Trekking through fusion meadows and fission valleys

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One of the major aspects of today's nuclear physics research is the understanding of the reaction mechanism to produce heavy element (HE) and super heavy elements (SHE). This will provide us an experimental guidance on which reactions are best suited for the production of SHE.

In order to synthesise SHE, fusion of two heavy nuclei is required. After the two fusing nuclei comes into the contact configuration, the di-nuclear system may evolve in shape to form a compact equilibrated mono-nucleus, the compound nucleus (CN), or decay into fission like events before forming a CN, known as quasi-fission. The competition between these two processes exhibits complex behaviour. The production of SHE requires, in particular, the understanding of the mechanism of dynamical evolution that the system undergoes after contact. This dynamical evolution or the fusion path is actually governed by the multidimensional potential energy landscape. For example, depending upon the entrance channel deformations of the two touching nuclei, their mass asymmetry, beam energy etc; the composite system can reach a "*fusion meadow*" in the energy landscape where it equilibrates to a compound nucleus and cools down after the evaporation of a few particle and photon emission to a evaporation residue (ER); or it could undergo shape oscillations over an unconditional saddle to reach a "*fission valley*". In the case of quasi-fission, the system may bypass the fusion meadow to reach the fission valley.

The topography of the potential energy landscape is indeed complicated to enable to determine theoretically the path taken by the system in its evolution through fusion meadow and fission valley. This is even more so, because of the possible microscopic effects such as nuclear shell effects. Therefore, it is important to use experimental probes together with phenomenological understanding or microscopic calculation to elucidate the fusion meadows and fission valleys that determine the formation of HE and SHE. Recently, we have carried out a series of experiments to look for the possible microscopic effects (shell effects) in the fusion meadows [1,2] and presence or absence of quasi fission [3,4,5] in nuclei. Using the major accelerator facilities available in India, we have studied the fission dynamics of actinides and pre-actinides at beam energies close to the Coulomb barrier for different target projectile combinations.

We have used fission fragment mass distribution as a probe to look for the presence or absence of quasi-fission reaction. Since quasi-fission is a dynamical process which proceeds through a mass asymmetric conditional fission barrier, it may lead to asymmetric fragment mass distribution. An admixture of statistical fission events and quasi-fission will thus result in larger width of the mass distribution and it is expected to increase if there is enhancement of quasi-fission with change in the excitation energy. Besides, the deviation of shape (and width) of the measured mass distribution from those predicted by liquid drop model may be used as a probe to look for the presence or absence of shell effects at saddle point. We have shown [3] that, even one MeV shell correction at saddle causes appreciable change in the single hump Gaussian shape of the fission fragment mass distribution as predicted by liquid drop model.

The measurements of fission fragments mass distributions were carried out with two large area position sensitive gas proportional counters (20 cm x 6 cm) developed at VECC. The detectors were placed at folding angles. For each fission event, the time difference of the fast anode pulses of the detectors with respect to the pulsed beam, the X and Y positions together with the energy loss of fission fragments were measured. From these measurements, we extracted the masses of the correlated fission events [5].

Constraining the excitation energy at which the nuclear shell effect washes out has important implications on the production of super heavy elements. At VECC, we measured the fission fragment mass distribution in • induced reaction on an ^{232}Th target for wide excitation range in close energy interval and show that with decrease in beam energy, shape of the mass distribution changes from single hump symmetric to asymmetric mass distribution at excitation energy ~40 MeV [4] . This is a direct evidence of the washing out of nuclear shell effect for the actinide nuclei ^{236}U. Our calculation of fission valley also shows that the second peak of the fission barrier also vanishes around similar excitation energy.

We measured the mass distributions of the fragments in the fission of ^{206}Po and the N = 126 neutron shell closed nucleus ^{210}Po. The nuclei were populated with ^{12}C beam from TIFR Pelletron, Mumbai. No significant deviation of mass distributions was observed between ^{206}Po and ^{210}Po, indicating the absence of shell correction at the saddle point in both the nuclei [3]. This is contrary to the results reported from the angular anisotropy and pre-scission neutron multiplicity measurements (for references see [2]) that indicated the presence of shell correction at saddle. Our results provide a benchmark for different models that are used to predict the fission barriers for the production of spherical super heavy nuclei around the next closed neutron shell at N = 184.

In a recent experiment at VECC, Kolkata we have also populated the ^{210}Po nuclei at similar excitation energy with alpha induced reaction and measured the fission fragment mass distributions. This offers the population of the compound nuclei at relatively lower angular momentum compared to ^{12}C induced fusion reaction. Since the fusion meadows and fission valleys are affected by excitation energy and angular momentum, this measurement allow us to indicate if there is any influence of the angular momentum on the washing out of the shell effects in the mass distribution of ^{210}Po. Preliminary analysis indicates that the fission fragment mass distribution is still symmetric at excitation energy of 40 MeV.

To explore the fission valley of pre-actinide nuclei, in an experiment at IUAC, New Delhi we measured the fission fragment mass distributions in the reactions ^{16}O + ^{184}W and ^{19}F+ ^{181}Ta populating the same compound nucleus ^{200}Pb at similar excitation energies [1]. Earlier measurement indicated the suppression of evaporation residue (ER) for the symmetric reaction. However, two recent dynamical model calculations (for references see [1]) for the systems indicated the presence of quasi-fission reaction in the above mentioned reaction. In our measurement, it is found that the widths of the mass distribution increases monotonically with excitation energy, indicating the absence of quasi-fission for both reactions. This is contrary to the dynamical model calculations that indicated presence of quasi-fission in the above mentioned reactions.

Our study of fission dynamics in ^{243}Am and ^{254}Fm [2] clearly points to the gaps in our present understanding of the non-equilibrium fission phenomenon, which is phenomenological in nature and calls for a detailed microscopic study to chart the entrance channel dynamics using realistic multidimensional potential energy surfaces to have a clear understanding of the distinctive features of relaxation of various degrees of freedom at near-barrier region. Together with the results of our new measurements carried out at Dubna cyclotron facility to study the fission dynamics of super heavy elements will allow us to systematic understanding of the formation mechanism of the heavy and super heavy elements. A survey of the above activities will be presented in the talk.

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