Delta E_{\text{shell}})$$

The intercept on the $E$ axis when large temperature values of $S$ are extrapolated towards lower temperatures gives the shell correction. The variations in shell correction energy as a function of angular momentum is shown in Fig.1. The shell correction shows fluctuations with angular momentum. The nuclear level density is calculated using the relation

$$J^{(N)}(M, E, \delta, \theta) = \exp S(M, E, \delta, \theta)/S_{\text{MAX}}$$

where $S$ is the entropy and $S_{\text{MAX}}$ is the normalisation constant. The variation of nuclear density with angular momentum is shown in Fig.2. It is evident that for building up higher spins at a given nuclear level density a higher excitation energy is needed.

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