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5.1.7 Fusion measurements for ^{30,28}Si+^{156,158}Gd systems around the Coulomb barrier

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Efforts have been made to understand the effects of various degrees of freedom (*e.g.*, inelastic excitations, deformation, nucleon transfer, etc.) involved in heavy-ion collisions to interpret sub-barrier fusion enhancement relative to one-dimensional barrier penetration model (1D-BPM) [1,2,3]. Although the influence of inelastic excitations on nuclear scattering and sub-barrier fusion is somewhat established, a clear understanding of nucleon transfer with a positive Q-value is yet to be achieved. To study the effect of neutron transfers with positive Q-value, we performed an experiment on ^{30}Si+^{156}Gd and ^{28}Si+^{158}Gd reactions, with positive Q-values for 2n and up to 6n transfer, respectively. Another objective of this work was to extract the barrier distributions from measured fusion and back angle quasi-elastic (QE) scattering excitation functions.

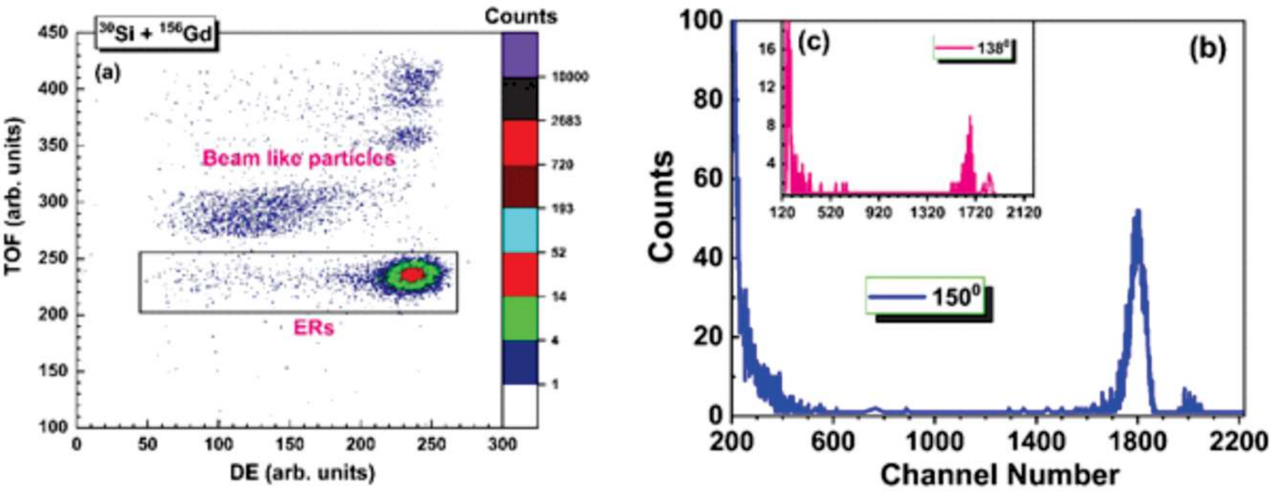

Fig. 5.1.7.1: (a) Two-dimensional spectrum showing the energy loss (DE) vs time of flight (TOF) of particles detected at the focal plane of the HIRA for ^{30}Si+^{156}Gd at E_{lab}=121.4 MeV. (b) and (c) Measured spectra of QE events recorded using solid state silicon detectors at back angles θ_{lab} = 150^0 and 138^0, respectively, for ^{30}Si+^{156}Gd. The area enclosed by black solid lines represent the group of ERs which are well separated from beam-like particles [in panel (a)].

The recoil mass spectrometer, *viz.* Heavy Ion Reaction Analyzer (HIRA) [4] at IUAC, was used for the experiment. Pulsed beams of ^{30}Siand^{28}Si with 2 μs and 4 μs pulse separation, respectively above and below the Coulomb-barrier energies, were bombarded on thin ^{156}Gd and ^{158}Gd targets, respectively. Isotopically enriched thin ^{156}Gd (thickness ≈100.7 μg/cm^2 on 30 μg/cm^2 carbon backing) and ^{158}Gd (thickness ≈134.4 μg/cm^2 on 50 μg/cm^2 carbon backing) target foils were fabricated and characterized at IUAC [5]. Incident projectile energies (E_{lab}) were varied between 108 – 140 MeV, to cover energies from well below to above the Coulomb barrier. A Multi-Wire Proportional Counter (MWPC), having dimensions of 15 cm × 5 cm in x and y direction, was used at the focal plane of HIRA to detect the evaporation residues (ERs). Two solid-state silicon detectors were placed inside the target chamber at an angle of 15.5^o with respect to beam direction for normalization of cross-sections. Two more silicon detectors were installed inside the target chamber at back angles of θ_{lab}=138^o and 150^o, to detect the QE events (including elastic, inelastic and transfer channels, which were indistinguishable). Two-dimensional spectrum between ER energy loss (ΔE) and ER time of flight (TOF) and the measured QE events at back angles for ^{30}Si+^{156}Gd are shown in Fig. 5.1.7.1 (a) and Fig. 5.1.7.1 (b) and (c), respectively. Complete analysis of fusion excitation function and back angle QE scattering data for both reactions is underway.

