Chapter 1

Introduction
Atomic nucleus is one of the most complex finite quantal systems that we encounter in our physical world. Understanding of the various properties through the many body nucleonic interaction in the finite fermionic system (nucleus) is the main motivation of the nuclear physics studies. To understand the properties of a nucleus it is not sufficient to know the interactions between its components but it is also necessary to reveal the arrangement of the nucleons which give rise to a definite characteristic, i.e. the structure of the nucleus. The advent of present day accelerators and detection technique enable us to make in-depth study of nuclear reaction mechanism, and also possible to observe nuclear structure at extreme condition i.e. at high angular momenta and excitation energies. The generation of angular momentum in atomic nucleus has been a topic of special interest in nuclear-structure studies. Like for molecules, violation of the spherical invariance in nuclei leads to the appearance of rotational excitations which manifest themselves in a specific sequence of levels called rotational bands connected by strong E2 transitions. An anisotropic distribution of nuclear mass in the atomic nuclei specifies an orientation and the rotation with respect to that orientation gives rise to band structures. In 1951 [1], Bohr pointed out that such rotational spectra are related to a stable nuclear deformation. However, nuclei are not rigid bodies. They have an internal shell-like structure formed by the nucleons moving in their quantum-mechanical orbitals with a well-defined angular momentum. The mid shell nuclei are the best examples of the deformed axially symmetric mass distribution leads to the observation of the rotational bands in their excitation spectra. As the mass number approaches to the shell closure, the nuclear deformation decreases accordingly and becomes perfectly spherical for a closed-shell nucleus.

In quantum mechanics, when a perfectly spherical system rotates, it appears identical when it is viewed from any direction and no point of reference exists by which the change in position can be identified. Therefore, rotation cannot be defined for spherical nuclei. If the shape deviates from spherical symmetry, rotational spectra are observed as the manifestation of rotation. Thus it may infer that the rotational bands would not be observed in closed-shell nuclei which are assumed to be spherical. In these nuclei, the angular momentum states
are generated via the coupling of the spin vectors of a few individual nucleons and/or the
holes created as a result of the promotion of protons and/or neutrons into higher lying orbits
(commonly known as single particle excitations). Such types of excitation results no definite
rule for the excitation energy as a function of angular momentum of the state. For spherical
or near spherical nuclei collective vibrations of the nuclear surface will also produce low lying
excited states, which are known as phonon vibrations.

In case of deformed nuclei, the occupation of nucleons in the partially filled orbitals plays a
crucial to their asymmetric mass distribution. Depending on the number of these nucleons,
the nuclear shape can be either prolate or oblate (axially symmetric shape). The deformation
can be without axial symmetry resulting in different elongations along the three axes of the
system, referred to as triaxial shape. In atomic nuclei with even numbers of neutrons and
protons, the low-lying excitation spectrum is generally formed by nucleon pair breaking and
nuclear vibrations or rotations. However, for certain numbers of protons and neutrons, a
subtle rearrangement of only a few nucleons among the orbitals at the Fermi surface can
result the existence of two stable shapes at some excitation region which has been termed
as shape coexistence. The lowest three $0^+$ states in the energy spectrum of the neutron
deficient nucleus $^{186}$Pb are spherical, oblate and prolate which is an excellent example of
shape coexistence [2].

Traditionally it has been understood that rotations can occur only in nuclei with a stable
deformation, while spherical or near-spherical nuclei exhibit spectra of single-particle exci-
tations. The observation of regular rotational-like sequences of strongly enhanced magnetic
dipole (M1) transitions in several light-mass Pb isotopes was therefore very surprising [3].
These isotopes were known to be spherical or near-spherical and previously only irregular
single-particle-type excitation spectra were known. For the M1 bands in the Pb isotopes,
the E2 crossover transitions are very weak, or were even not observed at all, in some cases.
Lifetime measurements confirmed later that the $B(E2)$ values are, indeed, very small, indi-
cating that the nuclear deformation is small. Another significant observation has come from
the accurate lifetime measurements of excited states in the $\Delta I = 1$ bands in the Pb isotopes.
The experimentally deduced reduced transition probabilities $B(M1)$ are large (up to several
and decrease characteristically with increasing spin. These surprising features of the M1 bands showed that they cannot be understood in terms of conventional rotation of deformed nuclei where the rotating charge density gives rise to E2 radiation.

