SYNOPSIS

A natural approach to study the properties of the atomic nucleus is to heat it up and measure the frequencies of the emitted electromagnetic radiations. In other words, by measuring the $\gamma$-decay of the excited compound nuclei, one can probe the structure of nuclei at finite temperature ($T$) and angular momentum ($J$). Since the photon interacts with the nuclear medium through the relatively weak Coulomb interaction, it is one of the cleanest probes to study the diverse properties of the nuclei. The photons are emitted from excited compound nucleus through several mechanisms. Low energy discrete $\gamma$-rays are emitted during the de-excitation of equilibrated nuclei, which is a statistical process. The high-energy $\gamma$-rays (8-20 MeV) are produced from the decay of Giant Dipole Resonance (GDR) built on excited states in heavy ion fusion reaction while the most energetic photons (> 20 MeV) originate from the bremsstrahlung phenomenon during the early stages of the reaction. The present thesis deals with the study of high-energy $\gamma$-rays from the decay of GDR built on the excited states for the investigation of the deformation in light $\alpha$ and non-$\alpha$ like systems and the emission of nucleus-nucleus coherent bremsstrahlung $\gamma$-rays from the spontaneous fission of $^{252}$Cf.

The GDR, a particularly interesting mode of collective vibration, can be understood as out of phase oscillations of the protons and the neutrons in the hot nucleus. Since, the decay of GDR occurs on a time scale that is sufficiently short ($\sim 10^{-22}$ s), it can provide information on the shape evolution of the nuclei at finite temperature and fast rotation which occurs in a much larger time scale. The resonance energy being inversely proportional to the nuclear radius, one gets a single lorentzian strength function for spherical nuclei since the vibrations along the three principal axes are same. However, the GDR
strength function splits in the case of deformed nuclei and the investigation of this strength distribution gives a direct access to look into nuclear deformations. The decay of GDR $\gamma$-rays from hot $^{47}$V and $^{32}$S nuclei have been studied to explore the deformed shapes of light $\alpha$ and non-$\alpha$ systems using GDR lineshape and compare them with the corresponding predictions for equilibrium Jacobi shapes.

Rapidly rotating light nuclei in general are likely to undergo Jacobi shape transition, an abrupt change of shape from an oblate ellipsoid rotating around the symmetry axis to an elongated prolate or triaxial shape rotating perpendicularly around the symmetry axis, at an angular momentum value near the fission limit. Signatures of such shape transitions in $^{45}$Sc and $^{46}$Ti have been reported from the study of lineshapes of GDR built on excited states. Recently, in an experiment at VECC, the deformation of the excited $^{47}$V and $^{32}$S nucleus has been estimated from the inclusive $\alpha$-particle spectrum. The large deformations observed in light $\alpha$-like systems are believed to be due to the occurrence of either quasimolecular resonances or nuclear orbiting, which has the origin in the $\alpha$-cluster structure of these nuclei. The enhancement of fragment yield near the entrance channel as well as $\alpha$-spectroscopic studies for $^{32}$S have strongly indicated a highly deformed orbiting dinuclear shape from the previous studies. The $\alpha$-spectroscopic studies, however, can only indicate effective deformation in an indirect way. Hence, it is worthwhile to complement the above study by exploring the relationship between the shapes of the light $\alpha$-like systems and the corresponding Jacobi shapes directly via the GDR $\gamma$ decays in more direct manner.

The $\gamma$-ray yield from the decay of the GDR in self-conjugate nuclei ($^{32}$S) populated by $T = 0$ entrance channel depends strongly on the isospin mixing due to the isovector nature of the electric dipole radiation. The E1 emission associated
with the GDR (\(\Delta T=1\)) decay is hindered because the density of \(T=0\) levels is always much higher than the density of \(T=1\) levels. However, the yield of high energy \(\gamma\)-rays from \(N=Z\) compound nuclei increases in the presence of isospin mixing. In heavy ion collisions at projectile energies above 6 MeV/nucleon, incomplete fusion and pre-equilibrium nucleon emission processes also occur. Hence, the statistical emission of \(\gamma\)-rays may also arise following incomplete fusion or pre-equilibrium nucleon emission. Thus, a decaying compound nucleus may not be a \(N=Z\) nucleus. The mass and charge of the compound nucleus as well as the excitation energy are expected to be lower than in case of complete fusion.