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5.1.8 Fission time scale measurements around mass ~200 region

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Fission times cales provide singular insight into the underlying dynamics of the fusion-fission reactions. The evolution of the Compound Nucleus (CN) from initial equilibrium state to final fission state is governed by various attributes of the said nucleus including its excitation energy, shell structure at equilibrium state, shape deformation and viscosity. Fission timescale proves to be a key parameter for investigating the aforementioned attributes of nuclei populated through fusion reactions. Neutron emission is the fastest and most dominant process which occurs as the CN transitions from equilibrium to fission. This makes neutron multiplicity measurement the most sensitive probe for fission timescale calculations [1]. In the present work, neutron multiplicity measurements have been performed for ^{201,203,205}Bi nuclei. Pulsed beam of ^{19}F was accelerated to lab energies of 120 – 150 MeV using the 15UD Pelletron+LINAC accelerator at IUAC and bombarded on carbon backed ^{182,184,186}W targets (~700 μg/cm^2 thick ^{182,186}W and ~200 μg/cm^2 thick ^{184}W). Two MWPCs with an active area of 20 cm × 10 cm were kept at folding angles for the detection of fission fragments (FFs). Neutrons emitted in coincidence with the fission fragments were detected using 80 organic liquid scintillators (BC501A) of the National Array of Neutron Detectors (NAND) [2] with 16 detectors in the reaction plane. Multi parameter Acquisition Root-based Storage (MARS) software [3] was employed to acquire the list-mode data. Neutron-gamma discrimination was achieved using the zero cross-over based Pulse Shape Discrimination (PSD) and Time of Flight (TOF) information. A correlation plot between PSD and TOF is shown in Fig. 5.1.8.1 (a). As can be seen from the figure, the neutron lobe is well separated from the γ-rays. Further a two-dimensional gate, obtained from the correlation plot between the timing signals of both the MWPCs, was applied on the neutron TOF spectra in order to ensure identify neutrons from fission events. The TOF spectra were then converted to energy spectra and corrected for the energy-dependent neutron detection efficiency using the code FLUKA [4], details of which are mentioned elsewhere [5]. The pre-scission (M_{pre}) and post-scission (M_{post}) contributions were then extracted using Watt's three source moving formula [6].

