Chapter 1

Introduction

The atomic nucleus is a complex many body quantum system composed of nucleons bound by the strong interaction within a very small volume of dimensions $\sim 10^{-15}$ m. Though very complex in nature, the nucleus is a very fascinating object and intense research in this field has provided useful applications in many fields e.g., nuclear medicine, imaging, dating in geology & archeology, power, weapons to name a few. In spite of tremendous advances in nuclear physics research many facets of the properties of the nucleus is still unknown.

A natural approach to explore the properties of the atomic nucleus is to excite it and measure the frequencies of the emitted electromagnetic radiations. The nuclear excitation is one of the finest and the most important tool to get a deep insight into the atomic nucleus viz., the single particle excitation and the collective excitation. In order to study the properties of nucleus or nuclear structure under extreme conditions of excitation energy, spin and iso-spin, the collective excitation modes come in handy as they enable one to study the nucleus in terms of macroscopic variables which in turn give a deeper insight into it.

Among all the collective modes, the giant dipole resonance is very special due to its unique properties. The high frequency, small amplitude collective mode of nuclei bears large resonance widths indicating large damping inside the
nuclear matter. The present thesis deals with these resonance phenomena and their damping mechanism within the nuclear system.

### 1.1 Giant resonances (GR)

Giant resonance is a collective mode of vibration of nucleons in a nucleus where all the nucleons take part. It can be viewed as a high frequency, damped and nearly harmonic shape vibration around the equilibrium shape of the nuclear system. It occurs in all nuclei starting from very light nuclei \(^4\)He to the very heavy nuclei \(^{238}\)U. The resonance energy is inversely proportional to the nuclear radius. The resonance is called ‘giant’ since it has large resonance width which indicates towards the large damping mechanism present within the nuclear system. The amplitude of this giant vibration is very small (a few percent of nuclear radius) because of large damping width (5–10 MeV) and the frequency of the vibration is very high \((3 \times 10^{21})\). The nature of the giant resonance is Lorentzian which is characterized by three observables (Strength function, Centroid energy and width of the resonance) [Har01] which are discussed in section 1.4.

### 1.2 Classification of Giant resonances

In quantum mechanical terms, the resonance corresponds to a transition between the ground states and the collective states, which depends on the different quantum numbers such as multi-polarity, spin and isospin. Giant resonances are generally classified according to their transferred multi-polarity \((\Delta L)\), spin \((\Delta S)\) and isospin \((\Delta T)\) quantum number. The transition operators for the excitation of giant resonance are the electromagnetic operator which is, in long wavelength approximation \((kr << 1)\), given as [Har01, Sri08a]
where \( L \) is the order of multipoles, \( Y_{LM} \) are the spherical harmonics, \( r \) is the radius of the nucleus, \( \rho \) is the charge density and \( k \) is the wave vector. The transition operator can be electric or magnetic depending on the spin quantum number. In the electric vibrational mode, no spin (\( \Delta S = 0 \)) is involved. The magnetic vibrational mode (\( \Delta S = 1 \)) involves the coordinated precession of the nucleon spins and thus the nucleus can acquire a net spin or net magnetic moment that oscillates at the precession frequency. Depending on the nuclear isospin quantum number (\( T \)), the electric and magnetic GRs are further classified as isoscalar (IS) and isovector (IV) modes. In the IS mode (\( \Delta T = 0 \)), the neutron and proton fluids vibrate in phase whereas the IV mode (\( \Delta T = 1 \)) corresponds to their vibrations out of phase. The isoscalar and isovector mode of vibration can be excited for different multipoles depending on the value of \( L \) such as monopole, dipole, quadrupole, etc.

\( \Delta L = 0 \) means the monopole vibration which is basically the radial vibration of the nucleus. \( \Delta L = 0, \Delta T = 0 \) mode, the breathing mode, is the isoscalar giant monopole resonance (ISGMR). This “breathing mode” is of particular interest since its excitation energy is directly related to the incompressibility \( (K_A) \) of the nucleus, which is a fundamental quantity of nuclear matter and important input parameter in the nuclear equation of state [Spe91]. \( \Delta L = 0, \Delta T = 1 \) correspond to the isovector giant monopole resonance (IVGMR) which is the compression modes of the nucleus that can be thought of as a compression and expansion of the whole nucleus which leads to a fluctuation of the nuclear radius. GMR is also studied very extensively.

\( L = 1 \) means the collective dipole vibration. \( \Delta L = 1, \Delta T = 0 \), the isoscalar
giant dipole resonance mode is the translation of the nucleus as a whole, and this mode of excitation generally cannot exist within the nucleus. $\Delta L = 1, \Delta T = 1$ is the isovector giant dipole resonance (IVGDR) mode in which the neutrons and protons oscillate out of phase against each other. The IVGDR mode is the most cleanly observed and best known of the various giant resonance modes.

