Abstract

The study of heavy ion (HI) induced reaction dynamics at projectile energy below 8 MeV/nucleon has been topic of considerable interest for last few decades. In general, when two heavy ions are brought in contact, a variety of nuclear reactions may take place at energy near and/or above Coulomb barrier. The HI induced reactions provide a possibility of producing and studying the nuclei with high excitation energy and angular momentum. Enough evidences are available in literature to believe that complete fusion (CF) and incomplete fusion (ICF) are dominant mode of reaction at energy below 8 MeV/nucleon [1-6].

In complete fusion (CF) reaction, two nuclei interact at sufficient projectile energy (near and/or above the coulomb barrier) and at small values of the impact parameter, projectile amalgamates with the target nucleus leading to fully equilibrated 'compound nucleus'(CN), in which all the angular momentum of the system is retained. In CF process, attractive nuclear potential overcomes the sum of repulsive coulomb and centrifugal potentials during projectile-target interaction. This implies the large transmission probability, even for partial waves ($\ell \leq \ell_{crit}$), which involves all the nucleonic degrees-of-freedom of the projectile-target. For the entrance channel angular momentum carried by the system lying in the range $0 \leq \ell \leq \ell_{crit}$, the probability of CF is supposed to be maximum. In CF process, total linear momentum carried by the projectile is given to composite system which recoils in the beam direction and traverse the larger range in the stopping medium. In this process, mass of the composite system is equal to mass of the projectile-target nucleus. At higher angular momentum of the projectile ($\ell > \ell_{crit}$) or relatively higher values of impact parameter, minimum mass overlap between projectile and target nuclei takes place, where incompletely fused composite system is formed as a result of partial linear momentum transfer from projectile to target nucleus. This is referred to ICF reaction mechanism. In case of incomplete fusion (ICF), a part of the projectile fuses with target nucleus while remnant moves with the same beam velocity as that of incident ion beam. It is assumed that un-fused part does not interact with target nucleus and behaves as a spectator. It is obvious from above description that most of the time either α-particle or cluster of α-particles (^{16}O, ^{12}C and ^{8}Be) depending upon incident ion, escapes as unfused spectator. In case of ICF reaction dynamics, an incompletely fused composite system is formed, where partial linear momentum of the projectile is given to the target nucleus and relatively less nucleonic degrees-of-freedom are involved as compared to CF. This incompletely fused composite system having less charge and mass in comparison to completely fuse composite nucleus. The entrance channel angular momentum carried by the projectile $\ell > \ell_{crit}$, upper limit of angular momentum of CN, CF gradually gives the way to ICF, where centrifugal potential increases due to large impact parameter. Under the influence of centrifugal force field, driving angular momentum exceeds its critical limit (ℓ_{crit}) for CF, where attractive nuclear potential is no more strong enough to capture the entire projectile by the target nucleus [4]. The work presented in the thesis is organized into five Chapters.

Chapter 1 introduces the field of nuclear reaction in general, and heavy ion physics in particular and their dependence of impact parameter as well as projectile energy. In this chapter, some important issues related to incomplete fusion (ICF) and their characteristic features have been discussed in detail. Some relevant terminology and brief summary of literature is also presented in this chapter. The present work has been undertaken with the objective to make systematic study related to ICF reaction dynamics at energies near and just above the Coulomb barrier (i.e., 3-8 MeV/nucleon), for different projectile-target system and extracted information of considerable values has been obtained from the three types of measurements like; (i) excitation function measurement; (ii) recoil range distribution measurement; (iii) spin distribution measurement.

In Chapter 2, the information of considerable value has been obtained from the measurement of excitation function of several radio-nuclides populated via CF and/or ICF in three projectile-target systems ^{20}Ne + ^{55}Mn, ^{20}Ne + ^{159}Tb and ^{16}O + ^{156}Gd in the energy range ~3-8 MeV/nucleon. A list of reactions for which excitation functions have been measured is given below:

^{55}Mn(^{20}Ne, p4n)^{70}Se, ^{55}Mn(^{20}Ne, 2pn)^{72}As, ^{55}Mn(^{20}Ne, α)^{71}As,

^{55}Mn(^{20}Ne, αn)^{70}As, ^{55}Mn(^{20}Ne, αpn)^{69}Ge, ^{55}Mn(^{20}Ne, αp3n)^{67}Ge,

^{55}Mn(^{20}Ne, αp4n)^{66}Ge, ^{55}Mn(^{20}Ne, 2α) ^{67}Ga, ^{55}Mn(^{20}Ne, 2αn)^{66}Ga,

