LOW ENERGY INCOMPLETE FUSION AND THE ROLE OF INPUT ANGULAR MOMENTA*

R. Kumar[a], Vijay R. Sharma[b], A. Yadav[a], Pushpendra P. Singh[c]
S. Appanababu[d], A. Aggarwal[e], B.P. Singh[b], S. Mukherjee[f]
S. Muralithar[a], R. Ali[g], R.K. Bhowmik[a]

[a]GDA Group, Inter University Accelerator Centre, New Delhi 110 067, India
[b]Department of Physics, A.M. University, Aligarh 202 002, India
[c]Department of Physics, I.I.T., Roopar, Panjab 140 001, India
[d]INFN — Laboratori Nazionali di Legnaro, 35020 Legnaro, Italy
[e]Physics Department, Bareilly College, Bareilly 243 005, India
[f]Physics Department, M.S. University of Baroda, Vadodara 390 002, India
[g]Physics Department, G.F. College, Shahjahanpur 242001, India

(Received January 29, 2015)

Aiming to investigate the incomplete fusion processes at low projectile energies, experiments have been carried out for the ^{14}N + ^{169}Tm system at $\approx$ 4–7 MeV/A. Excitation functions for several residues likely to be populated via complete and incomplete fusion processes have been measured for the first time using heavy recoil residue catcher technique followed by γ-ray spectroscopy. The measured excitation functions are compared with the calculations based on the available statistical model codes. The incomplete fusion strength function is found to increase with the projectile energy. An attempt has been made to compare the present system with an semi-empirical code MARC for incomplete fusion.

DOI:10.5506/APhysPolB.46.453
PACS numbers: 25.60.Dz, 25.70.–z, 25.70.Gh, 25.70.Jj

1. Introduction

The study of heavy ion (HI) induced reactions has been used as an important tool to understand the reaction dynamics at energies near and above the Coulomb barrier (V_{b}). Much interest has aroused during the last decade to study incomplete fusion (ICF) reactions in HI interactions at low energies $\approx$ 4–7 MeV/A. In some recent reports, a large fraction of ICF has been observed at these low energies [1], which triggered the resurgent interest to understand the low energy ICF reaction dynamics.

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 31–September 7, 2014.

In recent years, high quality data on excitation functions (EFs) [2], spin distributions (SDs) [3], and linear momentum distributions [4] of individual reaction products have been obtained at the Inter University Accelerator Centre IUAC, New Delhi in a variety of experiments. These studies conclusively demonstrate the low energy ICF but are limited only for a few projectile–target combinations. In the present work, the excitation function (EFs) of individual reaction channels populated in ^{14}N+^{169}Tm system at energies $\approx$ 4–7 MeV/A have been measured and analyzed within the framework of statistical model to look for the influence of ICF in the light of Morgenstern's mass asymmetry systematics [5].

2. Experimental details

The present experiment has been carried out at IUAC. A stack of 3 target foils of natural ^{169}Tm of abundance = 100% and thickness $\approx$ 1.2 to 1.7 mg/cm^2 each backed by aluminium-foils of thickness $\approx$ 1.5 to 2.5 mg/cm^2 to stop the most energetic recoils was bombarded with ^{14}N beam of energy range of 4–7 MeV/nucleon with beam current 20–30 nA. The activities produced in the samples were recorded off-line by pre-calibrated HPGe detector.

3. Results and discussions

Experimentally measured EFs are analyzed within the framework of the statistical model code PACE4 [6]. In this code, ICF is not taken into consideration, as any such enhancement over the theoretical calculations may be attributed to ICF. Figure 1 (a) shows the sum of complete fusion (CF) cross section for xn ($x = 4$) and pxn ($x = 3$ and 4) channels extracted experimentally (star/red) and matches satisfactorily with PACE4 at the level density parameter $a = A/K$ at $K \approx 8$ (solid line). Further, the sum of all identified α-emitting channels (*i.e.* $\approx \alpha 2n$, $\alpha 3n$, $\alpha 4n$ and $\alpha 5n$) cross section is plotted in Fig. 1 (a) with filled circles and is compared with PACE4 at the same a. As can be seen from the figure, the total cross section associated with α's (*i.e.* $\Sigma\sigma_{\alpha'}$s; circles/black) is higher when compared to PACE4 (dashed line). This enhancement over the theoretical prediction may be attributed to ICF. Further, the ICF cross section has been deduced by subtracting the experimental αs cross section with PACE4 (dashed line) and is plotted in Fig. 1 (b) with respect to projectile energy. From the figure it can be concluded that ICF cross section increases as projectile energy increases. In order to have a better understanding of ICF processes, an attempt has been made to deduce ICF strength function (*i.e.* the percentage fraction of ICF ($F_{\rm ICF}$%)) and is plotted in the inset of Fig. 1 (b) with $E_{\rm lab}$. The ICF strength function defines the empirical probability of ICF at different projectile energies. The value of $F_{\rm ICF}$ is found to be 7.1% at $\approx$ 72 MeV *i.e.* 1.13 $V_{\rm b}$ (13% above the barrier), and increases smoothly up to the highest energy *i.e.* 24.5% at $\approx$ 82 MeV.

