Role of quantum shells in fusion-fission and quasi-fission processes

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Quantum shells are very important in providing extra stability to a many body quantum system such as atomic nuclei. Magic numbers are responsible for large abundance of certain elements in the universe and existence of new island of stability. The spherical and deformed shell closed nuclei also play a crucial role in the process of fusion-fission and quasi-fission. New results obtained on S2 and super-short mode of fission from the heavy compound nuclei will be presented here. A new shell closed nucleus observed to govern the mechanism of slow quasi-fission process will be presented.

1. Introduction

Presence of shells in a many body quantum system has particular importance in determining the stability of the system. This is also relevant in case of atomic nuclei where protons and neutrons while filling up their respective shells produce larger gap between two shells leading to the so called magic numbers. The nuclei with magic number of protons and/or neutrons are more tightly bound than the others and hence they are more stable as compared to non-magic nuclei. Due to their extra stability they are relatively more abundant in nature. Also due to the possible existence of highest proton magic number near Z=114 and neutron magic number near N=184, there is a existence of new island of stability made of super-heavy elements (SHE). These shell closed nuclei are generally spherical in shape at ground state. However if they are forced to be deformed, they no-longer remain as magic nuclei, rather new magic numbers start appearing. Z=36,40, 52-56 are such examples of deformed shell closed nuclei.

These magic numbers are observed to play a decisive role in spontaneous fission or fission induced by photon, neutron and charged particles. The long standing puzzle of asymmetric fission of actinides was solved by invoking the concept of deformed shell closed nuclei. Actually different shell closed nuclei depending upon the mass of the fissioning nuclei play the decisive role during neck-rupture of the fission process. If the mass of the actinide fissioning nuclei lies in the range of 226-256 u, the mass distribution is asymmetric for compound-nuclear excitation energy even up to 40 MeV, due to the persistence of magicity of the deformed shell closed nuclei near Z=54 and A=142. The fission mode which proceeds through the yeilding of the above deformed shell closed nuclei as one of the fragments is known as $S2$ mode. There are few fissioning nuclei such as ^{242}Pu where one of the fragments produced at lower excitation energies is ^{132}Sn, a spherical doubly magic nucleus. This particular mode of fission is called $S1$ mode. A very interesting and rare mode of fission which is observed when both of the fragments are as close to as doubly magic spherical ^{132}Sn, is known as $S1 - S1$ or super-short mode of fission, generally seen from the fissioning nuclei in the range of Fm-Rf.

Further, theoretical investigations suggest that shell closed nuclei play a vital role in quasi-fission (QF) process, a process known for opposing super-heavy elements synthesis. Using time dependent Hartree Fock calculation on ^{50}Ca+^{176}Yb reaction partners, it was shown that the same deformed shell $Z_H \sim 54$ as that of $S2$ mode in asymmetric fission of actinides is responsible for stopping mass equilibration in the fast quasi fission process, without allowing the system to form a compound nucleus.

Presently, we have performed several experiments on heavy ion induced fusion -fission reactions to explore the role of different fission modes . Firstly we aim to find out the compound nuclear excitation energy upto which

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the $S2$ mode can play a role in the fission process by experimentally studying ^{11}B+^{238}U reaction. Secondly, we search for the super-short mode of fission in the neutron rich nuclei ^{257}Md populated by ^{19}F+^{238}U reaction. Our third objective is to explore the role of shell closed nuclei in slow quasi-fission process, if any.

2. Experimental Details

The experiments were performed at 14-UD BARC-TIFR Pelletron- Linac facility, Mumbai using pulsed beam of ^{11}B and ^{19}F and two multiwire proportional counter detectors developed inhouse. The details of the experimental setup and analysis methods have been described in Ref.[1, 2]

3. Results and Discussions

Mass distributions (MD) obtained from the fissioning nuclei ^{249}Bk for the excitation energy ranges 36-70 MeV[3], are fitted using three gaussian functions, out of which two represents asymmetric splitting and one represents symmetric splitting as described by liquid drop model. It was quite surprising to observe that contributions from asymmetric fission ($S2$ mode) persists up to compound nuclear excitation energy up to as large as 70 MeV, which is in contradiction to some literature data for nearby fissioning nuclei. In principle, the shell effect should vanish if a particular nucleus is excited beyond 40 MeV excitation energy. However, the survival of the shell effect up to such high excitation energy is understood in terms of multi chance fission where successive neutrons get evaporated with reappearance of shell effect in the residual fissioning nuclei. Present data has been compared with the literature data and GEF model calculations, both of which are consistent with the present observation.

Further, mass and TKE distributions were obtained from the fissioning nuclei ^{257}Md for the excitation energy ranges 37-88 MeV [2]. Due to the skewness of the measured TKE distributions, two Gaussian distributions were required to explain the data. The events with high TKE must originate from the supershort mode of fission, the presence of which has been confirmed by measuring two additional reactions: ^{19}F+^{232}Th and ^{18}O+^{238}U involving first a different target and then a different projectile leading to compound nuclei ^{251}Es and ^{256}Fm, respectively, at similar excitation energies and comparing their mass-TKE correlation plots. The existence of considerable super-short mode of fission for the ^{257}Md nucleus up to E* $\sim$48 MeV, observed for the first time, reveals that such rare fission modes for neutron-rich exotic nuclei are far off from the liquid drop model predictions, even at high excitation energies.

In the above cases we assumed that all fission events followed by full momentum transfer correspond to fusion-fission events. However, it was suggested in literature that those events may contain some contributions from slow-quasi-fission (SQF) process which can be separated out by subtracting the calculated mass distributions obtained from a compound nuclear fission model from the measured total mass distribution data. MD for SQF process have been obtained for the present systems as well as for the systems for which MD data are available in literature[4]. Consistently all MD corresponding to SQF processes are observed to be doubly peaked, with fixed peak centroid, indicating shell effect in SQF process. Further from the comparison of the peak position of heavy and light fragments, one can interestingly observe that the peak position corresponding to lighter fragment is almost constant (A$\sim$96) whereas the peak position corresponding to heavier fragment is linearly increasing with the mass of the fissioning nucleus. Using the analogy of asymmetric fission in actinides and pre-actinides one can confirm the role of a new shell closed nucleus in SQF process.

References

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