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SHAPE TRANSITION AND ISOVECTOR GIANT QUADRUPOLE RESONANCE DECAY IN HOT ROTATING NUCLEI*

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We provide a brief review of our activities involving high energy gamma decay from hot-rotating nuclei. The two primary goals of this ongoing programme is to search for rare shape-phase transitions in heavy ($A \sim 190$) nuclei, from the analysis of the giant dipole resonance (GDR) gamma ray spectra and also to search for the Isovector Giant Quadrupole Resonance (IVGQR) based upon excited states. The efforts to carry out the exclusive measurements have resulted in the setting up of a sum-spin spectrometer in complete 4π configuration. The performance of this spin-spectrometer will be presented in brief. In addition, this paper also presents the results of our studies with lanthanum bromide detectors of different sizes and configurations using low energy sources and in-beam measurements. The finite temperature potential energy surface calculations, carried out to guide the measurements, will also be discussed.

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1. Introduction

The nuclear giant resonances (GR) are based on both ground states as well as excited states. The giant resonances of different types (electric or magnetic) and different multiplicities based upon the ground states are studied using inelastic scattering, charge exchange reactions and photo nuclear reactions. Whereas the heavy-ion induced fusion evaporation reactions have

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been primarily responsible for studying the isovector giant dipole resonance (IVGDR) based upon excited states. The study of high energy gamma-rays from the decay of the IVGDR states built upon highly excited states has established itself as one of the primary tools to understand the dynamics of the hot rotating nuclei. The spectral shape and angular anisotropies of the GDR gamma rays are expected to manifest a variety of shape-phase transitions in the atomic nuclei with increasing temperature and angular momentum.

The importance of the studies in hot GDR decay is two-fold. To understand the basic physics of the persistence and damping of the collective oscillation of the nuclear many-body system, as manifest in the temperature and angular momentum dependence of the GDR parameters, $E_{\rm GDR}$ and $\Gamma_{\rm GDR}$. On the other hand, the detailed analysis of the GDR spectral shape and angular anisotropies of the GDR gamma rays provide valuable insights in a variety of dynamical effects in hot nuclei. The dynamical effects which are probed using hot GDR spectra are nuclear shape-phase transitions, fission hindrance, internal pair decay, entrance channel effect in heavy-ion reactions, isospin mixing at finite temperature *etc.* [1]. While this paper concentrates on shape-phase transition, the spectacular observation of nuclear dissipative effect in the GDR spectrum of heavy fissioning nuclei is worth noting. A series of measurements of fission gated GDR spectra have shown the inadequacy of statistical model analysis based upon Bohr's transition state model in reproducing the experimental multiplicity of GDR gamma rays from the fissioning nuclei. A modified form of the statistical model, incorporating both Kramer's theory and dynamical effects, suggested by Weidenmuller, exactly reproduces the enhanced yield of GDR gamma rays from the compound nucleus [2]. These studies have shown no temperature dependence of the viscosity parameter. It is of great current interest to connect the viscosity parameter, so studied in GDR decay spectra, with the dissipative parameter used in the analysis of collisions of heavy-ions at relativistic energy (RHIC physics) [3].

The studies of shape-phase transition from GDR spectra requires suitable choice of the nuclei and the regions of phase space to be probed. The choices are guided by the predictions of theoretical calculations, both microscopic and macroscopic. All mean field calculations predict a transition temperature T_{c1}, at which the nucleus, irrespective of its ground state deformation, becomes spherical and on rotation becomes oblate, rotating about its symmetry axis [4]. Goodman has made the interesting prediction of two critical temperatures in several heavy nuclei [5]. Our previous measurements of phase space selected GDR gamma rays from ^{194}Au provided a definite indication of shape transition [6]. This provided further impetus to carry out the investigations in other neighbouring nuclei.

