

Investigating entrance channel influences in the fusion of some heavy-ion systems

Abstract

The dynamics of heavy-ion fusion reaction involved in the interaction of ^{12}C , ^{14}N and ^{16}O projectiles with, ^{59}Co , ^{51}V , ^{128}Te and ^{165}Ho targets at $\approx 3\text{--}8\text{ MeV/nucleon}$ specific energies was studied. This study focus on the correlation between entrance channel properties and incomplete fusion reaction. The experimentally measured excitation functions of various reaction products populated by complete and/or incomplete fusions of $^{12}\text{C}+^{59}\text{Co}$, ^{128}Te , $^{14}\text{N}+^{128}\text{Te}$ and $^{16}\text{O}+^{51}\text{V}$, ^{165}Ho projectile-target systems available in the literature. Were compared and analyzed with the predicted excitation functions, using the statistical model code PACE4. For representative non- α -emitting channels, the experimentally measured excitation functions were, in general, found to be in good agreement with the theoretical predictions. However, for α -emitting channels in the present systems, the measured excitation functions were higher than the predictions of the theoretical model code, which may be credited to incomplete fusion reactions at these energies. An attempt was made to approximate the incomplete fusion fraction that explains the relative importance of incomplete fusion processes. The incomplete fusion fraction was found to be sensitive to the projectile energy and mass-asymmetry of the entrance channel.

Keywords: alpha emitted, CF reaction, entrance channel, heavy-ion fusion, ICF reaction, non-alpha emitted

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Introduction

The atomic nuclei consist of proton and neutron and have complicated static and dynamic property.¹ Extensively experimentally and theoretical effort over the past century have explained many of the nuclear properties but in spite of these efforts there are still many unresolved problems that motivate further studies. A common method of gaining information about the nuclear property is to perform nuclear reaction (scattering) experiments in which different observable of scattered particles and residue nuclei are measured. A nuclear reaction is considered to be the process in which two nuclear particles (two nuclei or a nucleus and a nucleon) interact to produce two or more nuclear particles (nuclei) and/or γ -rays. Nuclear Physics studies the dynamics of heavy-ion collisions and the structure of nuclei far from stability. Hence the collision of two nuclei give place to nuclear reaction and similarly to chemical reaction and the final products can be different from the initial one. This process happens when a target is bombarded by particles coming from an accelerator or a radioactive substance.² Nowadays, the study of heavy-ion fusion is of special interest in nuclear physics and still attracts the attention of both experimentalist and theorists.³ In such reaction, after overcoming the Coulomb barrier, projectile and target nuclei stick together to form an intermediate state compound nucleus (CN). It is also known that plays a special role in the so-called fusion evaporation reaction that leads to the formation of heavy or super-heavy elements. However, for systems with charge products $Z_p Z_t \geq 1600\text{--}1800$, a second barrier or an inner barrier appears and heavy-ion is thus considerably hindered. In that case, additional energy is needed to form CN in the fusion reactions. Heavy-ion physics is concerned with the reactions induced by nuclear projectiles whose mass number A is greater than 4.⁴

Recent studies show that there are different reaction mechanism in heavy-ion reaction at energies around Coulomb barrier to well above depending upon the time at which they occur the nuclear reaction is

classified as, direct, compound nucleus and pre-equilibrium reaction. Thus, the study of heavy-ion interactions is quite specific due to its complex structure and large momentum carried, and heavy-ion interactions may be categorized in many ways, one of them is in terms of impact parameter. The direct reactions play an important role at higher values of impact parameter, leading to few nucleon transfer processes. However, at smaller values, complete fusion (CF) reaction in which Projectile is completely fused with the target nucleus and highly excited compound nucleus decays by evaporating low-energy nucleons and α particles, incomplete fusion (ICF) in which only a part of the projectile fuses with the target nucleus, leading to the formation of an excited incompletely fused composite system with a mass and/or charge lower than that of the CN, while the remaining part escapes in forward cone with approximately the beam velocity.⁵ Various dynamical models, such as Sum rule model,⁶ break-up fusion (BUF) model⁷ and promptly emitted particle model⁸ have been proposed to explain the mechanism of ICF reactions. However, no theoretical model is available so far fully to explain the gross features of experimental data available below $E/A=10$ MeV/nucleon. And none of the proposed models can reproduce the experimental data obtained at energies as low as $\approx 4\text{--}8$ MeV/nucleon. Recent experimental studies have been shown that significant ICF contribution even at energies just above the Coulomb barrier. The finding have inspired many researchers in the field to investigate ICF at relatively low bombarding energies. Suprnasody et al.,⁹ investigated the effect of entrance channel parameters on the fusion of $^{16}\text{O}+^{66}\text{Zn}$ and $^{37}\text{Cl}+^{45}\text{Sc}$ system.

