EPJ Web of Conferences 66, 03079 (2014)
DOI: 10.1051/epjconf/20146603079

Incomplete fusion reactions at low energies in $^{13}C+^{169}Tm$ system

Vijay R. Sharma[1,a], Abhishek Yadav[1], Devendra P. Singh[1], Pushpendra P. Singh[2], Indu Bala[3], R. Kumar[3], M. K. Sharma[4], S. Gupta[5], S. Murlithar[3], R. P. Singh[3], B. P. Singh[1] and R. Prasad[1]

[1]Department of Physics, Aligarh Muslim University, Aligarh - 202 002, (U.P.), India
[2]GSI Helmholtz Centre for Heavy Ion Research GmbH, Planckstasse 1, D-64291 Darmstadt, Germany
[3]NP Group, Inter University Accelerator Centre, New Delhi - 110 067, (U.P.), India
[4]Physics Department, S. V. College, Aligarh - 202 001, (U.P.), India
[5]Physics Department, Agra College, Agra - 282 001, (U.P.), India

Abstract. Aiming to investigate the incomplete fusion processes at low projectile energies, experiments have been carried out for the ^{13}C + ^{169}Tm system at ≈ 4-7 MeV/A. Excitation functions for several heavy residues likely to be populated via complete and incomplete fusion processes have been measured using heavy recoil residue catcher technique followed by γ- ray spectroscopy. The measured cross-sections for the complete fusion (*xn* and *pxn*) channels are compared with the statistical model code PACE4, consistently using the same set of parameters. The complete fusion channels are found to be consistent with the model calculations. However, the cross-sections for all the measured α-emitting channels are found to be significantly enhanced over the calculations. Analysis of data indicate a significant fraction of incomplete fusion even at energies as low as 17% above barrier. The present results are discussed in light of the Morgenstern's systematics. Incomplete fusion strength function is found to be relatively large for alpha cluster projectile i.e. for ^{12}C as compared to one neutron excess ^{13}C projectile.

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) [1, 2]. At these energies the complete fusion (CF) and incomplete fusion (ICF) are the dominant modes of reaction processes. Hence, the study of incomplete fusion at slightly above barrier energies ($E_{lab} \approx V_b$) and the strong influence of ICF on complete fusion (where an excited composite system is formed after intimate contact and transient amalgamation of projectile and target nucleus) at relatively higher energies gained resurgent interest in recent years [3,4]. However, the first evidence of ICF reactions was presented by Kauffmann and Wolfgang [5] by studying $^{12}C+^{nat}Rh$ system at ≈ 7-10 MeV/nucleon, where strongly forward peaked angular distributions of light-nuclear-particles were observed. Britt and Quinton [6] found similar observations in the $^{16}O+^{209}Bi$ reactions at energies ≈ 7-10 MeV/nucleon. In these measurements, significantly large yield of direct-α-particles of mean energy roughly corresponding to the projectile velocity at the forward angels has been observed. The results

[a] Corresponding author: phy.vijayraj@gmail.com

of these experiments suggested that the process involved in the production of fast-α-particles is the projectile break-up (BU), in the nuclear field of the target nucleus. Several dynamical models [7-10] have been proposed to explain the ICF reaction dynamics. The SUMRULE model of Wilczynski et al.[10], considers that ICF processes mainly originate from peripheral interactions and they are localized in the angular momentum space above the critical angular momentum (ℓ_{crit}) for the CF. The BUF-model of Udagawa and Tamura [7], is based on the Distorted Wave Born Approximation formalism for elastic breakup, where the projectile is supposed to break-up into its constituent α-clusters (e.g., ^{12}C may break-up into $\alpha+^{8}Be$) as it approaches the nuclear field of the target nucleus. One of the fragments of the projectile is assumed to fuse with target nucleus to form an incompletely fused composite system and unfused fragment continues to move in the forward cone with almost projectile velocity. As a matter of fact, the above models qualitatively explain the experimental data at E/A ≥ 10.5 MeV, however, none of the existing models is able to reproduce the experimental data obtained at energies as low as ≈4-7 MeV/nucleon, therefore, the study of ICF is still an active area of investigation.