$L \geq 2$ represents the shape vibration of the nucleus. $L = 2$ represents the quadrupole vibration which means a change in electric quadrupole moment of the nucleus. A pictorial representation of the different collective vibration is shown in Fig 1.2. The resonance energy of the GR can be well described by $A^{-1/3}$ dependence, where $A$ is the mass number and the proportionality constant being equal to about 79 MeV for GDR, 80 MeV for GMR, 65 MeV for isoscalar giant quadrupole resonance (ISGQR) and 140 MeV for isovector...
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Figure 1.2: Schematic representation of various collective modes inside the nucleus with $L = 0$ (monopole), $L = 1$ (dipole) and $L = 2$ (quadrupole) (adopted from thesis [Sup12b]).

The first experimental evidence for the giant resonance type phenomenon was observed in 1937 in the measurements of the radioactivity produced in variety of targets by a source of 14 MeV photons from $\text{Li}(p, \gamma)$ reactions [Bot37]. They observed an increase in experimental cross sections compared to the averaged theoretical cross sections, which led to the conclusion of strong resonance absorption in those nuclei. Later on (In 1947), Baldwin and Klaiber conducted photo absorption experiments at higher excitation energies that also showed the resonance behavior [Bal47]. These resonances were found to exhibit electric dipole character which means an out of phase vibration of neutron and proton.
fluids in a spatial dipole pattern and hence named as giant dipole resonance. The isovector giant dipole resonance (IVGDR) is the best known giant resonance due to the fact that the IVGDR has a very specific decay ($\gamma$-decay) mode with the highest probability compared to other higher multipolar modes. The spin-parity of these resonance states are $1^{-}$ and they lie at the energy $\sim 80A^{-1/3}$ MeV [Har01]. The phenomena of GDR can be classified into two categories, the cold GDR i.e GDR built on ground state and the hot GDR i.e GDR built on excited states of atomic nuclei.

1.3.1 IVGDR built on ground state

The GDR built on ground state means all the available excitation energy transferred to the nucleus goes into the GDR vibration. This was studied historically via photon-absorption process where a beam of monochromatic photons is illuminated on the target nucleus and the absorbed frequencies are determined through ($\gamma$, $n$) reaction channels [Bot37]. In this case, the wavelength of the photon ($\lambda \approx 100$ fm) exciting the vibration is large compared to the diameter of the system ($R = 5-7$ fm). Hence, all the protons experience a time dependent, uniform electric field and move in the same direction under the influence of the field. Since in the photo-absorption process, the center of mass of the nucleus is at rest or in uniform motion, the neutrons, although unaffected by the field have to move in opposite direction. The strong force acting among the nucleons provides the restoring force of this vibrational mode.

1.3.2 IVGDR built on excited state

The GDR built on excited states implies that the GDR is actually built on one of the excited states of atomic nuclei. In this case, the nucleus remains in excited states and oscillates collectively. David Brink first suggested that the GDR can be populated on any excited state of atomic nucleus [Bri55]. The
first evidence of GDR built on excited states in favour of Brink hypothesis was found in 1974, during the study of high energy $\gamma$-rays from the fission fragments in spontaneous fission of $^{252}$Cf [Die74]. The existence of GDR built on excited states using a reaction study was first observed in a proton capture ($p,\gamma$) experiment on $^{11}$B [Kov79] where the GDR built on first excited states of $^{12}$C was observed. For studying the GDR built on excited states, one must excite the nucleus and then measure the frequencies of the photons it emits during the de-excitation of the nucleus. There are two experimental methods to study the GDR built on excited states. First one is the nuclear fusion reactions where a large amount of excitation energy and angular momentum can be imparted to the compound nucleus. In these reactions, a compound nucleus is formed at high excitation energy with a broad angular momentum distribution. Another one is the inelastic scattering of light/heavy ion on a target where the excitation energy would be large but the populated angular momentum would be relatively low. In analogy to the cooling process, the hot nucleus de-excites via particle evaporation (neutron, proton, alpha etc). In competition with the particle emission, the system can also decay by high energy ($>8$ MeV) $\gamma$-emission with a much smaller probability, of the order $10^{-3} - 10^{-5}$. This high energy $\gamma$-rays are emitted due to the decay of giant dipole resonance. Experimentally, these $\gamma$-rays appear as a prominent bump around $10-25$ MeV in the energy spectrum, riding over the exponentially decreasing statistical $\gamma$-rays (as shown in Fig 1.4a).

