5 RESEARCH ACTIVITIES

5.1 NUCLEAR PHYSICS

S. Muralithar, N. Madhavan and P. Sugathan

The articles on nuclear structure and reaction dynamics studied by gamma ray spectroscopy, which were published in 2021-22, covered the following topics: observation of multi-phonon transverse wobbling in ^{133}Ba, parity identification of 5^- state in ^{126,128}Xe, antimagnetic rotation and role of gradual neutron alignment in ^{103}Pd, octupole correlations in ^{127}I, evidence of antimagnetic rotational motion in ^{103}Pd, collective and non-collective states in ^{66}Zn, shape coexistence and octupole correlations in ^{72}Se, shape coexistence in proton-rich Se isotopes, evolution of nuclear structure through isomerism in ^{216}Fr, level structure in the transitional nucleus ^{215}Fr, systematic study of fusion-fission events in ^{19}F+^{175}Lu at low energies, projectile break-up effect in ^{16}O+^{156}Gd fusion reaction at energy 4.3 – 6.3 MeV/A, effect of neutron excess in the entrance channel in the ^{18}O+^{93}Nb system, systematic study of fusion suppression for tightly bound projectiles at above-barrier energies and role of the entrance channel in the experimental study of incomplete fusion of ^{13}C with ^{93}Nb. Ten experiments were carried out using the Gamma Detector Array (GDA) and the Indian National Gamma Array (INGA) in this year in addition to commissioning of a VME-based data acquisition system. The upgradation helped in collecting more data in each in-beam experiment. Preliminary results of some of these experiments are included in this report. Ms. Arunita Mukherjee from Guru Ghasidas University, Bilaspur, who presented her work done with the INGA in the DAE-BRNS Symposium on Nuclear Physics 2021, won the best poster award titled "Octupole correlations and g-vibrational band in ^{72}Se nucleus".

Nuclear reaction experiments using the Heavy Ion Reaction Analyzer (HIRA) and the HYbrid Recoil mass Analyzer (HYRA), which were carried out last year, addressed inelastic and transfer channel-coupling effects on sub-barrier fusion cross section enhancement, viscosity effects on fission hindrance, survival probability of heavy evaporation residues (ERs) as a function of entrance channel, excitation energy and angular momentum and extraction of barrier distribution from fusion and quasi-elastic backscattering excitation functions. Some of the results obtained from the analysis of data from earlier experiments include clear evidence of transfer channel-coupling effects on sub-barrier fusion cross section as one increased the number of neutrons in the target for a spherical projectile, reduction in ER survival probability for more symmetric entrance channel due to competing quasifission channels, importance of ER angular momentum in understanding fusion-fission dynamics, etc. Measurement of ER angular momentum distributions were undertaken for the heaviest CN, ^{240}Cf*, using the HYRA in gas-filled mode coupled to TIFR 4p spin spectrometer using beam from Pelletron+SC-linac. The HIRA was used in five experiments using beams from the Pelletron. All these experiments were part of PhD thesis work of students from the universities and other institutes. Development of a Monte Carlo simulation program for calculating transmission efficiency of recoil separators for target-like recoils from quasi-elastic backscattering and transfer reactions were successfully completed and tested for several systems. A nuclear reaction school, an orientation programme for HIRA/HYRA usage and a two-day workshop on "Physics with Recoil Separators" were conducted. Research scholars, planning to begin their work or already working with recoil separators, were especially benefitted by these events.

Fission fragment (FF) mass distribution and neutron multiplicity measurements were carried out in the National Array of Neutron Detectors (NAND) facility using heavy ion beams from the Pelletron plus licac. These experiments focused on study of shell effects, shape deformation, nuclear viscosity, entrance channel effects and quasi-fission influencing the pre-scission neutron multiplicity and FF mass distribution. The dynamical effects were investigated by analyzing the mass-gated neutron multiplicity and FF mass-angle correlation. The mass-gated pre-scission neutron multiplicities and FF mass distributions were measured for actinide and pre-actinide compound nuclei (CN) formed at different excitation energies. The studied nuclei showed interplay of various fission modes, manifested by shell effects, that changed with excitation energies. FF mass-neutron correlation was measured at different excitation energies to study the influence of multi-chance fission on fission modes. Other experiments measured average neutron and charged particle multiplicities in various systems investigating the entrance channel effects and nuclear dissipation. For charged particle multiplicity measurements, a CsI-based detector array was used in combination with neutron and fission detectors. All these experiments were part of PhD thesis work of research scholars from various universities. Preliminary results from some of these experiments are presented in this report.