2. Experimental setup

The experiments involved measurement of high energy GDR gamma rays in coincidence with low energy discrete gamma rays for angular momentum gating. The high energy gamma rays were measured in an array of seven large hexagonal NaI(Tl) detectors. The array was surrounded by an annular plastic detector for rejection of cosmic rays. The entire array is kept at around 75–80 cm from the target position for effective separation of the neutron and gamma rays. The pileup rejection is carried out using zero crossover technique as discussed in [7]. The high energy gamma rays were measured at different angles with respect to the beam direction for measuring the angular anisotropies. Targets of very high isotopic enrichment ($> 95\%$) and chemical purity were used to populate the different compound nuclei.

The measurements involved two different spin spectrometers. The measurements for ^{194}Au and ^{188}Os were carried out using a spin-spectrometer of 14 straight NaI(Tl) detectors of hexagonal cross-section, arranged in the so-called castle geometry. The measurements for ^{192}Pt were carried out using a spin-spectrometer comprised of 32 conical NaI(Tl) detectors arranged in a 4π soccer ball configuration.

3. The 4π spin-spectrometer

The spectrometer is a close packed array of 32 conical NaI detectors of pentagonal and hexagonal cross-sections. The 12 pentagonal and 20 hexagonal detectors form a spherical shell of 10 cm inner diameter. The detectors are 7.6 cm long and are viewed by photomultiplier tubes of 2" diameter. An aluminium scattering chamber of 14 cm diameter is placed centrally inside the spherical shell. For in-beam experiments two of the pentagonal detectors placed 180° apart in the array are removed for the beam inlet and outlet. The primary role of the array is to measure the multiplicity and sum-energy of the discrete low energy gamma rays emitted in heavy-ion induced fusion-evaporation reactions. This spectrometer is primarily to be used in conjunction with a high energy gamma ray spectrometer for the detection of phase space selected Giant Dipole Resonance (GDR) gamma rays. In addition, the spin spectrometer can also be used in conjunction with charged particle or/and array of neutron detectors for measuring angular momentum gated charged particle and neutrons. The detailed design and associated electronics are to be discussed and presented elsewhere [8]. The efficiencies of the detector and the full array was measured using calibrated low energy gamma sources. Extensive simulations were carried out using GEANT4 package to determine the efficiency and the response of the array and are compared with measurements with calibrated sources (^{137}Cs, ^{60}Co) [9]. Fig. 1 shows the variation of photo peak efficiency with the gamma

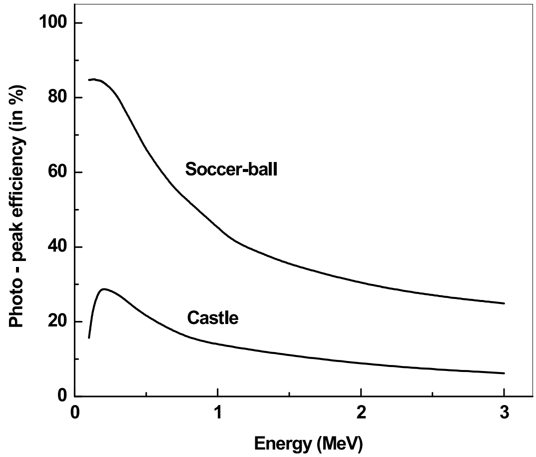

Fig. 1. Variation of the photo peak efficiency with gamma ray energy as simulated by GEANT4 for the 4π array and the 14 elements array in castle geometry.

ray energy for the 4π array and the 14 elements array in castle geometry as calculated by GEANT4 with the source at the centre of both the arrays. Fig. 2 shows a measured spectrum of 662 keV gamma rays from a calibrated ^{137}Cs source compared with the GEANT4 simulation at an absolute scale. The primary goal of the spin-spectrometer is the angular momentum gating of the high energy GDR gamma rays detected in coincidence with the low energy discrete gamma rays in the 4π spectrometer. A fuller knowledge of

