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Experimental study of quasi-fission and shell effects in fission of heavy nuclei.

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Nuclear fission, one of the most profound decay mechanisms a nucleus undergoes in its quest for stability, entails the division of a fissioning nucleus into two or more nuclei with similar masses, typically resulting in the liberation of a substantial amount of energy. The fission fragment mass distributions (FFMD) of actinide systems are generally asymmetric, with the heaviest fragment commonly found around the mass number 140 at low excitation energies. However, in 2010, a notable discovery was made by A. N. Andreyev *et al* [1]., who observed a new type of asymmetric fission in ^{180}Hg. The FFMD of ^{180}Hg displayed asymmetry, with observed peaks at mass numbers 80 and 100, posing a challenge to existing models. Peter Moller's macroscopic-microscopic model provides an explanation for the asymmetric mass distribution of ^{180}Hg and has successfully computed the FFMD of several other nuclei in this specific region. This comprehensive model appears to have global applicability in this domain, although experimental verification is essential to get a clear picture.

Motivated by this requirement,, we conducted an experiment aimed at identifying fragment shell effects in the fission of the pre-actinide nucleus ^{214}At. The experimental setup took place at the BARC-TIFR pelletron LINAC facility in Mumbai, where ^{9}Be beam with energies ranging from 40 to 47 MeV was bombarded on thin targets of ^{205}Tl to create the ^{214}At nucleus. We employed two Multiwire Proportional Counters to detect the binary fragments.

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The fission fragment folding-angle and mass distributions were measured at energies E_{lab} = 42, 43.5, 45, and 47 MeV. Despite using a weakly bound ^{9}Be projectile, the folding angle distribution did not exhibit any significant signature of projectile breakup in the reaction. Slight asymmetry in mass distributions was observed at excitation energies E* = 31.1 and 32.6 MeV This asymmetry was identified at the mass numbers 80 and 134 [2]. The observed asymmetry indicated that the role of the fragment shell effect in determining the fate of the mass distribution for the pre-actinide nuclei.

The influence of a weakly bound projectile on the actinide system has attracted significant interest. Earlier reports indicate that reactions involving loosely bound projectiles, compared to those with tightly bound nuclei, exhibit a notably distinct dependence of excitation energies on fission fragment mass and folding angle distributions. In this thesis work, the role of a weakly bound projectile ^{9}Be in the fission reaction with an actinide ^{238}U near the Coulomb barrier has been investigated both experimentally and theoretically. In the experiment, a pulsed beam of ^{9}Be was bombarded on a thin ^{238}U target using the BARC-TIFR facility. The folding angle, velocity and mass distributions at the energies E_{lab} = 37.5, 39, 42, and 47 MeV near the Coulomb barrier (V_B = 44.7 MeV) were measured. This investigation aimed to uncover the contributions of incomplete fusion-fission to total fission dynamics.

The analysis revealed that the folding angle distributions at lower energies were notably influenced by a higher contribution of low-energy neutron-induced incomplete fusion-fission events. Through the application of folding-angle analysis, the total contribution of incomplete fusion fission events (ICF) across all measured energies was estimated [3]. The estimated fractions of ICF were then compared with both existing data and theoretical predictions generated using the distorted wave Born approximation-based theoretical code DWUCK4 and the coupled reaction channel code FRESCO.

For reactions forming heavy and superheavy elements (SHE), the competition between fusion-fission (FF) and quasifission (QF) following capture plays a major role in determining the reaction outcome. Orientation-dependent QF is usually observed around the Coulomb barrier and experiments of FF and QF dynamics were earlier studied for ^{16}O+^{2}38U around the Coulomb barrier. In order to study the fission dynamics we have populated ^{254}Fm well above the Coulomb barrier for the reaction ^{16}O+^{2}38U where orientation dependent QF is not expected. The experiment was carried out at the VECC K-130 Cyclotron, Kolkata, India. A pulsed beam of ^{16}O beam was bombarded on the thin ^{238}U target.

The present experiment has been performed for the same reaction in the energy range (1.1V_B to 1.8V_B) where the orientation-dependent QF is not expected for this reaction. Width of the experimentally-obtained mass distributions have been compared with GEF calculations, statistical model calculations and with existing data. The low energy existing data showed deviation from the the theoretical calculations which might be a signature of contribution of quasi-fission events. However in our present observation which are at higher excitation energies, well above the Coulomb barrier, fusion-fission events dominates.

In summary, this thesis work deals with the detailed study of the processes undergoing during nuclear fission in pre-actinide region (^{214}At) and actinide region (^{247}Cm, ^{254}Fm), using experimental data and theoretical calculations. The shell effects in the pre-actinide nucleus ^{214}At were investigated in one experiment and validated the predictions from the recently developed macroscopic-microscopic dynamical model. In another experiment to study ICF and FF processes, the role of the loosely bound projectile ^{9}Be in the reaction ^{9}Be+^{238}U was investigated through the folding-angle, velocity, and mass distribution of binary fragments. The FF and ICF components were separated from the folding angle distribution of the reaction. The total ICF fraction was estimated from folding-angle distributions at measured energies, and these estimates agreed well with the theoretical calculation. The mass distribution for the reaction at highest energy (E_{lab} = 47 MeV) was analysed using TCSM calculation. The calculation did not provide any evidence of shell effect, and the asymmetry in the measured mass distribution at that energy for gated events showed that there might be an inseparable admixture of ICF with FF. To study the fusion-fission dynamics of 254Fm through the reaction ^{16}O+^{238}U, an experiment was carried out above the barrier where QF is not expected. The widths of the measured FFMD were compared with the theoretical values obtained from saddle point model, scission point model and GEF calculations and it was observed that GEF and saddle point model could reproduce the experimental data in this energy region for the system, whereas scission point model could not do so. Additional fusion-fission research for the other energy and nuclear regions can be performed to advance the results and understandings obtained through the present studies. This thesis work has successfully verified the shell effects in sub-Pb region, showed the significant effect of loosely bound projectile in fission with actinide nucleus near Coulomb barrier and observed the fusion- fission process above the barrier for actinide system through detailed experiments and theoretical estimations.

References

[1] A. N. Andreyev *et al.*, Phys. Rev. Lett **105**, 252502 (2010).

[2] D. Paul *et al.*, Phys. Rev. C **102**, 054604 (2020).

[3] D. Paul *et al.*, Phys. Rev. C **104**, 024604