The \(^{47}\text{V}\) and \(^{32}\text{S}\) nuclei were formed by bombarding pure 1 mg/cm\(^2\) thick \(^{27}\text{Al}\) and \(^{12}\text{C}\) targets, respectively, with accelerated \(^{20}\text{Ne}\) beams from the K-130 cyclotron at the Variable Energy Cyclotron Centre, Kolkata, India. The \(^{47}\text{V}\) nucleus was populated at an excited energy of 108 MeV corresponding to a projectile energy of 160 MeV. Similarly, the initial excitation energies of \(^{32}\text{S}\) nucleus were 73 & 78 MeV corresponding to projectile energies of 145 & 160 MeV, respectively. The critical angular momenta for the two systems \(^{47}\text{V}\) and \(^{32}\text{S}\) were \(38\hbar\) and \(24\hbar\), respectively, and extend well beyond the critical angular momenta values of 29.6\(\hbar\) and 21.5\(\hbar\) at which the Jacobi transitions are predicted to occur for these nuclei (according to systematic \(J_c = 1.2A^{5/6}\)). The angular momentum values are also well below their fission limits for the two systems making it possible to probe these nuclei at these conditions. The high-energy photons were detected using the Large Area Modular BaF\(_2\) Detector Array (LAMBDA) in coincidence with low energy \(\gamma\)-ray multiplicities measured with the multiplicity filter detector. The LAMBDA spectrometer arranged in a \(7\times7\) matrix was centered at 55\(^\circ\) to the beam direction and at a distance of 50 cm from the target. Apart from the LAMBDA spectrometer, another BaF\(_2\) based
50-element gamma multiplicity filter has been designed & developed in-house to measure the angular momentum in an event-by-event mode. The 50-element filter was split into two blocks of 25 detectors each and was placed on the top and the bottom of the scattering chamber at a distance of 10 cm from the target center (covering ∼30% of 4π) in castle geometry to measure the γ-multiplicities in coincidence with the high-energy photon events.

The high-energy gamma spectra were extracted from the off-line analysis of the data recorded in the event-by-event mode by applying proper cuts on the Time-Of-Fight (TOF) and Pulse Shape Discrimination (PSD). After application of different conditions, in a valid event, the energy deposited in the detectors was summed using a nearest neighbor event reconstruction technique. Finally, the energies were Doppler corrected. The measured fold distributions from the multiplicity filter were mapped onto the angular momentum distributions using a realistic approach based on Monte Carlo GEANT simulation. Next, the experimental high-energy γ-ray spectra were analyzed using a modified version of the statistical model code CASCADE along with a bremsstrahlung component folded with the detector response function.

The linearized GDR lineshapes for the systems 47V and 32S are remarkably different from which one usually gets in the case of a spherical or a near spherical system and indicate large deformations. The most striking feature for 47V is the strong enhancement in the γ-ray yield at ∼10 MeV similar to the one observed in 46Ti earlier. It is the characteristics of Jacobi shape transition and Coriolis effect due to high angular momentum in the system undergoing giant dipole vibration. Since the statistical model code CASCADE used in the thesis does not include the effect of isospin, the data for 20Ne + 12C have been analyzed twice i.e. considering pre-equilibrium emission and without pre-equilibrium emission. For both the cases, the GDR parameters are very similar except for
the overall GDR strength function indicating that, with the inclusion of isospin effect, the spectral shape of the GDR will not alter rather the magnitude of the overall strength function will be modified. Interestingly, no enhancement at $\sim 10$ MeV is seen for the $^{32}$S nucleus although it is populated well above the Jacobi transition point. The shape looks more like a highly extended prolate (one component at $\sim 14$ MeV and another at $\sim 26$ MeV) and is seen for the first time for this nucleus.

