CHAPTER 1

INTRODUCTION

Our present understanding of the atomic nucleus is not at all complete since the nature of the strong interaction, which holds the nucleons together inside the nucleus, is very complicated. The ultimate goal of nuclear structure physics is to account for the properties of complex nuclei in terms of the interaction between two nucleons. Such a microscopic description of the nucleus in terms of the properties of its constituents is, of course, very difficult. Hence it has become necessary to use simplifying models which generally concentrate on a few aspects of the many facets of the nucleus. Our knowledge concerning the structure of nuclei has been tremendously improved through the development of such nuclear models. Simple mathematical assumptions and the underlying simple physical pictures have been very successful in obtaining a systematic interpretation of an enormous amount of experimental data. Very often, due to continuing improvements of the models, it was possible not only to reach a qualitative description of the observed phenomena, but also to account them quantitatively.

Although a nucleus consists of a fairly small number of nucleons, the early experimental results were best explained by analogy with a charged liquid drop [1,2]. This model emphasized the strong coupling between the motion of the individual nucleons in the nucleus. The fission process discovered in 1939
[3] could also be qualitatively understood from this simple model. However, subsequent measurements of nuclear binding energies showed a variation from nucleus to nucleus that could not be explained by the liquid drop model. With the shell model [4], it was possible to explain such variations and also to get a general understanding of ground state spins and parities for nuclei with an odd number of particles. In this model, each nucleon is thought of as moving in an independent orbital in a field created by the rest of the nucleons. One then had a nuclear model for single-particle degrees of freedom (the shell model) and another for collective degrees of freedom (the liquid drop model). The shell model, in spite of its great successes, failed to predict the large values of the observed quadrupole moments of nuclei with many particles outside the closed shell. This led Rainwater [5] in 1950 to the assertion that a single odd particle could polarize the nuclear core. He, in fact, showed that the single particle could have a lower energy if its potential well was deformed. This suggestion thus indicated for the first time that a nuclear system of a single particle (or perhaps a group of particles) coupled to a core may achieve a relative minimum energy configuration if the core is deformed from the spherical shape. A unified description of single particle motion and collective excitations of the surface as vibrations and rotations, was developed by Bohr and Mottelson [6]. The recognition of rotational bands in deformed nuclei [7] was an important support for this model. In this simplest case, such a band obeys the rotations - energy formula $E^* = \hbar^2 I(I + 1)/2J$ where
I is the spin and J the moment of inertia of the nucleus. The strength of the unified model was subsequently demonstrated by Nilsson[8], who developed a model for the motion of independent particles in the intrinsic deformed field. It now becomes possible to interpret intrinsic excitations and to calculate equilibrium shapes.

It was, however, noted that the deformations extracted from measurements of quadrupole moments were not consistent with the moments of inertia evaluated from rotational spectra. The latter were found to be appreciably smaller than that of a rigid body, expected for a nucleus consisting of independent particles moving in an average nuclear field [9]. The discrepancy was qualitatively [9] and quantitatively [10] explained in terms of a residual interaction, the pairing interaction, which was also evidenced by other experimental data. A qualitative estimate of the effect of the pair correlations on nuclear moment of inertial using Bohr - Mottelson formula has been undertaken in ref.[11]. The simple rotation - energy formula mentioned above might be considerably changed, as the rotation of the nucleus disturbs the individual particles in it. This disturbance is, in classical mechanics, realised by the Coriolis and centrifugal forces acting in the intrinsic reference frame of the nucleus. The Coriolis force strives to get a moving particle to align its spin vector along the axis of rotation. The above mentioned pairing force couples the nucleons pairwise together to spin zero and thus counteracts such an alignment. However, in an odd nucleus, where for axially symmetric
shape and no rotation the spin vector of the odd particle is quantized along
the symmetry axis, the Coriolis force will especially act on the odd particle,
trying to decouple its spin vector from the symmetry axis of the nucleus, and
instead align it along the rotation axis. Decoupled rotational spectra
formed in this way have been observed in several odd nuclei. The rotation of
the nucleus can affect the paired nucleons also. If the Coriolis force is strong
enough, i.e., the rotational frequency of the nucleus is high enough, it can
break up a pair of nucleons, that previously were rotating in opposite direc-
tions, will now both rotate in the same direction and follow the rotation of
the nucleus. If this alignment occurs suddenly, the total angular momentum
will increase fairly much for a small change in rotational frequency. This
mechanism is supposed to be the main explanation for the pronounced ir-
regularity called 'backbending', seen in the rotational spectra mainly in
some rare-earth nuclei.