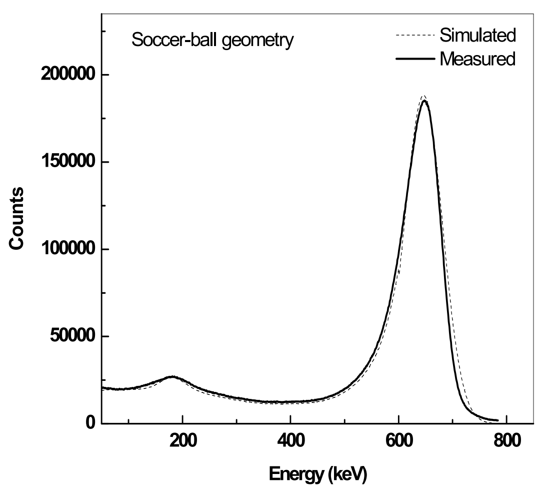

Fig. 2. Measured and simulated spectrum for 662 keV for the 4π array.

the response of the array to multiple discrete low energy gamma rays is essential for this purpose. Fig. 3 shows the fold to multiplicity distributions for different gamma-rays multiplicities as calculated by GEANT4 for the 4π array.

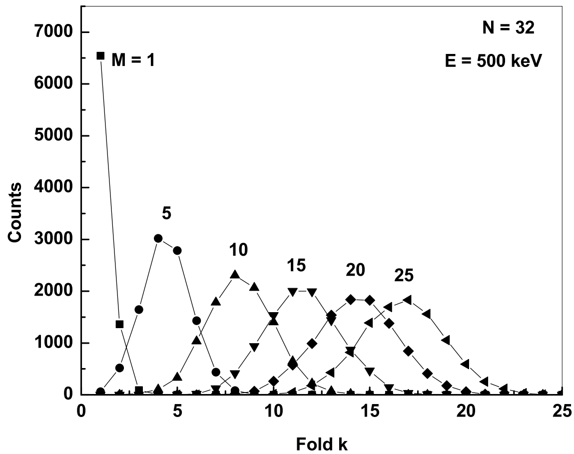

Fig. 3. GEANT4 simulated fold to multiplicity distributions for the 4π array.

4. Finite temperature PES calculations

In general any theory of hot nuclei starts with a mean field approximation: the Hartree–Fock method and Hartree–Fock–Bogoliubov theory, the Landau theory of shape transitions *etc.* All these theories calculate the critical temperature of shape transition for a given nucleus [10]. The Hartree–Fock–Bogoliubov Cranking calculations at finite temperatures (FTHFB) by Goodman has predicted two critical temperatures for a large number of nuclei [4, 5]. A fully microscopic approach within the framework of the static path approximation (SPA) has also been proposed in more recent times. We use a simpler yet very effective formalism [10] to evaluate the nuclear shapes and structural transitions with temperature and angular momentum. The macroscopic binding energy (B_{ldm}) is calculated using the mass formula of Moller–Nix and the Strutinsky shell corrections are invoked to take care of the microscopic effects. The excited and high spin states are treated by using the statistical theory which involves the determination of the grand partition function of the nuclear system of N neutrons and Z protons. The free energy of the system is minimised with respect to the deformation parameters (β, γ) for a fixed temperature T and angular momentum M. The details are discussed in our recent publication [10] and references therein.

The calculations have been carried out for all the heavy nuclei, namely, ^{194}Au, ^{188}Os, ^{192}Pt and ^{196}Hg for which we have carried out measurements. The results of the calculations are found to be in qualitative conformity with results arrived at by more microscopic FTHFBC methods of Goodman. The results of these calculations are to be published in fuller details in a separate publication [11].