The contribution of non-compound processes like transfer and incomplete fusion (ICF) reactions to the cross-sections of different evaporation residues were deduced from the experimental value using the statistical model code PACE2. And the results showed that non-compound processes become a significant fraction of the total reaction cross-section in $^{16}\text{O}+^{66}\text{Zn}$ systems, while $^{37}\text{Cl}+^{45}\text{Sc}$ gives mainly compound nucleus products. Further, the result indicated

that the contributions of non-compound processes are more in mass-asymmetric system. Abhishek et al.,¹⁰ studied the effect of entrance channel properties in the incomplete fusion of ¹²C+ ¹⁵⁹Tb at energies ≈4- 7MeV/ A. The results indicated that incomplete fusion contribution found to be sensitive to the projectile type, energy, and entrance channel mass-asymmetry. Pushpendra et al.,¹¹ studied the dynamics of incomplete fusion by the spin distribution of ¹⁶O +¹⁶⁹Tm system at ≈5.6 MeV/nucleon. The result showed that the measured normalized production yields of fusion-evaporation xn/αxn-channels in good agreement with the predictions of theoretical model code PACE4. Further, the study indicated that residues from the complete fusion process are strongly fed over a broad spin range, while residues from incomplete fusion process are found to be less fed and/or the populations of lower spin states are strongly hindered.

Recently, Amanuel et al.,¹² studied the suppression of complete fusion process by incompletely fused ¹²C projectile on different targets. It was found that the contribution ICF reaction more in mass-asymmetric systems. Further, the observation of high ICF fraction is attributable to the prompt breakup of the projectile into α-clusters wherein the projectile ¹²C breaks up into, ⁸Be + ⁴He and/or ⁴He + ⁴He leading to an ICF reaction. It was found that the probability of breakup increases with an increase in the incident projectile energy. Thus, it may be inferred that, in general, the ICF fraction is sensitive to the incident projectile energy and mass-asymmetry of the entrance channel. These finding have motivated many to investigate ICF at relatively low bombarding energies. However, clear and robust modeling of ICF processes are still lacking, especially at ≈4-8MeV/nucleon, where a clear systematic study and compiled data are available for only a few projectile-target combinations. The present thesis deals with investigation of incomplete fusion reaction and entrance channel effect in the interaction of ¹²C +⁵⁹Co, ¹²C + ¹²⁸Te, ¹⁴N +¹²⁸Te and ¹⁶O + ⁵¹V and ¹⁶O +¹⁶⁵Ho systems at ≈3-8 MeV/nucleon. For predictions of the measured excitation functions available in the literature,¹⁴⁻¹⁶ the theoretical model code PACE4 will be used at 100000 cascades and the Morgenstern et al.,¹³ systematic used to separate ICF contribution.

Formulations and computer code

There are different computer codes to calculate the theoretical excitation functions. Those are PACE4, CASCADE, ALIC-91 AND COMPLET codes. However, PACE4 predictions were found to be in good agreement for complete fusion channels for the present projectile-target system. And analysis with computer code PACE4 within the consideration of Hauser-Feshbach formulation also discussed in this section.¹⁰