In the absence of charge deformation, no collective rotation is possible, and the magnetic dipole bands also entail a new mechanism of generating the angular momentum in which the symmetry of the quantal system is broken by the anisotropic currents distribution of a few high-spin particles and holes. The angular momenta of the valence particles align coherently along one direction, and those of the valence holes along a perpendicular direction to that. The spin of the levels in the band is produced by gradual alignment of the two angular momenta vectors. This has been dubbed as shears mechanism, because it resembles the closing of a pair of shears used for cutting the sheep wool. This mechanism gives rise to a large perpendicular component of the magnetic dipole moment which rotates about the total angular momentum vector. Therefore, the new type of excitation has been named “magnetic rotation” (MR) [4] to distinguish it from the long-known rotation of deformed nuclei, which might then be called “electric rotation”.

The shears mechanism emerges from a nearly perpendicular coupling of the angular momentum vectors produced by the high-\( j \) proton-particle and neutron-hole or vice versa. This is due to the repulsive interaction between these two types of particles. Thus, if one (particle) angular momentum is pointing towards the symmetry axis, the other (-hole angular momentum) should be aligned perpendicular to it \( i.e. \) along the rotational axis. Therefore, one kind of particles should be the nucleons in high-\( \Omega \) orbitals whereas the other kind should be in low-\( \Omega \) orbitals. It can be argued that any other type of combination of the particles among the neutrons and protons does not lead to shears mechanism. These properties are fulfilled only by the nuclei whose neutron number \( (N) \) and/or proton number \( (Z) \) are close to the magic numbers. Thus possible existence of the magnetic rotational excitations can occur for nuclei having proton and/or neutron near the shell closure. The magnetic rotational bands are seen in weakly deformed nuclei near magic or semi-magic proton numbers \( Z = 80 - 83, 55 - 64, 45 - 50 \) and \( 35 - 37 \) and/or neutrons near \( N = 110 - 120, 75 - 82, 55 - 64 \) and \( 44 - 48 \) in mass \( A \sim 190, 140, 100 \) and 80 regions [5]. The largest number of magnetic rotational
bands has been identified in mass $A \sim 190$ region. Fig. 1.1 shows the characteristic decrease of $B(M1)$ values with spin for the above mentioned mass regions establishing MR phenomena for weakly deformed systems across the periodic table.

A special case of rotational band-like structure in weakly deformed nuclei may occur when the symmetry is broken with respect to the total angular momentum vector of two shears-like configurations produced due to the high-spin particle-hole excitation. The perpendicular components of magnetic dipole moment vectors for the two shears-like configurations are anti-aligned and cancel each other and, therefore, the $B(M1)$ values vanish. This type of shears coupling has been called “antimagnetic rotation” (AMR) [4]. It resembles the cancellation of magnetic moments in an antiferromagnet. In an antiferromagnet one half of the atomic dipole moments are aligned on one sublattice and the other half are aligned in the opposite direction on the other sublattice. Thus, the state is ordered and breaks the isotropy, like a ferromagnet, but there is no net magnetic moment. For the AMR, the magnetic moment of each of the two shears specifies the orientation like the magnetization of one of the sublattices in an antiferromagnet. For the antimagnetic rotational bands the angular momentum

---

**Figure 1.1:** The characteristic diagram of $B(M1)$ values with spin ($I$) for the magnetic rotational bands in $^{82}$Rb, $^{108}$Cd, $^{139}$Sm and $^{196}$Pb nuclei [6–9].
Figure 1.2: The observed antimagnetic rotational bands in the atomic nuclei in $A \sim 100$ mass region.

is generated by the simultaneous step-by-step closing of the two shears. Since the antimag- netic rotor is symmetric with respect to rotation by $180^\circ$ about the angular momentum axis, the bands should consist of sequences of energy levels differing in spin by $2\hbar$. Due to the small deformation of the core they should decay by weak E2 transitions, with $B(E2)$ values decreasing with increasing spin.