5. GDR decay from ^{188}Os

The experimental details and the important parameters of the compound nucleus are given in [12] and will not be presented here. The initial data reduction resulted in multiplicity fold gated gamma rays spectra for the two beam energies and for all the four angles of measurements. Two narrow windows, corresponding to 4–6 and 9–12 folds were chosen to extract the spectra from low and high spin regions of the distribution. The lowest folds of 1–3 were not considered to avoid spurious counts due to possible target contaminants. The spectra were analysed by fitting with statistical model calculations using a modified version of the code CASCADE [2]. The temperature dependence of the level density was calculated using the Ignatyuk/Reisdorf formalism [13]. The fits were carried out in an iterative manner considering spherical, prolate and oblate shapes and the GDR parameters were extracted from the best fits to the spectra. Considering the strong temperature dependence of the GDR width the GDR widths were reduced in each successive stages of decay in the CASCADE calculations. The robustness of the GDR centroid energy further constrained the calculations. The result of the analysis seems to favour oblate shapes more over spherical or prolate shapes for the 84 MeV data. However, for the 65 MeV spectra, the shape could not be ascertained unambiguously from the statistical model fits. The value of the deformation parameter β obtained from these fits were used in the calculations to fit the angular anisotropy of the high energy gamma rays for the two beam energies. The amplitude of the anisotropy for 84 MeV was found to be marginally less than that of 65 MeV. The anisotropy at 84 MeV could be reproduced assuming a non-collective oblate deformation with the β obtained from the statistical fit (see Fig. 1. in Ref. [14]). This apparent consistency between the statistical model fit and the angular anisotropy is also in conformity with the theoretical prediction of a non-collective oblate shape beyond 1.6 MeV temperature [4, 5]. However, unlike the case of ^{194}Au [6], the angular anisotropy pattern remains the same at both the energies and does not show any compelling evidence of non-collective prolate shape. The nucleus, being an ensemble of finite number of particles, is expected to experience shape fluctuations. The deformations of minimum energy that we calculate are the so-called most probable or mean field deformations and may be different from the average deformation. A necessary fuller analysis including fluctuation effects to have better understanding of the data is in progress and is to be reported elsewhere.

6. GDR decay from ^{192}Pt

The compound nucleus ^{192}Pt was populated by bombarding a self supporting ^{180}Hf target of 2 mg/cm^2 thickness by 65 MeV ^{12}C beam from the TIFR Pelletron accelerator. The experimental arrangement was similar to that of the measurements for ^{188}Os. However, the multiplicity measurements were carried out by the 4π sum-spin spectrometer. The high energy gamma rays were measured at two different angles w.r.t. the beam direction in order to measure the angular anisotropy of the GDR gamma rays. Extensive numerical simulations were carried out to calculate the response matrix and efficiency of the 4π array for the low energy discrete gamma rays. Numerical calculations were also carried out to extract the multiplicity distribution of the gamma rays from the observed coincidence fold distributions (see Fig. 3). The analysis of the spectral shape and the angular anisotropy indicate a deformed non-spherical shape for the nucleus at 65 MeV beam energy. The angular anisotropy data with a fit assuming prolate non-collective shape [14] is found to be very similar to what was observed earlier in case of ^{194}Au and hints towards a non-collective prolate phase. A fuller analysis of the experimental data for both the energies including the fluctuations are in progress and will be reported elsewhere.

7. Search for GQR decay in excited ^{188}Os

In addition to the studies in shape transitions, we have also embarked upon a comprehensive programme to search for the hitherto unobserved IVGQR based on excited states. The various non-GQR events that submerge the low yield GQR events are the (a) high energy tail of the GDR, (b) the Bremsstrahlung gamma rays due to the target/projectile interaction and (c) the cosmic ray background. In addition, one also have to ensure that there are not considerable pileup events remaining in the region of interest. All these sources of background are to be peeled off to dig out the IVGQR yield. The estimation of the remnants of all these backgrounds that cannot be fully eliminated by electronics or subtractions is also of paramount importance. The cosmic ray background was measured by switching off the beam and collecting the data for exactly the same duration as that of the beam time. The background data were collected with the same electronics setup and time windows as with the beam. We have observed the excess yield of high energy gamma rays in the 18–26 MeV region after a meticulous subtraction of the cosmic ray contribution for both beam energies and at all the four angles of measurements [14]. This observation of a definite peak-like structure exactly around the GQR region is interesting enough to encourage further measurements and hints towards a possible first observation of the IVGQR on excited state.