In order to understand the equilibrium deformation in these hot and rotating nuclear systems, a calculation is performed for estimating the equilibrium shape of a nucleus by minimizing the total free energy under the framework of rotating liquid drop model (RLDM) and thermal shape fluctuation model (TSFM) for a given temperature and angular momentum. It has been observed that our prediction of GDR strength function for an equilibrated shape from a minimized free energy (with thermal fluctuation included) describes the data for $^{47}$V remarkably well for both the experimentally measured spin windows. The enhancement of the strength at $\sim 10$ MeV and the goodness of description are characteristic signatures of Jacobi transition in the case of $^{47}$V nucleus at these spin values. However, the same free energy calculation fails miserably to explain the GDR strength function for $^{32}$S performed at both low and high angular momentum. The shapes suggest a strongly prolate deformed nucleus ($\beta \sim 0.76$ for $E_{\text{proj}} = 160$ MeV, corresponding to an axis ratio of 1.94:1). The occurrence of such a large deformation without showing the characteristics of Jacobi transition is possible only if some other reaction mechanism is responsible. This unusual deformation, seen directly for the first time, has been speculated due to the formation of either the orbiting dinuclear configuration or molecular structure of $^{16}$O + $^{16}$O in $^{32}$S super deformed band.

Apart from the heavy ion fusion reaction, the high-energy coherent brem-
sstrahlung $\gamma$-rays (> 20 MeV) are also believed to be produced from the spontaneous fission of $^{252}$Cf due to the acceleration of fission fragments in their Coulomb field. However, the high-energy $\gamma$-ray spectra, above 20 MeV, emitted in the spontaneous fission of $^{252}$Cf have been one of the fundamental problems of nuclear fission physics. From earlier studies, it has been seen that for energies above 20 MeV, the experimental data and theoretical calculations are contradictory. In few experiments, such high-energy $\gamma$-rays were not detected while in some experiment the high-energy $\gamma$-ray spectrum was measured. The yield of $\gamma$-rays with energies 20 - 120 MeV has been calculated using various models, but the calculations in different models differ by several orders of magnitude. Thus, the conflicting theoretical work as well as the experimental results motivates one to carry out further investigation of the high energy $\gamma$-rays (> 20 MeV) emitted in the spontaneous fission of $^{252}$Cf.

An extensive experimental study was carried out using $^{252}$Cf source to investigate the photon emission accompanying the spontaneous fission at Variable Energy Cyclotron Centre (VECC), Kolkata. High energy $\gamma$-rays from the spontaneous fission of $^{252}$Cf were detected in coincidence with the low energy discrete $\gamma$-rays emitted from the decay of excited fission fragments in order to establish a correlation (photons/fission) between the high energy $\gamma$-rays and the fission process. The high-energy $\gamma$-rays were measured using the LAMBDA array and the prompt $\gamma$-rays with multiplicity detector. Four small BaF$_2$ detectors were placed as close as possible to the source to determine the start signal for each event. The LAMBDA array arranged in a 7×7 matrix was kept at a distance of 35 cm from the source. Time of flight measurement distinguished the $\gamma$-rays from neutrons while long/short gate technique was applied to reject the pile up events. Data were collected in this $\gamma$-$\gamma$ coincidence mode for 450 hours. At the photon energies $E_\gamma > 25$ MeV, cosmic ray showers are major source
of background, therefore, extreme precautions were taken to obtain the experimental data free from any cosmic impurity. Finally, the background events were subtracted by collecting the data for another 450 hours without the source.

Interestingly, high-energy $\gamma$-rays above 20 MeV were detected in the experiment pointing towards the evidence of nucleus-nucleus coherent bremsstrahlung. The photon spectrum was measured up to 80 MeV using the $^{252}$Cf source. The low energy (8 - 20 MeV) part of the photon spectrum is mainly associated with direct excitation of the giant dipole resonance (GDR) from the daughter nuclei arising in the fission process. However, the photons above 20 MeV can only be emitted by nuclear bremsstrahlung phenomenon since at start the nucleus has zero energy. It is also evident from the high-energy $\gamma$-ray spectrum since the slope changes sharply after 20 MeV clearly indicating that the mechanisms of the emission of photons below and above 20 MeV are completely different in origin.

A theoretical calculation was performed based on the classical Coulomb acceleration model to predict the yield of these photons above 20 MeV. The photon yield was estimated for a distribution of the most probable masses and charges arising from the fission of $^{252}$Cf including a pre-scission kinetic energy for the fragments. An attempt was also made to include the conservation of energy by multiplying the bremsstrahlung yield with a factor of $(1 - \hbar\omega/E)$, where $\hbar\omega$ is the energy carried away by the bremsstrahlung photons. This approximate calculation represents the experimental result quite well when the pre-scission kinetic energy is taken into account. However, a complete quantum mechanical calculation is desirable to predict the yield of bremsstrahlung $\gamma$-rays in nucleus-nucleus collision and is beyond the scope of this thesis.