Study of high energy photons from hot nuclear systems

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A natural approach to study the properties of the atomic nucleus is to heat it up and measure the γ-decay of the excited compound nuclei. It is one of the cleanest probes to study the diverse properties of the nuclei as the photon interacts with the nuclear medium through the relatively weak Coulomb interaction. The γ-rays are emitted from the excited compound nucleus during the de-excitation which is a statistical process, from the decay of giant dipole resonance (GDR) (8-20 MeV) and the bremsstrahlung phenomenon (>20 MeV) during the early stages of the reaction [1]. The present thesis deals with the study of high-energy γ-rays from the decay of GDR built on the excited states and the emission of nucleus-nucleus coherent bremsstrahlung γ-rays from the spontaneous fission of ^{252}Cf.

Earlier, in a series of experiments at the Variable Energy Cyclotron Centre (VECC), Kolkata, the deformation of the excited ^{47}V and ^{32}S nucleus has been estimated from the inclusive α-particle spectrum [2]. The large deformations observed in light α-like systems (^{32}S) are believed to be due to the occurrence of either quasimolecular resonances or nuclear orbiting, which has the origin in the α-cluster structure of these nuclei. On the other hand, rapidly rotating light nuclei in general are likely to undergo Jacobi shape transition [3]. Hence, it is worthwhile to complement the above study by exploring the relationship between the shapes of the light α-like systems and the corresponding Jacobi shapes directly via the GDR γ-decays in more direct manner.

The ^{47}V and ^{32}S nuclei were formed by bombarding pure 1 mg/cm^2 thick ^{27}Al and ^{12}C targets, respectively, with accelerated ^{20}Ne beams from the K-130 cyclotron at the VECC. The ^{47}V nucleus was populated at an excited energy of 108 MeV corresponding to a projectile energy of 160 MeV. The initial excitation energies of ^{32}S nucleus were 73 & 78 MeV corresponding to projectile energies of 145 & 160 MeV, respectively. The critical angular momenta for the two systems ^{47}V and ^{32}S were 38ħ and 24ħ respectively, and extended well beyond the critical angular momentum values for Jacobi transitions ($J_c = 1.2A^{5/6}$). The high-energy photons were detected emplying the Large Area Modular BaF$_2$ Detector Array (LAMBDA) [4] in coincidence with the low energy γ-ray multiplicities measured with the multiplicity filter detector [5], which were indigenously developed in house.

It is very interesting to note that the linearized GDR lineshapes for the systems ^{47}V & ^{32}S are remarkably different from each other. In fact, the lineshapes are also very different from which one usually gets in the case of a spherical or a near spherical system and indicate large deformations (Fig. 1). In order to understand the equilibrium deformations, a calculation was 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 the prediction from the TSFM describes the data for

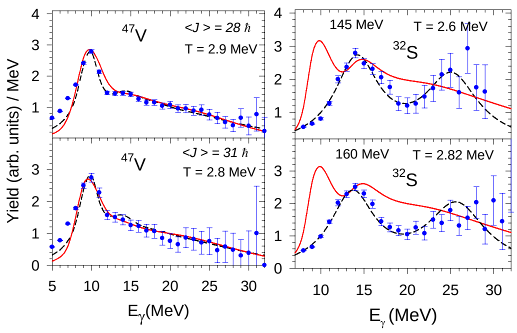

Fig.1. The linearized experimental GDR strength function (filled circles) for ^{47}V and ^{32}S. The dashed lines represent the GDR strength functions used in the CASCADE calculation while the continuous lines represent the TSFM calculation (J = 22ħ & T = 2.8 MeV for ^{32}S).

^{47}V remarkably well for both the experimentally measured spin windows. The enhancement of the strength at ~ 10 MeV and the goodness of description are characteristic signatures of Jacobi transition and Coriolis splitting in the case of ^{47}V nucleus at these spin values [3]. 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 (β ~ 0.76 for E_{proj} = 160 MeV, corresponding to an axis ratio of 2:1). 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 [3].

Apart from the heavy ion fusion reactions, an extensive experimental study (900 hrs) was also carried out to study the nucleus–nucleus coherent bremsstrahlung γ-rays produced from the spontaneous fission of ^{252}Cf [6]. The high-energy γ-ray spectra, above 20 MeV, emitted in the spontaneous fission of ^{252}Cf have been one of the fundamental problems of nuclear fission physics. In few experiments, such high-energy γ-rays were not detected while in some experiment the high-energy γ-ray spectrum was measured. The yield of γ-rays with energies 20–120 MeV has been calculated using various models, but the calculations in different models differ by several orders of magnitude [6]. Thus, the conflicting theoretical work as well as the experimental results motivates one to carry out further investigation.

The high-energy γ-rays accompanying spontaneous fission of ^{252}Cf were measured using the LAMBDA array in coincidence with the prompt γ-rays, employing the multiplicity detector, in order to establish a correlation (photons/fission) between the high-energy γ-rays and the fission process. Moreover, extreme precautions were taken to obtain the experimental data free from any cosmic impurity. Interestingly, high-energy γ-rays upto 80 MeV were detected in the experiment pointing towards the evidence of nucleus-nucleus coherent bremsstrahlung (Fig 2). The photons above 20 MeV can only be emitted by the nuclear bremsstrahlung since at start the nucleus

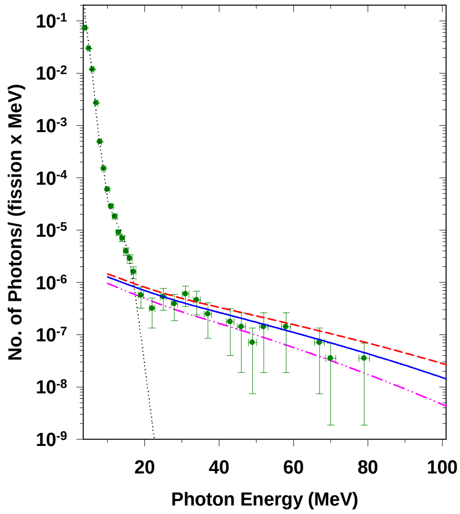

Fig.2. The experimentally measured γ-ray spectrum (filled circles) from ^{252}Cf. The pure Coulomb calculation (dashed line), including conservation of energy (solid line) and including both conservation of energy and pre-scission kinetic energy (double dot dashed line) is also shown. The dotted line represents the CASCADE calculation.

has zero energy. The experimental result has also been substantiated by a theoretical calculation based on the classical Coulomb acceleration model. The photon yield was estimated for a distribution of the most probable masses and charges arising from the fission of ^{252}Cf. This approximate calculation represents the experimental result quite well when the pre-scission kinetic energy (30 MeV) and conservation of energy (multiplying the yield with $1-\hbar\omega/E$ where $\hbar\omega$ is the energy carried away by the bremsstrahlung photons) is taken into account.

References

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