### 1.3.3 High energy $\gamma$-ray spectrum from the decay of GDR built on excited state

The high energy $\gamma$-ray spectrum from an excited compound nucleus can be divided into different regions in terms of $\gamma$-ray energies. A high energy $\gamma$-ray spectrum of $^{97}$Tc compound nucleus is shown in Fig 1.4a. The spectrum for 4
< \gamma < 10 \text{ MeV} \) is mainly dominated by the statistical E1 \( \gamma \)-rays emitted from the decay of the excited compound nuclei below the particle threshold line. The exponentially decaying slope of the spectrum is due to the fact that the \( \gamma \)-decay probability decreases approximately exponentially with increasing \( E_\gamma \) \( \left[ P(E_\gamma) \propto e^{-E_\gamma/T} \right] \). For \( E_\gamma > 10 \text{ MeV} \), a broad bump is observed which is the signature of the GDR decay. Above \( E_\gamma = 25 \text{ MeV} \), the slope of the spectrum changes and is mainly dominated by the bremsstrahlung \( \gamma \)-rays due to the nucleon-nucleon collisions during the early stages of the compound nucleus formation.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{nuclear_shape_from_gdr_lineshape.png}
\caption{Nuclear shape from GDR line shape. The strength function \( S_{\text{GDR}} \) directly gives the types of nuclear deformation.}
\end{figure}

1.4 Parameters for characterizing the GDR vibration

Like any other damped oscillation, the GDR excitation function \( \sigma_{\text{GDR}}(E_\gamma) \) is Lorentzian in shape and characterized by three parameters: Centroid energy
(E_{GDR}), width of the resonance (Γ_{GDR}) and strength function (S_{GDR}). The excitation function of the GDR is given by

\[ \sigma_{abs}(E_\gamma) = \frac{\sigma_m \Gamma_{GDR}^2 E_\gamma^2}{(E_\gamma^2 - E_{GDR}^2)^2 + \Gamma_{GDR}^2 E_\gamma^2} \]  \hspace{1cm} (1.2)

where \( \sigma_m \) is the peak cross section.

### 1.4.1 Strength function \( S_{GDR} \)

The strength of the resonance is given by

\[ S_{GDR} = \int_0^\infty \sigma_{abs}(E_\gamma) dE_\gamma \]  \hspace{1cm} (1.3)

The GDR strength function is directly coupled to the nuclear shape degrees of freedom and therefore can be used to probe the nuclear deformation (as shown in Fig 1.3). In case of spherical nuclei, the vibrations along all three axes are identical and correspond to a single Lorentzian strength function. However, in case of deformed nuclei the vibration along each axis will have a different energy corresponding to different axial dimensions leading to more than one component in GDR line shape. For example, in a prolate or oblate system there will be two components. The separation between these various components and their relative strengths directly provides quantitative information of the nuclear shape. On the other hand, the strength function is a very useful benchmark to check whether a resonance qualifies as giant resonance or not. The parameter \( S_{GDR} \) is basically the area subtended by the Lorentzian curve and thus gives the total resonance cross-section. The number of nucleons participating in the collective vibration can be obtained by comparing the experimentally obtained cross-section to the theoretical limit, known as Thomas-Reiche-Kuhn (TRK) sum rule given by \( \sim 60NZ/A \) [Sno86], where \( N, Z \) and \( A \) are neutron, proton and mass number, respectively. If the experimentally observed resonance exhaust
a major part (> 50%) of the corresponding sum rule, then it is called a giant resonance [Har01]. Here, it has been observed that the dipole vibration exhausts essentially 100% of the oscillator strength which confirms that all the nucleon participate in the collective dipole vibration.

![Graph](image)

Figure 1.4: [a] A typical high energy γ-ray spectrum (filled circles) from the decay of compound nucleus along with the CASCADE calculation (continuous line). Dashed line represents the bremsstrahlung contribution whereas dotted line represents the CASCADE calculation without bremsstrahlung component. [b] The GDR cross-section is Lorentzian in nature and its parameters.

### 1.4.2 Resonance energy, $E_{GDR}$

The centroid energy of the resonance is inversely proportional to the nuclear radius and provides an idea about the nuclear size. Moreover, the centroid energy is strongly correlated with the nuclear symmetry energy, which is a fundamental quantity for studying the properties of a highly asymmetric nuclear medium e.g the structure of a neutron star [Tri08]. Macroscopically, the systematics of centroid energy of the GDR built on ground state of the nucleus, is generally expressed as a combination of two different mechanisms of vibration as given by
two theoretical models, Goldhaber-Teller (GT) [Gol48] and Steinwedel-Jensen (SJ) [Ste50] model, given by $E_{GDR} = 31.8A^{-1/3} + 20.6A^{-1/6}$.

![Schematic diagram of Goldhaber-Teller and Steinwedel-Jensen dipole modes. For each cases, one half cycle of the vibration is shown as a function of time.](image)

Steinwedel-Jensen (SJ) model assumes that the nucleus is like a resonating cavity [Ste50]. Motion of neutrons and protons cause density changes in the neutron and proton field. The restoring force per unit mass will be proportional to the gradient of these densities. Therefore, for a given displacement the density change is inversely proportional to the nuclear radius $R$ and the gradient will be proportional to $1/R^2$. Thus, the frequency of the density vibration is proportional to $1/R$ and thus to $A^{-1/3}$.