PACE4 code

An analysis of experimentally measured excitation functions was also made using the theoretical predictions of the PACE4 code. The code PACE4 is based on Hauser Feshbach theory for CN-decay and uses a statistical approach of CN de-excitation by Monte Carlo procedure. The code uses the BASS model for CF cross-section calculation. The default optical model parameters for neutrons, protons, and α-particles are used. Besides code has been modified to take into account the excitation energy dependence of the level density parameter using the prescription Kataria et al.¹⁶ It should be pointed out that the ICF and PE-emission are not taken into consideration in this code. The process of de-excitation of the excited nuclei was calculated using code PACE4 which follows the correct procedure for angular momentum coupling at each stage of de-excitation. The

code PACE4 used as Monte-Carlo procedure to determine the decay of sequence of an excited nucleus using formalism. To compare the measured EF's with theoretical predication obtained from PACE4 for possible residues populated in reaction. Cross-section is deduced using Morgenstra approach¹³

$$\sum \delta_{CF}^{(Theo)} = \sum \delta_{non\alpha - emit}^{(exp)} + \sum \delta_{\alpha - emit}^{(theo)} \dots\dots\dots (1)$$

$$\delta_{TF}^{(exp)} = \sum \delta_{CF}^{(theo)} + \sum \delta_{ICF} \dots\dots\dots (2)$$

From this cross-section of ICF

$$\sum \delta_{ICF} = \delta_{TF}^{(exp)} - \sum \delta_{CF}^{(Theo)} \dots\dots\dots (3)$$

The ICF fraction which tells the contribution of ICF in the total process is calculated

$$P_{ICF} (\%) = \frac{\sum \delta_{ICF}}{\delta_{TF}} \times 100 \dots\dots\dots (4)$$

To see the correlations between the deduced incomplete fusion fraction and entrance channel properties (normalized projectile energy, mass-asymmetry, and projectile structure) instead of projectile energy (Ep) we used the normalized projectile energy (Ep/VCB) that swallowed the effect coming from different coulomb barrier.

$$V_{CB} = \left[\frac{Z_p Z_T}{\frac{1}{A_p^3} + \frac{1}{A_T^3}} \right] \dots\dots\dots (5)$$

To see the correlation between P_{ICF} with normalized projectile velocity (Vrel/c)

$$V_{rel} = \sqrt{\frac{2(E_{cm} - V_{CB})}{\mu_A}} \dots\dots\dots (6)$$

Where $\mu_A = \frac{A_p A_T}{A_T + A_p}$ And $E_{cm} = \frac{A_T}{A_T + A_p} E_{lab}$

The ICF fraction which tells the contribution of ICF in the total process is calculated

Results and discussion

The EFs ¹²C +⁵⁹Co, ¹²⁸Te, ¹⁴N+¹²⁸Te and ¹⁶O+⁵¹V, ¹⁶O+¹⁶⁵Ho systems were evaluated and analyzed using predictions of the statistical model code PACE4 . In this code the value of level density parameter, a, which is an important parameter largely affects the equilibrium component of a cross-section is evaluated by, $a = A / KMeV^{-1}$ where A is the nucleon number of a CN and K is an adjustable parameter, which can be tuned to fit the experimental data. The measured EFs were compared with the predictions of PACE4 using different level density parameter values for residues populated via CF and/or ICF processes.^{10,12}

Systems with I6O projectile

¹⁶O+¹⁶⁵Ho system

The measured excitation functions and the theoretical predictions obtained from PACE4 for ¹⁷⁶Re residue populated via (¹⁶O, 5n) channel

is shown in Figure 1a. Obviously in this channel, there is no likelihood of ICF reaction, and therefore, this channel is populated only by the CF process. It may be observed from Figure 1a that the theoretically calculated excitation functions for the level density parameter $K = 12$, in general, reproduced satisfactorily the experimentally measured excitation functions for the residue ^{178}Re produced in the CF ^{16}O projectile with ^{165}Ho target. The fact that the measured CF cross-sections for a representative non- α -emitting (non- α -emit) channels in system, $^{16}\text{O} + ^{165}\text{Ho}$, could be reproduced satisfactorily by PACE4 predictions, gives confidence in the input parameters chosen to fit the EFs of all other non- α and α - emitting channels considered in the $^{16}\text{O} + ^{165}\text{Ho}$ system. Figure 1b displayed the measured cross-sections for the representative ($^{16}\text{O}, \alpha 3n$) channel. Note that in the case of ($^{16}\text{O}, \alpha 3n$) channels, the residues may be formed by two different processes:

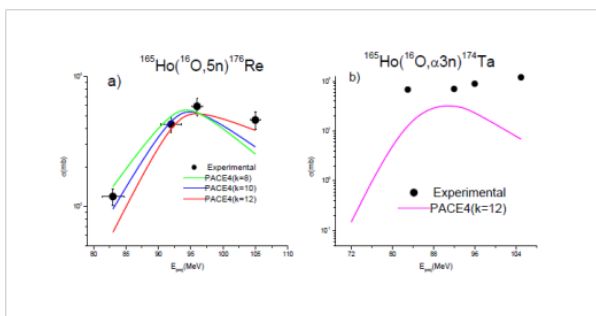
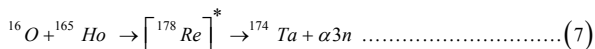
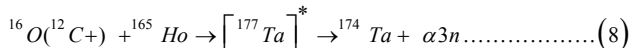


Figure 1 Sum of measured EFs for all CF channels along with PACE 4 calculations for ($^{16}\text{O}, 5n$) and (b) alpha-emitted channels ($^{16}\text{O}, \alpha 3n$) system.

i) Complete fusion of ^{16}O , i.e.,



ii) Incomplete fusion of ^{16}O , i.e.,



(α -as spectator)

As can be seen from Figure 1b the experimentally measured EFs are relatively higher as compared to the theoretical predictions. Since the code PACE4 doesn't take ICF into account, therefore the enhancement in the experimentally measured cross-sections are attributable to the contributions of ICF of ^{16}O with ^{165}Ho target.

For $^{16}\text{O} + ^{51}\text{V}$ system

Similarly, in $^{16}\text{O} + ^{51}\text{V}$ system values of the level density parameter ($K=8, 10, 12$) were varied to fit to the experimentally measured EFs for a representative non- α -emitting ($^{16}\text{O}, p4n$) channel. Figure 2a displayed the experimentally measured and theoretically calculated EFs for ^{62}Zn residue populated via ($^{16}\text{O}, p4n$) channel. In this channel also there is no likelihood of ICF reaction occurring and therefore, this channel is populated only by CF process. As can be seen from this figure, the PACE4 prediction with $K=10$, in general, reproduced satisfactorily the experimentally measured EFs. For all possible channels in the interaction $^{16}\text{O} + ^{51}\text{V}$ system, all calculations and analysis were done consistently using $K=10$. The measured EFs along with the PACE4 prediction for representative residue populated via α -emitting channel is shown in Figure 2b. A representative ^{54}Mn residue may be populated through CF and/or ICF processes as:

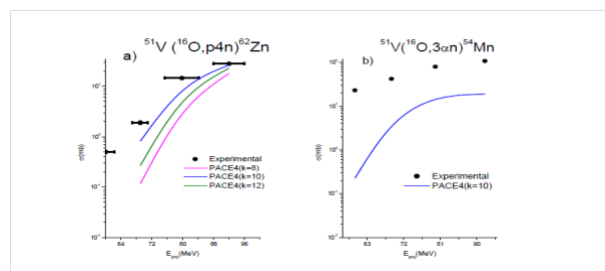
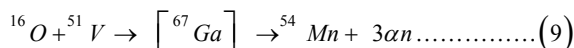
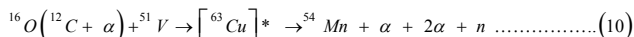


Figure 2 measured EFs for ($^{16}\text{O}, p4n$) channels along with PACE4 prediction and (b) alpha emitted channels for ($^{16}\text{O}, \alpha 3n$) system.

i) Complete fusion of ^{16}O , i.e.,



ii) Incomplete fusion of ^{16}O , i.e.,



(α -as spectator)