What happens to a nucleus when it rotates very fast? This is a question
of great current interest. From the experimental point of view, this interest
is explained by the fact that it is today possible to accelerate heavy nuclei
also to very high energies. If such a nucleus hits another heavy nucleus in
a non-central collision, the eventually formed compound nucleus will rotate
very fast. This fast rotating nucleus is highly excited and deexcites in the
first steps by particle emissions and gamma rays, with a small loss of angular
momentum. It will then reach a highly ordered state where almost all the
energy is tied up in the rotational motion. The study of such rapidly rotating nuclear systems provides the opportunity for exploring new aspects of nuclear dynamics and comprises one of the most exciting fields in recent nuclear structure research.

Nuclei have some of the classical properties of liquid drops, as attested by the success of the liquid drop model, but are finite quantal systems. This imposes certain restrictions on their rotation. In addition, there is a competition between the single particle motion and a collective rotation to carry angular momentum most efficiently. This interplay becomes increasingly important at high spin where a compromise between the two limiting situations appears to occur. That is, at lower spins we may observe in well-deformed nuclei relatively pure collective rotation that follows the geometrical relationships very well, or we may find in nuclei near closed shells that the shell model does an excellent job in explaining states up to several MeV in excitation and carrying tens of units of angular momentum. But at very high spins, nuclei seem to have some characteristics from each of these limiting cases, and it is of interest to understand this compromise.

The first systematic investigation, trying to understand what happens to a nucleus with very high spin, was undertaken in 1974 by Cohen, Plasil and Swiatecki. In their work the nucleus was considered as a structureless, charged liquid drop subject to coulomb and surface forces. They furthermore assumed that the drop was rotating with the rigid body moment of inertia.
One interesting result from their investigation concerns the shape changes that the nucleus undergoes with increasing spin. At rest the liquid drop has a spherical shape. When the nucleus begins to rotate the larger moment of inertia associated with oblate shapes minimizes the total energy of the system in the same way that the rotation of the Earth gives rise to such shape. For very high angular momenta the stability associated with axial symmetry is lost leading to an equilibrium shape with a triaxial form and ultimately to the disappearance of the fission barrier.

Extensions of the classical model of Cohen et al [15] have been attempted in two directions. Thus Faessler et al [16,17,18] have done completely microscopic calculations of the deformation energy using a many-body model Hamiltonian and trial wave functions representing the different shapes, while a Dubna - Rossendorf [19,20] and a Lund - Warsaw group have carried out investigations based on the Strutinsky shell correction method [21]. In the latter type of calculations the Nilsson single particle potential was always applied. However, from the fact that the Nilsson model gives a value for the Strutinsky smoothed moment of inertia which deviates essentially from the rigid body one, which is expected to govern the average behaviour of the yrast line at sufficiently high angular momenta, both groups were led to the suspicion that this model might not be well suited for calculations at very high spins. This difficulty was found to be mainly connected with the $l^2$- term of the Nilsson potential and hence the deformed Woods-Saxon potential was
used in Julich[22,23] in order to overcome this difficulty. One can, however
use the Nilsson potential for the study of high spin states in light and f-p
shell nuclei since for the latter the $l^2$ - term of the Nilsson potential vanishes
or is very small. The above mentioned calculations which initially covered
the rare earth region have also been extended for the sd shell nuclei and the
mass range $75 \leq A \leq 100$ [24]. They have yielded complete results for the
deformation behavior of the considered nuclei at high spin and give valuable
insight into the appearance of oblate configurations on the yrast line that
cannot collectively decay.

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 take place
in such nuclei. The combined effect of spin and temperature has created
a variety of shape transition phenomena in nuclei. One such shape transi-
tion from non-collective oblate to collective prolate or nearly prolate(triaxial)
shape has been recently predicted and observed. This shape transition which
is similar to the Jacobi transition in gravitating rotating stars has generated
a lot of interest in recent times. The prediction of such Jacobi transition
in $^{45}$Sc by Alhassid[25] and its subsequent experimental confirmation by
the Seattle group[26] have further kindled our interest in looking for such
interesting shape transitions in fp shell nuclei.
The aim of this thesis is to detect the possibility of the so called Jacobi transition in fp shell nuclei. For this purpose, we use a finite temperature cranked Nilsson Strutinsky method modified suitably to take in large deformations. In order to fix the spin in our calculations we use the method[27] of tuning the angular velocity. Variation of total energy as a function of the non-axial degree of freedom is obtained which can give direct information about the drastic shape changes we are looking for in this study. To investigate how these Jacobi transitions are evolved we construct the Potential Energy surfaces also to get a clear picture[28].

The rotating liquid drop model(RLDM)[29] has already predicted that nuclei should experience a shape transition at very high spins from non-collective oblate to collective prolate (or nearly prolate) with the superdeformed major to minor axes ratio of 2:1 or more. The shape evolution of hot rotating nuclei ultimately produce the above shape transition called Jacobi shape transition when the shell effects probably melt away. The Jacobi transition is not only a shape transition but it is a second order phase transition from non-collective to collective phases in nuclei. It is further interesting to note that such shape transition is analogous to the Jacobi shape instability occurring in gravitating rotating stars[30]. Thus this study is very interesting and most important.
This thesis contains six chapters. The first chapter gives an introduction and proper background for the study of the considered problem namely Jacobi phase transition and its detection in the Giant Dipole Resonance (GDR) built on excited states.