Goldhaber-Teller (GT) Model assumes that the neutrons and protons are two separate rigid interpenetrating distributions [Gol48]. During the dipole vibration, they undergo harmonic motions with respect to each other. The restoring force of this harmonic vibration will be proportional to surface area, i.e $R^2$. The frequency of the vibration will be proportional to $\sqrt{(F/A)}$ and hence
to $A^{-1/6}$. Thus, the centroid energy of the GDR built on ground state of the
nucleus, is expressed as the combination of the above two model description and
is given by $E_{GDR} = 31.8A^{-1/3} + 20.6A^{-1/6}$ [Gaa92]. The schematic diagrams
of Goldhaber-Teller and Stenwedel-Jensen dipole modes are shown in Fig 1.5.

Microscopically, the GDR can be viewed as a coherent superposition of non-
collective 1 particle-1 hole configurations, known as collective particle-hole door-
way resonance state [Wil56]. The term doorway implies that the excited nucleus
passes from the entrance channel through the doorway state before the full com-
plexity of the compound nuclear states are populated. The energy for this 1p-1h
excitation is $\sim 41A^{-1/3}$. However, the experimental systematic show twice of
this value i.e $80A^{-1/3}$. This difficulty was overcome by Brown and Bolsterli
[Bro59] who suggested that the residual p-h interaction has to be taken into
account in describing such configurations.

1.4.3 Width of the resonance, $\Gamma_{GDR}$

One of the basic problems in the study of giant dipole resonance is the un-
derstanding of how the collective vibration of nucleons (GDR vibration) get
damped. The width of the GDR is a very special observable as it gives an idea
about the damping mechanism of the GDR vibration and has been the focus
of many experimental and theoretical studies for last few decades. The width
of the resonance arises due to the transfer of energy from the orderly vibration
into other modes of nuclear motion. The typical value of the GDR width for
heavy nuclei is $\sim 5$ MeV implying that the vibration is completely damped after
a few vibrations. The general trend of the GDR width as observed from the
experimental results shows that it is smallest for the closed shell nuclei, $\sim 4$ MeV
for nuclei around $^{90}$Zr and $^{208}$Pb, and increases to 5-6 MeV for nuclei between
shells. The present thesis is related to the GDR width and its evolution as a
function of temperature. The details of the origin of GDR width, experimental observation and theoretical explanation are discussed as below.

1.5 Origin of the GDR width

1.5.1 Macroscopic description

Macroscopically, the large GDR width built on ground state is mainly caused by two processes, which are collisional damping and in-homogeneous damping. Collisional damping occurs due to the binary collisions between nucleons and collisions between a nucleon & the nuclear surface. In the binary collision between two nucleons, a nucleon can change its state of motion by promoting a particle in the Fermi sea into a state above the Fermi surface. Since the particle-particle correlations are considerably larger than the particle-hole correlations and Pauli blocking is more effective in the bulk than in the nuclear surface, the probability of nucleon-nucleon collision (2-body collision) is negligible compared to the nucleons colliding with the nuclear surface. Thus, the nuclear surface plays a central role in the collisional damping process. On the other hand, inhomogeneous damping occurs due to the deformation of the nucleus. If the ground state of the nucleus is deformed, there is a possibility of nucleons vibrating along the different principle axes, producing different centroid energy components. Thus, the GDR line shape splits according to the dimension of different principle axes producing a large width [Bor98].

1.5.2 Microscopic description

Microscopically, the GDR can be described as a coherent superposition of the non-collective 1p-1h configuration [Wil56] and it is found to have large width even if it is built on the nuclear ground state. The width mainly comprises of three different parts: Landau width ($\Gamma_{\text{landau}}$), Escape width ($\Gamma^{\uparrow}$) and the
spreading width ($\Gamma^\downarrow$) in general [Har01], and is given by

$$\Gamma_{GDR} = \Gamma_{\text{landau}} + \Gamma^\uparrow + \Gamma^\downarrow \quad (1.4)$$

The Landau width ($\Gamma_{\text{landau}}$) arises owing to the coupling of collective 1p-1h state (GDR state) with the non-collective 1p-1h configuration in the same excitation energy range.

![Diagram of GDR width](image)

**Figure 1.6:** Microscopic picture of the GDR width built on excited states of atomic nuclei. The collective 1p-1h state couples with the non-collective 1p-1h state ($\Delta \Gamma$) and more complex 2p-2h, 3p-3h,.....np-nh configurations ($\Gamma^\downarrow$). It can also decay via particle emission ($\Gamma^\uparrow$).