5.1.1 Study of completely mass symmetric fusion-evaporation reaction at various energies

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Nuclear reaction in the energy domain E ~ 5 MeV/A are dominated by compound nuclear processes. In various mass-symmetric reaction studies, the particle spectra evaporated from the fusion-evaporation reaction show the influence of deformation on α-particle and proton spectra [1,2,3,4]. The statistical model with inclusion of dynamical effects have been necessary in some of the studies to explain the experimental spectra [5]. In order to inquire more about this discrepancy and understand the dynamics of a mass-symmetric reaction, we studied the reaction ^{48}Ti+^{48}Ti at various energies. The dynamics of the reaction was studied by observing inclusive as well as exclusive charged particle and neutron spectra. The experiment was performed using the National Array for Neutron Detectors (NAND) facility at IUAC.

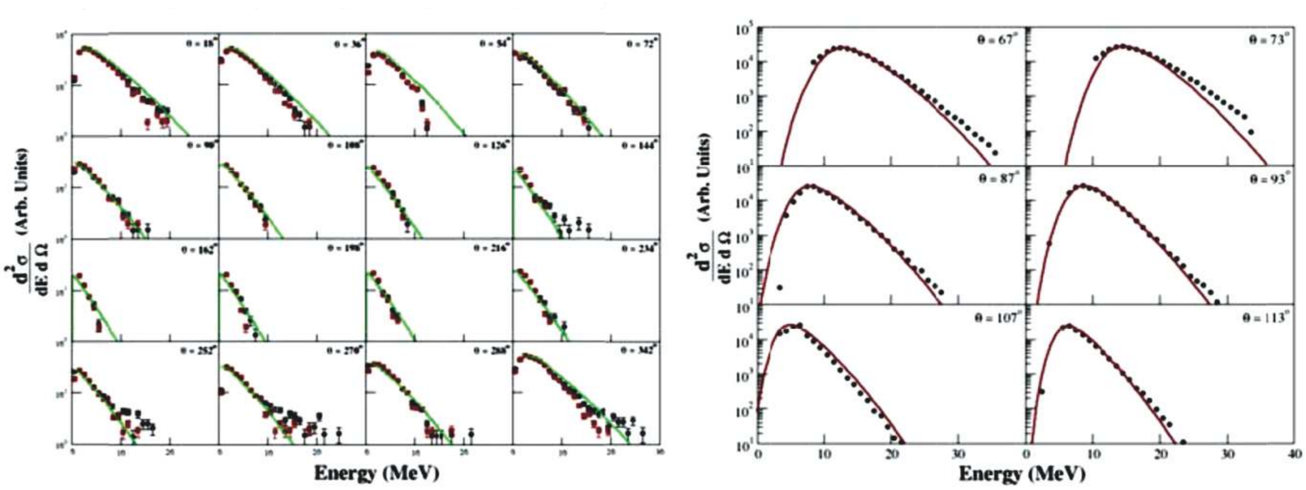

Fig. 5.1.1.1: (a) (left) Neutron spectra for ^{48}Ti+^{48}Ti at 150 MeV. The figure shows inclusive (black circles), exclusive (red diamonds) and CASCADE calculations (green solid line) with default parameters, and (b) (right) a-particle spectra for ^{48}Ti+^{48}Ti at 150 MeV. Black circles show the experimental spectra, and red solid line represents CASCADE calculations with default parameters.

The ^{48}Ti pulsed beam was accelerated at energies of 130 MeV, 140 MeV and 150 MeV using the 15UD Pelletron accelerator. The beam was bombarded onto 500g/cm^2 thick ^{48}Ti target to study the neutrons and charged particles emitted from a completely symmetric reaction. For the experiment, 16 in-plane neutron detectors, placed at a distance of 175 cm from the target, in the NAND array were utilized. A CsI(Tl) detector array, placed at a distance of 16.2 cm from the target inside the NAND chamber, had an angular coverage of 46° – 114°. These detectors were used to study the light charged particles emitted from the reaction. The evaporation residues (ERs) were detected with the help of two multi-wire proportional counters (MWPCs), each having an active area of 2''×4'', placed at either side of the beam direction in the horizontal plane. These detectors were kept at a distance of 50 cm from the target, and had an angular coverage of 4° - 17.5°.

