A SYSTEMATIC STUDY: SOME INSIGHTS INTO THE LOW-ENERGY INCOMPLETE FUSION REACTIONS*

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In the present work, a systematic attempt has been made to understand the dependence of low-energy ($\approx$ 4–7 MeV/nucleon) incomplete fusion reactions on different entrance channel parameters through the excitation functions and recoil range distribution measurements of evaporation residues populated through the complete and incomplete fusion reactions. The present analysis clearly demonstrates that the xn/pxn channels are populated, to a large extent, through the complete fusion processes. However, the production cross sections of the α emitting channels were found to be significantly under-estimated by the statistical model predictions. Dependence of low-energy incomplete fusion reactions on various entrance channel parameters was studied. Additionally, efforts have been exerted to explore certain general systematics, with the system parameter (ζ) appearing to provide a more satisfactory explanation for the low-energy incomplete fusion data compared to other entrance channel parameters.

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1. Introduction

Understanding the dynamics of heavy-ion fusion reactions at low incident energies (*i.e.*, $\approx$ 4–7 MeV/nucleon) is one of the areas of active research interest [1, 2]. At these energies, the complete fusion (CF, defined as the capture of the entire charge/mass of the projectile by the target nucleus) is

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supposed to be the dominant contributor to the total fusion cross section [3]. However, a significant fraction of incomplete fusion (ICF, defined as the fusion of a part of the projectile with the target nucleus) has been observed at near-barrier energies [1, 2]. In general, the central and/or near-central trajectories ($0 < \ell < \ell_{\mathrm{crit}}$, when the attractive nuclear potential influences the sum of repulsive Coulomb and centrifugal potentials) lead to the CF reaction processes. However, at higher ℓ values ($\geq \ell_{\mathrm{crit}}$), the repulsive potentials overcome the attractive nuclear potential, therefore, the fusion pocket in the effective entrance channel potential disappears, which hinders the fusion of the entire projectile with the target nucleus and gives way to the break-up fusion processes. In such a case, the projectile breaks up to release the excess driving angular momentum through the emission of α particle(s) or a group of nucleons [3].

Since the very first experimental observations of the direct energetic alpha-particles by Britt and Quinton [4], several models/theories have been proposed to understand the dynamics of these projectile-like fragments (PLFs) [5–10]. Further, Morgenstern *et al.* [8] correlated the onset of the ICF reactions with the relative velocity (v_{rel}) and the entrance channel mass asymmetry. Despite numerous studies [3, 5–8], our understanding of the dynamics of ICF reactions at low incident energies remains inadequate, thus making it a continuing focus of active research interest, and the most debated issues related to ICF are: *(i)* the dependence of the onset of ICF on different entrance channel parameters, *(ii)* the projectile and/or mass asymmetry effect on the ICF fraction, *(iii)* the role of other entrance channel parameters in the break-up of the projectile, and *(iv)* the localization of ℓ values.

To gain a better insight into some of these issues, several experiments were planned and performed at the Inter-University Accelerator Center (IUAC), New Delhi for various projectile–target combinations [1, 2, 11–15]. Selected results along with the experimental details are presented in this paper.

2. Experimental details and data analysis

Excitation functions (EFs) and forward recoil range distributions (FRRDs) of the individual reaction residues populated via CF and/or ICF in the interactions of ^{12,13}C,^{16,18}O, ^{19}F beams with ^{159}Tb, ^{169}Tm, ^{181}Ta, ^{175}Lu targets at energies $\approx$ 4–7 MeV/nucleon were measured at IUAC [1, 2, 11–15]. Details on the experimental setup and methodology are given in Refs. [2, 11]. However, a brief account of experimental details and analysis is given here for ready reference. Natural (abundance = 100%) targets of thickness $t_m \approx$ 1–1.5 mg/cm^2 were prepared by the rolling technique. Irradiations were carried out with a beam current of $\approx$ 20–30 nA. All targets were backed by Al catcher foils of appropriate thicknesses to stop the recoiling reaction products in the case of EFs measurements. For the FRRD measurements, a stack of thin Al-catcher foils of thicknesses in the ≈ 20–$55\ \mu\text{g/cm}^2$ range has been placed downstream of the target foil, so that the recoiling CF and/or ICF products could be stopped at different cumulative distances. The γ-ray decay of reaction products was measured off-line using a pre-calibrated HPGe detector. Reaction products were identified by their characteristic decay-γ-ray lines and by the decay-curve analysis, and the cross sections (σ_{ER}) were deduced [1].