System with ^{12}C projectile

$^{12}\text{C} + ^{128}\text{Te}$ system

In this system also values of the level density parameter ($K=8, 10, 12$), were varied to fit to the experimentally measured EFs for a representative non- α -emitting ($^{12}\text{C}, 5n$) channel, in this channel also there is no likelihood of ICF reaction occurring and therefore, this channel is populated only by CF process. As can be seen from Figure 3a the PACE4 prediction with $K=10$, in general, reproduced satisfactorily the experimentally measured EFs. For all possible channels in the interaction $^{12}\text{C} + ^{128}\text{Te}$ system, all calculations and analysis were done consistently using $K=10$. The measured EFs along with the PACE4 prediction for representative residue populated via α -emitting channel is shown in Figure 3b. A representative ^{131}Ba residue may be populated through CF and/or ICF processes as:

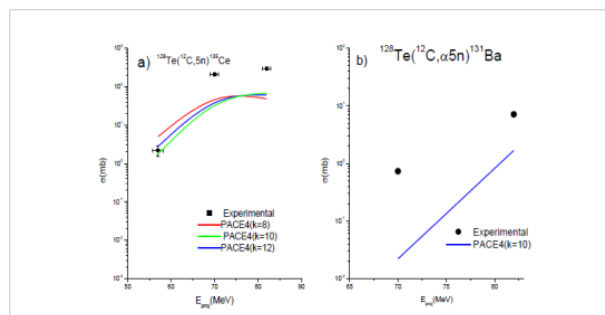
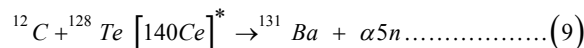
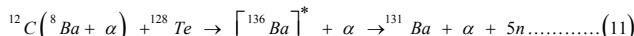


Figure 3 non- α - emitted channels for ($^{12}\text{C}, 5n$) and (b) alpha emitted channels for ($^{12}\text{C}, \alpha 5n$).

i) Complete fusion of ^{12}C , i.e.,



ii) Incomplete fusion of ^{12}C , i.e.,



(α -as spectator)

12C+ 59Co system

Values of the level density parameter (K= 8, 10, 12) were varied to fit to the experimentally measured EFs for a representative non- α - emitting channel, (^{12}C , 2p2n) in this channel also there is no likelihood of ICF reaction occurring and therefore, this channel is populated only by CF process. As can be seen from this Figure 4a the PACE4 prediction with K=10, in general, reproduced satisfactorily the experimentally measured EFs. For all other possible channels populated in the interaction $^{12}\text{C} + ^{59}\text{Co}$ system, all calculations and analysis were done consistently using K=10. The measured EFs along with the PACE4 prediction for representative residue populated via α -emitting channel is shown in Figure 4b. A representative ^{65}Ga residue may be populated through CF and/or ICF processes as:

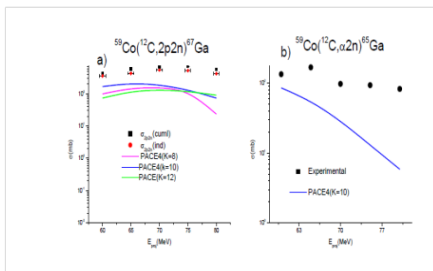
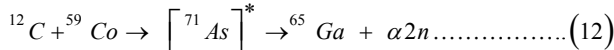
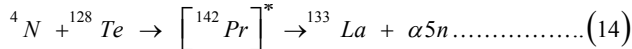


Figure 4 (a) measured EFs for (^{12}C , 2p2n) channels along with PACE4 prediction and (b) alpha emitted channels for (^{12}C , $\alpha 2n$) system.)

i) Complete fusion of ^{12}C , i.e.,



ii) Incomplete fusion of ^{12}C , i.e.,



(α -as spectators).