Results at 150 MeV are shown in Fig. 5.1.1.1. For the neutron spectra, the exclusive measurements were carried out by gating with the ERs obtained from MWPCs. The neutron spectra at various angles are shown in Fig. 5.1.1.1 (a). CASCADE calculations were performed using level density parameter, $a = \frac{A}{8}$ and r = 1.25 fm. These values fit the experimental spectra well. The calibrated -particle spectra, obtained from the CsI (Tl) detectors at some of the angles, are shown in Fig. 5.1.1.1(b). The spectra were fitted using the default value of deformation parameters in this case. Rest of the values were same as what were considered to fit the neutron spectra at most of the angles. It is observed that the experimental spectra cannot be fitted at some forward angles at higher energies. If the level density parameter is changed to $a = \frac{A}{9}$,the spectra might be fitted, which suggests that α-particles are emitted from a higher temperature of the compound nuclei in such cases. In order to get more insight into the observations, dynamical HICOL calculations were performed at 150 MeV (Fig. 5.1.1.2). The maximum possible value of angular momentum was found to be 37'. From CASCADE calculations, the maximum possible value of angular momentum was 34', which was nearly the same as obtained from HICOL calculations. The formation time of the system, from HICOL calculations was 5.43×10^{-21} s, while the decay time (from PACE calculations) was 6.40×10^{-21} s. As the decay time and the formation time are approximately the same, it can be said that there is no influence of fusion hindrance at this energy.

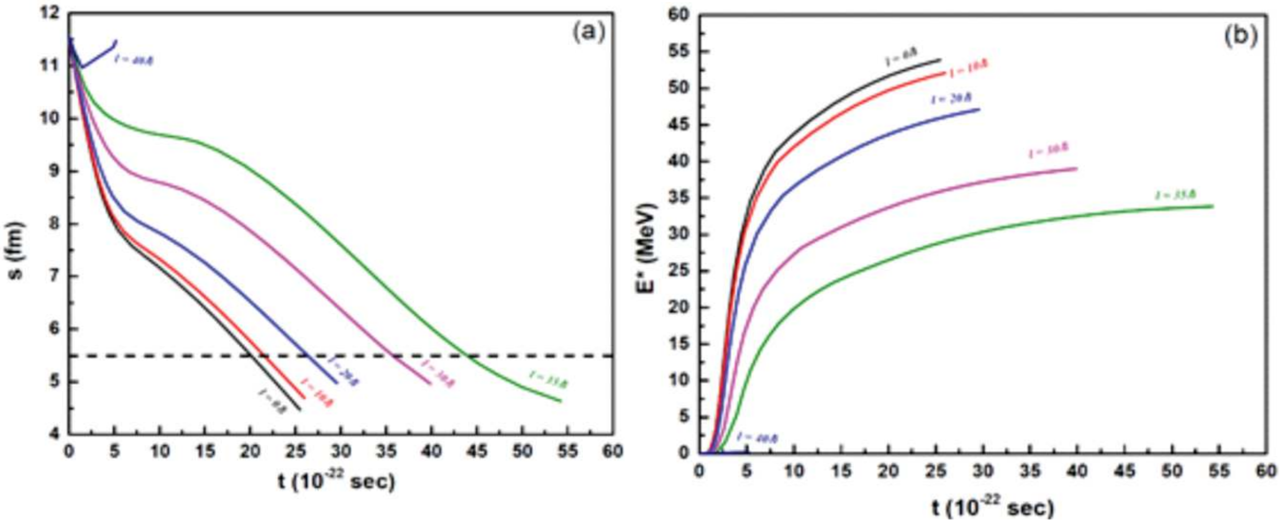

Fig. 5.1.1.2: HICOL calculations for $^{48}Ti + ^{48}Ti$ at 150 MeV showing (a) the evolution of nuclei in terms of change in fusing distance s with time and (b) the evolution of excitation energy with time for different angular momenta.

