Indian Journal of Pure & Applied Physics
Vol. 58, May 2020, pp. 376-379

Variation of ICF strength function with projectile energy for ^{12}C + ^{165}Ho system at $E_{lab} \leq 7MeV/A$

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Received 4 May 2020

During the last few decades, research in heavy-ion induced nuclear reactions has opened numerous fields, in its theoretical and experimental domains. At energies, from near the Coulomb barrier to well above it, the complete fusion (CF) and incomplete fusion (ICF) reactions compete with each other. The relative contribution of these processes depends on various entrance channel parameters. In order to study the dependence of CF and ICF reaction dynamics on various entrance channel parameters, comparative studies with different parameters of the statistical model codes have been done. In this paper, an attempt has been made to study the dependence of incomplete fusion strength function on incident energy for ^{12}C + ^{165}Ho system at energies ≤ 7 MeV/A. The analysis of data has been done within the frame work of statistical model code PACE4, which do not take ICF into account; and thus predicts cross-section values only due to complete fusion process. For the present reaction system, the excitation functions (EFs) of xn/pxn channels, predicted by PACE4 code, well reproduces the experimentally measured values, indicating their production via CF process only. However, for α and 2α-emitting channels, calculated EFs through PACE4 code underpredict the experimentally measured cross-sections by ≈25-30%, in general. The enhancement of experimental cross-sections for α and 2α-emitting channels as compared to the PACE4 predictions, indicates that the major contribution of their production comes from the ICF of ^{12}C, if it breaks up into ^{8}Be and α-fragments, and one of the fragments fuses with the target nucleus. The incomplete fusion strength function (F_{ICF}), which gives relative importance of ICF processes over CF process has also been deduced and is found to depend sensitively on beam energy.

Keywords: Incomplete fusion strength function, PACE4 code, EMPIRE 3.2

1 Introduction

The study of heavy-ion (HI) induced reactions explores various interesting features of nuclear structure and complex reaction dynamics. At energies, from near the Coulomb barrier (V_b) to well above it, presence of incomplete fusion (ICF) in the comparison of strong existence of complete fusion (CF) has been observed in last few decades[1]. In the case of ICF reactions, a part of the projectile fuses with target nucleus, as compared to CF reactions, where entire projectile fuses with target nucleus[2,3]. In CF process ($l < l_{crit}$), entire momentum of projectile is transferred to the composite nucleus (CN), whereas, in ICF process ($l \geq l_{crit}$), partial momentum is transferred to the target nucleus. Observations of different reaction channels indicate that ICF starts competing with CF just above the Coulomb barrier (V_b). Although, at these energies, CF is the main contributor to the fusion cross-section[4,5]. The ICF process around the V_b in HI interactions is still not clearly understood and remains interesting topic of investigation. Further, the ICF leads to the formation of a 'hot' metastable incompletely fused composite system with less mass, charge and excitation energy as compared to the CF population. In heavy ion reactions, the ultimate state has a heavy residual nucleus, light ion (like n, p, α…..etc.) and/or γ-rays. Further, excitation function (EF) of a particular reaction is measured with the study of emitting channels and characteristic γ-rays. Apart from some other characteristics like, the fractional linear momentum transfer and entirely distinct spin distribution patterns for CF and ICF residues, enhancement in the fusion cross-section for α-emitting channels is an important characteristic of ICF reactions.

In this paper, comparative study has been done for available experimental data of ^{12}C + ^{165}Ho system at energies ≤ 7 MeV/A[6] with theoretical predictions made in the frame work of statistical model using computer code PACE4[7]. The work has also been compared with that of ^{12}C + ^{169}Tm system[8].

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2 Statistical Model Code: PACE4

This code is based on Hauser-Feshbach theory of CN decay. In this code, angular momentum conservation is taken into account and CF cross-sections of the evaporation residues (ERs) are calculated using Bass formula[9]. The code calculates transmission coefficients for neutron (n), proton (p) and alpha particles (α) using the optical model potentials (OMP). The OMP has many parameters which are phenomenonlogically determined from fitting of elastic scattering data. As such, the choice of parameters is not unique. Several sets of OMP parameters have been reported for different range of mass numbers and energies in the literature. According to the mass number and energies involved in present case, modified OMP have been used for the calculations of cross-sections predicted by PACE4. It may be pointed out that the code PACE4 predicts cross-sections only for CF channels and does not take ICF channels into account. Any deviation in the experimental EFs with respect to the PACE4 may be attributed due to the existence of ICF process. An important parameter of this code is, the level density parameter 'α' (α = A/K MeV^{-1}, A being the mass number of CN). Here the free parameter 'K' may be varied to match experimental data.