The Escape width ($\Gamma^\uparrow$) arises due to coupling of GDR state to the continuum. This is because the GDR state remains above the particle threshold line and it can directly decay to state in the daughter nuclei and attain the escape width. For heavy nuclei, it comprises mainly of neutron decay width and for light nuclei the charged particle decay width has also to be taken into account.
The spreading width ($\Gamma_↓$) arises due to the coupling of coherent 1p-1h state with more complex and numerous 2p-2h configuration which have the same spin and parity. The resulting state can also be coupled to more complex 3p-3h, 4p-4h,... np-nh states till a completely equilibrated system is reached. In medium and heavy nuclei, it turns out that the escape and landau widths only account for a small fraction and the major contribution of the large resonance width comes from the spreading width. Recently, an empirical formula has been derived for the spreading width with only one free parameter by separating the deformation induced widening from the spreading effect, and is expressed as $\Gamma_↓ = 0.05E_{GDR}^{1.6}$ [Jun08]. The microscopic description of GDR width has been displayed in Fig 1.6 schematically.

1.6 Evolution of GDR width built on excited states of atomic nuclei

1.6.1 Experimental observation

In the past few decades, a lot of experiments have been performed to study the evolution of GDR width as a function of temperature (T) and angular momentum (J) of the system. These experiments and their results are discussed in this section.

In 1981, Drapper et al., [Dra82] first suggested the excitation energy dependence of GDR properties. They performed an experiment of 1150 MeV $^{136}$Xe beam on $^{181}$Te target. They suggested that the 10–20 MeV $\gamma$-ray spectra at low excitation energy are reproduced by theoretical calculation using the ground state value of resonance energy and resonance width, but at high excitation energy the better agreement is obtained with a smaller resonance energy and increasing the resonance width.

In 1983, Germann et al., [Ger83] studied the spectral line shape of $\gamma$-rays
emitted from $^{76}$Kr, $^{63}$Cu and $^{127}$Cs to study the J-dependence of line shape. But they could not find any J-dependence of line shapes because the populated angular momenta were very low.

In 1984, Gaardhoje et al., [Gaa84] observed the increase of GDR width with excitation energy. They populated $^{108}$Sn nuclei at excitation energy $E^* = 51$ and 61 MeV and obtained $\Gamma_{GDR} = 6$ and 6.5 Mev, respectively. The same group in 1986, studied the GDR $\gamma$ decay from $^{111}$Sn nuclei populated at excitation energy $E^* = 66$ and 110 MeV and extracted $\Gamma_{GDR} = 7.5$ and 11 MeV, respectively [Gaa86].

In 1987, Chakraborty et al., [Cha87] studied the excitation energy dependence of GDR width in $^{110}$Sn, $^{112}$Sn nuclei. They found that the GDR width increases almost quadratically up to the highest excitation energy. This group also suggested an empirical formula to explain the excitation energy dependence of GDR width which is $\Gamma_{GDR} = 4.8 + 0.0026E_{GDR}^{1.6}$, where 4.8 is the ground state GDR width. In 1988, Chakraborti et al., [Cha88] gave a new parametrization $\Gamma_{GDR} = 4.5 + 0.0004E_{GDR}^2 + 0.003J^2$ and included it within the statistical model code CASCADE, instead of taking GDR width as a free parameter.

In 1989, Bracco et al., [Bra89] populated $^{110}$Sn nuclei at $E^* = 230$ MeV for measuring the GDR width at very high excitation energy and found an abrupt change in the smooth dependence of GDR width with excitation energy. They measured the GDR width at $E^* = 230$ MeV in this mass region which is similar the one observed at $E^* = 130$ MeV, indicating the onset of saturation effect above 130 MeV, which correspond to $T \sim 2.5$ MeV. Further evidence of saturation effect at very high excitation was also obtained by Enders et al., [End92] in 1992 and Hofmann et al., [Hof94] in 1994.

In 1992, Kasagi et al., [Kas92] performed an experiment at RIKEN, Japan
by populating the nuclei $^{132}$Ce and observed that the GDR width increased from 8 to 13 MeV due to the increase of $E^*$ from 80 to 120 MeV.

In 1994, Noormann et al., [Noo94] studied the angular momentum dependence of GDR width in the temperature domain $1 \leq T \leq 1.6$ MeV. They measured the GDR $\gamma$-rays emitted from the compound nucleus $^{154}$Dy populated at an excitation energy of 69 MeV in three angular momentum windows $< J > = 31, 42$ and $50 \hbar$ and showed that the GDR width increased with increasing angular momentum.

In 1996, Viesti et al., [Vie96] did an experiment by employing a high resolution $4\pi \gamma$-ray spectrometer to select the spin region in the fusion evaporation reaction ($^{64}$Ni + $^{92}$Zr @ $E_{lab} = 241$ MeV) forming the excited $^{156}$Er nuclei. They also showed that the GDR width increased with increasing angular momentum.