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5.1.2 Low-lying electromagnetic properties of Zn-isotopes studied with Coulomb excitation

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The evolution of shell structure around ^{68}Ni has been a part of several experimental and theoretical investigations [1] because of its doubly magic *(Z = 28, N = 40)* characteristic. Adding or removing few nucleons across the N=40 sub-shell closure, leads to a rapid increase of collectivity or vice versa with an interplay of collective and single-particle excitations. The neutron rich Zn-isotopes are investigated using the well-known technique of Coulomb excitation at Radioactive Ion Beam (RIB) facilities. Attempts have been made to study the shell structure in stable Zn-isotopes as well through lifetime measurements and earlier with Coulomb excitation [2–9]. However, in Coulomb excitation, the higher lying states could not be sufficiently populated. Lack of sufficient data impeded understanding the nature of such states explicitly. A recent Coulomb excitation experiment [2] revealed some details on the low-lying electromagnetic structure of ^{66}Zn and demonstrated that this nucleus had a complex structure which cannot simply be explained by general collective models. Theoretical calculations along with the experimental results obtained show that triaxial degree of freedom has an important role to play in the low-lying structure of ^{66}Zn along with a unique structure for 0_2^+ state.

While measurements of B(E2; $2_1^+ \rightarrow 0_1^+$) values are useful to investigate the evolution of collectivity along isotopic chains, even more insight into the collective behaviour can be gained by measuring lifetimes of higher-lying states. A strong increase of collectivity of the 4_1^+ state was observed for ^{70}Zn and could not be explained in the framework of nuclear structure models. A recent lifetime measurement yielded a considerably longer lifetime for this state, yet its accuracy was not sufficient to draw any firm conclusions. While the reduced transition strength measured at GANIL [7] for ^{70}Zn yielded a low collectivity, a higher value was obtained at YALE university [5]. Given the complex structure of low-lying states in ^{70}Zn including many nearly degenerate transitions, Coulomb excitation seemed a more appropriate method to study this nucleus. The recent results obtained at LNL [2] for ^{66}Zn also demonstrated the failure of general collective models for the explanation of general characteristic in these isotopes.

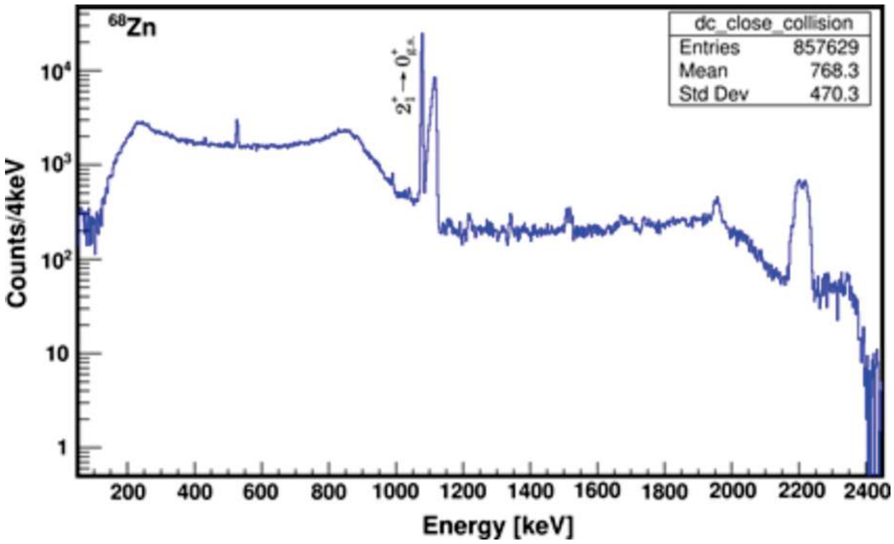

Fig. 5.1.2.1: A Doppler-corrected and background subtracted γ-ray spectrum for ^{68}Zn. The spectrum is only corrected for the target excitation.

We recently performed a Coulomb excitation experiment of ^{64,68,70}Zn to measure the several reduced transition strengths in low-lying level-structure of these isotopes including the B(E2; $4_1^+ \rightarrow 2_1^+$) along with the deformation parameters for 0_2^+ states using quadrupole sum rules, in order to look for any evidence of shape coexistence. With a high Coulomb excitation probability, an attempt to measure the quadrupole moment will also be made.

The experiment was performed at Gamma Detector Array (GDA) beamline using a ^{32}S beam of 72 – 76 MeV from the Pelletron Accelerator. The stable Zn-targets were available from IUAC Target Laboratory which were used in the experiment. The de-excited γ-rays were measured with Clover detectors pooled from the Indian National Gamm Array (INGA), in coincidence with PPAC in forward angles. A demonstrative spectrum is shown in Fig. 5.1.2.1. Further analysis of data is currently underway.