^{55}Mn(^{20}Ne, 2α2n)^{65}Ga, ^{55}Mn(^{20}Ne, 2αp3n)^{63}Zn, ^{55}Mn(^{20}Ne, 3α2n)^{61}Cu,

^{55}Mn(^{20}Ne, 3α3n)^{60}Cu, ^{159}Tb(^{20}Ne, p4n) ^{174}W, ^{159}Tb(^{20}Ne, α)^{175}Ta,

^{159}Tb(^{20}Ne, α2n)^{173}Ta, ^{159}Tb(^{20}Ne, α3n)^{172}Ta, ^{159}Tb(^{20}Ne, αpn)^{173}Hf,

^{159}Tb(^{20}Ne, 2αp6n)^{164}Yb ^{159}Tb(^{20}Ne, 3αn)^{166}Tm, ^{159}Tb(^{20}Ne, 3α2n) ^{165}Tm,

^{159}Tb(^{20}Ne, 3α4n)^{163}Tm, ^{159}Tb(^{20}Ne, 3αp5n)^{161}Er, ^{156}Gd(^{16}O, 4n)^{168}Hf,

^{156}Gd(^{16}O, 6n)^{166}Hf, ^{156}Gd(^{16}O, p4n) ^{167}Lu, ^{156}Gd(^{16}O, αn)^{167}Yb,

^{156}Gd(^{16}O, α4n)^{164}Yb, ^{156}Gd(^{16}O, α6n)^{162}Yb, ^{156}Gd(^{16}O, αpn)^{166}Tm,

^{156}Gd(^{16}O, αp2n)^{165}Tm, ^{156}Gd(^{16}O, αp4n)^{163}Tm, ^{156}Gd(^{16}O, αp5n)^{162}Tm^{g},

^{156}Gd(^{16}O, 2α3n)^{161}Er, ^{156}Gd(^{16}O, 2α5n)^{159}Er, ^{156}Gd(^{16}O, 2αpn)^{162}Ho^{m},

^{156}Gd(^{16}O, 2αp4n)^{159}Ho^{g} and ^{156}Gd(^{16}O, 3α3n)^{157}Dy.

Some of the residues are populated both directly and in the decay of the populated pre-cursor isobars. In such cases, independent cross-section have been deduced from the measured cumulative cross-sections, using Cavinato *et al.,* [7] formalism. The experimentally measured independent cross-sections have been compared with the prediction of statistical model code PACE-2 [8]. Sizable enhancement in the measured cross-sections have been observed in case of α-emitting channels over theoretical predictions, which has been attributed to incomplete fusion of the projectile at these energies. Analysis of the experimental data indicates that incomplete fusion is in competition of complete fusion, and is observed the dominant mode of the reaction mechanism at these energies. An attempt has been made to estimate the ICF contribution for individual α-emission products in ^{20}Ne + ^{55}Mn, ^{20}Ne + ^{159}Tb and ^{16}O + ^{156}Gd systems and have been deduced by subtracting the CF-cross-section (obtained from PACE-2) from the measured cross-section at energy range, E ~3-8 MeV/nucleon. Further, fraction of ICF has been deduced and plotted as a function of projectile energy and mass-asymmetry of above studied systems and found that ICF-fraction has been found to be sensitive for projectile energy and is maximum at higher energy. It has also been found that ICF-fraction is sensitive for mass-asymmetry of interacting partners. The present observation thus supports the Morgenstern systematics [9].

Chapter 3 deals with the measurement of recoil range distributions of the ERs produced in 4-8 MeV/nucleon energy. In order to confirm the findings of measurements and analysis of excitation functions (EFs) presented in the Chapter-2, and also to investigate partial linear momentum transfer (LMT) from projectile to target nucleus in ICF reactions, the forward recoil range distributions (FRRDs) of nine ERs; ^{174}W, ^{175}Ta, ^{173}Ta, ^{172}Ta, ^{173}Hf, ^{164}Yb, ^{166}Tm, ^{165}Tm and ^{163}Tm populated in ^{20}Ne + ^{159}Tb system at energy, E ~164 MeV, and eight ERs; ^{168}Hf, ^{167}Lu, ^{167}Yb, ^{162}Yb, ^{165}Tm, ^{163}Tm, ^{159}Ho and ^{157}Dy populate in ^{16}O + ^{156}Gd system at three different energies , E ~ 72, 82 and 93 MeV, have been measured. The above residues are populated through the following reactions:

