Chapter 1

Introduction

The study of the structure of hot rotating nuclei at extreme limits of angular momentum and temperature has been the subject of several publications in nuclear physics. Heavy ion fusion reactions [1-11] are routinely used to populate nuclei with large angular momenta and excitation energies. The very high relative angular momentum of the colliding partners in these reactions is transferred to the final hot compound system as intrinsic spin. Because of the very high excitation, the spacing between the levels is progressively reduced and the nature of the excitation becomes very complicated involving a number of degrees of freedom. The interplay of temperature and spin of the final compound system along with the deformation degrees of freedom [2] provides important and interesting problems such as phase transition, shape transition, shape co-existence and superdeformation for theoretical investigation.

In this thesis work, a statistical theory [12-21] incorporating deformation, collective and noncollective rotational degrees of freedom, shell effects and pairing
correlations (BCS formalism) is used to study

a) the influence of pairing correlations in hot nuclei at low spin,
b) the structural properties of hot nuclei at high spin,
c) the particle emission from hot nuclei at high spin and
d) the structural effects like superdeformation at high spin.

The success of statistical theory in explaining asymptotic fission which is a consequence of shell structure of nuclei and its application in the investigations reported in this thesis provide enough support of its usage. As an extension of Strutinsky’s [22] prescription for extracting shell correction of liquid drop energies, Ramamurthy et al. [1] proposed a statistical method which yielded results as accurate as the former prescription. This fact has proved that the statistical theory of nuclei can yield microscopic as well as macroscopic details. The development of the statistical theory by Bethe [23], Ericson [24], Ignatyuk [25], Moretto [12], and Rajasekaran et al. [15-21] has also resulted in the successful application of this theory to high spin hot nuclei.

The basic ingredient to the statistical theory is a suitable shell model level scheme [26-30] generated for various nuclear deformations. Great care has been taken to choose various parameters involved in the deformed harmonic oscillator Hamiltonian [27, 31] for rotating nuclei in accordance with the experimentally fitted values. Tri-axial deformations are assumed in the diagonalisation of the Hamiltonian depending upon the situation. For all calculations reported in this thesis, single particle data
are obtained by diagonalising nonrotating Nilsson Hamiltonian and Cranked Nilsson Hamiltonian. Methods of obtaining biaxial, triaxial and Cranked Nilsson oscillator levels are described in Chapter 2.

In view of the very high spins possible in the nucleus formed in collisions, the statistical theory of hot rotating nuclei [12-16] is used here. There are two ways of generating angular momentum states in the statistical theory i.e., Statitical Theory of Hot Rotating Nuclei (STHRN) and Cranked Nilsson Model (CNM) for hot rotating nuclei. In the first method formulated by Moretto [12] triaxially deformed single particle levels are used and Lagrangian multipliers project out different angular momentum states of the system from the grand partition function [14, 27, 32]. This method can be applied only for nuclei rotating around the symmetry axis since single particle spin projections are good quantum numbers and the matrix elements of different spin projections $m_z$ do not mix. However this method cannot be applied for the deformed nuclei rotating around an axis perpendicular to the symmetry axis as the single particle spin projections $m_z$ are not good quantum numbers and the matrix elements of the Hamiltonian of a triaxially deformed nuclei connects states of different $m_z$.

In cranked Nilsson model [33-35] the rotational part $\omega \cdot \vec{j}_z$ of the Hamiltonian is diagonalised using oscillator basis, $\omega$ being the rotational frequency. The effect of $\omega \cdot \vec{j}_z$ is to split states with spin projections $\pm m_z$, and for triaxial deformations, the matrix elements for the system connects states of different $m_z$. Since the
Hamiltonian [31,36] for a triaxially deformed nuclei connects states of different \( m_z \), the introduction of \( \mathcal{H} \cdot \vec{J} \) gets contribution from all \( m_z \) states and \( \langle j_z \rangle \) only are known. The mean value \( \langle j_z \rangle \) vanishes when the spins align in a direction perpendicular to the symmetry axis. In this cranking model, the increasing \( \omega \) of the nucleus is accomplished by the rearrangement in the set of occupied states and consequently to get the required angular momentum states the cranking frequency \( \omega \) has to be adjusted and fine tuned together with the temperature. In fact any given spin may be generated for many \((\omega,T)\) pairs. This process though laborious is the correct method of generating the spin both for nuclei around the symmetry axis and for nuclei rotating perpendicular to the symmetry axis.