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5.1.3 Fission fragment mass angle correlations for the reaction ^{28}Si + ^{160}Gd populating ^{188}Pt compound system

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Fission fragment (FF) mass distribution, angular distribution and mass angle correlation are considered as sensitive tools to investigate the presence or absence of quasi-fission (QF) in a given reaction [1-3]. In the present work, we performed mass angle correlation analysis of FFs produced in the reaction ^{28}Si+^{160}Gd populating ^{188}Pt compound system at various excitation energies. The experiment was carried out in the General-Purpose Scattering Chamber (GPSC) facility of IUAC. Pulsed beam of ^{28}Si from the Pelletron accelerator, in the laboratory energy range of 120 – 140 MeV, was bombarded on ^{160}Gd target having thickness of 220 g/cm^2. The target was fabricated on a 20 g/cm^2 carbon backing. FFs were detected using two large area (16 cm × 11 cm) multi-wire proportional counters (MWPCs), mounted on the two arms of the chamber.

The calibrated position and time of flight (TOF) information from the two MWPCs were used to obtain the emission angles of the FFs. The time difference method was used to extract the masses of complementary FFs [4]. The experimentally measured mass angle correlations for the reaction ^{28}Si+^{160}Gd populating ^{188}Pt at different laboratory energies are shown in the Fig. 5.1.3.1. No significant mass angle correlation was observed for the studied reaction indicating the absence of any fast QF contribution at all energies. The experimentally measured FF mass ratio (M_R) distribution [1] for the same reaction is symmetric around M_R = 0.5 and well fitted with a single Gaussian. However, the width of fitted mass distribution is relatively broader than the theoretically calculated mass width, using statistical saddle point model (SSPM), indicating the presence of slow QF or non-compound nucleus fission. Therefore, our results of mass angle correlation are in reasonable agreement with the earlier conclusions drawn from the measured mass distribution for the fission of ^{188}Pt populated via ^{28}Si+^{160}Gd reaction.

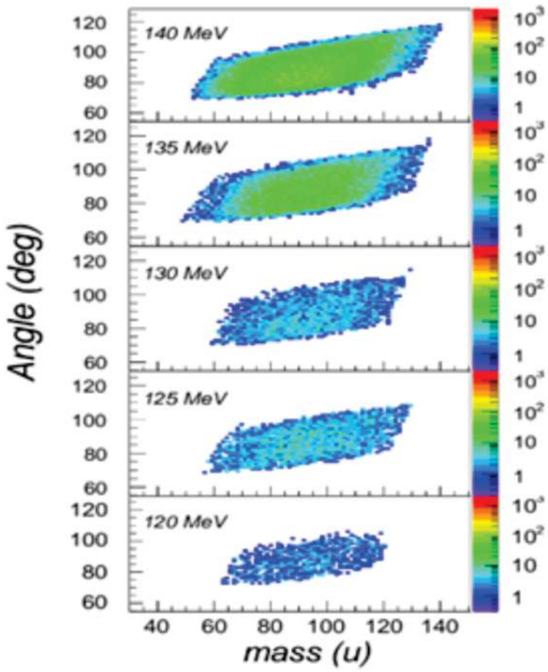

Fig. 5.1.3.1 : Mass angle correlations for the fission of ^{188}Pt.

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5.1.4 High-spin spectroscopy in ^{207}At

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The region of neutron-deficient nuclei around the doubly magic ^{208}Pb displays various interesting nuclear structure phenomena which include, but are not limited to, shape coexistence, shears bands, different types of low- and high-spin isomers. The nuclei lying in the proximity of the shell closure show single-particle behaviour, while the collective modes of excitation are observed as one departs from the doubly magic ^{208}Pb. In the region with $N < 126$, the spherical or near spherical shapes can be observed for the neutron-deficient polonium and astatine isotopes [1,2] near the shell closure. When neutron number decreases, the shape changes to prolate and further to oblate deformed structure near the neutron mid shell at $N \approx 104$ [3-5]. The nucleus ^{207}At ($Z = 85$, $N = 122$) is situated in the transitional region, where level structures are expected to be governed by the interplay between single-particle and collective degrees of freedom. Also, the availability of both proton-particles and neutron-holes in ^{207}At, provides a suitable experimental ground to understand the interplay between the particle-hole excitations. In addition, several high-spin isomers have been reported in astatine isotopes [2,8]. Particularly, a $29/2^+$ isomer has been reported in odd-A astatine nuclei with $199 \leq A \leq 211$, except for the ^{207}At [2,8]. The lack of data concerning the $29/2^+$ isomeric state in the ^{207}At nucleus prompted us for a detailed high-spin study of this nucleus.