2.1. Analysis of excitation functions

In order to understand the production mechanism of reaction products, the experimentally measured EFs have been reviewed within the framework of the widely used statistical model code PACE4 [17]. The details of the code are given in Refs. [11, 17]. For ready reference, a brief account of the same is given here: the basis of this code is the equilibrated CN decay of the Hauser–Feshbach theory. In this code, the level-density parameter ($a = A/K$ MeV^{-1}, where A is the mass number of the nucleus and K is a free adjustable parameter) is one of the important parameters. The value of the free parameter K may be varied to reproduce the experimentally measured EFs. It should, however, be pointed out that the break-up and pre-equilibrium processes are not taken into consideration in this code. As one can observe in Fig. 1 (a), the sum of cross sections of all experimentally observed xn/pxn channels (solid circles) in the interactions of ^{12}C+^{159}Tb is satisfactorily reproduced by the statistical model calculations done using the level density parameter $K = A/8$ MeV^{-1}, thus indicating that these channels are mainly populated via the CF reaction processes. However, in the case of $\alpha xn/2\alpha xn$ channels (see Fig. 1 (b)) the experimental cross sections were underestimated by the PACE4 predictions for the same set of parameters as those used to understand the xn/pxn channels. This enhancement has been attributed to a contribution coming from ICF processes.

2.2. Analysis of the recoil range distributions

In order to obtain the FRRDs of heavy recoils, the normalized yields of the reaction products have been plotted as a function of the cumulative thickness of catcher foils, and fitted with a Gaussian function to deduce the most probable recoil range ($R_{\text{P}}^{\text{expt}}$) in the stopping medium. Figure 1 (c) shows the distribution of FRRDs for ^{167}Lu ($4n$ channel) populated in the ^{12}C+^{159}Tm system at ≈ 87 MeV, which can be fitted by a Gaussian peak ($R_{\text{P}}^{\text{expt}} \approx 374\ \mu\text{g/cm}^2$) indicating a single linear momentum transfer (LMT) component involved in the production of this residue. However, Fig. 1 (d)

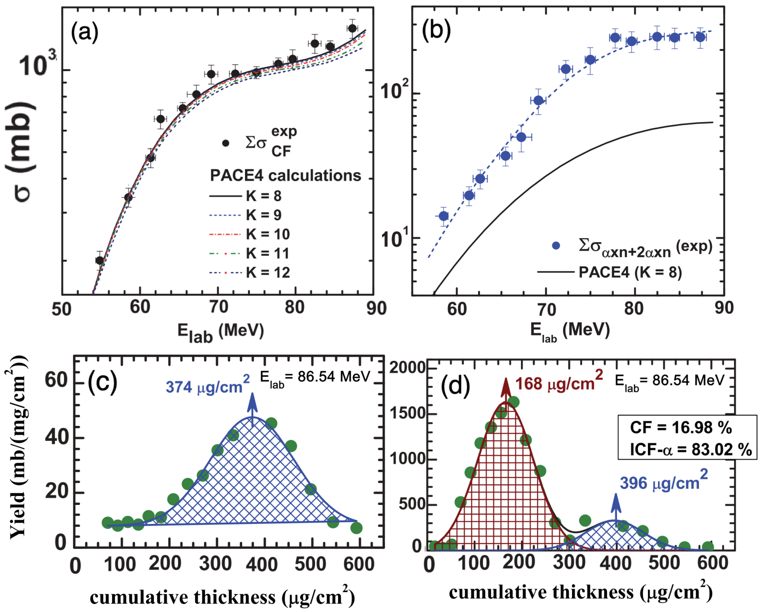

Fig. 1. (a)–(b) The EFs of xn/pxn and αxn channels along with the theoretical predictions, (c)–(d) the FRRDs for CF and ICF residues for the ^{12}C+^{159}Tb system (see the text for details).

shows the distribution of FRRDs for the ^{165}Tm residues ($\alpha 2n$ channel), which can be resolved into two Gaussian peaks, revealing the presence of LMT components associated with the fusion of ^{12}C and ^{8}Be with the target nucleus. The values of $R_{\rm P}^{\rm expt}$ for different residues were also compared with $R_{\rm P}^{\rm theo}$ of ERs estimated using SRIM [18], and they were found to be in good agreement. Also, the range of the ICF residues was found to be decreasing with the decrease in the incident projectile energy [2]. The values of $F_{\rm ICF}$ deduced from EFs and FRRDs were found to be in good agreement with each other, which gives confidence in our measurements and data reduction procedure.