3 Analysis

3.1 xn/pxn channels

In the present work, experimentally measured EFs of xn/pxn channels in^{12}C + ^{165}Ho system have been compared with code PACE4 predicted EFs at different level density parameter K= 8, 10, 12. As can be seen from Fig.1, that the experimentally measured EFs for 3n, 4n and 5n channels match with PACE4 predictions in general. However, as can be seen from Fig. 2, the experimentally measured EFs of p3n and p5n channels are found to be higher as compared to PACE4 calculations, which indicates the contribution of precursor i.e. ^{173}Ta (4n) in ^{173}Hf (p3n) and ^{171}Ta (6n) in ^{171}Hf (p5n) reactions. Overall, a good agreement between experimental and theoretical EFs values of xn/pxn channels indicates the production of these channels via CF process only. Further it can be seen from the figures, that the experimentally measured EFs of these channels have good agreement with level density α=A/10 MeV^{-1}, in general. Therefore the value of K = 10 has been used consistently as fixed parameter for further analysis.

Further, in Figs 3 and 4, to get a better insight, the available experimental data [6] has been compared with another computer code EMPIRE 3.2 [10]along with PACE4 predictions at K=10. The trend is found to be almost same for the channels, except 3n channel at higher energies, where, there is an enhancement in the cross-section predicted by the code EMPIRE 3.2, while PACE4 predictions underestimate the cross-section.

3.2 α-emitting channels

EFs for (αxn) and (2αxn) channels have been plotted in Fig. 5. As can be seen, experimentally measured EFs of α and 2α-emitting channels are underpredicted by PACE-4 calculations taken by

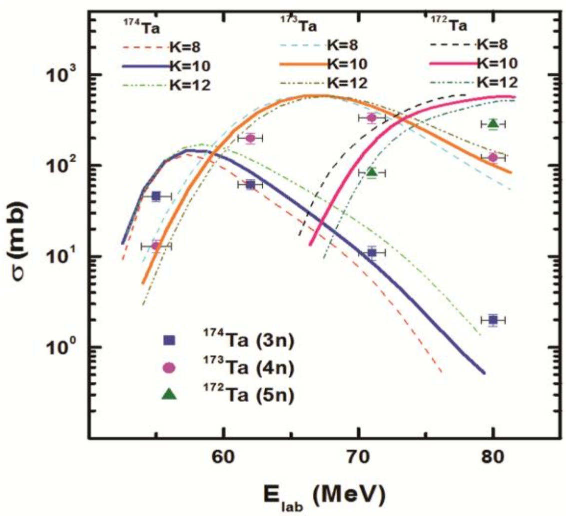

Fig. 1 — Experimental EFs of ^{174}Ta (3n),^{173}Ta (4n), ^{172}Ta (5n) residues populated in ^{12}C + ^{165}Ho system. The lines are predictions of PACE4 code with different values of K (= 8, 10, 12).

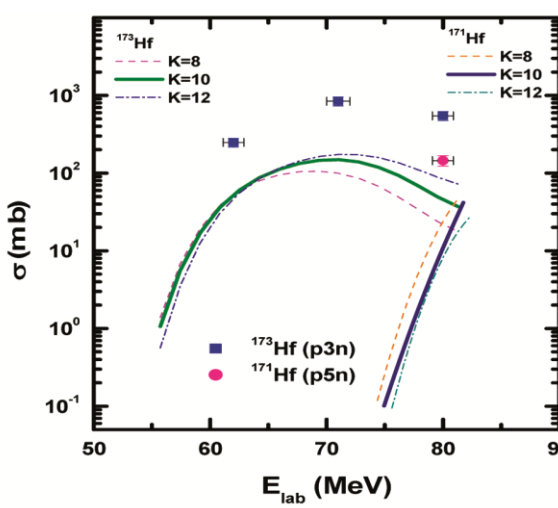

Fig. 2 — Experimental EFs of ^{173}Hf (p3n) and ^{171}Hf (p5n) residues compared with PACE4 predicted values.

