Quasi-fission in fragment mass distribution of ^{225}Pa

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Introduction:

Quasi fission (QF) and fusion fission (FF) are two competing processes affecting the formation probability of Super Heavy Elements (SHE). To optimize the exploration of the super heavy element landscape, the key challenge is to understand the competition between QF and FF. Several experiments are being carried out worldwide to understand the dynamics of QF and FF [1], though there are scarcity of reliable theoretical models that efficiently predicts the amount of QF in a reaction. However, any new models that are being developed, needs to be tested from experimental data.

The dynamics of the fusion process is strongly influenced by several entrance channel properties such as charge product of nuclei (ZpZt), mass asymmetry (α), deformation of nuclei (β), shell effects and collision energy. Experimental investigation of mass-energy and angular distribution of fission products are employed for efficiently identifying compound (FF) and non-compound (QF) nuclear processes. According to standard statistical model of fission, the mass distribution of fission products follows Liquid Drop Model (LDM) predictions showing symmetric mass distribution and the width of mass distribution vary smoothly as a function of excitation energy.

A recent state of the art theoretical calculation [2] performed in the frame work of the di-nuclear system (DNS) and advanced statistical models, predicted dramatic increase of QF with increase in excitation energies for fusion of ^{16}O, ^{19}F induced reactions on pre-actinide targets ^{181}Ta, ^{184}W. This was explained [2] by the increase in the quasi-fission and fast fission contributions to the fission cross section. This is surprising as ZpZt for the entrance channel (<700) is well below the expected charge product (~ 1600) to set in QF. Interestingly, measurement [3] of fission fragment mass distributions for these systems near the barrier energies, indicated the absence of quasi fission. It is, however, to be mentioned that the measurement [3] was restricted to near barrier energies.

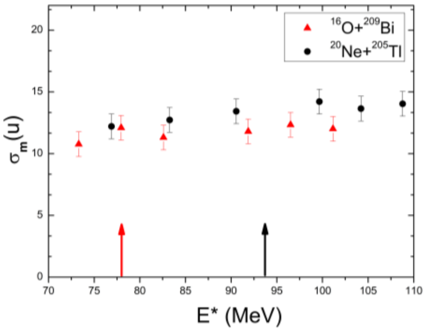

Fig. 1. Width of the mass distribution as a function of excitation energy. The arrow indicates the corresponding Coulomb barrier.

New measurements were carried out at VECC for similar systems ^{20}Ne+^{205}Tl (ZpZt = 810) and ^{16}O+^{209}Bi (ZpZt = 664), this time even at much higher energy beyond the Coulomb barrier, populating the same compound nucleus ^{225}Pa [4]. The variation of the width of the mass distributions as shown in Fig 1, clearly shows the monotonic variation of the width of the mass distribution with excitation energy, indicating no quasi-fission, contrary to the predication of the state of the art theoretical model. In this work, we present the possible reason for the deviation of the predicted and experimentally measured mass width. The findings remarkably suggest new refinement in the method of measurement of width of the mass distribution, with the detection of more light fission fragments that are usually excluded in the conventioanl measurements.

Calculation of quasi-fission yield:

The transport master equations have been used to calculate the mass and charge distribution [5]. The characteristics of the mass distribution of the reaction products are defined by the potential energy surface of nuclear system, shell structure of protons and neutrons in nuclei and excitation energy of the di-nuclear system (DNS). The main difference between the QF and deep inelastic collision is that in the former case, the lifetime of the DNS is longer and in the latter case the full momentum transfer does not take place. The nucleon exchange takes place between fragments of the DNS before its decay and during its transformation into a compound nucleus. The charge and mass numbers of a DNS fragment are changed from the ones of the projectile (P) and target (T) nuclei.