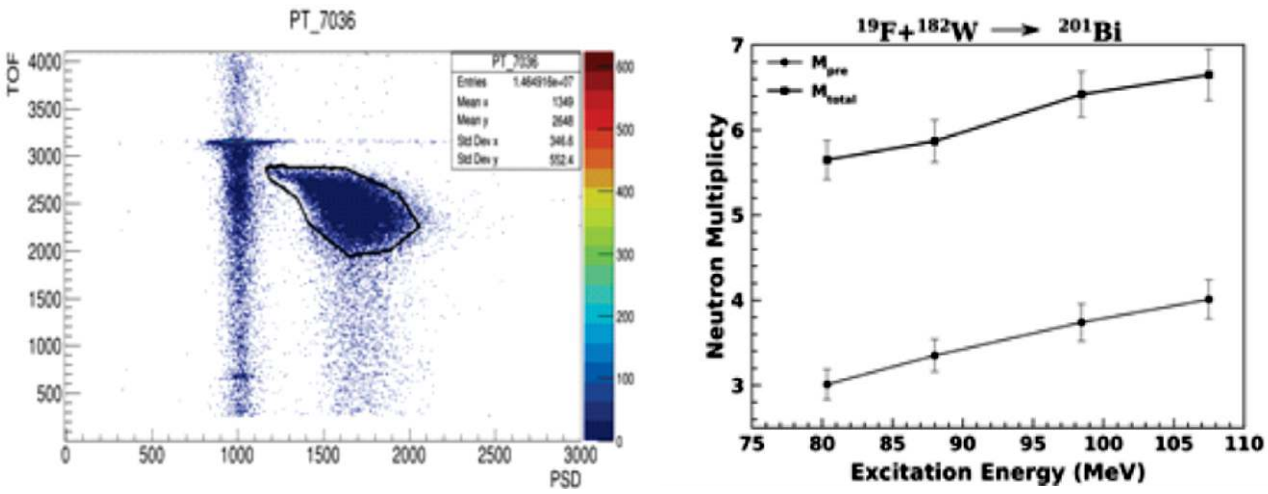

Fig. 5.1.8.1: (a) Scatter plot between TOF and PSD, the neutron lobe is shown within a contour. (b) Variation of M_{pre} and M_{total} with excitation energy for ^{201}Bi.

Variation of M_{pre} and total neutron multiplicity ($M_{total} = M_{pre} + 2M_{post}$) with excitation energy has been shown in Fig. 5.1.8.1 (b) for the case of ^{201}Bi. Further analysis to extract M_{pre} and M_{post} for the remaining two isotopes along with relevant theoretical calculations to extract fission time scales is in progress.

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5.1.9 Few-nucleon transfer and fusion dynamics around the Coulomb barrier for ^{28}Si+^{116,120,124}Sn systems

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The study of heavy-ion collisions around the Coulomb barrier offers an excellent opportunity to explore several spectacular effects which lead to a better understanding of reaction mechanisms as well as the sublime effects of nuclear structure. One such phenomenon is sub-barrier fusion enhancement. A large enhancement in the sub-barrier fusion cross sections (one to two orders of magnitude) over the predictions of One-Dimensional Barrier Penetration Model 1D-BPM [1] is observed experimentally. The roles of static deformation and surface vibrations in the sub-barrier fusion enhancement have been unambiguously established but the precise effect of transfer channels has been seemingly elusive in most of the cases. Also, based on the quantum tunnelling concept, quasi-elastic scattering (a sum of elastic scattering, inelastic scattering, and transfer channels) serves as a good alternative to fusion for extracting the barrier distribution as the former is related to the reflection probability of a potential barrier while the latter is related to the penetration probability. Therefore, the quasi-elastic scattering measurements can be used as a complementary probe in deciphering the dynamics of the heavy-ion reactions. In order to ascertain the aforementioned aspects, fusion and quasi-elastic excitation function measurements have been performed for ^{28}Si +^{116,120,124}Sn systems using the Heavy Ion Reaction Analyzer (HIRA) at IUAC [2]. The coupled-channels (CC) formalism has been employed in an attempt to explain the mechanisms that are responsible for the experimentally observed enhancement in fusion cross sections at sub-barrier energies. Woods-Saxon parametrization of Akyuz-Winther (AW) potential has been used for CC analysis using the code CCFULL [3]. The fusion excitation function for ^{28}Si+^{116}Sn (Fig. 5.1.9.1) has been well reproduced by the CCFULL after inclusion of inelastic couplings (rotational for ^{28}Si, and vibrational for ^{116}Sn). However, a similar coupling scheme fails to reproduce the fusion cross section for ^{28}Si+^{124}Sn even after inclusion of one pair transfer channel coupling along with projectile and target inelastic couplings as shown in Fig. 5.1.9.2.

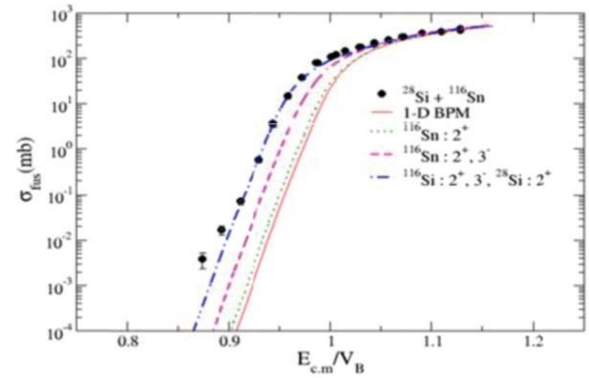

Fig. 5.1.9.1: Experimental fusion excitation function for ^{28}Si+^{116}Sn along with coupled-channels calculations using CCFULL.