Chapter 3 outlines the two ways of producing angular momentum states used in the estimation of nuclear properties on the basis of a shell model level sequence with and without the inclusion of pairing correlations. High spin systems are treated in the framework of the statistical mechanics by the inclusion of rotation in the thermodynamic potential. Probably this could be one of the effective ways to treat very high spin nuclei formed in highly excited states in an elegant manner. The methods of statistical mechanics adopted by Moretto [12] are used in this work. The common procedure in statistical mechanics which describes the average behaviour of the compound nucleus and its decay involves the determination of the grand partition function [14, 27, 32] of the system. The Lagrangian multipliers in the grand partition function are fixed by the conservation of proton number, neutron number, total
angular momentum and total energy of the system. The occupational probability in each single particle level is calculated. In this work statistical definitions are employed for calculating entropy, level density etc.

Chapter 4 describes the influence of pairing correlations on the structural properties of hot rotating nuclei such as level density parameter $a$, single neutron separation energy $S_n$ and single proton separation energy $S_p$ using STHRN. These parameters are extracted as a function of angular momentum $M$, temperature $T$, and deformation parameters for superfluid nuclei.

Calculations have been carried out for the nuclei $^{152}Gd$, $^{154}Dy$, $^{156}Er$, $^{164}Er$, $^{168}Yb$, and $^{188}Hg$ with and without pairing correlations [16-19]. It is observed from the results that the influence of pairing reduces the value of level density parameter $a$ and also considerably alters the variation of parameter with respect to angular momentum $M$. The decrease in the values of $a^{BCS}$ because of pairing effect may be due to the smearing out of the single particle occupational probability near the Fermi surface even at low temperature. It is also observed that the values of the neutron separation energy $S_n^{BCS}$ are significantly altered when compared to the values of $S_n$ without pairing correlations. The neutron pairing gap $\Delta_N \to 0$ at angular momentum $M > 20 \hbar$ shows the occurrence of phase transition from superfluid state to normal nuclear state. This pairing collapse may be due to the fact that the collective rotation tends to break the quasi-particle pairs as angular momentum increases. During the phase transition, the fluctuations due to pairing disappear at
temperature $T > 0.6$ MeV and $M > 20 \hbar$. Similar trends are observed for proton separation energy $S_p$, where the fluctuations disappear at $T > 0.5$ MeV and $M > 10 \hbar$. Thus, the calculations performed within the framework of statistical theory of nuclei involving shell structure of nuclei are able to predict the phase transition from superfluid to normal nuclear matter around $T = 0.6$ MeV and $M > 30 \hbar$. It may be pointed out, here, that the pairing correlations are ineffective beyond $T = 0.5$ MeV [37], $T = 0.65$ MeV [38], $T = 0.7$ MeV [39], $T = 0.8$ MeV [40] and $T = 1.0$ MeV [41]. Experimentally, Rekstad et al. [42] have observed the occurrence of phase transitions around these temperatures.

When the pairing correlations in nucleus are completely destroyed beyond temperature $T = 0.6$ MeV and angular momentum $M = 30 \hbar$, an outstanding question arises about the nature of the equilibrium shape of the nucleus. As the angular momentum increases, there is a general tendency that the nuclei with neutron number in the range $N = 88 - 98$ and proton number in the range $Z = 62 - 70$ should experience a broad spectrum of transition from prolate to triaxial and possibly to oblate shapes in deformed rare earth nuclei or transition from weakly oblate to superdeformed shapes in the neutron deficient rare earth systems [15-21,40,43,44].

In Chapter 5, a comprehensive study of the structural changes in certain nuclei taking into account the role of deformation, spin, and temperature using statistical theory [12-16] is presented. All these degrees of freedom have been incorporated and it is found that each degree of freedom and the interplay among them contribute
significantly in the determination of structural changes in the nuclei.