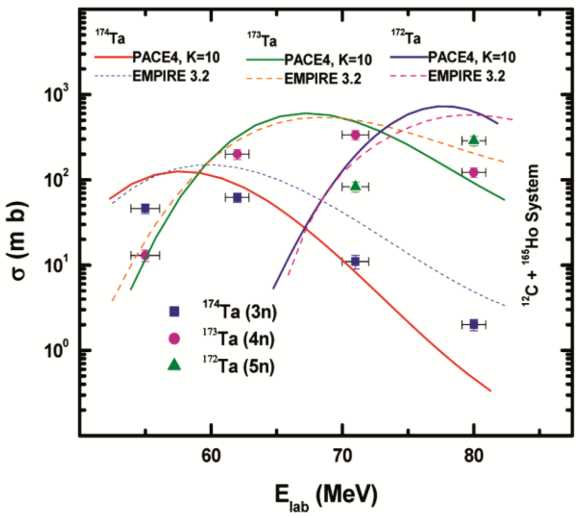

Fig. 3 — Experimental EFs of ^{174}Ta (3n), ^{173}Ta (4n), ^{172}Ta (5n) residues populated in ^{12}C + ^{165}Ho system. The lines are predictions of PACE4 code and EMPIRE 3.2.

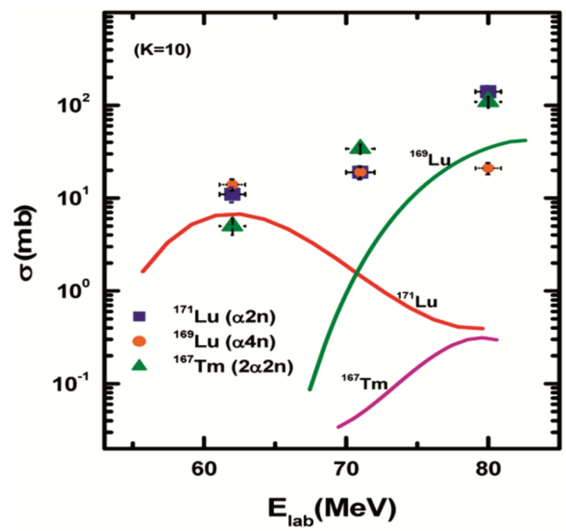

Fig. 5 — Experimental EFs of ^{171}Lu (α2n), ^{169}Lu (α4n) and ^{167}Tm (2α2n)are compared with the PACE4 predictions with K=10.

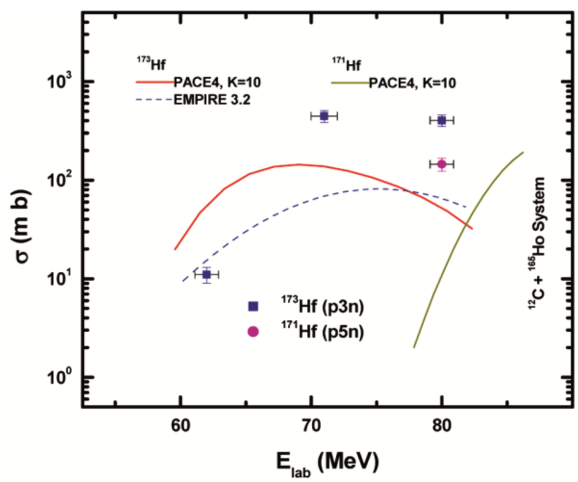

Fig. 4 — Experimental EFs of ^{173}Hf (p3n) and ^{171}Hf (p5n) residues compared with PACE4 & EMPIRE 3.2 predicted values.