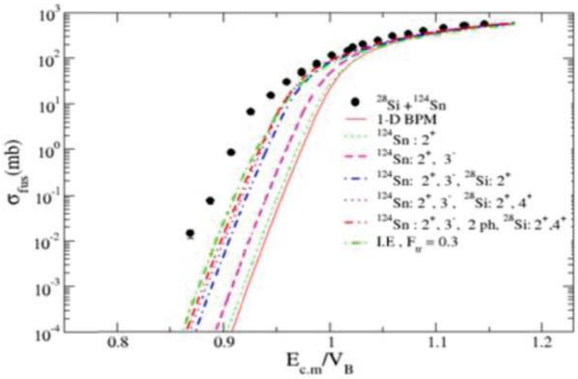

Fig. 5.1.9.2: Experimental fusion excitation function for ^{28}Si+^{124}Sn along with coupled-channels calculations using CCFULL.

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5.1.10 Multi-nucleon transfer and fusion studies for $^{16}O+^{107,109}Ag$ reactions

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The systems $^{16}O+^{107,109}Ag$ were studied using the Heavy Ion Reaction Analyzer (HIRA) [1] recoil mass separator at the 15UD Pelletron accelerator facility of IUAC. The experimental setup consisted of two silicon detectors at 15° with respect to the beam direction in the scattering chamber. These were used for normalization of cross sections. A multi-wire proportional counter (MWPC) was placed at the focal plane of the HIRA to detect the recoiling particles at 0°. A pulsed beam of ^{16}O, with pulse separation of 2 μs, was bombarded on isotopically-enriched thin (approximately 400 μg/cm^2) targets of ^{107}Ag and ^{109}Ag. The motive of this experiment was to study the mechanism of multi-nucleon transfer and investigation of sequential and simultaneous transfer probabilities. Collected data were analyzed using CANDLE and ROOT softwares. The transmission efficiency of the HIRA was determined by TERS Monte Carlo simulation code [2,3]. The transfer probability (P_{TR}) of each channel *viz.*, 1*n*- and 2*n*-pickup and 1*p*-stripping at energies 50, 54, 58 and 62 MeV were extracted. Transfer probability, as a function of the distance of closest approach, for the two systems are shown in Fig. 5.1.10.1 and Fig. 5.1.10.2. If the 2*n*-pickup is sequential transfer of two neutrons, it follows the relation $P_{TR}(2n) = [P_{TR}(1n)]^2$. If there is enhancement in 2*n*-pickup channel, the enhancement factor (*EF*) is given by [4,5], $\frac{P_{TR}(2n)}{[P_{TR}(1n)]^2}$. Higher *EF* indicates higher chance of 2*n*-cluster transfer. Considering the systems $^{16}O+^{109}Ag$ and $^{16}O+^{107}Ag$, the *EF* is higher for the system $^{16}O+^{109}Ag$ compared to $^{16}O+^{107}Ag$. Thus, 2*n*-transfer is more favourable for the system $^{16}O+^{109}Ag$.

Evaporation residues (ERs) were also measured using the same experimental setup. The data were collected in the energy range of 50 – 62 MeV in steps of 2 MeV for both the systems. The ER cross-sections, in both the cases, were found to be enhanced compared to the predictions of one-dimensional barrier penetration (1D-BPM) model. By including the target excitation in the coupled channel calculation, in both cases, the data could be reproduced [6,7]. No enhancement of ER cross-sections was observed due to transfer of nucleons in case of $^{16}O+^{109}Ag$.

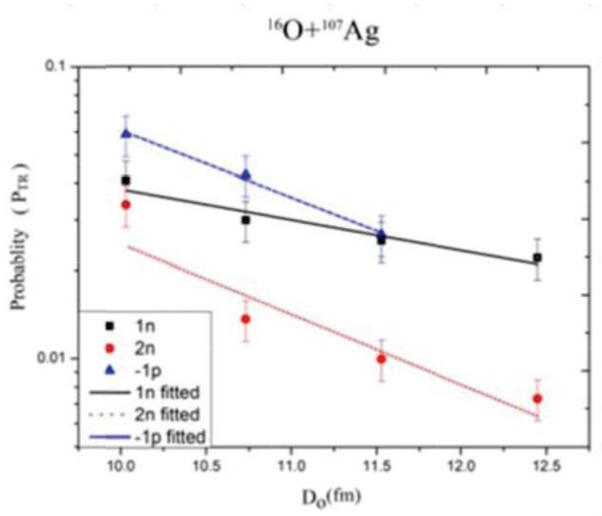

Fig. 5.1.10.1: Transfer probability versus distance of closest approach for the system $^{16}O+^{107}Ag$.