^{159}Tb(^{20}Ne, p4n)^{174}W,	^{159}Tb(^{20}Ne, α)^{175}Ta,	^{159}Tb(^{20}Ne, α2n)^{173}Ta,
^{159}Tb (^{20}Ne, α3n)^{172}Ta,	^{159}Tb(^{20}Ne, αpn)^{173}Hf,	^{159}Tb(^{20}Ne, 2αp6n)^{164}Yb,
^{159}Tb(^{20}Ne, 3αn)^{166}Tm,	^{159}Tb(^{20}Ne, 3α2n)^{165}Tm,	^{159}Tb(^{20}Ne, 3α4n)^{163}Tm,
^{156}Gd(^{16}O, 4n)^{168}Hf,	^{156}Gd(^{16}O, p4n)^{167}Lu,	^{156}Gd(^{16}O, αn)^{167}Yb,
^{156}Gd(^{16}O, α6n)^{162}Yb,	^{156}Gd(^{16}O, αp2n)^{165}Tm,	^{156}Gd(^{16}O, αp4n)^{163}Tm,

$^{156}Gd(^{16}O, 2\alpha p4n)^{159}Ho^{g}$ and $^{156}Gd(^{16}O, 3\alpha 3n)^{157}Dy$.

It has been observed that some residues have additional peaks in FRRDs at cumulative thicknesses relatively smaller than the expected range of the residues produced via complete fusion (CF). It clearly indicates that peaks appearing at different cumulative thicknesses in the stopping medium are related with different degree of linear momentum transfer from projectile to target nucleus by adopting the break-up fusion model consideration. Different full and partial linear momentum transfer components are possible only when projectile break-up in to their fragments; like projectile i.e., $^{20}Ne \Rightarrow$ ^{16}O + ^{4}He (α) and/or ^{12}C + ^{8}Be (2α) and/or ^{8}Be + ^{12}C (3α) and $^{16}O \Rightarrow$ ^{12}C + ^{4}He (α) and /or ^{8}Be + ^{8}Be (2α) and/or ^{4}He + ^{12}C (3α) fragments, followed by the fusion of one of the fragments with the target nucleus. As such, an attempt has been made to separate out the relative contribution of CF and/or ICF from the analysis of experimentally measured forward recoil range distributions (FRRDs) of the ERs in ^{20}Ne + ^{159}Tb and ^{16}O + ^{156}Gd systems at respective energies. In general, it has been found that the residues are not only populated via CF but ICF also plays an important role at respective projectile energies. An attempt has also been made to validate the experimentally measured forward recoil ranges $R_p(\exp)$ deduced from fitting of experimentally measured FRRD data points. The experimentally measured most probable recoil ranges have been compared with theoretically calculated most probable ranges $R_p(theo)$ for CF and /or ICF component, using range-energy relation for the reaction products produced in the interaction of ^{20}Ne, ^{16}O with ^{159}Tb and ^{156}Gd are found to be in good agreement.

In order to deduce the angular momentum involved in various CF and/or ICF reaction products, spin distribution and side-feeding intensity profiles of eleven radio-nuclides ^{172}Hf, ^{171}Hf, ^{170}Hf, ^{169}Yb, ^{168}Yb, ^{167}Yb, ^{165}Er, ^{164}Er, ^{167}Tm, ^{166}Tm and ^{163}Ho populated via CF and ICF channels in ^{16}O + ^{160}Gd system at projectile energy, E ~ 5.6 MeV/nucleon, have been studied and presented in Chapter 4. On the basis of the results presented in this chapter, spin distribution of ICF products (ICF- α and 2α-emission in forward direction) are found to be distinctly different than that observed from CF products (CF-xn and α and 2α-emission in backward direction), which indicates entirely different de-excitation patterns in CF and ICF products towards band head. For the ICF products, yields are found to almost constant up to certain angular momentum and then decreases with transition spin, while for CF products, yields decreases exponentially with transition spin. It clearly indicates that significant side-feeding takes place in broad spin range in case of CF products, while narrow spin population arises in case of ICF products (low spin states are strongly hindered), where projectile like fragments (PLFs) are emitted to release excess angular momentum. It is concluded that in ICF-products, mean input angular momentum increases with fusion incompleteness as compared to CF-products. The present observation clearly indicates that production of fast α-particles arises from relatively high angular momentum, which leads to peripheral interaction.

In chapter 5, summary and conclusion drawn from the present work has been presented and references are given at the end of each chapter.

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