Moreover, some of the most debated and outstanding issues related to low energy ICF have been, (i) the localization of the angular momentum window, (ii) the usefulness of ICF to populate high-spin states in final reaction products, and (iii) the effect of entrance channel parameters on the onset and strength of ICF. In recent years, high quality data on excitation functions (EFs) [3,4], spin distributions (SDs) [11], and linear momentum distributions [12] of individual reaction products have been obtained at the IUAC, New Delhi in a variety of experiments. These studies conclusively demonstrate the low energy ICF but limited only for a few projectile-target combinations. In the present work, the EFs of individual reaction channels populated in $^{13}C+^{169}Tm$ system at energies ≈ 4–7 MeV/nucleon have been measured and analyzed within the framework of statistical model to look for the influence of ICF in light of Morgenstern's mass asymmetry systematics [13].

2 Experimental Details

Experiments have been performed using $^{13}C^{6+}$ beam from 15UD pelletron accelerator at the IUAC, New Delhi, India. The target foils of isotopically pure (99.9%) Thulium and Aluminium catchers were prepared using rolling technique. The thickness of each target and catcher foil was determined by α-transmission method. The thickness of the samples was determined from the observed change in the energy of the α- particles by using stopping power values and were found to be ≈ 1.5 – 2.5 mg/cm^2 for Tm-targets and 1.0 – 3.0 mg/cm^2 for Al- catchers. The thickness of the Al-catchers was chosen keeping in view the fact that even the most energetic residues produced due to the complete momentum transfer (CMT) may be trapped in the catcher thickness. It may be pointed out that the recoil energy of the composite system (^{182}Re) formed as a result of CMT in 86 MeV $^{13}C+^{169}Tm$ is ≈ 6 MeV. The ranges of these ≈ 6 MeV heavy residues in Al is ≈ 0.334 mg/cm^2. As such, they are completely stopped in the catcher thickness used in the present work. The ^{169}Tm foil samples and Al-catchers were cut into 1.2 X 1.2 cm^2 size and pasted on Al-holders having concentric holes of 1.0 cm diameter. Each target was followed by Al- catchers. The irradiation has been carried out with a beam current ≈ 2-3 pnA. The beam energy incident on the first target was 86 MeV. After an energy loss of ≈ 4.78 MeV, while passing through first target-catcher assembly the beam energy incident on second ^{169}Tm target was ≈ 81.21 MeV and on third target ≈ 75.84 MeV after a loss of 5.37 MeV. Thus, in a single bombardment, three samples are irradiated. Several such stacks were irradiated to cover a broad energy range. Keeping in view the half-lives of interest, irradiations have been carried out for ≈ 8 hours. The beam flux was monitored using an ORTEC current integrator. The activities produced in the samples were recorded off-line by pre-calibrated HPGe detector of 100 c.c. active volume coupled to a CAMAC based software CANDLE [14]. The target-detector separation was suitably adjusted so as to keep the dead time < 10 %. In order to detect and follow the residues of longer half-lives, the counting of irradiated samples has been done for a week or so. Further experimental details along with the factors that may introduce uncertainties in the measured cross sections are given elsewhere [15].

3 Measurements and Analysis

The identification of reaction products have been done by their characteristic decay γ- lines as well as by the decay-curve analysis. In the present work 3n, 4n, 5n, 6n, p4n, α3n, α4n, α5n, 2α2n & 2α3n channels populated via CF and/or ICF processes have been identified. It may be pointed out that the most intense decay γ-lines have been used to calculate the production cross-section of identified residues. In order to understand up to what extent the decay of these radionuclide's can be justified by compound nucleus decay, experimentally measured EFs are analyzed within the framework of the statistical model code PACE4 [16]. In this code, ICF is not taken into consideration, as such any enhancement over the theoretical calculations may be attributed due to ICF. Fig. 1(a) shows that the total CF cross-section (*xn+pxn*) extracted experimentally (σ_{CF}; black squares) matches satisfactorily