The above experimental investigations were performed mostly using the heavy ion fusion reactions where the compound nuclei are populated at very high excitation energy with broad angular momentum distributions. These experimental data showed that the GDR width increased up to $\Gamma_{GDR} = 11$ MeV when the excitation energy increases up to $E^* = 130$ MeV. This increase was interpreted as arising from the change of nuclear shape deformation induced by the combined effect of temperature and angular momentum. In order to understand their individual effect on GDR width, these two effects must be separated and measurement should be carried out at fixed temperature for different angular momenta, and for different temperatures at fixed (or low) angular momentum.

In 1995, Bracco et al., [Bra95] studied the GDR width and angular distributions as a function of angular momentum at an approximately constant temperature $T \sim 1.8$ MeV, in order to see only the angular momentum effect
on GDR width. They populated $^{109,110}$Sn nuclei by fusion evaporation reaction at excitation energy $E^* = 80.92$ MeV and at the angular momentum region $40 - 54 \hbar$. They found that the GDR width increased from 10.8 to 12.8 MeV due to increase of angular momentum from 40 to 54 $\hbar$.

In 1996, Ramakrishnan et al., [Ram96] performed a pioneering experiment to decouple the effects of angular momentum and temperature on GDR width through inelastic scattering of $\alpha$ particles at 30 and 40 MeV/nucleon. They populated $^{120}$Sn nuclei in the excitation energies range of 30 – 130 MeV and at very low angular momentum states ($< J > = 15 \hbar$). Because of the low angular momentum populated, it was possible to study the variation of GDR width with excitation energy without having any significant effect of J.

From the experimental results of Bracco et al., [Bra95] and Ramakrishnan et al., [Ram96], it was clear that at low angular momentum the GDR width is controlled by the temperature induced effect and at high angular momentum the GDR width is controlled by the angular momentum effect. It seems that at particular temperature, the angular momentum effects begin to be important only above a certain value. The experimental confirmation of this hypothesis required a large number of experimental data and it was later confirmed by several works.

In 1997, Mattiuzzi et al., [Mat97] measured the GDR width in $^{106}$Sn nuclei at $E^* = 80$ MeV ($T \sim 2$ MeV) and for average spin values of 24 and 36 $\hbar$. These results, together with the previous existing exclusive measurements in the same excitation energy and mass region, confirmed that the GDR width is roughly constant up to spin $J \leq 35 \hbar$ for Sn mass region and thereafter increases with the angular momentum.

In 1998, Baumann et al., [Bau98] studied the evolution of the giant dipole
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In 1999, Kelly et al., [Kel99] did an interesting experiment by populating $^{118}$Sn nuclei using $^{18}$O as beam and $^{100}$Mo as target. They pointed out that at higher bombarding energies ($E_{\text{lab}} > 5$ MeV/nucleon), pre-equilibrium effects come into picture which substantially lowers the average excitation energy and hence the nuclear temperature. They measured the corresponding loss of excitation energy of the compound nucleus due to pre-equilibrium particle emissions. Their detailed measurements along with the re-analysis of previous experimental results, showed that the GDR width does not saturate at $T > 2.5$ MeV but continues to increase up to temperatures of $T \sim 3.2$ MeV. Later, in 2006, Wieland et al., [Wie06] did an experiment by populating highly excited $^{132}$Ce compound nucleus through heavier target-projectile combinations where pre-equilibrium effects were very small and found that the GDR width does not saturate but increases steadily with temperature of at least up to 4 MeV. At very high temperatures ($T > 4$ MeV), Gaardhoje et al., [Gaa87] observed the lower $\gamma$-ray yield from GDR decay which signified the quenching of GDR at very high temperature and suggested that there might be loss of collectivity within the nucleus. This quenching of $\gamma$-ray yield with increasing $E^*$ was also observed by Faou et al., [Fao94] when they studied GDR $\gamma$-rays emitted form...
hot nuclei of $A\sim 115$ and $E^*$ between 350 to 500 MeV.

![Diagram showing experimental data for GDR width at low temperatures with theoretical calculation (TSFM, CTFM) for $^{63}Cu$, $^{120}Sn$ and $^{208}Pb$.](image)

Figure 1.7: Previous experimental data of GDR width at low temperatures with theoretical calculation (TSFM, CTFM) for $^{63}Cu$, $^{120}Sn$ and $^{208}Pb$. (a) The filled circles are from Ref [Dee12a] while open circles are from Refs. [Kus98, Kic87]. (b) Our $^{119}Sb$ data (filled circles) measured earlier [Sup12a] are shown along with the data of $^{120}Sn$ (open circles [Bau98], open squares [Kel99], up triangle [Kus98], down triangle [Hec03a]). (c) $^{201}Tl$ data (filled circles) [Dec12a] along with $^{208}Pb$ [Bau98] data (open circles). The dashed lines correspond to the TSFM calculation while the continuous lines are the results of CTFM calculation.

