Dynamics of heavy ion induced fusion-fission reactions at energies near and above the Coulomb barrier

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Heavy ion fusion is a topic of great interest in experimental as well as theoretical nuclear physics research for several years as it is one of the successful methods for the superheavy element (SHE) [1] synthesis. Fusion-fission and quasifission [2] are the two competing processes that severely inhibit the SHE formation. Because of the extremely low evaporation residue (ER) cross section in SHE region, it is important to understand the complex reaction dynamics in the medium heavy mass (200-220 amu) region so that one can extrapolate the knowledge gained from this region to the superheavy region. The present works focus on the importance of entrance channel effects on the fusion-fission reaction dynamics and the competition between fusion and quasifission processes in heavy ion reactions.

To understand the importance of the entrance channel effect on the fusion-fission reaction dynamics, we have studied the fission fragment mass ratio distributions for the reaction ^{30}Si+^{180}Hf and compared with the more asymmetric reaction ^{16}O+^{194}Pt, forming the same compound nucleus (CN) [3]. Measurement was performed at the 15UD Pelletron accelerator facility of Inter University Accelerator Centre (IUAC), New Delhi, using the General Purpose Scattering Chamber (GPSC). The fission fragments were detected using two large area position sensitive multiwire proportional counters (MWPCs) of active area 20 cm × 10 cm operated with isobutane gas of 3 Torr pressure. Fission fragment mass-angle and mass ratio distributions were obtained at energies above and below the Coulomb barrier. Kinematic coincidence method has been used for obtaining the M_R distribution in this work.

No mass angle correlation has been observed in the entire energy range of the present study. However, the widths of the fragment M_R distributions are significantly larger for ^{30}Si+^{180}Hf reaction when compared with that of ^{16}O+^{194}Pt reaction. Calculations assuming the saddle point and scission point models indicated the presence of quasifission events in this reaction, along with a major fusion-fission component. These quasifission events are interpreted as slow quasifission with longer sticking times as they could not exhibit any mass-angle correlation. Dinuclear system (DNS) model [4] calculations have been performed to estimate the relative yields of quasifission in the ^{16}O+^{194}Pt and ^{30}Si+^{180}Hf reactions. The model predicted negligible quasifission probabilities for the former reaction, in agreement with the experimental observations [5]. A 5-15% contribution from quasifission is predicted for the ^{30}Si+^{180}Hf reaction, in the energy range studied in this work. The onset of quasifission observed in the ^{30}Si+^{180}Hf reaction hints the entrance channel dependence of fusion at near barrier energies. To analyze this influence of entrance channel parameters on reaction dynamics, we have studied the excitation functions of ERs measured for different reactions populating Rn compound nuclei.

ER cross sections of ^{28,30}Si+^{180}Hf reactions [6] were measured using the the 15UD Pelletron + LINAC accelerator facility of IUAC. The recoil mass spectrometer, HYRA (HYbrid Recoil mass Analyzer) [7] was used for the identification and separation of ERs from the intense beam background. The ERs guided to the focal plane of HYRA were detected using a position-sensitive MWPC of active area 15 cm × 5 cm operated with isobutane gas of about 2.5 mbar pressure.

A comparison of the relative ER yields from the two reactions ^{28,30}Si+^{180}Hf measured show larger ER cross sections for the ^{30}Si induced reaction populating the heavier isotope of radon. This could be explained by considering the fusion and survival probabilities of the compound system formed. Increase of neutron number (and hence the mass number) decreases the neutron binding energy and the fissility of the CN- both favour the neutron evaporation over fission decay in heavy isotopes.