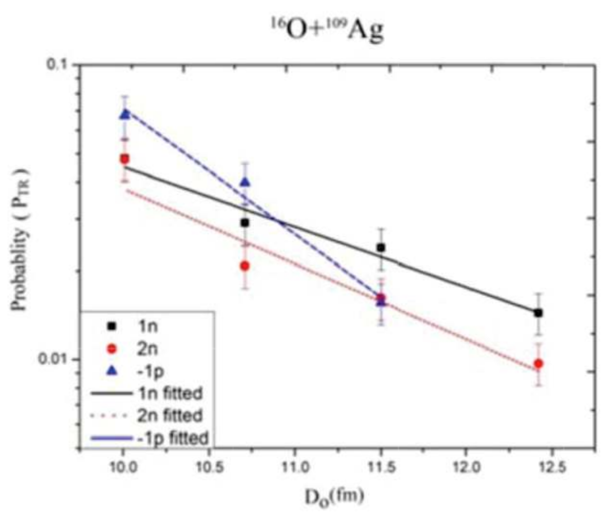

Fig. 5.1.10.2. Transfer probability versus distance of closest approach for the system $^{16}O+^{109}Ag$.

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5.1.11 Lifetime measurement in ^{104}Cd using plunger device

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The nuclei in A ≈ 100 region have drawn a lot of attention in the recent times due to the existence of various dynamical symmetries. For example, the collective excitations like wobbling, chirality, magnetic and anti-magnetic rotation have been reported in these nuclei along with non-collective single-particle excitations [1-3]. The lifetime of the nuclear states in the sub-nanosecond range can be measured using the Recoil Distance Method (RDM), also referred to as the *plunger method.* The lifetime measurement, reported for ^{104}Cd in the literature, had been carried out mainly using the conventional decay method [4] and the differential decay curve method [5]. The aim of the present experiment was in-beam test of the new plunger device by measuring the lifetime of low-spin states in ^{104}Cd.

The high spin states of ^{104}Cd were populated using ^{93}Nb(^{14}N, 3nγ) fusion evaporation reaction at a beam energy of 56 MeV. The ^{14}N beam was delivered by the 15UD Pelletron accelerator at IUAC. The self-supporting target and stopper (thickness ~1 mg/cm^2 and ~8 mg/cm^2, respectively), were prepared by the cold rolling method in the Target Laboratory of IUAC. The prepared stretched target and stopper foils were kept parallel to each other in the target chamber known as the *plunger device*. The distance between the target and the stopper could be varied by changing position of the target with respect to the stationary stopper with the help of the piezoelectric motor. The de-exciting γ-rays were detected by the Indian National Gamma Array (INGA) [6], having 14 Clover detectors during this experiment. The detectors were mounted at six different angles with respect to the beam direction. The data were recorded in the list mode by CANDLE data acquisition system [7] and sorted into the angle-dependent asymmetric matrices. The energy and efficiency calibration were done by using the ^{152}Eu source.

The recoiling nuclei were allowed to fly between the target and the stopper in vacuum before getting stopped in the stopper. The residual nuclei emitted two types of γ-rays, shifted γ-rays (I_s) emitted during the flight and unshifted γ-rays (I_u) emitted when the recoiling nuclei were completely stopped in the stopper. The ratio of unshifted and the shifted intensities depend on the distance between the target and the stopper. Therefore, the lifetime of the states can be estimated by measuring the relative intensities at different target and stopper distances. For the present experiment, data were collected for 15 different target and stopper distances. The unshifted and shifted intensities of the 658 keV ($2^+ \rightarrow 0^+$) γ-transition at ~20 μm and ~7000 μm are shown in Fig. 5.1.11.1.