The evolution of the charge distribution Y_Z between the DNS fragments at its excitation energy E^*_Z is estimated by the solution of the transport master equation:

$$\begin{aligned}\frac{\partial}{\partial t} Y_Z(E^*_Z, t) = {} & \Delta^{(-)}_{Z+1}(E^*_Z) Y_{Z+1}(E^*_Z, t) \\ & + \Delta^{(+)}_{Z-1}(E^*_{Z-1}) Y_{Z-1}(E^*_Z, t) \\ & - \Big(\Delta^{(-)}_Z(E^*_Z) + \Delta^{(+)}_Z(E^*_Z) \\ & + \Lambda^{qf}_Z(E^*_Z) \Big) Y_Z(E^*_Z, t),\end{aligned} \qquad (1)$$

where $Z = 2, 3, \ldots, Z_{tot} - 2$ and the transition coefficients $\Delta^{(\pm)}_Z$ determine the probability of nucleon transfer between the interacting nuclei "P" (projectile) and "T" (target) of the DNS characterized with the charge numbers Z and $Z_{tot} - Z$, where Z_{tot} is the total charge number of the system; E^*_Z is its excitation energy which is determined by the initial energy of collision $E_{c.m.}$, the minimum value of the potential well $V^{(Z)}_{min}$ in the nucleus-nucleus interaction and the energy balance of the nucleon transfer $\Delta Q^{(Z)}gg = B_P + B_T - B_Z - B_{Ztot-Z}$: $E^*_Z = E^{c.m.} - V^{(Z)}_{min} + \Delta Q^{(Z)}gg$, where B_P, B_T, B_Z and B_{Ztot-Z} are the binding energies of the projectile and target nuclei, DNS fragments Z and Z_{tot}–Z, respectively. The contribution of the QF products to the yield of the ^{20}Ne+^{205}Tl and ^{16}O+^{209}Bi reactions products at different beam energy has been estimated by the numerical solution of eq. (1) with the initial conditions $Y_Z (Z_P = 8,10) = 1$ and $Y_Z (Z_T = 205, 209) = 1$. The corresponding mass numbers are found by the minimization of the total energy of DNS as a function of *A*.

Results and Discussions:

In Fig 2 we show the calculated yields of the events originated from quasi fission at different beam energies for ^{16}O+^{209}Bi and ^{20}Ne+^{205}Tl reactions. It is interesting to observe that a significant amount of quasi-fission events is near the projectile mass region, though the yield drastically reduces in the symmetric mass region.

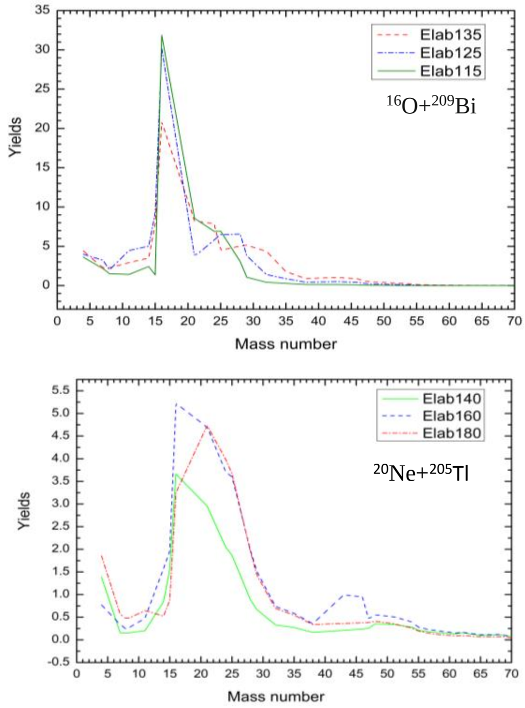

Fig. 2. Quasi-fission yields for both reaction w.r.t. mass number at different lab energies

In the standard method of the measurement of the mass distributions, emphasize are given to get rid of the projectile like events using gas detectors operating at lower pressure. Since the width of the mass distributions are calculated only from the measured symmetric events, it deviates from the predication of model calculations that considers all the events. The present calculation indicates the need of detection of projectile like events in the experiment to test the reliability of the newly developed theoretical models to better understand the dynamics of quasi fission and fusion fission reaction mechanism.

References:

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