INVESTIGATION OF HEAVY-ION INDUCED FUSION REACTIONS AT NEAR AND ABOVE BARRIER ENERGIES

A THESIS

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Thesis Summary

My thesis work is focused on the study of effect of entrance channel mass symmetry on fusion dynamics using light particles evaporation spectra, spin distribution and cross-section measurements as probes. This work is motivated from the studies of various light particle evaporation spectra existing in the literature. These studies have established that the fusion dynamics of asymmetric and symmetric target-projectile combination populating the same compound nucleus (CN) is different. While the light particle spectra for the asymmetric systems could be explained by using the statistical model, the spectra for the symmetric systems were having deviations from the statistical model predictions. These were explained in terms of the deformation of the emitter nucleus or existence of pre-equilibrium processes or non-fusion of higher partial waves. These results were conjectured on the basis of the calculations involving the modification of important ingredients of the statistical model codes by using spin dependent level density or lower values of level density parameter. Motivated by these studies, we carried out a systematic study of the level density parameter, 'a', for different systems in the mass region $A \sim 50$-110, populated through the asymmetric target-projectile combinations. This study indicates that the deviations in the experimental spectra for the symmetric systems may not always due to the incorrect value of the level density parameter. Moreover, most of the existing measurements of the light particles evaporation spectra are inclusive measurements, so we have performed the ER-gated measurements of α-particle, neutron and proton evaporation spectra. Since dynamical calculations for different systems existing in the literature indicate that the maximum values of l contributing to the fusion are lesser than the asymmetric system, so it is interesting to see how the various partial waves contribute to the fusion process. To investigate this we have performed the spin distribution and the cross-section measurements for two systems, differing in the entrance channel mass asymmetry but populating the same CN. These measurements have been performed using HIRA facility at IUAC, New Delhi.

In the present thesis work, we have performed exclusive (ER-gated) and simultaneous experimental measurements of the light particle (α-particles, neutrons, protons) spectra. For this we have chosen ^{28}Si+^{45}Sc system populating ^{73}Br with an excitation energy of 78 MeV and classical l_{max} = 47ħ and ^{32}S+^{45}Sc system populating ^{77}Rb at an excitation energy of 71 MeV and l_{max} = 43ħ. The shapes of both the inclusive and exclusive spectra were found to be same. The theoretical calculations were performed out using the CASCADE code. The charged particles spectra were found softer than the theoretical predictions. In neutron spectra a bump-like structure was observed in inclusive as well as exclusive spectra which is a signature about the presence of pre-equilibrium process. Various attempts were made to explain these deviations. The increased values of deformation parameters explain the α-particle spectra but not the proton and neutron spectra. Application of dynamical theories to the reactions under study suggests that

the fusion of higher partial waves (l > 30ħ) is inhibited leading to delayed shape equilibrium which results in the formation of deformed intermediate di-nuclear system. The dynamical deformation modifies the Yrast line and enhances the level density of high spin states compared to the low spin states as compared to the spherical or equilibrated CN. The dynamical deformation increases the binding energy for α-particles and protons significantly while for neutrons the binding energy decreases with increase in deformation in comparison to the spherical or equilibrated shape. This inhibits the participation of α-particles emission through the di-nuclear system formed by higher partial waves. However, both these approaches could not explain the proton and neutron spectra. Different values of 'a' were used to explain the proton and neutron spectra. The comparison between the neutron and proton spectra revealed that for neutrons the effective 'a' is lower while for protons it is higher than default value 'a' = A/8 MeV^{-1}. This results in the modification of level density of the CN which indicates there are pre-equilibrium contributions from the higher partial waves over the different energy ranges of the tail portion of the spectra. However, due to the difference in binding energy in the deformed system the effective contribution from neutrons and protons is different. The contribution of neutrons is dominant at the higher energy tail of the spectra while for protons the contribution towards the pre-equilibrium is from the lower energy side of the tail of the spectra. So, the consistent picture for explaining the deviations of the experimental spectra can be obtained in terms of the dynamical evolution of the fusion process. The dynamical effects are revealed in a better way through the spin cross-section and spin distribution measurement. For the cross-section and spin distribution measurements, we have chosen asymmetric $^{16}O+^{64}Zn$ and symmetric $^{32}S+^{48}Ti$ reactions which populate the same CN ^{80}Sr. The evaporation spectra studies for these systems, studied earlier, have indicated that the contribution of higher partial waves to the fusion is hindered for the symmetric system. The measurement of ER cross-sections gives the information of fusion dynamics, whereas ER spin distribution gives the detailed information about the contribution of different partial waves to the fusion process.