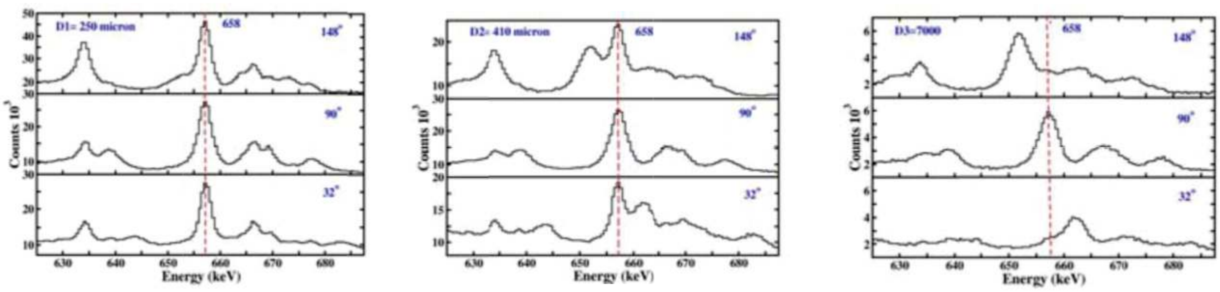

Fig 5.1.11.1. Representative γ-spectra to show the intensities of the shifted and the unshifted component of 658 keV ($2^+ \rightarrow 0^+$) γ-transition in ^{104}Cd at three different angles (θ= 148°, 90°, 32°) and for three different distances ~250μm, ~410 μm and ~7000 μm, between the target and the stopper.

Detailed analysis to determine lifetime of the states of interest is ongoing.

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5.1.12 Study of entrance channel effect on the fusion-fission dynamics via light particle multiplicities

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In order to investigate the effect of entrance channel on heavy ion induced fusion-fission reactions, neutron and charged particle multiplicities were measured using the National Array of Neutron Detectors (NAND). Light particles emitted during the de-excitation of compound nucleus (CN) contains valuable information about the dynamical nature of the CN [1]. For lighter projectiles, the fusion process is fast since the projectile is completely swallowed by the target. On the other hand, for heavier projectiles, the fusion process is slow. We selected two different projectile target combinations ($^{12}C+^{198}Pt$ and $^{18}O+^{192}Os$) leading to the same compound nucleus ^{210}Po. The energy of the projectile was selected such that the CN would be populated with the same excitation energy for the two cases. Out of these two reactions, $^{12}C+^{198}Pt$ was studied. A ^{12}C beam, accelerated to an energy of 81 MeV using the Pelletron facility of IUAC, was bombarded on a self-supporting target of ^{198}Pt with thickness ~2.1 mg/cm^2. The detection system consisted of two large area position-sensitive Multi Wire Proportional Counters (MWPCs), placed at folding angle of 166^o, to catch the fission fragments. Charged particles were detected using 16 CsI(Tl) crystals (2 cm × 2 cm) coupled to photodiodes. Neutrons were detected using 16 BC501 liquid scintillators.

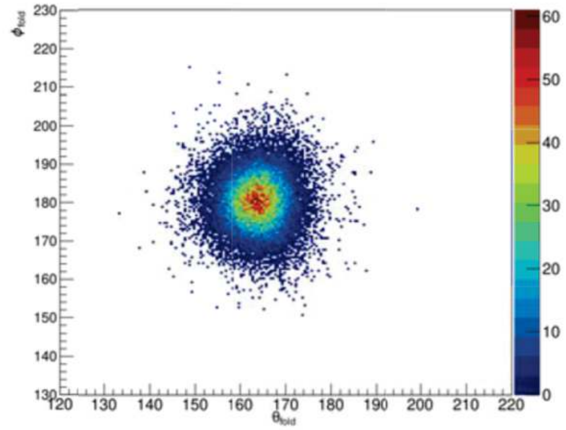

Fig. 5.1.12.1: Folding angle distribution of fission fragments for the reaction $^{12}C+^{198}Pt$ at projectile energy of 81 MeV.

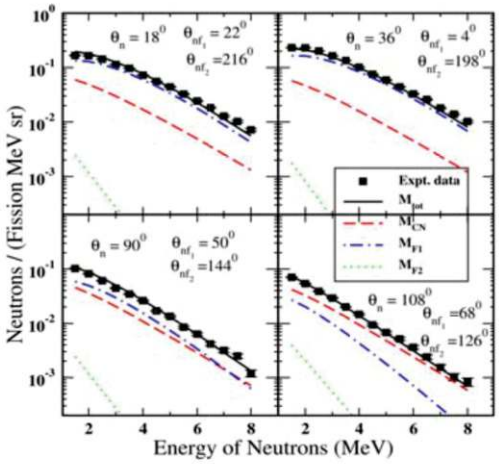

Fig.1 Folding angle distribution

Fig. 5.1.12.2: Neutron energy spectra (filled squares) at various angles for the reaction $^{12}O+^{198}Pt$ at E_{lab} = 81 MeV, along with the fits for the pre-scission (dashed lines) and post-scission contributions (dotted and das-dotted lines) from the two fragments, are shown. The solid black line represents the total contribution.

