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Dependence of low energy incomplete fusion on projectile's α-Q-value

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Abstract. An attempt has been made to understand the effect of entrance-channel parameters on low-energy incomplete fusion and a strong projectile dependence in terms of projectile's α-Q-value has been observed. In the present work, the excitation functions of ^{16}O,$^{13,12}C$+^{159}Tb systems have been measured and compared with PACE4 predictions to study the involvement of different reaction processes. The strength of incomplete fusion reactions for all the studied systems have been extraced and compared to find out the systematics.

1 Introduction

During the last couple of decades, with the observation of incomplete fusion (ICF) reactions at low energies ≈ 4-7 MeV/nucleon[1], considerable efforts are being employed to look for the systematics of ICF reactions at these energies, where complete fusion (CF) is supposed to be the sole contributor to the total fusion cross-section [2, 3]. The ICF reactions comes into picture with the first experimental observation of "fast α-particles" at energies ≈ 10.5 MeV/nucleon [4] and soon after it variety of experimental & theoretical studies have been devoted to understand the ICF-reactions [1–3, 5, 6]. Some of these studies are summarized in a review article by Gerschel [7], where the localization of the entrance channel angular momentum window with target deformation has been studied. In general, the CF and ICF-reactions are categorized on the basis of driving angular momenta (ℓ-values) [8]. For central and/or near-central interactions, ℓ-values are ranging from 0 to ℓ_{crit}, the CF is expected to be the dominant process, where a composite nucleus is formed with the intimate contact of transient amalgamation of the projectile and target nuclei. Such a composite nucleus may either last for a long time to become a compound nucleus, or disrupted into two fragments known as fission fragments after a short life-time as equilibrium is not entirely achieved, particularly in the shape of the system. However, for ICF-reactions there is no definitive amalgamation between the projectile and target nuclei and these processes favour at peripheral collisions or at sufficiently higher energies for which the ℓ-values will be higher than ℓ_{crit}, and the fusion of entire projectile is hindered and gives way to the ICF. Thus the composite system formed have less mass/charge and excitation energy (due to partial fusion of projectile), but have high angular-momenta (imparted due to non-central/peripheral interactions) as compared to the CN formed via CF [9, 10]. The important characteristics of the ICF-reactions are; (*i*) enhancement in the fusion cross-section for α-emitting channels [1], (*ii*) fractional linear momentum transfer [11], (*iii*) entirely distinct spin distribution patterns for CF and ICF-residues [9], etc. The additional break-up degrees of freedom make the fusion process more complicated and the possible reaction processes may be; *i*) the non-capture break-up, when none of the breakup fragments is captured, *ii*) ICF, when one of the breakup fragments is captured, *iii*) sequential complete fusion (SCF), the successive capture of all fragments by the target nucleus. Experimentally, it is not possible to disentangle the cross-sections for direct (σ_{DCF}) and sequential (σ_{SCF}) complete fusion, because both channels lead to the same final reaction residues. Hence, the CF cross-section (σ_{CF}) is taken as the sum of σ_{DCF} and σ_{SCF}, whereas the sum of σ_{CF} and incomplete fusion cross-section (σ_{ICF}) may be referred to as the total fusion cross-section ($\sigma_{TF} = \sigma_{CF}+\sigma_{ICF}$) [6].

Further, it may be pointed out that the existing models/theories fairly explain ICF data obtained at energies E ≥ 10.5 MeV/nucleon or so, but there is no theoretical model available to predict ICF at lower energies [1–3]. Apart from this, several contradicting dependences of the fraction of incomplete fusion (F_{ICF}), which is a measure of relative strength of ICF to the total fusion, have been discussed in recent reports [6, 12–16]. In refs. [12, 13] it has been reported that the F_{ICF} is independent of the tar-

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get charge (Z_T). However, Gomes *et al.* [6] found a trend of systematic behavior for the F_{ICF} as a function of the Z_T. Morgenstern et al. [16] correlated the ICF fraction with entrance channel mass asymmetry (μ_A). Recently, Singh et al. [1] has modified the Morgenstern's mass-asymmetry systematics by introducing the importance of projectile structure through the ProMass-systematics. Apart from this, one of our recent works [14] reported the dependence of F_{ICF} on the target mass or $Z_P \cdot Z_T$ of interacting partners for a wide range of projectile-target combinations.