Numerical calculations [16-19] have been carried out for the nuclei $^{150}Sm$, $^{152}Gd$, $^{154}Dy$, $^{156}Er$, $^{166}Er$, $^{168}Yb$, and $^{168}Hg$ employing the theory described in Chapter 3. The dependence of nuclear level density parameter, single neutron separation energy and single proton separation energy on the nuclear temperature is studied for different spins. It is seen that the calculated parameters as a function of angular momentum $M$, temperature $T$, and deformation parameters $\epsilon$ and $\gamma$ should experience an abrupt change for these heavier systems beyond the angular momentum $M = 50 \hbar$. This abrupt fall causes a minimum in the parameter values and it corresponds to a shape transition from prolate collective to oblate noncollective. This seems to be a feature of $N = 88$ systems, since similar structural changes have been reported by Simpson [10] for $^{158}Er$, by Rajasekaran et al. [15] for $^{156}Er$, and by Cranmer et al. [44] for $^{154}Dy$.

In Chapter 6 the method of computing single neutron emission probability [45, 46] from fused compound systems with high spins formed in heavy ion reactions using a statistical theory [12-16] incorporating deformation degree of freedom, collective and noncollective rotational degree of freedom, and shell effects is given.

The emission spectra for various angular momenta are obtained [16, 20] for nuclei $^{156}Er$, $^{166}Er$, $^{168}Yb$, and $^{188}Hg$. The increase in the rotational energy of the systems at higher spins due to greater contribution of excitation energy associated with the collective rotational degree of freedom is brought out from this study.
Various parameters such as (a) excitation energy, (b) nucleon separation energy, (c) level density parameter, (d) moment of inertia and (e) collective rotational energy that are essential to compute the single neutron emission probability $\phi(E_N) \rightarrow \phi(E_N) \rightarrow$ are extracted as a function of angular momentum $M$ and temperature $T$. The effect of angular momentum and temperature on these parameters is also investigated.

Another major area of current research in the study of nuclei at high angular momentum is superdeformation. The development of heavy-ion accelerators and tremendous improvements in gamma-ray detection systems have enabled the study of superdeformed (SD) nuclei with different values of quadrupole deformation parameter $\epsilon$ at high spins in the mass regions $A \sim 60, 80, 100, 130, 150, \text{ and } 190$ [47]. Such SD nuclei have very large moment of inertia and very small transition energy between the SD levels with increase in angular momentum. Recently, Svensson et al. [8] have reported the discovery of SD bands in $^{60}Zn$ and these bands are unique in the sense that they belong to one of the lightest mass regions where superdeformation has been observed. The SD nuclei in this mass region are self-conjugate or nearly self-conjugate. Dudek [48] have predicted pronounced shell gap for $N = 86$ and $Z = 66$ at prolate shape with quadrupole deformation around $\epsilon = 0.6$ and shown the existence of SD band in $^{154}Er$ using cranked Nilsson Strutinsky method.

In Chapter 7, superdeformation in the high spin states of $^{60}Zn$ and $^{154}Er$ is predicted using the statistical theory described in Chapter 3. A shape evolution from normal deformed (ND) states to superdeformed (SD) states with increasing angular
momentum is investigated. A comparison of dynamical moment of intertia $J^{(2)}$ values with the available experimental data is also provided. The results obtained in this work [21] are fairly in agreement with the experimental observations of Svensson et al. [8] and Lagergren et al. [11].

In Chapter 8, a comparative study of the two methods, viz., (i) the Statistical Theory of Hot Rotating Nuclei and (ii) the Cranked Nilsson Model for hot rotating nuclei described in Chapter 3 is presented for $^{188}$Hg. It is observed that the values of the Lagrangian multiplier $\gamma$ in the STHRN are the same as the values of the rotational frequency $\omega$ in CNM for nuclei rotating around the symmetry axis [12-16, 33-35]. As the triaxial deformation sets in, the values of $\gamma$ and $\omega$ are not the same.

Summary and Conclusions are presented in the last chapter.