System with 14N projectile

14N + 128Te system

In $^{14}\text{N} + ^{128}\text{Te}$ system the values of the level density parameter (K=8, 10, 12) were varied to fit to the experimentally measured EFs for a representative of α emitting, (^{14}N , 4n) channel. In this channel also there is no likelihood of ICF reaction occurring and therefore, this channel is populated only by CF process. As can be seen from this Figure 5a the PACE4 prediction with K = 12, in general, reproduced satisfactorily the experimentally measured EFs. For all possible channels in the interaction $^{14}\text{N} + ^{128}\text{Te}$ system, all calculations and analysis were done consistently using K = 12. The measured EFs along with the PACE4 prediction for representative residue populated via α -emitting channel is shown in Figure 5b. A representative ^{133}La residue may be populated through CF and/or ICF processes as:

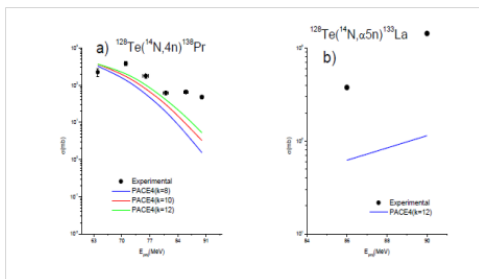
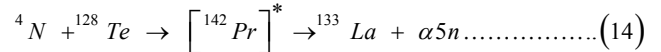
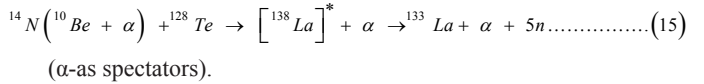


Figure 5 (a) non -alpha contaminated channels (^{14}N , 4n) vs projectile energy and (b) alpha contaminated channel vs projectile energy (^{14}N , $\alpha 5n$).

i) Complete fusion of ^{14}N , i.e.,



ii) Incomplete fusion of ^{14}N , i.e.,



Incomplete fusion contributions

In this section, an attempt has been made to separate the contributions of ICF in all α -emitting channels populated in the interactions of a ^{12}C , ^{14}N and ^{16}O projectiles with ^{59}Co , ^{128}Te , ^{51}V and ^{165}Ho targets. The sum of the ICF cross-section for the respective systems $\sum \delta_{\text{ICF}}$, was assigned to the difference between the higher charged isobaric precursor decay corrected measured cross-section for possible α -emitting channels, $\sum \delta\alpha^{(\text{exp})}$ and the calculated cross-section $\sum \delta\alpha^{(\text{theo})}$ for best fitted K value. It is clearly seen in Figure 6 from (a) to (e) that ICF production cross-section $\delta_{\text{ICF}} = \sum \delta\alpha^{(\text{theo})} - \sum \delta\alpha^{(\text{exp})}$ increase significantly with an increase in beam energy

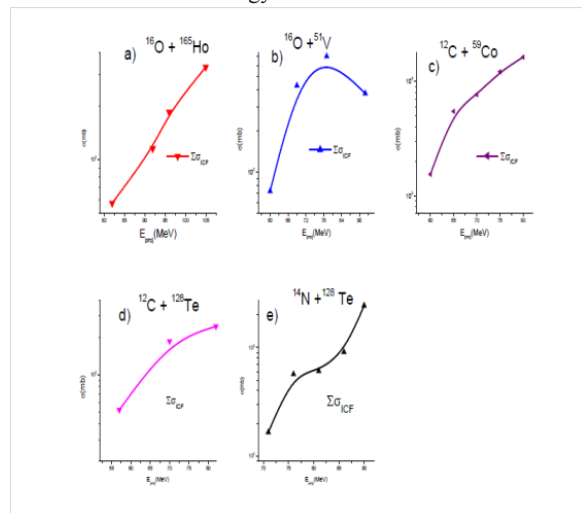


Figure 6 $\sum \delta_{\text{ICF}}$ versus Eproj. It has been mentioned that all the α -emitting channels identified in the present systems are expected to have significant contributions from ICF reactions.

Figure 7 (a) to (e) displayed the sum of contributions coming from all ICF channels $\sum \delta_{\text{ICF}}$ and the sum of all CF channels $\sum \delta_{\text{CF}}$ were plotted along with the total fusion cross-section $\sigma_{\text{TF}} = \sum \delta_{\text{ICF}} + \sum \delta_{\text{CF}}$ for all α and non- α emitting channels in $^{12}\text{C} + ^{59}\text{Co}$, ^{128}Te and $^{16}\text{O} + ^{51}\text{V}$, ^{165}Ho systems. As can be observed from these figure the CF components have dominant contribution up to $\approx 70\text{MeV}$, $\approx 73\text{MeV}$, $\approx 72\text{MeV}$, and $\approx 75\text{MeV}$ for $^{16}\text{O} + ^{51}\text{V}$, $^{14}\text{N} + ^{128}\text{Te}$, $^{12}\text{C} + ^{59}\text{Co}$ and $^{12}\text{C} + ^{128}\text{Te}$ systems, respectively, while ICF contribution seems start to influence from these points