8. Studies in lanthanum bromide detectors

The recent discovery of lanthanum-halide (LaX_3:Ce) crystals seems to be a major step forward in the field of scintillation detectors. The production and marketing of the $LaCl_3$:Ce and $LaBr_3$:Ce crystals have resulted in a flurry of activities in further developmental work and also testing and characterisations. We have initiated a programme to carry out detailed investigations of the properties and performances of lanthanum bromide ($LaBr_3$:Ce) detectors. These studies are aimed towards the setting up of a lanthanum bromide based high energy gamma ray spectrometer replacing our NaI(Tl) based detection system. We have carried out measurements using $LaBr_3$:Ce of different sizes and configurations. The energy and timing resolutions and also the absolute detection efficiencies, both, total detection and photo-peak, using known activity sources have been measured for a small 1"×1" cylindrical crystal [15]. The energy dependence of the resolution has been studied using a variety of low energy gamma rays sources. The measured absolute efficiencies have been compared with the simulated values using GEANT4. We have extended our simulations to reproduce the recent measurements [15] of absolute photo peak efficiencies of a 1.5"×1.5" cylindrical $LaBr_3$:Ce detector up to 5 MeV. Fig. 4 shows a typical spectrum recorded in the 1"×1" detector using five different gamma ray sources. A detailed comparative study of the energy dependent absolute efficiencies, both total detection and photo peak, of cylindrical $LaBr_3$, NaI(Tl), and BaF_2 scintillators of different sizes for a wide range of gamma rays from 662 keV to 50 MeV have been carried out.

We have also simulated the energy dependent efficiencies for compact assemblies of (a) $LaBr_3$:Ce and NaI(Tl) and (b) $LaBr_3$:Ce and BaF_2 in two different configurations. The efficiencies, so simulated, for these configurations, have been compared with the efficiencies of single scintillators of equivalent volumes. The primary aim of this work is to take a step forward in combining the excellent properties of lanthanum halide detectors which are presently not available in very big volumes, in a cost effective way with the time tested NaI(Tl) and BaF_2 scintillators for efficient detection of high energy gamma rays in the range of 5 to 50 MeV.

We have tested a Phoswich of $LaBr_3$:Ce and NaI(Tl) [16] to be used for high altitude measurements of X-rays using balloons or satellites. We have used a pulse shape discrimination circuit based on zero-crossover technique

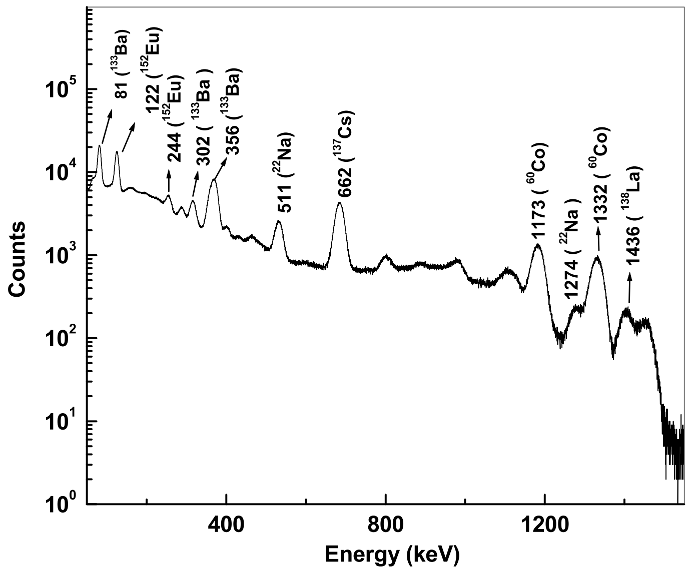

Fig. 4. The typical spectrum recorded in a 1"×1" cylindrical $LaBr_3$:Ce using five different low energy gamma sources.

to segregate the events recorded in the individual layers. Working in the anti-coincidence mode separates out the signals from the two crystals of the Phoswich and substantially reduces the background in the $LaBr_3$:Ce due to partial absorption of energies in both the segments. The internal activity counts around 30 keV is also reduced to some extent. The energy resolution of the $LaBr_3$:Ce is found to be inferior in the Phoswich configuration due to the absorption of the photons in the thicker NaI(Tl) and possibly due to the loss of photons at the optically coupled junction of the two crystals. This work, to the best of our knowledge, reports for the first time, the testings and performance of a Phoswich of $LaBr_3$:Ce and NaI(Tl). The results obtained from the measurements and simulations are expected to guide further work in this direction.

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