In 2003, Rathi et al., [Rat03a] observed that the experimental GDR width was almost constant with increasing $J$ at a particular temperature but increased with increasing temperature for a particular angular momentum, for the study of GDR width in excited $^{86}Mo$ nuclei. In the same year, Heckmann et al., [Hec03a] did an another inelastic scattering experiment and extracted $\Gamma_{GDR} = 4$ MeV at $T = 1$ MeV in the decay of $^{120}Sn$ nuclei. This was the lowest finite-
temperature GDR width measurement at that time. Surprisingly, the extracted GDR width shows almost same value as that of the ground state.

In 2008, Srijit Bhattacharya et al., [Sri08b] measured the angular momentum gated GDR width at low temperatures ($T \leq 2$ MeV) and high angular momentum ($J = 49 - 59 \hbar$) on $^{113}$Sb nuclei. They observed that the GDR width increased with increasing temperature (or angular momentum) for a given angular momentum (or temperature). There is an extensive compilation of GDR parameters built on excited states for $A=39-240$ by A Schiller and M Thoennessen in Ref [Sch07].

Until now, there are very few experimental data on the measurement of GDR width at low temperature ($T < 1.5$ MeV). Experimentally, the measurement of GDR width at low temperature ($T < 1$ MeV) is a very complex and challenging problem due to the difficulties in populating the nuclei at low excitation energies. Previously, the low temperature measurements were performed through inelastic scattering of lighter projectile by heavier target with a disadvantage of getting imprecise excitation energies with an uncertainty about 10 MeV. The heavy ion induced fusion reactions are limited to the excitation at higher temperature due to presence of Coulomb barrier in the entrance channel and are always associated with broad J distributions. Recently, at the Variable Energy Cyclotron Centre (VECC), Kolkata, India, exclusive experiments were performed using the alpha beams to investigate the low temperature region [Sup12a, Dee12a]. The previous experimental data at low temperatures are shown in Fig 1.7. It has been shown that the effect of $T$ and $J$ becomes noticeable only above a critical angular momentum ($J_c = 0.6A^{5/6}$) and $T \sim 1$ MeV, and after that the GDR width increases with increase in $J$ and $T$. Till now, there are no experimental data at low temperatures in $A \sim 100$ mass region. This thesis deals with the measurement of GDR width at very low temperatures.
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for $^{97}\text{Tc}$ nuclei.

1.6.2 Theoretical explanation

Along with the experimental efforts, a number of theoretical approaches have been proposed to demonstrate the behavior of GDR width as a function of $T$ and $J$. Microscopically, the increase of GDR width as a function of $T$ is described reasonably well within the Phonon Damping Model (PDM) [Dan98]. The PDM calculates the GDR width and the strength function directly in the laboratory frame without any need for an explicit inclusion of thermal fluctuation of nuclear shapes. According to PDM, the increase of GDR width with $T$ is due to the coupling of GDR phonons to the incoherent particle-particle, hole-hole and particle-hole configurations, which appears due to the distortion of the Fermi surface at finite $T$. This model can predict the data at low temperature as well as the saturation of GDR width at higher temperature by including the thermal pairing fluctuation.

On the other hand, the macroscopic Thermal Shape Fluctuation Model (TSFM) [Alh88] is based on the fact that large amplitude thermal fluctuations of nuclear shape play an important role in describing the increase of GDR width as a function of $T$. According to TSFM, at finite temperature, the nucleus does not have any particular shape, rather it will be an weighted average of all possible shapes and orientations. The nuclear shape fluctuates around the equilibrium deformation and this fluctuation increases with increase in temperature. As a result, the GDR line shape will also be a superposition of line shapes due to all possible nuclear shapes and thus producing a larger width. Therefore, the GDR width has been found to increase monotonically with temperature. The basic assumption (adiabacity) of this model is that the nuclear shape does not change during the time GDR takes to damp. This model explains the experi-
mental data very well at the temperature region $1.5 < T \leq 3.0$ MeV and at low angular momentum region ($J < 50\hbar$). However, it is unable to explain the $T$ dependence below 1.5 MeV and at higher angular momentum in different mass regions [Sup12a, Dee12a, Sri08b]. Later, Kusnezov et al., [Kus98] proposed a very simple parametrized formula for the GDR width as a function of $T$ and $J$ of the system under the framework of the TSFM. The Kusnezov parametrization has been tested for large number of nuclei and found to be consistent with the prediction of TSFM calculation only above $T = 1.5$ MeV.