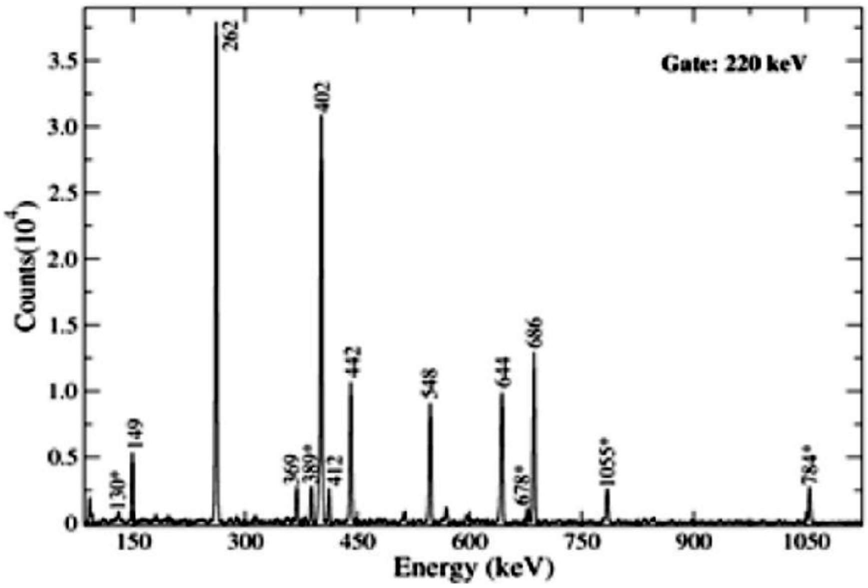

Fig. 5.1.4.1: The gamma-gamma coincidence spectrum illustrating the transitions in coincidence with the known 220 keV gamma ray. The new transitions are marked with an asterisk.

In the present work, high-spin states in the ^{207}At were populated via the reaction ^{198}Pt(^{14}N, 5n)^{207}At. A self-supporting target of ≈ 7 mg/cm^2 thickness was bombarded with a ^{14}N beam in 80 – 87 MeV energy range, provided by the 15UD Pelletron accelerator at IUAC. The γ−rays from the deexcitation of the residual nuclei were detected by an array of 13 Compton-suppressed Clover HPGe detectors and a Low-Energy Photo Spectrometer (LEPS). The γ-γ coincidence data were acquired using a VME-based data acquisition system. Both online and offline energy calibration (using standard ^{152}Eu and ^{133}Ba radioactive sources) were used in order to extract exact energies of the γ-ray transitions. Further, the data were sorted into various two- and three-dimensional histograms using the codes developed at IIT Roorkee. These histograms are now being analyzed using the ROOT [6] and RADWARE suite of software packages [7].

Preliminary analysis of data shows evidence of several new transitions in the level scheme of ^{207}At. Fig. 5.1.4.1 illustrates the γ-ray transitions in coincidence with a known 220 keV γ−ray, which depopulates the $25/2^+$ isomeric state at 2117 keV [8]. Each new transition is marked with an asterisk. These transitions were not placed in the earlier reported level scheme. Further analysis of data for placement of the observed new transitions, construction of the level scheme using γ-γ coincidence relationships, DCO and polarization measurements is in progress.

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5.1.5 High-spin states in ^{216,217}Ra

Madhu[1], A. Y. Deo[1], Khamosh Yadav[1], S. K . Tandel[2], Saket Suman[2], A. Sharma[3], I. Ahmed[4], K. Rojeeta Devi[4], S. Dutt[4], K. Katre[4], Sushil Kumar[4], Yashraj[4], S. Muralithar[4] and R. P. Singh[4]

