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ENTRANCE CHANNEL EFFECT ON INCOMPLETE FUSION*

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In the present work, the onset and strength of incomplete fusion were studied in terms of various entrance channel parameters. Excitation functions for individual evaporation residues were measured in the ^{12}C+^{169}Tm system at energies from 5 to 7.5 A MeV, and analysed in the framework of the statistical model code PACE-IV to deduce the fraction of incomplete fusion. It was found that the probability of incomplete fusion increases with the incident energy as well as with the mass asymmetry of interacting partners for individual projectiles. Moreover, the critical value of the input angular momentum ($\ell_{\rm crit}$) obtained from the experimental cross sections was compared with that calculated using the Wilczyński formula and a slight difference has been found.

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1. Introduction

Heavy-ion induced nuclear reactions are an area of extensive investigations due to their complex nature and capability to explore a wide variety of systems for nuclear astrophysics and structure studies. Generally, at

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energies near and above the Coulomb barrier, the complete fusion (CF) is believed to be the dominating mode of reaction. However, at these energies, a substantial fraction of incomplete fusion (ICF) has been observed [1, 2], and it has also been found that the fission becomes pronounced in neutron-deficient compound-nucleus systems [3]. The first evidence for ICF has been achieved by Knox *et al.* [4], and Britt and Quinton [5] in their outstanding work. Since then, the dynamics of ICF has been studied using α-cluster beams, and a few theoretical models have been proposed to predict ICF cross sections at energies near and above the Coulomb barrier [1, 2, 6, 18]. These models reproduce, to some extent, the ICF data at energies $\geq$ 10 MeV/nucleon. However, there is no theoretical model which can predict ICF at lower incident energies, thus it continues to be an active area of investigations.

2. Experimental details

The experiments were carried out at IUAC, New Delhi using the experimental techniques and methodologies presented in Refs. [2, 7]. A brief account of experimental conditions is given here for ready reference. In the experiments, the recoil catcher activation technique followed by the off-line γ spectroscopy was employed. Isotopically pure ^{169}Tm targets of thickness $\approx$ 900 μg/cm^2 were irradiated using ^{12}C beams of 54–90 MeV energy and

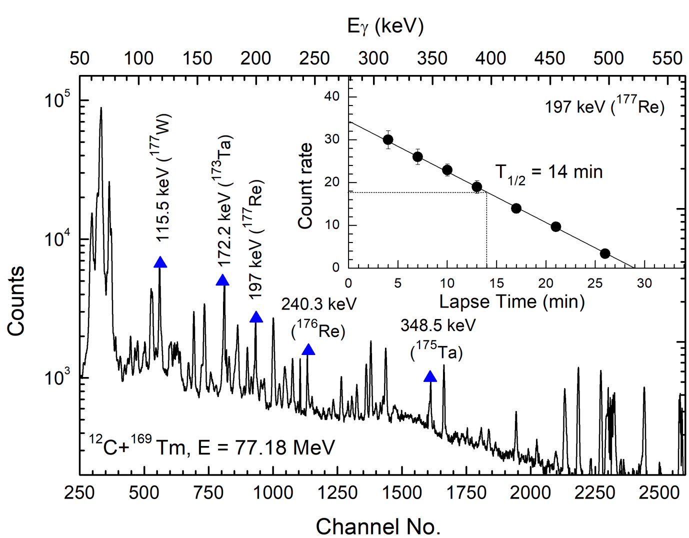

Fig. 1. Part of the γ-ray spectrum obtained at E_{lab} = 77.18 MeV for the ^{12}C+^{169}Tm system. Gamma-ray lines assigned to different evaporation residues are marked. The inset shows the decay curve for the ^{177}Re residue indicating a half-life of $\approx$14 min in agreement with the literature value [10].

current of $\approx$ 20–30 nA. The irradiated target foils were taken out from the irradiation chamber, and the radioactivities produced during the bombardment were followed off-line using two High Purity Germanium (HPGe) detectors read out with a CAMAC-based data acquisition system. A relevant part of a γ-ray spectrum obtained at $E_{\mathrm{lab}} = 77.18$ MeV is presented in Fig. 1, and the peaks assigned to different evaporation residues are marked. The evaporation residues were identified by their characteristic γ rays, and confirmed by the decay-curve analysis. The cross sections to produce evaporation residues were calculated using the standard formulation given in Ref. [7]. The overall error of the cross sections is estimated to be $\leq 13\%$.