From the position and TOF spectra of MWPCs, folding angle distribution (Fig. 5.1.12.1), velocity distribution and mass-angle distribution were extracted. Presence of a single group of events at the centre of Fig. 5.1.11.1 shows that only fusion-fission is dominating in the system under study. No contribution from non-compound nucleus processes were observed. Neutron energy spectra (Fig. 5.1.12.2) were generated for all the 16 detectors and those were fitted simultaneously with Watt expression [2] to extract neutron multiplicities. The analysis for charged particles multiplicities is in progress.

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5.1.13 Average neutron multiplicity measurements for ^{32}S+^{194,198}Pt systems with energy ranging from 203 – 173 MeV

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The intricate process involved in the collective re-arrangement of nuclear fission dynamics is still an unconfirmed topic. A few systematic studies are present in the literature related to neutron multiplicities where the experimental data covers wide range of mass and energy. Pre-scission neutrons are extensively studied to understand fusion-fission dynamics involved in the population of heavy and super-heavy nuclei. The main advantage of using this probe is the absence of Coulomb barrier. It also serves as a clock for the measurement of time-scale of the reaction. Current study is based on the average neutron multiplicity measurements for ^{226,230}Pu (Z=94) compound nuclei populated by ^{32}S+ ^{194,198}Pt reactions.

Facility used	Pelletron + LINAC
Beam	^{32}S
Targets	^{194,198}Pt (thickness: ~ 1.7 mg/cm^2 and 2.1 mg/cm^2, respectively)
Detectors used	National Array of Neutron Detectors (50 scintillator detectors used during the experiment), 2 MWPCs (dimensions: (10 cm × 20 cm) for detection of fission fragments, placed at θ_{fold} = 144^o, one monitor detector placed at 12.5^o with respect to the beam direction

In the past few years similar kind of measurements were carried out, but with lighter projectiles, *viz.*, ^{16,18}O+^{194,198}Pt [1], ^{19}F+^{194,196,198}Pt [2] and ^{12}C+^{194}Pt [3]. The investigators studied effect of N/Z, shell closure on nuclear dissipation and shell correction energies at saddle point using pre-scission neutron multiplicity. The present experiment ^{32}S+^{194,198}Pt $\rightarrow$ ^{226,230}Pu* is a representative case of investigation of average neutron multiplicity at lab energies of 203, 193, 183, 178 and 173 MeV. The motivation behind this work is to get insight into the entrance channel effects, shell closure effects and to determine the timescale of quasi-fission and fusion-fission components. This may further help in the optimal selection of target-projectile combinations and bombarding energies to maximize the formation probability of heavy and super-heavy nuclei. For the data acquisition, a VME-based controller ROSE and NiasMARS software were used. Pulse shape discrimination based on zero-cross over technique and time-of-flight (TOF) were used for the discrimination of neutrons and γ-rays. TOF spectra were calibrated using a precise time calibrator and the prompt γ-ray peak was used as a time reference. These spectra were then gated with neutrons and fission events. The calibrated and gated neutron timing was then converted into neutron energy as shown in Fig. 5.1.13.1.

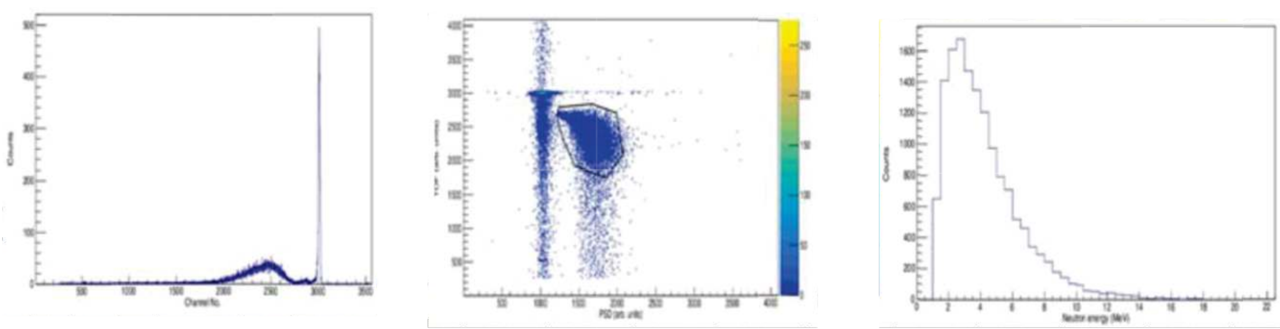

Fig. 5.1.13.1: (left) Raw neutron TOF spectrum for ^{32}S+^{198}Pt at beam energy of 203MeV; (middle) PSD vs TOF spectrum for the same reaction with neutrons marked within a closed loop; (right) Calibrated neutron energy spectrum.