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Nuclear structure investigations in the transitional region beyond doubly magic ^{208}Pb has been a topic of considerable interest due to presence of diverse structural phenomena. The nuclei lying in the vicinity of ^{208}Pb are spherically symmetric and are well understood in terms of the shell model. As one moves away from the proton and neutron shell closure, collective degrees of excitations become important. The nuclei in the Ra-Th region with $Z \sim 88$ and $N \sim 134$ exhibit static octupole deformation which is manifested in the form of alternating parity sequences connected by enhanced $E1$ transitions [1,2]. The region between spherical and deformed nuclei is known as the transitional region and the study of nuclei lying in the transitional region can provide information on the interplay between single particle excitations and collective motion of nucleons. The level structures in ^{216}Ra ($Z = 88$, $N = 128$) are described in terms of the shell model [3-5], while the earlier studies of ^{217}Ra show that the low-lying levels of ^{217}Ra, grouped as three bands, can be qualitatively understood in terms of excitations originating from three valence neutrons [6,7]. However, strong $E1$ transitions connecting the two bands suggest the existence of octupole correlations in the case of ^{217}Ra. Hence, an extensive study of high-spin states in ^{216,217}Ra will provide insight into the evolution of nuclear structure along the isotopic chain.

Excited states in ^{216,217}Ra were populated using the reaction ^{208}Pb(^{12}C, 4/3n)^{216,217}Ra. The ^{12}C beam in 68 – 80 MeV energy range, provided by the 15UD Pelletron accelerator at IUAC, was impinged on a self-supporting ^{208}Pb target of ~ 9 mg/cm^2 thickness and isotopic enrichment ~ 99%. The Indian National Gamma Array (INGA), which comprised of 13 Compton-suppressed Clover detectors and one Low Energy Photon Spectrometer (LEPS) at the time of the experiment, was used to detect the γ-rays originating in the de-excitation process of the residual nuclei. The γ-γ coincidence data were acquired using a VME-based data acquisition system. The energy and efficiency calibration were performed using standard ^{152}Eu and ^{133}Ba radioactive sources. The calibrated data were further sorted into various 2- and 3-dimensional histograms, compatible with RADWARE [8] and ROOT [9], using a code developed at IIT Roorkee.

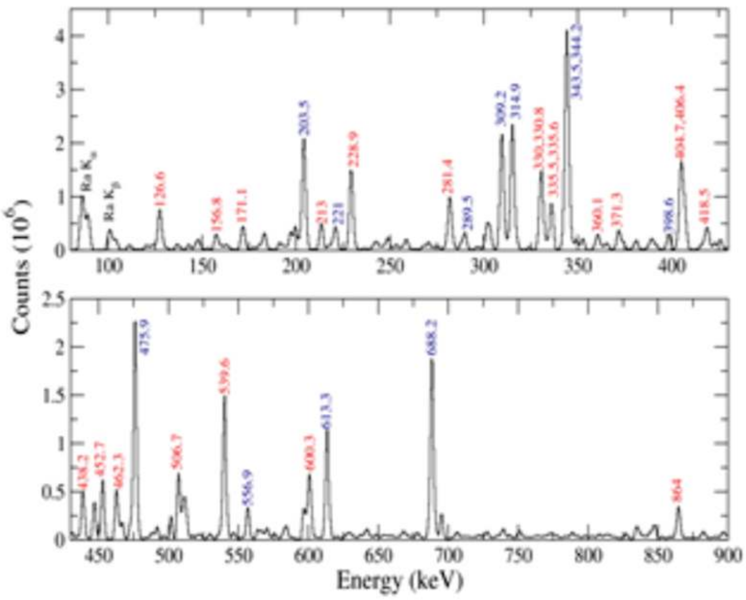

Fig. 5.1.5.1: Total projection spectra showing the transitions (a) up to 430 keV (b) 430 – 900 keV energy range. The transitions labelled with red are from ^{217}Ra, while the transitions from ^{216}Ra are marked with blue.

In the present experimental study, excitation function measurements were performed to estimate relative cross-sections of the nuclei of interest (^{216}Ra and ^{217}Ra) at different beam energies. At 68 MeV, 3n channel corresponding to population of ^{217}Ra was found to be dominant, whereas ^{216}Ra was observed to be populated with highest cross-section at 80 MeV. Both these nuclei were populated with comparable cross-section at 72 MeV and thus, most of the data were collected at this energy. The data at different energies were combined for analysis. Fig. 5.1.5.1 shows the total projection spectrum of the symmetric γ-γ histogram. Preliminary analysis indicates that all the known transitions up to the highest spin reported in earlier studies are observed in both ^{216}Ra and ^{217}Ra. Further analysis with DCO and PDCO matrices is in progress.