3. Results and analysis

In the present work, excitation functions for individual evaporation residues populated via complete and/or incomplete fusion in the $^{12}\mathrm{C}+^{169}\mathrm{Tm}$ system at excitation energies ranging from 35 to 70 MeV have been measured, and analysed in the framework of the statistical model code PACE-IV. It is based on the Hauser–Feshbach formalism of the compound nucleus formation and decay, and takes only CF into account [8, 9]. In the PACE-IV code, the level density parameter $a = A/K$, where K is a free parameter, plays a crucial role to reproduce the cross sections of evaporation residues. As a representative case, Fig. 2 presents the excitation function for the $^{177}\mathrm{Re}(4n)$ residue, which is expected to be populated via emission of 4 neutrons from the excited compound nucleus $^{181}\mathrm{Re}^*$, compared with PACE-IV predictions for three different values of K ($K = 8, 9, 10$). As can be seen from this figure, the excitation function for $^{177}\mathrm{Re}$ is very well reproduced by PACE-IV for

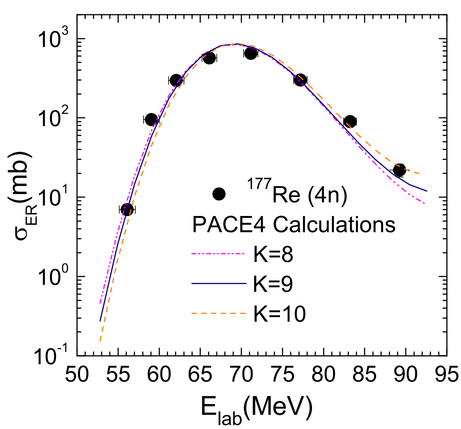

Fig. 2. Experimentally measured excitation function for the $^{177}\mathrm{Re}(4n)$ residue compared with the predictions of the statistical model code PACE-IV for different values of the level density parameter.

$K = 8$. Therefore, it was assumed that the value of level density parameter $a = A/8$ MeV^{-1} may be taken as a default for the analysis of other residues populated in ^{12}C+^{169}Tm system at the studied energy range.

The excitation functions for xn, αxn, pxn, $2\alpha xn$ channels were compared with PACE-IV predictions assuming $K = 8$. The experimentally measured excitation functions for the xn/pxn channels agree reasonably well with those predicted by PACE-IV for $K = 8$, indicating the population of these residues via complete fusion of ^{12}C with ^{169}Tm target nuclei. However, for $\alpha xn/2\alpha xn$ channels, the experimentally measured cross sections are found to be significantly enhanced as compared to PACE-IV calculations. This enhancement may be attributed to a contribution of ICF. A similar analysis has been performed for ^{178,177,176,175}Re(xn), ^{177,176}W(pxn), ^{176,175,174,173}Ta(αxn), and ^{172,171}Lu($2\alpha xn$) residues populated via complete and or incomplete fusion of ^{12}C with ^{169}Tm. To get a clear picture of this effect, the incomplete fusion contribution in the aforementioned α-emitting channels has been deduced by subtracting the complete fusion cross section ($\sigma_{\text{CF-theory}}$) from the experimentally measured total fusion cross section ($\sigma_{\text{TF-exp}}$) at each studied energy, via $\sum\sigma_{\text{ICF}} = \sum\sigma_{\text{TF-exp}} - \sum\sigma_{\text{CF-theory}}$. The data reduction procedure used in the present work can be found in Ref. [1, 2]. To show how the strength of incomplete fusion changes with energy, the value of $\sum\sigma_{\text{ICF}}$ was plotted in Fig. 3 (a) as a function of projectile energy along with the values of $\sum\sigma_{\text{CF}}$ and $\sum\sigma_{\text{TF}}$ at different energies. The increasing separation between $\sum\sigma_{\text{CF}}$ and $\sum\sigma_{\text{TF}}$ with energy, visible in this figure, indicates a larger incomplete fusion contribution at higher energies.