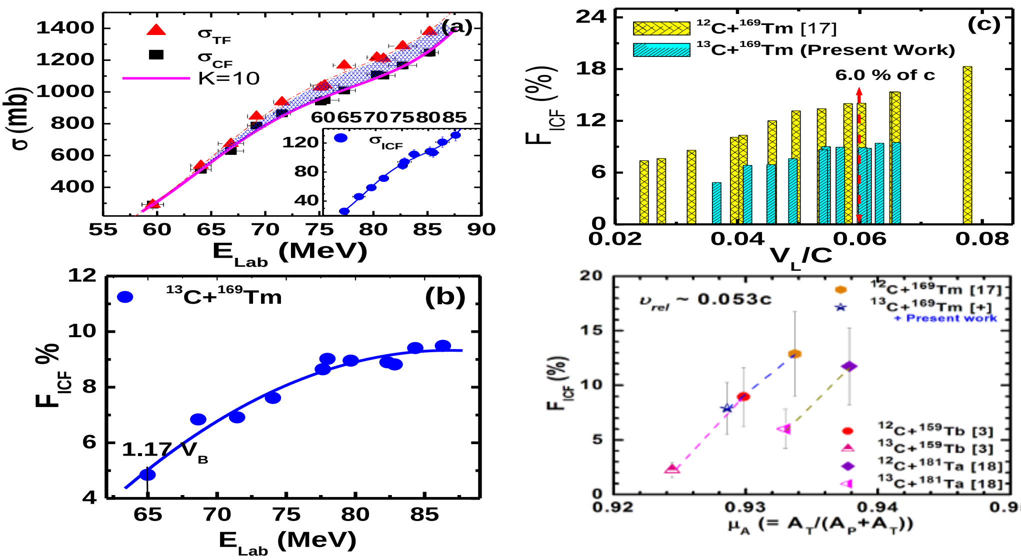

Figure 1 (a). Experimental measured total CF alongwith total fusion and incomplete fusion cross-sections (b) the ICF strength function as a function of projectile energy, (c) the value of F_{ICF} as a function of V_L/c for ^{12}C,^{13}C+^{169}Tm systems. (d) the values of F_{ICF} obtained for ^{12,13}C+^{159}Tb, ^{181}Ta and ^{169}Tm as a function of entrance channel mass asymmetry (μ_A) at a constant value of $v_{rel} \approx 0.053$. For details see text.

with theoretical simulations using code PACE4 at level density parameter 'K' ≈ 10 (solid pink line), however inclusion of cross-section for α-channels made cross-sections higher (σ_{TF}; red triangles) over theoretical simulations based on CF model (solid pink line). This enhancement over the theoretical prediction may be attributed due to the ICF. The inset of this figure shows the σ_{ICF} (= σ_{TF} - σ_{CF}) as well. The increasing separation between σ_{CF} and σ_{TF} (shaded region in fig 1(a)) with E_{lab} indicates strong energy dependence of ICF. Detailed discussion on the data reduction procedure and obtained results can be found elsewhere [15]. In order to have a better understanding of incomplete fusion process, an attempt has been made to deduce ICF strength function (i.e., the percentage fraction of ICF (% F_{ICF})) and is plotted with E_{lab} in Fig.1(b). The ICF strength function defines empirical probability of ICF at different projectile energies. The value of F_{ICF} is found to be ≈ 5 % at ≈ 64 MeV, i.e., at 1.17V_b (17 % above the barrier), and increases smoothly up to ≈ 9 % at highest measured energy. According to Morgenstern's systematics [13], ICF contributes significantly above V_L/c (≈ $A_T/(A_P+A_T).v_{rel}$) = 0.06, and the fraction of ICF increases with entrance channel mass-asymmetry (μ_A ≈ $A_T/(A_P+A_T)$). To test the Morgenstern's systematics, the values of % F_{ICF} obtained for ^{13}C +^{169}Tm system is plotted with V_L/c in Fig.1(c). In this figure the value of % F_{ICF} for ^{12}C +^{169}Tm [17] system is also plotted, in order to see the effect of an alpha cluster projectile on incomplete fusion processes. As can be noticed from this figure, the values of V_L/c are in the range from ≈ 0.037 to ≈ 0.066 for ^{13}C-beam, and from ≈ 0.026 to ≈ 0.078 for ^{12}C beam. At these values of V_L/c, no significant ICF contribution is expected according to Morgenstern's systematics at lower energies (V_L/c < 6%). Results presented in Fig.1(c) clearly demonstrate the onset of ICF at relatively lower value of V_L/c i.e, ≈ 0.037 (F_{ICF} ≈ 5 %) in $^{13}C+^{169}Tm$, and at ≈ 0.026 (F_{ICF} ≈ 7 %) in $^{12}C+^{169}Tm$ system. Hence, in both cases, the observed value of F_{ICF} is significant even at well below the proposed onset value of V_L/c (i.e., 6 %) [13]. Further, the value of F_{ICF} for ^{13}C is lower than ^{12}C-projectile for the entire measured energy range. The differences in the F_{ICF} values for two systems ($^{13,12}C+^{169}Tm$) can be seen quite clearly, which indicates the dependence of F_{ICF} on the projectile mass and/or on μ_A. The difference in the percentage ICF may be due to different behaviour in the breakup phenomenon considering that ^{12}C is a strong α-cluster nucleus. In order to refine this effect, the values of F_{ICF} for nearby systems, $^{13,12}C+^{159}Tb$ [3] and $^{13,12}C+^{181}Ta$ [18] are plotted with μ_A in Fig. 1(d) at a constant value (i.e. ≈ 0.053) of v_{rel} ($\approx \sqrt{2(E_{cm}-V_b)/\mu}$) [13]. As shown in this figure (Fig. 1(d)), the Morgenstern's systematics [13] explains the increasing of F_{ICF} with μ_A for our systems, but the $^{12,13}C+^{181}Ta$ data are not completely in agreement with $^{12,13}C+^{159}Tb$, ^{169}Tm data. It may also be pointed out that, inclusion of error bars in the data is not likely to change increasing trend observed. Moreover, the values of F_{ICF} for systems with the same μ_A and different projectiles ($^{13}C+^{181}Ta$ Vs. $^{12}C+^{181}Tm$) are very different, due to possible projectile α-cluster phenomena. These observations based on six projectile-target combinations which supplement the earlier proposed Morgenstern's mass asymmetry systematics [13].