2.3. Systematics for low-energy ICF reactions

In order to have a better understanding of the ICF reaction dynamics, the ICF fractions were deduced for all the systems and compared with the low-energy ICF data available in the literature. The analysis indicates strong dependence of $F_{\rm ICF}$ on some entrance channel parameters such as the incident beam energy, the mass asymmetry, fissility, Q_α value of the projectile, and the Coulomb factor. The $F_{\rm ICF}$ increases with the incident beam energy as more angular momentum is introduced to the system. In addition to this, as the Coulomb factor ($Z_{\rm P}Z_{\rm T}$) of the system increases, the break-up probability of the projectile also increases, which is expected. The dependence of $F_{\rm ICF}$ on the mass asymmetry, fissility, and $Z_{\rm P}Z_{\rm T}$ strongly varies with projectile type, which can be explained by including the Q_α value of the projectile along with these parameters [2]. Further, in order to achieve better understanding of the dependence of low-energy ICF reaction dynamics on various entrance channel parameters, the low-energy ICF data were evaluated for about 45 different projectile–target combinations with $Z_{\rm P}Z_{\rm T}$ values spanning a wide range (138–670), and an attempt has been made to find out a more general parameter, which should include the charge and mass dependency of the ICF reactions. In this regard, two parameters, *(i)* the total asymmetry parameter ($\alpha_{\rm total} = \alpha_{\rm mass}\,\alpha_{\rm charge}$), and *(ii)* the system parameter ($\zeta = Z_{\rm P}Z_{\rm T}\sqrt{\mu}$, where $Z_{\rm P}$, $Z_{\rm T}$ are atomic charges and μ is the reduced mass of the interacting partners) were considered (see Fig. 2 (a)–(b)). It was concluded that the system parameter ζ, which includes the Coulomb factor ($Z_{\rm P}\,Z_{\rm T}$) as well as the mass dependence of the interacting partners, provides a reasonable description of the ICF reaction dynamics at such low energies.

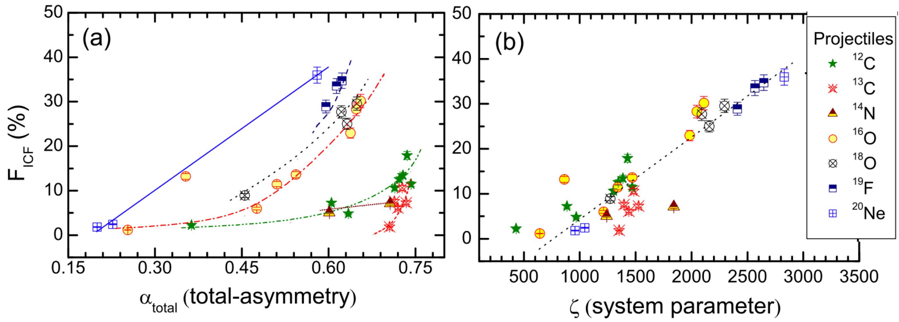

Fig. 2. The dependence of $F_{\rm ICF}$ on the total asymmetry and system parameters (see the text for details).

3. Summary

The present work reports the EF and FRRD measurements of several evaporation residues populated in the interactions of the ^{12,13}C, ^{16,18}O, and ^{19}F beams on the ^{159}Tb, ^{169}Tm, ^{181}Ta, and ^{175}Lu targets. The experimentally measured EFs were analyzed using the PACE4 code. The analysis of the experimentally measured EFs suggests that the production of xn/pxn channels proceeds mainly through the CF reaction processes. However, the experimentally measured EFs for all the α emitting channels show notable enhancement compared to the PACE4 predictions, which may be assigned to a contribution of ICF reaction processes. The ICF fraction has been deduced for all the studied systems using EFs and FRRDs measurements, yielding consistent results, which gives confidence in the analysis procedure. The analysis indicates strong dependence of the ICF strength function on several entrance channel parameters. Further, an attempt was made to propose a more general parameter, which should include the charge and mass dependency of the ICF reactions. In this regard, two parameters: the total asymmetry parameter (α_{total}), and the system parameter (ζ) were considered, and the latter has been demonstrated to reasonably describe the ICF reaction dynamics at such low energies.

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