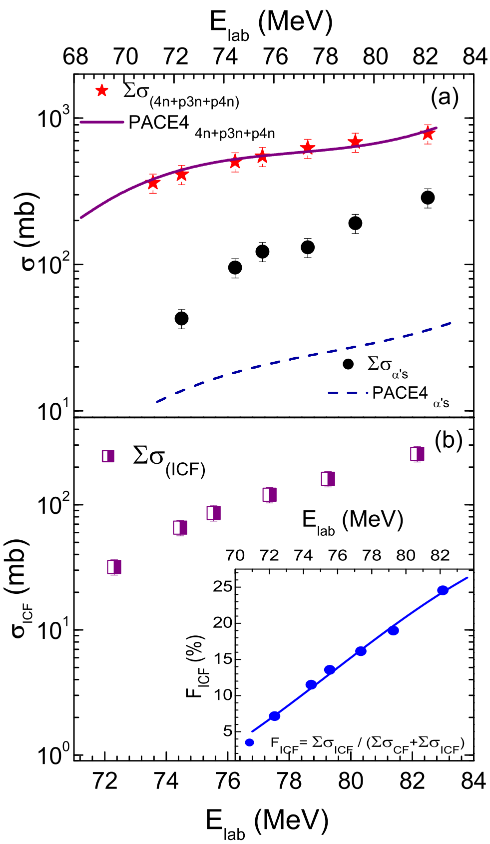

Fig. 1. (a) Experimentally measured total CF cross section (filled star), total αs cross section (filled circle). A comparison with PACE4 (k = 8) channel has also been shown. (b) The deduced ICF cross section as a function of projectile energy. In the inset, ICF strength function is plotted. (For details, see the text.)

An attempt has been made to obtain the relation contributions of CF and ICF, with the prescription given by Wilczynski *et al.* [7] to describe the total fusion cross section. For a given partial wave, the relative contributions of CF and ICF are given by $\sigma_{\rm CF} = \sigma_\ell\, f_\ell$; $\sigma_{\rm ICF} = \sigma_\ell\,(1 - f_\ell)$, where f$_\ell$ is a Fermi-like function $f_\ell = \frac{1}{1+\exp\frac{(\ell-\ell_{\rm crit})}{\Delta}}$, where ($\ell_{\rm crit}$) is the critical value of the angular momentum. The critical value of the angular momentum for different projectile–target combinations have been calculated using standard formulation [8]. The partial cross sections have been calculated using code

PACE4 which is based on the Bass fusion cross section algorithm. The transmission probability associated with the partial waves can be calculated using the one dimensional barrier penetration model. To the best agreement, experimental excitation functions (EFs) have been obtained for the values of $a = A/8.0$ MeV^{-1} and the value of the diffuseness parameter has been set to 0.2 for the calculations.