In the second chapter the prediction of Jacobi transition by the Rotating Liquid Drop Model (RLDM) is studied. The RLDM shows that the nucleus should experience the shape transition at very high spins from an oblate non-collective shape to a collective prolate or triaxial shape with superdeformed major to minor axis ratios of 2:1 and larger. In light and medium mass nuclei this highly deformed prolate or triaxial shapes are predicted to exist as equilibrium shapes of the rotating nucleus. In an infinite system this shape change is a second order phase transition similar to the Jacobi shape instability in gravitating rotating stars. These features are discussed in this chapter in relation to nuclei in fp shell region.

The third chapter contains the study of Jacobi phase transitions both for even and odd A nuclei in the considered region. The theoretical framework for obtaining Potential energy surfaces for the considered nuclei
by the finite temperature Cranked Nilsson Strutinsky method is studied. By minimizing the free energy with respect to $\beta$ and $\gamma$ at constant spin and temperature the potential energy surfaces for the nuclei are constructed and shape transitions were detected. The non-inclusion of thermal fluctuations in the formalism does not pose any problem since Jacobi transitions are found to occur only at low temperatures in the fp shell nuclei considered in this work.

The fourth chapter explains the use of GDR measurement to study the Jacobi shape transitions. The experimental investigation of the shapes and the shape evolution of the hot rotating nuclei at very high excitation energy and spin has been possible through studies of GDR gamma decays of compound nuclei formed in heavy ion fusion reactions[31,32,33]. Both the GDR spectrum shape and angular distributions are sensitive to nuclear shape and deformations in the deformed nucleus. The GDR splits into components corresponding to vibrations along the different principal nuclear axes. The fractional energy splitting is proportional to the fractional difference in the axes lengths, which is simply related to the nuclear deformations. In hot nuclei the energy splitting of the GDR is usually not resolved in part because of thermal shape fluctuations. In order to infer quantitative information about the equilibrium shape and shape evolution from GDR data, comparison with thermal fluctuation calculations may be necessary but for
low temperatures the role of thermal fluctuations may be insignificant. Ex- 
cited GDR spectroscopy has established itself as a powerful method to study 
nuclear shapes at high temperature and spin[34,35]. The splitting of the 
GDR in cold deformed nuclei is well known, as exhibited by the spectacular 
spectra from (γ,n) reactions on stable targets. Most of the early excitement, 
in the beginning of 1980s, about the excited-state GDR was indeed tied to 
the expectation that similar deformation effects would be observable in nuclei 
produced in nuclear reactions with high angular momentum and internal ex- 
citation energy. A determination of shapes of such nuclei would carry nuclear 
structure properties. It later became clear, however, that at finite temper- 
ature the GDR strength functions was much more featureless than in cold 
nuclei, which made the determination of nuclear deformations and shapes a 
complicated task. Indeed, with the exception of lowest excitation energies 
the individual components of the GDR were no longer apparent in the spec- 
tra. It was thus realized that the shape fluctuations play an important role in 
determining the effective GDR strength functions[36] at high temperatures. 
In spite of this the GDR in hot nuclei exhibits a strong dependence on the 
angular momentum and the temperature of nucleus in which it is excited. 
Hot and rotating atomic nuclei are expected to exhibit a rich variety of dif- 
ferent shapes [32] at various excitation energies. Close to the yrast lines, the 
shapes are determined by the shell structure. At higher temperatures the 
finite occupation probability of orbitals above and below the Fermi surface
limits the influence of specific valence orbitals. The temperature at which the shell effects should be substantially weakened can be estimated\cite{32,29} to approximately $T=1.5 \text{ - } 2.0 \text{ MeV}$, from the expected decrease of the shell energies as a function of temperature. Once shell effects are gone, nuclei are expected to follow the shape predicted for a charged liquid drop\cite{15}, that is, spherical shapes at zero rotation that develop into oblate shapes of increasing deformation with increasing angular momentum. At very high angular momentum nuclei should develop large prolate deformations prior to fission.

The study of latter shape transition which is the so called Jacobi transition can also be inferred through the study of GDR. The GDR properties in fp shell nuclei depicting the Jacobi shape transitions are presented in this chapter.

The fifth chapter describes the role of such thermal as well as oriental fluctuations on Jacobi transitions in the fp shell nuclei.

Finally the last chapter outlines the summary describing the salient features of this thesis and the conclusions drawn from the study of such Jacobi shape transition in fp shell nuclei.
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