Further, except for $^{16}\text{O} + ^{165}\text{Ho}$ system it is clearly seen from these figures that the separation between the plots of $\sum \delta_{\text{ICF}}$ and $\sum \sigma_{\text{TF}}$ in general decreases significantly from these points onwards with an increase in projectile energy, which indicates that the ICF contribution becomes larger at higher energy points in the respective systems. This may be due to an increase in the probability of projectile break up into α -clusters $^{16}\text{O} (^{12}\text{C} + \alpha \rightarrow ^8\text{Be} + \alpha + \alpha \rightarrow \alpha + \alpha + \alpha)$, $^{14}\text{N} (^{10}\text{B} + \alpha)$ and $^{12}\text{C} (^8\text{Be} + \alpha \rightarrow \alpha + \alpha + \alpha)$ as the projectile energy increases.

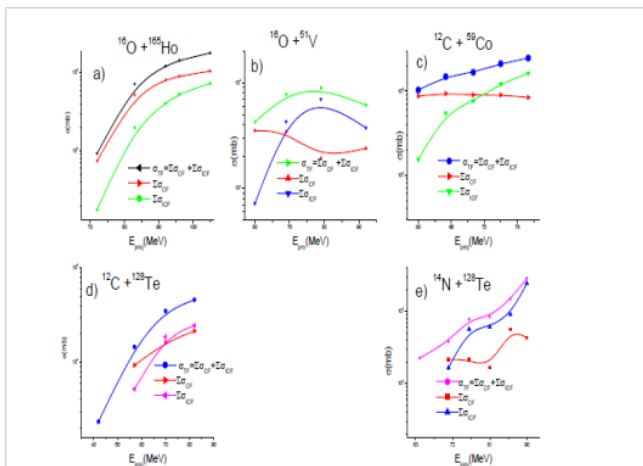


Figure 7 The total sum of the measured, σ_{TF} and the total sum of the CF cross-sections, $\sum \delta_{CF}$ along with the total sum of ICF cross-sections, $\sum \delta_{ICF}$ at various energies.

Incomplete fusion fraction

To study the dependence of ICF contribution on various entrance channel parameters, the percentage ICF fraction (FICF) is evaluated using the relation,

$$P_{ICF}(\%) = \frac{\sum \delta_{ICF}}{\delta_{TF}} \times 100 \dots \dots \dots (16)$$

Figure 8 Displayed the graph of the calculated FICF values as a function of normalized projectile energy, (E_{proj}/V_{CB}), for presently studied systems

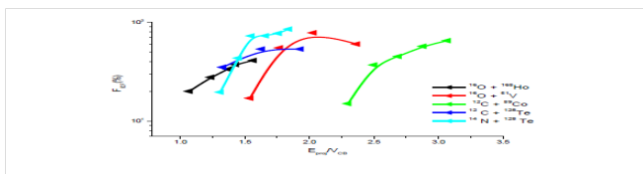


Figure 8 FICF values as a function of normalized projectile energy. It may be observed from this figure the incomplete fusion fraction (FICF) which represents a part of ICF contribution to all fusion processes, for all systems except $^{16}\text{O}+^{51}\text{V}$ in general smoothly increases with the increase in normalized projectile energy.