4 Summary

This paper briefly summarizes the measurements and analysis of recent experiments performed to study ICF at energies ≈ 4-7 MeV/nucleon in $^{13}C+^{169}Tm$ 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 μ_A, for individual projectiles.

5 Acknowledgements

The authors thank to the Chairman, D/o Physics, AMU, Aligarh & the Director, IUAC, New Delhi, for providing all the necessary facilities to carry out this work. RP, BPS, DPS and VRS thanks to the UGC (F. No. 40-418/2011 (SR)) and DST (SR/FTP/PS-025/2011) for providing financial support.

References

1. M. Cavinato et al., Phys. Rev. C **52**, 2577 (1995)
2. P. Vergani wt al., Phys. Rev. C **48**, 1815 (1993)
3. Abhishek Yadav et al., Phys. Rev. C **85**, 034614 (2012); ibid **86** , 014603 (2012)
4. P. P. Singh et al., Phys. Rev. C **77**, 014607 (2008)
5. Kauffmann and Wolfgang, Phys. Rev. **121**, 206 (1961)
6. H. C. Britt and A. R. Quinton, Phys. Rev. **124**, 877 (1961)
7. T. Udagawa and T. Tamura, Phys. Rev. Lett. **45**, 1311 (1980).
8. J. P. Bondrof, et al., Nucl. Phys. A**333**, 285 (1980).
9. R. Weiner and Westrom, Nucl. Phys. A**386**, 282 (1977).
10. J. Wilczynski, et al., Nucl. Phys. A**373**, 109 (1982)
11. Pushpendra P. Singh *et al.*, Phys. Lett. B **671**, 20 (2009)
12. D. P. Singh et al., Phys. Rev. C 81, 054607 (2010) and references therein.
13. H. M. Morgenstern, et al., Phys. Rev. Lett. **52**, 1104 (1984).
14. B. P. Ajith Kumar et. al., DAE Symposium on Nuclear Physics, 2001, Kolkata.
15. Vijay R. Sharma et al., communicated to Phys. Rev. C (2013).
16. A. Gavron, Phys. Rev.C 21, 230 (1980).
17. Pushpendra P. Singh, et al., Journ. of Phys. Conference series, **282**, 012019 (2011).
18. K. Sudarsan Babu et al., J. Phys. G **29**, 1011 (2003).