Exploring heavy ion fusion-fission dynamics around the Coulomb barrier using neutron multiplicity measurements

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The complex process involved in the collective rearrangement of the nucleons along nuclear fusion-fission is still a vividly debated topic in nuclear physics, on both the experimental and theoretical front. From the fundamental point of view, heavy ion fusion-fission is a rich laboratory for probing dynamical and structural properties of nuclear matter. Among these a few are related to the dynamical characteristics of the reaction mechanism such as entrance channel effects and dissipation of fissioning nuclei, while others are pertained to the nuclear structural aspects such as shell effects and collective enhancement of level density (CELD). Exact influence of the aforementioned parameters in fusion-fission dynamics are not clearly understood. Among many probes to explore fusion-fission dynamics, pre-scission neutron multiplicity (ν_{pre}) is one of the best probes to understand the evolution of the compound system from ground state configuration to scission configuration. Experimental studies of fusion-fission timescales via neutron multiplicity measurements have shown that the fission process is strongly hindered relative to standard statistical model predictions. This hindrance of fission process is attributed to the dissipative nature of the process, which also leads to an excess emission of neutrons and other particles. The intrinsic nature of the dissipation whether one body or two body, temperature dependent or not etc, are debatable questions even today.

Guided by the above considerations, we have studied fusion fission dynamics via neutron multiplicity as a probe in this thesis. A systematic study of pre-scission neutron multiplicity has been conducted over 26 reactions whose ν_{pre} values were available in the literature [1]. The study spanned the fissility range between 0.64 and 0.83. Among these systems, many of them are forming the same CN through different entrance channels at similar excitation energies. In a few systems, it is observed that the experimental ν_{pre} values are larger for symmetric reactions than the asymmetric cases. However in a few other reactions, a reverse trend in ν_{pre} is also observed, where the experimental ν_{pre} are observed to be larger for asymmetric cases. In order to investigate the effect of entrance channel mass asymmetry and fissility on pre-scission neutron emission, we have performed a systematic analysis of ν_{pre} data using a statistical model, which incorporates Bohr-Wheeler fission width with separate delays for the pre-saddle and post-saddle phases of fission [1]. The delay used in the ground state to saddle configuration is termed as the transient delay (t_d) and the delay from saddle to scission configuration is termed as saddle to scission delay (t_{ssc}). A remarkable observation is that the total fission delay deduced appear in two distinct groups according to their entrance channel mass asymmetry. It is also noticed that the difference in fission delay between systems with different entrance channel mass asymmetry increases with increase in fissility of the CN. This observation is attributed to the fact that in the lower fissility region the path to scission may be short and the fission delay is entirely in the pre-saddle phase. We also speculate that the dissipative effects at higher angular momentum may also be influencing the timescales deduced from the ν_{pre} data.

We next investigated the role of collective enhancement of nuclear level density, K-orientation effect and dissipation in fission dynamics of heavy fissile nuclei via neutron multiplicity measurements. For this, we performed neutron multiplicity measurements for the ^{30}Si+^{197}Au reaction leading to the formation of ^{227}Np, an actinide CN over an excitation range between 44 and 78 MeV [2]. The measurements were carried out using the National Array of Neutron Detectors (NAND) facility [3] of Inter University Accelerator Centre (IUAC), New Delhi, using pulsed beams of ^{30}Si from the 15UD Pelletron+LINAC accelerator systems. The neutrons emitted from the CN and fission fragments were detected in coincidence with the binary fission fragments using 50 organic liquid scintillator detectors (BC 501) of the NAND facility. The complimentary fission/fission like fragments were detected

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using a pair of identical position-sensitive multiwire proportional counters (MWPCs). The pre-scission and post-scission neutron multiplicities and temperatures were thus obtained from the experimental neutron energy spectra, using the multiple source fitting of Watt expression. Measurement of ν_{pre} for such a heavy fissile system explicitly provides direct evidence for the presence of a strong nuclear dissipation hindering the fission of hot and rapidly rotating CN. The emission of neutrons at higher excitation energies (or larger angular momentum results in vanishing of fission barrier) could only be understood in terms of nuclear dissipation. Temperature dependence of nuclear dissipation couldn't be observed as reported in few recent ν_{pre} measurements [6, 7]. Analysis show that the emission of saddle to scission neutrons which increases with excitation energy of the CN contribute more to the ν_{pre} than pre-saddle neutron emission. However the $\nu_{pre-sad}$ for ^{227}Np CN does not show dependence on excitation energy. Influence of CELD and K-orientation degrees of freedom in fission of such heavy nuclei are observed to be small unlike fission of pre-actinides.

We next studied the role of neutron shell closure of N=126, CELD and dissipation in pre-scission neutron emission. To this end, we performes neutron multiplicity measurements for the ^{30}Si+^{182,184,186}W reactions populating ^{212,214,216}Ra compound nuclei [4, 5]. Among these compound nuclei, ^{214}Ra has major neutron shell closure of N=126 and other two are two neutron numbers away from the shell closure on either sides. The measurements were performed at NAND array using pulsed beam from 15UD Pelletron+LINAC facility of IUAC. Beams with a pulse separation of 250 ns were used in the experiment to bombard on enriched isotopes of ^{182,184,186}W having thickness of 405 μg/cm^2, 450 μg/cm^2 and 331 μg/cm^2, respectively, with carbon backing of 25 μg/cm^2. Eventhough the experimental ν_{pre} excitation functions show a marginal isotopic dependence, which do not show any specific effect of neutron shell closure of N=126. A remarkable observation is that the strength of dissipation required to reproduce the experimental ν_{pre} data do not show any temperature dependence unlike that reported for a few neighbouring systems such as ^{210,212,214,216}Rn [6] and ^{213,215,217}Fr [7] isotopes. Influence of shell effect in fission barrier and level density parameter in ν_{pre} is observed to be negligible in the excitation energies considered, which may be due to the wash out of shell effects above 50 MeV excitation energy. Hence the strength of dissipation deduced does not show any noticeable dependence of N=126 even at the lowest excitation energy. Also the shell correction at the saddle point is found no more to be required to reproduce the measured ν_{pre} data. Although the ν_{pre} excitation function show only a marginal dependence on CELD, the pre-saddle component of ν_{pre} show a significant influence on CELD even at the highest excitation energies.

For the first time, we have insvestigated the effect of CELD in pre-scission neutron emission from the heavy ion fusion-fission reactions. The experiments and theoretical investigations were performed for both the actinide CN and pre-actinide CNs with neutron shell closure of N=126. The very small effect of CELD in the fission of ^{227}Np CN could be attributed to the large deformation at the ground state of the CN and the limit to populate maximum angular momentum in the CN, respectively. However significant effect of CELD observed in the pre-saddle neutron emission from ^{212,214,216}Ra is attributed to the relatively larger collective enhancement factor for nuclei with spherical closed shell than a deformed nucleus.

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