Experimental ER cross sections for the ^{30}Si+^{180}Hf reaction is compared with that of the ^{16}O+^{194}Pt reaction. Significant reduction in ER cross section for ^{30}Si+^{180}Hf has been ob-

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served, confirming the presence of quasifission in this reaction. Present results are in very good agreement with our previous observations in fission fragment mass ratio distribution in these reactions. The higher Coulomb factor (Z_PZ_T = 1008) and large deformation of the ^{180}Hf target (β = 0.273) could be favoring quasifission process in more symmetric reactions. The experimental results are analyzed using combined DNS and statistical models to understand the possible influence of potential energy surfaces (PES) and different entrance channel conditions in heavy ion fusion reactions. Calculations are in complete agreement with the experimental observations for the most asymmetric reaction, ^{16}O+^{194}Pt for which P_{CN} values are observed to be close to unity, yielding complete fusion in the entire range of energies over which experimental data are available. We also performed the model calculations for the ^{50}Ti+^{160}Gd [8] reaction, also populates ^{210}Rn as the CN, for which 4n+5n channel cross sections are known. The fusion probability drops to 60-70% for the ^{30}Si+^{180}Hf reaction and less than 20% for the ^{50}Ti+^{160}Gd reaction, reflecting the strong effect of Coulomb factor in shaping the PES to decide the final outcome of the reaction.

We also measured the fission fragment angular distributions for the reaction ^{30}Si+^{180}Hf to understand the fusion hindrance in these reactions. The experiment was performed using the Pelletron + LINAC accelerator facility of IUAC. Fission fragments were detected using the hybrid telescope array (HYTAR) [9], each consisting of a ΔE (gas) detector and E (silicon) detector, mounted in the 1 m diameter spherical scattering chamber of the National Array of Neutron Detectors (NAND) [10] facility. The present HYTAR set up has 16 telescopes arranged in three sets. One set has six telescopes placed on the right arm with an angular coverage of θ_{lab} - 60^o to 110^o and another six telescopes were mounted on the left arm that cover angles of 110^o to 160^o with an angular pitch of 10^o. Third group of four telescope detectors, two of them in-plane and another two out-of-plane, each at an angle of 173^o, were arranged in a symmetrical-cone geometry.

The observed angular anisotropies are compared with the statistical saddle point model (SSPM) calculations assuming complete fusion. The calculated anisotropies vary significantly from the experimental results in the energy range studied. The observed larger anisotropies are direct signatures of the presence of quasifission along with the major fusion-fission events in this reaction. The observations are in complete agreement with our previous findings.

The influence of entrance channel parameters on the fusion reaction dynamics is studied using the experimental observables, fission fragment mass and angular distributions and ER cross sections for different systems populating Rn nucleus. It is observed that quasifission is a dominant mechanism in all reactions except ^{16}O+^{194}Pt, clearly indicating the role of entrance channel in fusion. As we go to more symmetric systems, fusion probability decreases significantly, clearly indicating the escape of capture flux through non-compound nuclear channel, quasifission. The decrease in fusion probability with increase in charge product (Z_PZ_T) in these reactions indicates that the Coulomb factor plays a major role in the dynamics of nuclear collisions.

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References

[1] Yu. Ts. Oganessian *et al.*, Phys. Rev. Lett. **109**, 162501 (2012).
[2] D. J. Hinde *et al.*, Phys. Rev. Lett. **74**, 1295 (1995).
[3] A. Shamlath *et al.*, Nucl. Phys. A **945**, 67 (2016).
[4] A. K. Nasirov *et al.*, Eur. Phys. J. A **49**, 147 (2013).
[5] E. Prasad *et al.*, Phys. Rev. C **84**, 064606 (2011).
[6] A. Shamlath *et al.*, Phys. Rev. C **95**, 034610 (2017).
[7] N. Madhavan *et al.*, Pramana **75**, 317 (2010).
[8] D. A. Mayorov *et al.*, Phys. Rev. C **92**, 054601 (2015).
[9] Akhil Jhingan *et al.*, Proceedings of the DAE Symp. on Nucl. Phys. **59**, 830 (2014).
[10] P. Sugathan, Pramana **83**, 807 (2014).