To investigate the dependence of FICF on entrance channel mass-asymmetry ($M_a = \frac{A_T}{A_T + A_P}$), the incomplete fusion fraction, PICF is plotted in Figure 9 as a function of normalized relative velocity (V_{rel}/c) for presently studied systems V_{rel} is expressed as:

$$V_{rel} = \sqrt{\frac{2(E_{cm} - V_{CB})}{\mu}} \dots \dots \dots (17)$$

μ is the reduced mass of the entrance channel.

$$V_{rel} = \sqrt{\frac{2(E_{cm} - V_{CB})}{\mu}}$$

As can be seen from Figure 9 in general, for an approximately equal value of V_{rel}/c (vertical lines) the value of FICF is higher for mass-asymmetric system than symmetric. It may further, however,

pointed out that the probability of ICF is more in mass asymmetric than mass symmetric system, which is consistent with the systematic Morgenstern et al.¹³

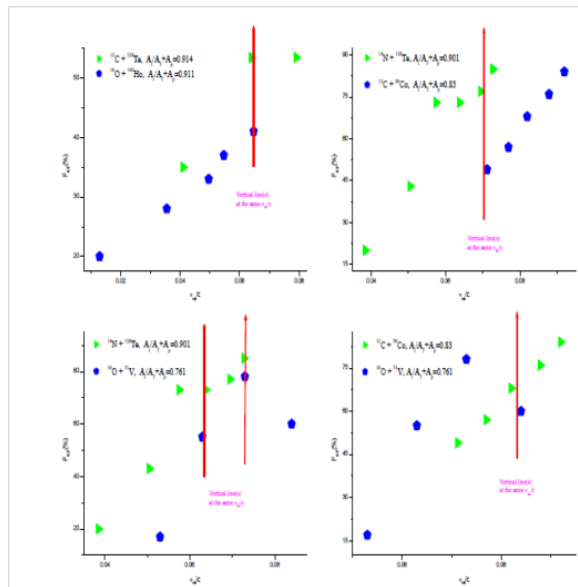


Figure 9 ICF fraction as a function of normalized relative velocity.

Conclusion

In this study the excitation functions of residues produced in the interaction of $^{12}\text{C}+^{59}\text{Co}$, ^{128}Te , $^{14}\text{N}+^{128}\text{Te}$ and $^{16}\text{O}+^{51}\text{V}$, $^{16}\text{O}+^{16}\text{Ho}$ system were investigated at $\approx 3-8$ MeV/nucleon to probe the correlation between entrance channel properties and incomplete fusion reaction. The measured data available in the literature [14-18] were compared with the calculation done using the statistical model code PACE4. For representative non- α -emitting channel from the respective systems, the experimentally measured excitation functions, after correcting them for possible contributions from higher charge isobaric precursor decays, were in general found to be in good agreement with theoretical predictions. However, for α -emitting channels, the measured excitation functions after correcting the HCIP contribution (if any) were significantly higher than the values predicted by PACE4. These enhancements may be attributable to processes from break-up effect. For $^{16}\text{O}+^{16}\text{Ho}$ system, the estimated ICF fraction was found to be less than, 20.2% at the starting point (≈ 72.9 MeV), but at the highest energy point (≈ 105 MeV) it reached approximately, 41% of the total fusion cross-section. However, the ICF fraction was found to be approximately, 17.3%, 15%, 0% and 19.5% of the total cross-section at the starting point of ICF influence and reached $\approx 60\%$, $\approx 65\%$, $\approx 53.42\%$ and $\approx 84.9\%$, at the highest energy point for $^{12}\text{C}+^{59}\text{Co}$, ^{128}Te , $^{14}\text{N}+^{128}\text{Te}$ and $^{16}\text{O}+^{51}\text{V}$, systems, respectively.

From the present investigation, it is found that the fraction of ICF increase with the increase in beam energy. Further, it may be pointed out that ICF fraction is found to be more in mass-asymmetric systems than mass-symmetric systems. Thus, it may be inferred that, in general, the ICF fraction is sensitive to the incident projectile energy and mass-asymmetry of the entrance channel. Moreover, the observation of high ICF fraction is attributable to the prompt breakup of the projectile into α -clusters where in the projectile, breaks up into

^{12}C ($^8\text{Be} + ^4\text{He}$), ^{14}N ($^{10}\text{B} + ^4\text{He}$) and/or ^{12}C ($^4\text{He} + ^4\text{He} + ^4\text{He}$) leading to an ICF reaction. The present observations are thus in agreement with the Morgenstern systematic.¹³

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Conflict of interest

The author declare that no conflict of interest.

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