Due to unavailability of reliable theoretical model and the presence of contradicting dependences of low-energy ICF reactions on entrance-channel parameters, the study of these reactions is still an active area of investigation. In recent years, the study of ICF at near barrier energies gained interest to correlate the onset of ICF with entrance channel parameters and to look for the general systematics. As such, we have undertaken a programme to measure the excitation functions for different projectile-target combinations at low energies. In order to explore the low-energy incomplete fusion and to find a consistent general systematics for low energy ICF reactions, the measurements of excitation function for $^{16}O,^{13,12}C+^{159}Tb$ systems at energies ≈ 4-7MeV/nucleon have been performed and compared. The present paper is organized as follows; section-2 deals with the experimental details and methodology, section-3 with analysis and interpretation of resuts, however, comment on the projectile effect on ICF-reactions are given in section-4.

2 Experimental methodology

In order to ascertain some of above aspects, experiments have been performed by our group at the Inter-University Accelerator Centre (IUAC), New Delhi to measure "*the excitation functions*" of radio-nuclides populated during the interaction of $^{16}O,^{13,12}C+^{159}Tb$ systems at energies ≈ 4-7MeV/nucleon. Here, brief experimental details are given for the ready reference; however, the details are given in refs [1, 14, 15]. In these experiments the activation technique followed by off-line γ-ray spectroscopy has been used. Natural ^{159}Tb targets (t_m ≈1.2–2.5mg/cm^2) and Al-catcher foils (t_m ≈ 1.5–2.8 mg/cm^2) were prepared by rolling technique. Each target was backed by an Al foil of appropriate thickness (hereafter called the target-catcher foil assembly) to stop heavy recoiling products produced in the reactions. To cover a wide energy range in the limited beam time, a stacked-foil energy degradation procedure was used. The irradiation of the samples have been carried out in the General Purpose Scattering Chamber having an in-vacuum transfer facility, which has been used to minimize the lapse time between the stop of the irradiation and beginning of the counting of the activity induced in the target-catcher assembly. Considering the half-lives of interest, the irradiations have been carried out for ≈ 8–10 h duration for each stack. A Faraday cup has been installed behind the target-catcher foil assembly to measure the beam current. Constant beam current has been maintained during all irradiations. The activities in-

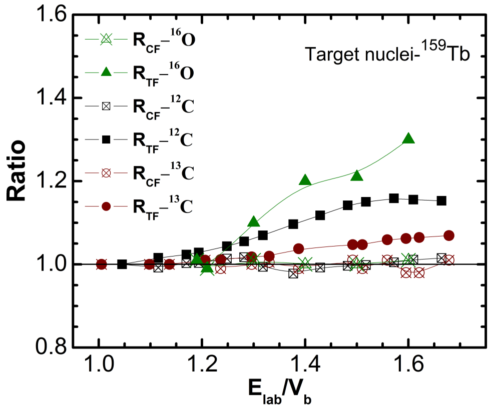

Figure 1. The comparison of experimentally measured and theoretically calculated cross-sections for $^{16}O,^{13,12}C+^{159}Tb$ systems have been shown in the form of ratios $R_{CF}=\Sigma\sigma_{CF}^{expt}/\Sigma\sigma_{CF}^{pace4}$ and $R_{TF}=\Sigma\sigma_{TF}^{expt}/\Sigma\sigma_{TF}^{pace4}$ (for details see the text).

duced in the target-catcher foil assemblies were recorded by counting each target along with the catcher foil, using a pre-calibrated high resolution HPGe γ-ray detector coupled to a CAMAC based data acquisition system CANDLE [17]. The efficiency calibration of the detector in the specified geometry was carried out using a standard ^{152}Eu source of known strength at various source (target-catcher foil assembly)-detector separations to wash out the solid angle effect. The energy resolution of the detector has been estimated ≈2.5 keV for 1408 keV γ-line of ^{152}Eu source. A 50 Hz pulser was used to determine the dead time of the detector. The source-detector separation has been adjusted to keep the dead-time below 10% during the counting so as to minimize the pile up effects. The characteristic γ-lines have been used to identify reaction products. Further, the decay curves of the identified reaction products have also been analyzed to confirm the identification. Nuclear data on radio-nuclides, such as the corresponding γ-ray abundances and half-lives were taken from ref [18]. The production cross sections of the reaction products have been determined using the standard formulation [1]. It may be pointed out that the errors in the measured production cross sections may arise due to (*i*) the non-uniformity of target/catcher foils, (*ii*) fluctuations in the beam current, (*iii*) the uncertainty in geometry dependent efficiency of HPGe detector, and (*iv*) due to the dead time of the spectrometer. Detailed discussion on the error analysis is given elsewhere [5, 6]. The overall errors including statistical errors are estimated to be ≤15%, excluding the uncertainty in branching ratio, decay constant, etc.