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5.1.14 Mass-gated pre-scission neutron multiplicity measurements in $^{19}F+^{208}Pb$ around the Coulomb barrier

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Fission of actinide nuclei, formed in heavy ion-induced fusion reactions, at medium excitation energies (30 – 60 MeV) has shown interplay of various fission modes manifested by shell effects [1]. Theoretical prediction shows that the relative yield of asymmetric modes (caused by shell effect) is enhanced in the fission followed by particle emission [2]. To investigate the role of particle emission in the fission of excited compound nucleus (CN) in actinide mass region, fission-neutron correlation studies were performed in ^{227}Pa in the excitation energy range of 32 – 60 MeV.

The experiment was carried out using the National Array of Neutron Detector (NAND) [3] at IUAC. Pulsed beam of ^{19}F from the 15UD Pelletron, with pulse separation of 250 ns and ~ 2 pnA current, was bombarded on ^{208}Pb target of thickness ~ 300 μg/cm^2. Projectile energies were varied from 5 % below to 28 % above the Coulomb barrier. A collimated silicon detector (diameter ~ 1.5 mm) was mounted at 12^o with respect to the direction of beam for beam monitoring and normalization. The binary fission events were detected by a pair of Multi-wire Proportional Counters (MWPCs) mounted at folding angles (40^o and 120^o). The fission detectors were mounted at a distance of 27 cm (forward angle) and 23.5 cm (backward angle) with respect to the target. A steady flow of isobutane gas was maintained at ~4 mbar pressure. The large area MWPC (20 cm × 10 cm) provided excellent time resolution (<1 ns) and two-dimensional position information of fission events. The fast neutrons emitted in the heavy ion-induced fission process were detected using organic liquid scintillators (BC501A) mounted on the geodesic dome structure of the NAND. Eighty neutron detectors from the array were used in the present study covering a wide range of angles (γ, γ). The fixed geometry of the dome structure provided 175 cm flight path to fast neutrons. The pulse shape dependency of the organic liquid cells was exploited electronically to discriminate fast neutrons from γ-ray background. The fast neutron signals were processed using pulse-shape discrimination modules tuned for ~ 0.5 MeV neutron energy threshold. Data were acquired in list-mode where a VME-based data acquisition software, NiasMARS was utilized.

The fission fragment mass distribution was extracted by velocity reconstruction method. Measured time of flight spectra of fragments were calibrated and were used for deriving their velocity in the centre of mass (c.m.) frame. Fission events after full momentum transfer were separated from other reaction channels by following their velocity correlation. And finally, the mass ratio distribution was extracted from the ratio of velocities in the c.m. frame. The pre-scission neutron multiplicity, which is the number of pre-scission neutrons emitted per binary fission, was extracted by moving source fitting method. Three sources of neutrons (two fragments and the CN) were considered in this model in which the relative yield from a source in a particular detector was decided by the angle between the neutron detector and the neutron source. Detailed analysis to find neutron multiplicities as a function of projectile energy and their inter-dependence with fragment mass is in progress.

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5.1.15 Mass-gated pre-scission neutron multiplicity measurements for $^{28}Si+^{238}U$

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For the quest of understanding the dynamics of quasi-fission phenomena near the barrier, mass-gated pre-scission neutron multiplicity measurements were carried out. The experiment was performed with the Pelletron+LINAC booster facility of IUAC. A pulsed ^{28}Si beam, with width ~ 700 ps and pulse separation of 250 ns, was bombarded on ^{238}U targets of areal thickness 290 μg/cm^2 at laboratory energies *(E)*) of 170, 180 and 192 MeV. These energies corresponded to $\frac{E}{V_B}$ = 1.09, 1.15 and 1.23; V_B is the Coulomb barrier. Eighty BC501A organic scintillator detectors