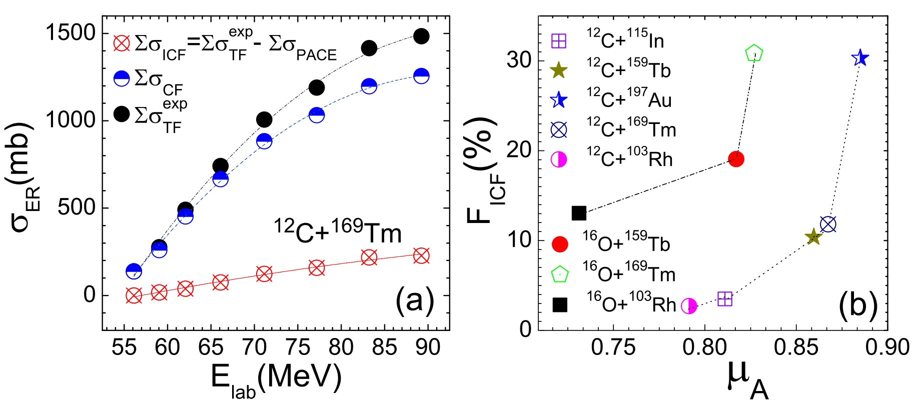

Fig. 3. (a) The values of $\sum\sigma_{\text{TF}}$, $\sum\sigma_{\text{CF}}$, and $\sum\sigma_{\text{ICF}}$ as a function of projectile energy, (b) percentage fraction of incomplete fusion (F_{ICF}) for different projectile–target combinations as a function of mass asymmetry (μ_{A}) at a constant value of $v_{\text{rel}} \approx 0.053\ c$.

Morgenstern *et al.* [11] proposed that the fraction of incomplete fusion increases with the mass asymmetry of interacting partners $\mu_{\rm A} = \frac{A_{\rm T}-A_{\rm P}}{A_{\rm T}+A_{\rm P}}$, only above the value $v_{\rm rel} \geq 0.06\, c$. Here, $v_{\rm rel} = \sqrt{2(E_{\rm cm} - V)/\mu}$ is the relative velocity between the colliding partners, $E_{\rm cm}$ is the energy in the centre-of-mass frame, V is the Coulomb potential, and μ is the reduced mass of the system. In light of Morgenstern's mass-asymmetry systematics, the percentage fraction of incomplete fusion ($F_{\rm ICF}$) for different projectile–target combinations is plotted in Fig. 3 (b) as a function of mass asymmetry at a constant value of $v_{\rm rel}$ [12–17]. As shown in this figure, the changes in contribution from the incomplete fusion with $\mu_{\rm A}$ do not follow the mass-asymmetry systematics for the presented projectile–target combinations. However, the value of $F_{\rm ICF}$ increases with $\mu_{\rm A}$ for each of the projectiles. Furthermore, it is interesting to note that the ^{12}C+^{169}Tm system is more mass-asymmetric than ^{16}O+^{169}Tm, but the value of $F_{\rm ICF}$ is $\approx 18\%$ higher for the former than that observed for the latter. This suggests an influence of the projectile structure along with the mass asymmetry of interacting partners on the observed strength of incomplete fusion. It may be pointed out that ^{16}O and ^{12}C projectiles are, respectively, four and three α-cluster nuclei, therefore, the probability of successive α-emitting channels may be higher in ^{16}O induced reactions as compared to those induced by ^{12}C for a given target.