The cross-section measurements were performed for center of mass energies ranging from 48 MeV to 73.5 MeV for $^{16}O+^{64}Zn$ and 52 MeV to 75 MeV for $^{32}S+^{48}Ti$. The cross-section measurement for $^{16}O+^{64}Zn$ at low energies was performed earlier by Gomes *et al.* For obtaining the cross-section measurements, the transmission efficiency of different ERs through HIRA, were required. For this we performed the efficiency measurement using the γ-ray co-incidence method. The experimental efficiency values were compared with the Monte carlo simulations using the TERS code. The weighted average of efficiency of ERs was obtained using the % yield of different ERs from PACE code. Finally using the weighted average of the transmission efficiency of all the ERs, the cross-section values were obtained. The experimental cross-section were compared with theoretical models using the CCDEF code. Further, TDHF calculations were performed taking into account the deformation of the targets. For both the systems the experimental cross-sections were in agreement with the theoretical calculations. However the fusion time scales obtained using the TDHF calculations for both the systems were found to be approaching the decay times showing that the fusion time scales are elongated that may lead to pre-equilibrium emission which may in turn modify the CN spin distribution.

To have a better picture of the contribution of various partial waves to the fusion process, we have also performed the ER-gated spin distribution measurements for $^{16}O+^{64}Zn$ for the center of mass energy range 53.3 MeV to 73.5 MeV and $^{32}S+^{48}Ti$ for the center of mass energy range 57

MeV to 75 MeV. Van der Werf's prescription was used for unfolding the -multiplicity distributions from experimental γ-fold distributions. A P(M) distribution was assumed with two free parameters. The values of these parameters were extracted by fitting the experimental γ-fold distributions using χ-square minimization technique. γ-multiplicity distributions were converted to spin distribution by assuming that average spin carried away by each non-statistical γ-ray is 1.6. This value was extracted by looking into the level schemes of the ERs. Corrections due to angular momenta carried by evaporated particles and statistical γ-rays were also incorporated. Using the experimental cross-sections obtained from the earlier experiment, the spin distributions of the CN were obtained. These were compared with spin distribution generated by fitting the experimental cross-sections using CCDEF. It was observed that for the symmetric system, the contribution of the higher partial waves towards fusion goes on decreasing with the increase in energy. For the asymmetric system as well, this effect was visible at the highest energies. These observations are in agreement with the results of the TDHF calculations for the extraction of fusion time scales. These observations were not reflected in the cross-section measurements as cross-sections correspond to the zeroth moment of the spin distribution, so there can be many shapes of the spin distribution, reflecting very different physical processes involved, but may yield the same fusion cross-section. The experimental spin distributions, for $^{32}S + ^{48}Ti$ at E_{lab} = 125 MeV, were give as an input to the PACE code and the α-particle spectrum thus generated was found to be in excellent agreement with experimental spectrum. So we conclude that shape of the spin distribution is a sensitive for the investigation of fusion dynamics.

Future outlook

The spin distribution measurements for the two systems under study indicate that the contribution of higher partial waves for the symmetric system is lowered as compared to the CCDEF calculations at all the energies. For the asymmetric system similar observations were found at higher energies. These observations are supported by the TDHF calculations for the fusion time scales. So we plan to carry out TDHF calculations in a more elaborate manner to account for these observations in a better way. Further, we plan to extend similar studies for the heavier systems for which the evaporation spectra studies have concluded the fusion hindrance of higher partial waves for the symmetric systems.