This type of excitation mechanism was first reported by Zhu et al. from the spectroscopic investigation of the $^{100}$Pd nucleus [10]. Antimagnetic rotational bands are observed only for few Cd and Pd nuclei in mass $A \sim 100$ region (Fig. 1.2). Such bands are characterized by decreasing electric quadrupole transition rates $[B(E2)]$ with increasing spin [11–17] and have been interpreted in the framework of a simple geometric model [4] and as well as in the fully self-consistent microscopic tilted axis cranking method based on covariant density functional theory [18]. Since both of these two types of quantized rotation, MR and AMR, are the consequence of the shears mechanism, it is expected to observe both of them in all the mass regions mentioned above. However, until today, simultaneous occurrence of these two phenomena has been observed only in the $A \sim 100$ mass region.
A deformed nucleus can generate its spin or angular momentum by collective rotation. However, because nucleus is a many-body quantal system, such regular rotational motion must have an underlying microscopic basis, with angular momentum being generated by small contributions from a sizable number of valence nucleons. Since the number of valence particles (and holes) and their individual spin contributions are both finite there is a limiting angular momentum that can be generated. At this point the rotational band loses its collectivity and is said to be terminated. The characteristic features of these bands are the decreasing trend of $B(E2)$ values which have been observed for several nuclei in the mass $A \sim 110$ and $160$ regions and has been interpreted as smoothly terminating bands [19]. At band termination, the nucleus can be considered as a doubly magic spherical core about which the several valence nucleons all move in equatorial orbits giving the nucleus an oblate appearance. Band termination spectroscopy enables a study of balance and interplay between two extremes of nuclear dynamics, namely collective and single-particle degrees of freedom. These bands show the characteristic of gradually decreasing dynamic moments of inertia with increasing spin in contrast to a fairly constant dynamic moment of inertia (without any collective contribution) in the case of AMR [20]. The difference between this mechanism and AMR is reflected in the variation of the dynamic moment of inertia $[J^{(2)}]$ and $B(E2)$ strength as a function of spin. In the case of smoothly terminating bands, the ratio $J^{(2)}/B(E2)$ remains almost constant in contrast to a sharp increase in the case of a AMR band [20].

Present thesis work aim to understand the mechanism of generating angular momentum in weakly deformed nuclei in mass $A \sim 140$ region. These nuclei exhibit irregular excitation at lower energies whereas band-like structures have been observed at higher excitation energy domain. The magnetic rotational bands which are the consequence of shears mechanism have been observed in $^{139}$Sm, $^{142}$Gd and $^{141}$Eu nuclei [6, 21, 22]. In this mass region, several rotational bands based on triaxial deformed shape have been observed in $^{142-144}$Eu, $^{138-140}$Nd and $^{142-144}$Gd [23–32]. The possible candidate of the AMR band which is another outcome of the shears mechanism has been identified in $^{144}$Dy on the basis of theoretical arguments. Though, in this mass region, the possible coexistence of the AMR and MR bands in a single nucleus yet not reported in literature. Thus, the main motivation of the thesis is to search the coexistence of the MR and AMR bands in a single nucleus in the $A \sim 140$ mass region.
In the present thesis, investigation of this region has been carried out using in-beam gamma-ray spectroscopy technique which is regarded as one of the most effective investigative tools for Nuclear Structure studies. The thesis reports the results of the spectroscopic investigations of $N = 80\ ^{142}\text{Sm}$ and $^{143}\text{Eu}$ nuclei populated through the fusion-evaporation reaction $^{31}\text{P} \left(^{116}\text{Cd}, p4n\right.$ and $4n)$. The de-exciting $\gamma$ rays were detected using the Indian National Gamma Array (INGA) an array of Compton-suppressed clover detector. The use of fusion evaporation reactions resulted in the population of high spin states and the clover detector facilitated linear polarization measurements which are of relevance for determination of the electromagnetic nature of the $\gamma$-ray transitions. The level scheme of $^{142}\text{Sm}$ nucleus has been extended up to excitation energy of $\sim 12.5$ MeV. The experimental signatures of the MR band and quadrupole bands in $^{142}\text{Sm}$ have been compared with the shears mechanism with the principal axis cranking model and cranked Nilsson-Strutinsky calculations, respectively, to infer the associated shape evolution and/or coexistence as discussed in Chapter 5. The precise level lifetimes of the dipole and quadrupole bands in $^{143}\text{Eu}$ have been measured using the Doppler shift attenuation method. The decreasing trend of the transitional probabilities of the dipole and quadrupole bands has been interpreted as a consequence of shears mechanism which has been illustrated in Chapter 6. The model calculations and interpretations of the experimental $B(M1)$ and $B(E2)$ values of the dipole and quadrupole bands are also given in the same Chapter.
Bibliography