3 Results & their interpretation

To understand the formation mechanism of reaction products during the interaction, the experimentally measured excitation functions of $^{16}O,^{13,12}C+^{159}Tb$ systems at energies ≈ 4-7MeV/nucleon have been analyzed within the framework of statistical model code PACE4 [19, 20], which is based on the equilibrated compound nucleus (CN)-decay of Hauser-Feshbach theory. It may, however, be pointed out that the ICF and pre-equilibrium-emission (PEE) couldn't be taken into consideration during the calculations through this code. In this code, level density parameter 'a' (=A/K; A is mass number of CN and K is free parameter) is an important input parameter which affects the CF cross-sections and may be varied to match the experimentally measured cross-sections. The experimentally measured EFs of all *xn+pxn*-channels populated in interactions of projectile and target have been found to be reproduced by calculations done with a suitable set of parameters. In the present work, at studied energy range and for these systems, the level density parameter "a=A/8" has been found to reproduce the data satisfactorily. The comparison of experimentally measured EFs and the theoretically measured cross-sections are shown in Fig.1. In this figure, the ratio of experimentally measured CF cross-sections, deduced from summing the cross-section of all *xn+pxn*-channels, to that of theoretically calculated using PACE4 and defined as $R_{CF}=\Sigma\sigma_{CF}^{expt}/\Sigma\sigma_{CF}^{pace4}$, are shown in Fig.1 by hollow symbols. It can be inferred from this figure that the ratio R_{CF} is nearly equal to 1.0, indicating the production of *xn+pxn*-channels via CF processes only. However, the ratio of measured total fusion cross-section (sum of all measured xn+pxn+αxn channels) to that of theoretically calculated using PACE4, $R_{TF}=\Sigma\sigma_{TF}^{expt}/\Sigma\sigma_{TF}^{pace4}$, has been found to be above the unity line, which increases as the energy increases. This clearly indicates that the cross-sections of α-emitting channels are found to be substantially higher than the PACE4 calculations done employing the same set of input parameters as used for CF-channels. It has already been mentioned that PACE4 do not take ICF, PEE into account and hence, this enhancement clearly reflects the importance of ICF processes at relatively higher energies. Almost similar behavior has been obtained for all the studied systems i.e., ^{16}O,$^{13,12}C$+^{159}Tb. The enhancement in R_{TF} above the unity line for these systems shows that apart from CF, the ICF processes also contribute to the TF cross-section.

These observations show that the α-emitting channels can be populated via two ways; (*i*) CF of the projectile with the target nucleus ^{159}Tb leading to the formation and decay of CN via light nuclear particles and/or one or two α clusters together with the neutrons and/or protons and (*ii*) ICF of the projectile with the target nucleus ^{159}Tb i.e., the projectile may break up into its constituent α clusters. One of the fragments fuses with the target nucleus to form a reduced CN, and the remnant behaves as a spectator.

3.1 Incomplete fusion fraction

It is established from the analysis of EFs measurements that ICF-reactions contribute significantly to the production cross-section of α-emitting channels at studied energies in case of all studied projectile-target system. Further, a close examination of Fig.1 reveals that the enhancement over the unity line for R_{TF} increases with energy for all the systems and is different in amount for different projectile, which reflects the sensitivity of ICF on the projectile energy as well as on the projectile type. For a better insight

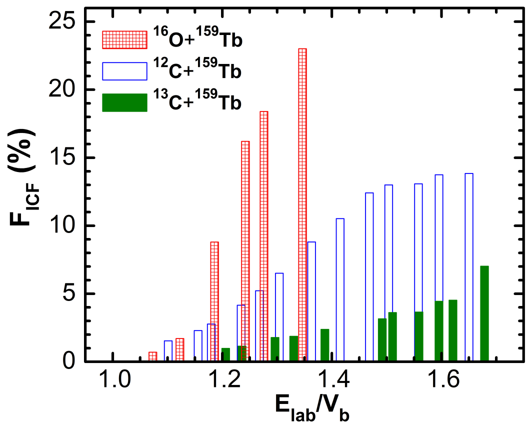

Figure 2. The comparison of F_{ICF} for ^{16}O, $^{13,12}C$ projectiles with ^{159}Tb target nuclei.

into the onset and influence of ICF processes in terms of various entrance channel parameters, the percentage fraction of ICF (F_{ICF}) has been deduced from the analysis of data for the presently studied systems. The fraction of incomplete fusion is defined as $F_{ICF} = (\Sigma\sigma_{ICF}^{expt}/\Sigma\sigma_{TF}^{expt})\times100$, where $\Sigma\sigma_{ICF}^{expt}= \Sigma\sigma_{TF}^{expt}-\Sigma\sigma_{CF}^{pace4}$. In order to investigate the projectile structure effects, the F_{ICF} values for all these systems are plotted in Fig. 2 and are referred to as the ICF strength function.

