Shell effect in slow quasi-fission process

A. Pal[1],* S. Santra[1,2], P.C. Rout [1,2], Ramandeep Gandhi [1,2], A. Baishya [1,2], and T. Santhosh [1,2]
[1]*Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai - 400085, India and*
[2]*Homi Bhabha National Institute, Anushaktinagar, Mumbai - 400094, India*
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While synthesizing super-heavy elements (SHE) using fusion reactions, a pre-equilibrium fission reaction mechanism, generically named as Quasi-fission (QF) is known since mid 1970 as a cause for the suppression of SHE formation. Since then many aspects of QF have been explored experimentally by measuring fission fragment (FF) mass and angular distributions and theoretically by developing many macroscopic and microscopic dynamical models. From the above studies, one can broadly classify the QF process into two categories: Fast and Slow quasi-fission. The fast quasi-fission (FQF) which is generally observed in reactions with heavy targets and projectiles, having charge product (Z_pZ_t) more than 1500, are characterized by very asymmetric mass -distributions, very fast time scales ($\sim 10^{-20}$ s) and presence of mass-angle correlation. In contrast, the slow quasi-fission (SQF) which is observed in reactions with much lighter projectiles such as ^{9}Be,^{11}B,^{12}C,^{16}O,^{19}F,^{24}Mg etc. and actinide targets, are characterized mainly by a time scale intermediate to FQF and compound nuclear fission (CNF), nearly symmetric mass distributions, absence of mass-angle correlations, larger mass width from the most symmetric entrance channel populating the same compound nucleus, sudden enhancement in the mass-width at lower incident energies and most importantly larger angular anisotropy compared to the statistical model predictions.

Based on a recent time dependent Hartree Fock calculation on ^{50}Ca+^{176}Yb reaction partners [1] forming ^{226}Th composite system, it was found that the same deformed shell $Z_H \sim 54$ as that of S-II mode in asymmetric fission of actinides is responsible for stopping mass equilibration in the FQF process, without allowing the system to form a compound nucleus. However till date, there is no investigation on the role of shell effect in SQF reaction mechanism. Actually in a slow quasi-fission reaction process, the nucleons exchange starts happening from heavier to lighter colliding partner, in contrast to the compound nucleus formation process. We can strongly anticipate that if one of the fragments becomes shell closed during the mass equilibration in SQF process, the di-nuclear system breaks into two fragments resulting in a double humped mass distribution, while mass-distributions in compound nuclear fission process are observed as a superimposition of several fission modes (super-long, S-I,S-II etc.) depending on the excitation energy and angular momenta populated in the system. However experimentally it is impossible to distinguish the fragments arising from CNF and SQF processes unless we take help from theoretical models incorporating compound nuclear fission.

In the present work we have exclusively obtained mass-distributions (MD) corresponding to SQF process for several systems by subtracting calculated MD from the total MD data following the method described in Ref [2]. Results for ^{19}F+^{238}U system, measured by us and reported in Ref [2] showed that MD for SQF process are indeed double humped at all the measured incident energies, with fixed peak centroid, as anticipated. Now in Fig. 1 (a-k), measured total MD and calculated MD following compound nuclear process using

*Electronic address: asimpal@barc.gov.in

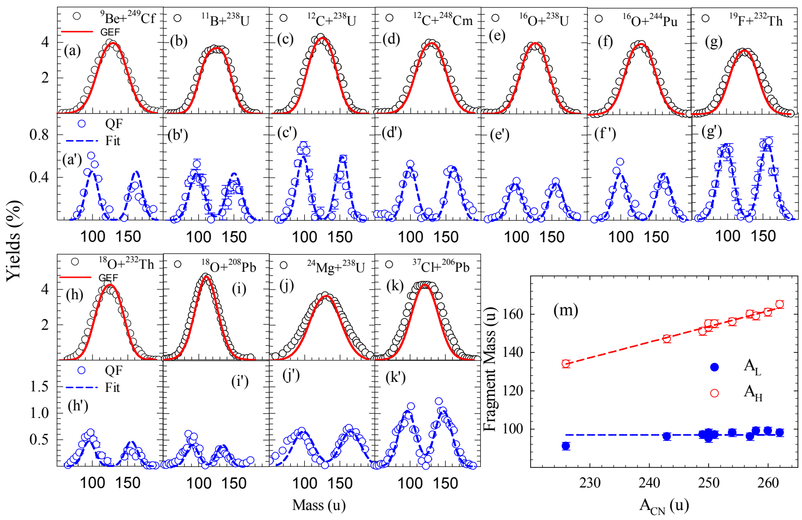

FIG. 1: (a-k) Comparison of measured data and normalized GEF calculations. (a′-k′) Derived mass distributions for SQF mode. (m) Peak positions of light and heavy fragments of MD in SQF process.

GEF model for ^{9}Be+^{249}Cf[3], ^{11}B+^{238}U [4], ^{12}C+^{238}U[5], ^{12}C+^{248}Cm [3],^{16}O+ ^{238}U[3], ^{16}O+ ^{244}Pu [3],^{18}O+ ^{208}Pb[6], ^{18}O+ ^{232}Th[5], ^{24}Mg+^{238}U [3],^{37}Cl+^{206}Pb [7] systems are shown by circles and solid lines respectively. Now the MD for SQF process obtained by subtracting those two are shown in Fig.1 (a′-k′). It is very interesting to observe that all the MD corresponding to SQF process consist of two peaks, indicating shell effect in the SQF process. Further, the above MDs are fitted using sum of two Guassian functions as shown by dashed lines in Fig.1 (a′-k′) and the peak position of heavy (red hollow circle) and light fragments (blue filled circle) are compared in Fig.1 (m). One can interestingly observe that the peak position corresponding to lighter fragment is almost constant (A∼96) whereas the peak position corresponding to heavier fragment is linearly increasing with the mass of the fissioning nucleus. This observation is in contrast to the one for asymmetric fission in actinides where mass of the heavy fragment does not change with the mass of the fissioning nuclei, but the light fragment does [8]. The constancy of the heavy peak in the asymmetric fission of actinides is attributed due to the role of deformed shell closed nuclei $\sim Z_H = 52 - 56$. Similarly, the constancy of the lighter peak in the fission of pre-actinides suggested the role of shell closed nuclei near $Z_{light} = 34$. Using the same analogy, the present observation (constancy of the lighter mass peak) can be treated as a clear evidence of shell effect in slow-quasi-fission process. Here the lighter fragment may correspond to nuclei around ^{96}Zr, a new doubly magic nucleus [9]. Thus the present work reports for the first time the role of a new shell closed nucleus governing the mechanism of SQF process.

References

[1] C.Simenel *et al.*, Phys. Lett. B **822**, 136648 (2021).

[2] A.Pal *et al.*, DAE-BRNS Symp. on Nucl. Phys. 65, 225 (2021).

[3] T.Banerjee *et al.*, Phys. Rev. C **102**, 024603 (2020) and **105**, 044614 (2022)

[4] S.Santra, A.Pal *et al.*, submitted

[5] C.Yadav *et al.*, Phys. Rev. C **86**,034606

[6] M.G.Itkis *et al.*,Nucl. Phys. A **944**,204

[7] G.Mohanto *et al.*, Phys.Rev.C **102**,044610

[8] K.F.Flynn *et al.*, Phys. Rev. C **5**,1725

[9] I. Boboshin *et al.*, Phys. Atom. Nuclei **70**,1363 (2007)