The diffuseness parameter Δ used in the Fermi function is adjusted to reproduce the shape of the measured ICF excitation function. Based on the above presently assumed prescription, a Multi-step pArtial Reaction Cross section (MARC) code has been developed, which is able to reproduce relative yields of CF and ICF. The total partial cross section $\Sigma\sigma_{\rm ICF}^{\rm MARC}$ value for the presently studied system using MARC at different scaling parameter Δ are compared with experimentally measured, and systematically deduced values of $\Sigma\sigma_{\rm ICF}^{\rm Exp}$ as a function of normalized angular momentum $(\ell_{\rm max}/\ell_{\rm crit})^2$ and plotted in Fig. 3. As can be seen from the figure, the values of $\Sigma\sigma_{\rm ICF}^{\rm Exp}$ shows fair agreement with that predicted by MARC. Further, the variation of $F_{\rm ICF}$ for different projectile–target combinations as a function of entrance channel mass asymmetry (as shown in Fig. 2) can be understood in terms of the corresponding variation of Δ with projectile and target mass. Moreover, results presented in Fig. 3 reveal a significant ICF contribution below $\ell_{\rm crit}$ which support our recent findings of ICF for system ^{13}C+^{169}Tm [2].

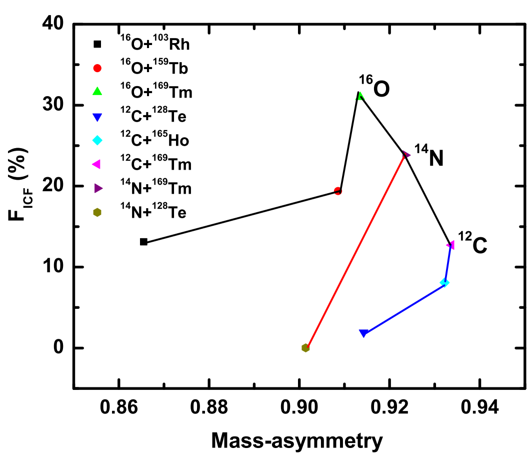

Fig. 2. The values of $F_{\rm ICF}$ for different projectile–target combinations as a function of entrance channel mass asymmetry at a constant relative velocity (*i.e.* $\nu_L \approx 0.053$). The lines drawn through the data points guide the eyes for individual (^{12}C, ^{14}N, ^{16}O) projectiles.

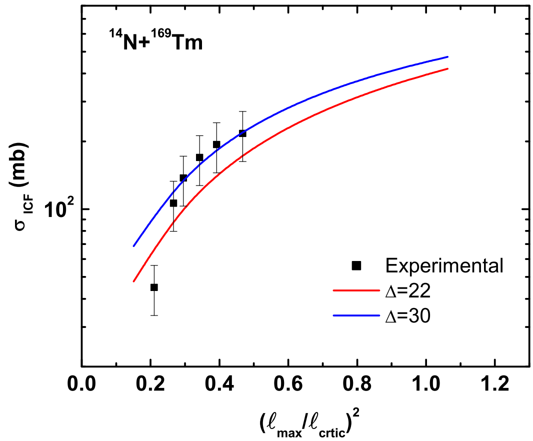

Fig. 3. Total partial cross section $\Sigma\sigma_{\rm ICF}^{\sf MARC}$ using MARC code at different scaling parameters Δ (read in the text) as a function of normalized angular momentum.

4. Conclusions

This paper briefly summarizes the measurements and analysis of recent experiments performed to study ICF at energies $\approx$ 4–7 MeV/nucleon in ^{14}N+^{169}Tm systems. It has been found that ICF significantly contributes to total reaction cross section even at slightly above barrier energies. The probability of ICF is found to increase with energy and with mass asymmetry, for individual projectiles. Calculations with an semi-empirical code MARC for the presently studied systems has been found to work satisfactorily. For testing the reliability of MARC code, we are planning to calculate the similar strength of other projectile–target combinations.

REFERENCES

[1] A. Yadav *et al.*, *AIP Conf. Proc.* **1609**, 20 (2014) and reference therein.

[2] V.R. Sharma *et al.*, *Phys. Rev.* **C89**, 024608 (2014) and references therein.

[3] P.P. Singh *et al.*, *Phys. Lett.* **B671**, 20 (2009).

[4] A. Yadav *et al.*, *Phys. Rev.* **C85**, 064617 (2012) and references therein.

[5] H.M. Morgenstern *et al.*, *Phys. Rev. Lett.* **52**, 1104 (1984).

[6] O.B. Tarasov *et al.*, *Nucl. Instrum. Methods Phys. Res.* **B204**, 174 (2003).

[7] J. Wilczynski *et al.*, *Phys. Rev. Lett.* **44**, 606 (1980).

[8] R. Kumar *et al.*, *DAE Symp. Nucl. Phys.* **56**, 614 (2011) and references therein.