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5.1.6 Mass-gated pre-scission neutron multiplicity measurements for $^{12}C+^{238}U$

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A recent study by Khuyagbaatar *et al* [1] had reported the influence of nuclear shells on fission fragment (FF) mass distribution even at moderate excitation energies. It is attributed to the multi-chance nature of fission where different fission chances have a considerable contribution in governing the dynamics of the fissioning nuclei. We carried out an experiment to measure mass-gated pre-scission neutron multiplicities in order to gain deeper insights of the dynamics as it is a quite sensitive tool to probe fission timescales.

The experiment was performed at the 15UD Pelletron accelerator facility of IUAC. A pulsed beam of ^{12}C (pulse width ~ 1 ns and pulse separation of 250 ns) was bombarded on ^{238}U targets of areal thickness 290 μm/cm^2 with lab energies 67, 75, 80, 85 and 94 MeV. Eighty BC501A organic scintillator detectors, placed at different polar and azimuthal angles in a geodesic dome structure of the National Array of Neutron Detectors (NAND) [2], were used for detection of neutrons. Each detector was at a distance of 175 cm from the target. FFs were detected using two large area (20 cm ×10 cm) position sensitive multi-wire proportional counters (MWPCs), placed at a folding angle of 170^o with respect to the beam direction. The online data acquisition was performed with the NiasMars (Multi-parameter Acquisition Root-based Storage) software. Analysis of data was carried out using ROOT [3]. Fig. 5.1.6.1 shows the correlation plot between the two anode signals from MWPCs.

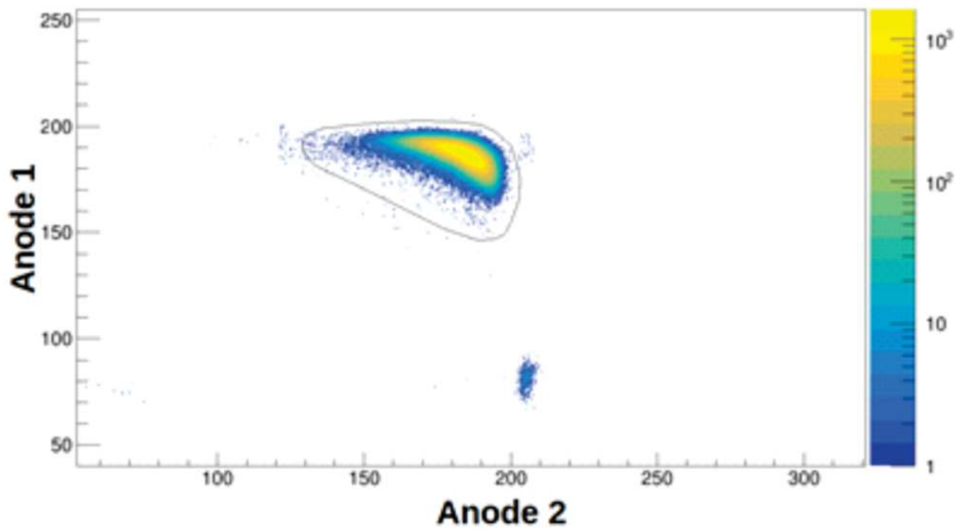

Fig. 5.1.6.1: Two-dimensional correlation plot between anode signals from both the MWPCs.
The black solid line delineates the fission events.

Fast-timing signal from the MWPCs were used to derive the time-of-flight (TOF) information of the FFs with reference to the beam arrival time, which enabled the separation of fission events from other competing channels. Event-by-event analysis of TOF data and position information were used to determine fragment velocities. The pre- and post-scission components of neutron multiplicities were obtained from the measured double differential neutron energy spectra, employing the three moving source least-square fit, using the Watt expression [4].

From the preliminary results at hand, we have observed that the pre-scission neutron multiplicity corresponding to asymmetric fragments are higher in comparison with the symmetric fragments, thus univocally indicating the presence of shells ascribed as multi-chance fission. With the increase in excitation energy, the influence of shell and consequent asymmetric mass fragmentation is significantly reduced which is reflected as lower pre-scission multiplicity for asymmetric fragments with respect to the symmetric fragments. Masses of FFs at higher energies follow a more realistic normal distribution in comparison with a flat-top distribution at the lowest studied excitation energy.

Further analysis of data, assimilation and interpretation of these results within a theoretical framework is ongoing.

REFERENCES:

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