In order to understand the discrepancy between experimental data and TSFM prediction at lower temperature, very recently, Deepak Pandit et al., [Dee12a] have proposed a new phenomenological model under the framework of pTSFM (kusnezov parametrization), named as Critical Temperature Fluctuation Model (CTFM). This new model emphasizes on an essential point, overlooked in the TSFM, that the GDR oscillations itself induce a quadrupole moment causing the nuclear shape to fluctuate even at $T = 0$ MeV. Consequently, the GDR vibrations cannot view those thermal shape fluctuations that are smaller than its own intrinsic fluctuations. Therefore, the experimental GDR width should remain nearly constant at the ground state value up to a critical temperature ($T_c$) and the effect of thermal fluctuations should become evident above $T_c$ once they become larger than the intrinsic GDR fluctuations. It has been shown that the CTFM better explain the experimental data of Mukhopadhyay et al., [Sup12a] and Heckmann et al., [Hec03a]. To verify this critical behavior, Deepak Pandit et al., [Dee12a] have performed another experiment in two other mass regions ($^{63}$Cu and $^{201}$Tl) and they have also observed that the CTFM better explain the experimental data than that of TSFM. They have concluded that the GDR width is not suppressed, rather the TSFM over predicts the experimental data at lower temperature. Therefore, the GDR in-
duced intrinsic fluctuation should be included in the TSFM calculation.

There was another theoretical calculation known as Collisional damping Model (CDM) [Bar96, Sme91], according to which the increase of GDR width is due to two body nucleon-nucleon or one body nucleon-nuclear surface collisions. This calculation showed that the one body collisional damping width has very weak dependence on T and remains almost similar to the ground state value. The two body collision comes into picture at higher temperature (T > 3 MeV) and leads to an extra contribution in the GDR width showing a T^2 dependence. However, this model is not suitable for the evolution of GDR width at low temperatures (T < 1.5 MeV).

The macroscopic TSFM is very easy to use and predicts the experimental data in the range of temperature 1.5 < T < 2.5 MeV well. On the other hand, the PDM depends on the complex microscopic configuration. But, the phenomenological CTFM explain the data better than that of TSFM in all the mass regions. Therefore, CTFM should be used universally in describing the GDR width as a function of T and J. The detailed description of TSFM, PDM and CTFM has been discussed in the next Chapter 2 (Section 2.3).

1.7 Motivation of the present work

The basic aim of the present work is to understand the evolution of GDR width at very low temperatures. The experimental studies, over the years, have shown that the GDR width increases with both the temperature (T) and angular momentum (J) after a certain critical value. The angular momentum effect on GDR width is now well established and well explained by the theoretical models. A wealth of experimental data on the measurement of GDR width at T > 1.5 MeV exists. The measured GDR widths for T > 1.5 MeV were well described by the most popular thermal shape fluctuation model (TSFM). However, at
lower temperature ($T < 1.5$ MeV) the picture is still unclear due to insufficient data. There are only a few experimental data in the mass region of $^{120}$Sn, $^{63}$Cu and $^{201}$Tl at lower temperature ($1.0 < T \leq 1.5$ MeV) where TSFM is not able to explain the data. Therefore, much more experimental data are required in other mass regions at this low temperatures to verify whether such a behavior is really true or not.

In order to understand the discrepancy between experimental observation and theoretical prediction at lower temperature, a new phenomenological model (CTFM) has been proposed. In CTFM, it was pointed out that the GDR width remains constant up to a critical temperature and thereafter increases with the increase in temperature. A very few experimental data exist for the confirmation of this critical behavior. Unfortunately, there are no experimental data below the critical point except for one measurement in $^{63}$Cu where only two data points exist below the critical value. As the situation stands now, the number of GDR width measurement till now at $T < T_c$ are inadequate to test the critical behavior or to conclude that the GDR width remains constant at its ground state value below the critical point and deserves further investigation in the wide range of mass at below and above the critical point.

In order to address the above queries regarding the critical behavior of the GDR width as a function temperature, a systematic measurement of GDR width in the unexplored region ($T = 0.8 - 1.5$ MeV) has been performed for $^{97}$Tc nucleus. The compound nucleus $^{97}$Tc has been taken mainly for two reasons. Firstly, $^{97}$Tc nucleus is very nearly spherical ($\beta = 0.134$), secondly, in $^{97}$Tc nucleus, no such GDR measurement exists till now. In the present work, alpha induced fusion reactions have been employed to investigate the low temperature region. The alpha beam has been chosen because of the low Coulomb barrier in the entrance channel so that a wide range of low excitation energies can be
achieved in the compound nucleus.

The present thesis is organized in seven chapters. In the present chapter, the basic introduction of GDR and the motivation of this work are discussed. In the $2^{nd}$ chapter, theoretical tools to interpret the GDR $\gamma$-ray spectra and different theoretical models (TSFM, CTFM, PDM) for the $T$ and $J$ dependence of GDR width are discussed. In the $3^{rd}$ chapter, the detector systems and their GEANT4 simulations are discussed. In the $4^{th}$ chapter, the details of experiments performed, data taking and analysis of the data are discussed. In the $5^{th}$ chapter, the results obtained from the data and their interpretations from different theoretical calculations are discussed. Along with the GDR studies, the neutron response of the LAMBDA spectrometer also forms a part of this thesis work, which has been presented in $6^{th}$ chapter. Finally, summary and conclusion with future outlook have been presented in $7^{th}$ chapter.