In the present work, the value of $\sum \sigma_{\rm TF}$ and $\sum \sigma_{\rm CF}$ are found to be ≈ 1484 mb and ≈ 1255 mb at $E_{\rm lab} = 89.25$ MeV, respectively, whereas the theoretically calculated complete fusion cross section is found to be 1310 mb. Using this cross section, the maximum input angular momentum ($\ell_{\rm max}$) and the value of the critical angular momentum ($\ell_{\rm crit}$) are deduced using the sharp cutoff approximation which assumes that the tunnelling probability is unity. The calculated values of $\ell_{\rm max}$ and $\ell_{\rm crit}$ at $E_{\rm lab} = 89.25$ MeV are found to be $48 \pm 3\hbar$ and $44 \pm 1\hbar$, respectively. The value of $\ell_{\rm crit}$ deduced from the experimentally measured cross sections differs slightly from the well-known Wilczyński formula [18] (*i.e.*, is found to be 42 $\hbar$). Detailed results and analysis will be presented in a forthcoming paper [19].

4. Summary and conclusions

In the present work, the excitation functions for different evaporation residues populated in the ^{12}C+^{169}Tm reaction were measured in order to study the effect of various entrance channel parameters on the onset and strength of incomplete fusion at low incident energies. A substantial fraction of incomplete fusion has been observed even at energies slightly above the barrier. The projectile structure and mass asymmetry of interacting partners were observed to influence the onset and strength of incomplete fusion.

The probability of incomplete fusion is found to be higher for ^{16}O-induced reactions as compared to those with the ^{12}C projectile for a given target, which is suggested to be due to the α-cluster structure of these projectiles.

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REFERENCES

[1] A. Yadav *et al.*, *Phys. Rev. C* **96**, 044614 (2017).

[2] P.P. Singh *et al.*, *Phys. Lett. B* **671**, 20 (2009); *Phys. Rev. C* **77**, 014607 (2008) and references therein.

[3] F. Soramel *et al.*, *Eur. Phys. J. A* **4**, 17 (1999).

[4] W.J. Knox *et al.*, *Phys. Rev.* **120**, 2120 (1960).

[5] H.C. Britt, A.R. Quinton, *Phys. Rev.* **124**, 877 (1961); *Nucl. Phys. A* **373**, 109 (1982).

[6] J. Galin *et al.*, *Phys. Rev. C* **9**, 1126 (1974); T. Udagawa, T. Tamura, *Phys. Rev. Lett.* **45**, 1311 (1980).

[7] U. Gupta *et al.*, *Nucl. Phys. A* **811**, 77 (2008); *Phys. Rev. C* **80**, 024613 (2009).

[8] A. Gavron, *Phys. Rev. C* **21**, 230 (1980).

[9] R. Bass, *Nucl. Phys. A* **231**, 45 (1974).

[10] http://www.nndc.bnl.gov/nndcscr/documents/online/

[11] H. Morgenstern *et al.*, *Phys. Rev. Lett.* **52**, 1104 (1984); *Z. Phys. A* **324**, 443 (1986).

[12] P. Vergani *et al.*, *Phys. Rev. C* **48**, 1815 (1993).

[13] B. Bindu Kumar *et al.*, *Phys. Rev. C* **59**, 2923 (1999).

[14] M.K. Sharma *et al.*, *Nucl. Phys. A* **776**, 83 (2006).

[15] A. Yadav *et al.*, *Phys. Rev. C* **85**, 064617 (2012); **85**, 034614 (2012).

[16] V.R. Sharma *et al.*, *Phys. Rev. C* **89**, 024608 (2014).

[17] M. Shuaib *et al.*, *Phys. Rev. C* **94**, 014613 (2016).

[18] J. Wilczyński *et al.*, *Phys. Rev. Lett.* **45**, 606 (1980).

[19] R.N. Sahoo *et al.*, to be submitted to *Phys. Rev. C* (2018).