4 Projectile structure effect on ICF: the α-Q-value systematics

In order to understand the projectile structure effect on ICF the incomplete fusion fraction have been deduced and plotted in Fig.2 for all studied systems as a function of normalized beam energy, to wash out the effect of different Coulomb-barriers, for comparison. It can clearly be pointed out from this figure that the values of F_{ICF} for ^{16}O are large than the $^{12,13}C$ projectiles and the F_{ICF} values for ^{12}C is larger than the ^{13}C as projectile at the entire energy range. This indicates a effect of the projectile structure on ICF reaction dynamics.

Further from Fig.2, other than the amplitude of incomplete fusion fraction, it can also be noticed that the onset of ICF are also differ for different type of projectile. In case of ^{12}C, the onset of ICF seems to start from a relatively lower energy (i.e., 1.1V_b) than for ^{13}C induced reactions. Further, in case of ^{16}O the onset of ICF is lowerer than the ^{12}C as projectile. This strikingly different feature of ICF fractions for ^{16}O, ^{13}C and ^{12}C induced reactions point mainly towards the projectile structure effect. However, the binding energies of ^{16}O, $^{12,13}C$ are 7.98, 7.68 and 7.47 MeV, respectively. Hence, the features revealed in Fig.2 could not be understandable as ^{16}O projectile (with more binding energy) having more incomplete fusion fraction. It may, further, be pointed out that ^{16}O & ^{12}C are well-known α-cluster nuclei with alpha-Q-value 'Q_α' ≈ -7.16 & -7.37 MeV, repectively. However, ^{13}C has a more negative Q_α value (≈-10.64 MeV) than ^{16}O and/or ^{12}C. This Q_α value for ^{13}C translates into the smaller breakup prob-

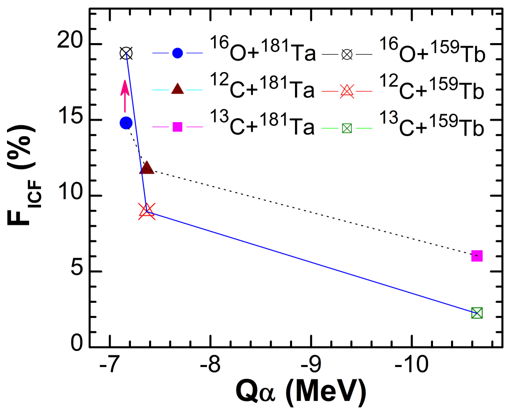

Figure 3. The comparison of F_{ICF} values for six different projectile-target combination at a constant relative velocity v_{rel}=0.053.

ability into constituent α clusters, resulting in a smaller ICF fraction than for ^{16}O/^{12}C induced reactions. In order to validate the above observed α-Q-value systematics, the probability of ICF (%F_{ICF}) has been deduced for ^{12}C, ^{13}C, and ^{16}O induced reactions on another target ^{181}Ta [11, 21] at a constant relative velocity v_{rel} = 0.053, and are plotted with Q_α values in Fig. 3. The probability of ICF is found to decrease for more negative Q_α-value of the projectiles. For example, the value of F_{ICF} deduced for the ^{16}O (Q_α $\approx$ -7.16 MeV) +^{159}Tb system is $\approx$19% and is only $\approx$3% for the ^{13}C ($Q_\alpha \approx -10.64$ MeV)+^{159}Tb system. The same systematics has been observed for the ^{181}Ta target as well. Hence, the comparison of these systems reveals that the Q_α value is an important entrance channel parameter which dictates the probability of ICF reactions at low energies $\approx$ 4-7MeV/nucleon. Further, from this figure it may also be pointed out that the F_{ICF} values support the Morgenstern's mass-asymmetry systematics [16], for a particular projectile, along with ProMass systematics given by Singh et al. [1].

5 Summary

In the present work the excitation functions have been measured for ^{16}O,^{13,12}C+^{159}Tb systems and the probability of low energy ICF have, also, been deduced. The comparison of F_{ICF} for six target-projectile combinations strongly follow the α-Q-value systematics for strongly bound projectiles. The fraction of ICF has been found to decrease for projectiles having large negative Q_α-values. If confirmed for other projectile-target combinations, this may provide an important input to achieve a general systematics for the complex ICF dynamics at low incident energies. More inclusive experiments with different projectile-target combinations are planned to cover this aspect thoroughly.

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