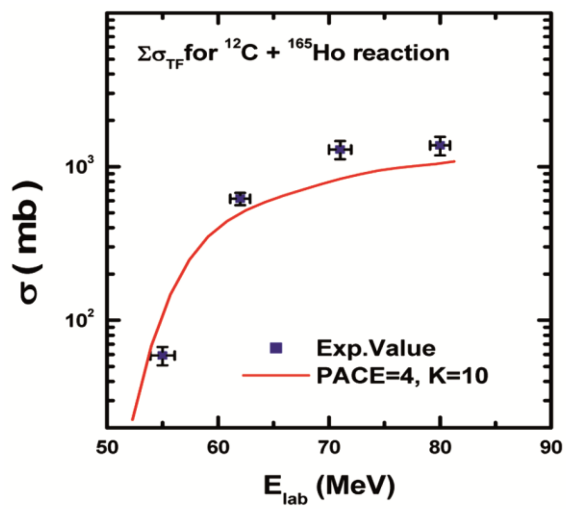

Fig. 6 — Comparison between experimentally observed and theoretically predicted total fusion cross-section ($\Sigma\sigma_{TF}$).

using same set of parameters as for xn/pxn channels with K=10. Enhancement of the experimental cross-sections for α and 2α-emitting channels as compared to the statistical model code PACE4 predictions, indicates that the major contribution of their production comes from the ICF of ^{12}C with the target ^{165}Ho, if it breaks up into ^{8}Be and α-fragments, and only one of the fragments fuses with the target nucleus.

3.3 ICF strength function

Comparison of total fusion (TF) cross-sections and PACE4 predictions has been plotted in Fig. 6. Experimental σ_{TF} values are the sum of cross-sections of CF and ICF both, whereas PACE4 predictions are only due to CF. It may be mentioned that a correction has been added in σ_{TF} for channels predicted by PACE4 but not measured experimentally because of limitations of experiment. Hence, the enhancement in the experimental values of σ_{TF} compared to corresponding PACE4 values, clearly, indicates the presence of ICF.

Further, the incomplete fusion strength function F_{ICF}[$F_{ICF} = (\Sigma\sigma_{ICF}/\Sigma\sigma_{TF})$x100]has been deduced from the experimental EFs and its dependence on beam energy has been tested.

Fig. 7 shows the deduced strength function F_{ICF} at different beam energies for ^{12}C + ^{165}Ho system. As can be seen from Fig. 7, the fraction of ICF has been

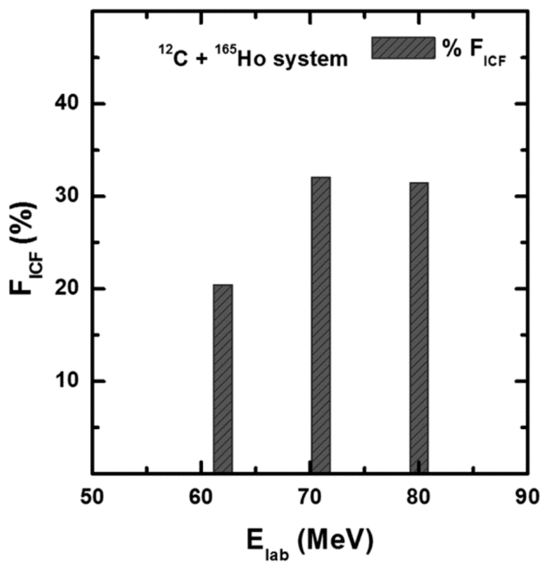

Fig. 7 — Percentage of fraction of ICF(F_{ICF}) as the function of beam energy(E_{lab}).

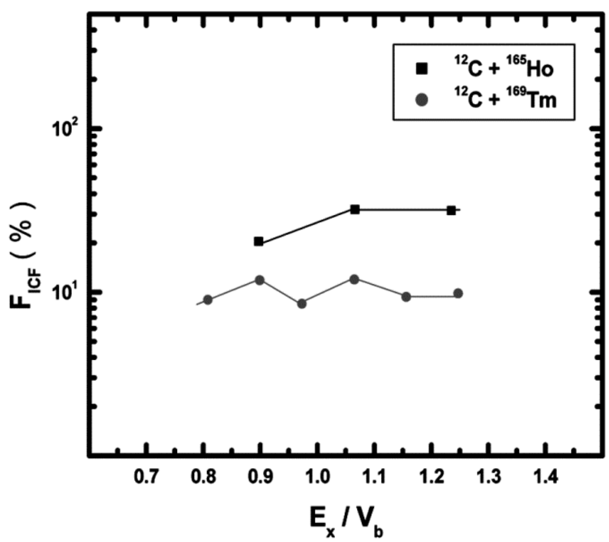

Fig. 8 — Comparative F_{ICF} (%) for two systems ^{12}C + ^{165}Ho and ^{12}C + ^{169}Tm as a function of excitation energy/ barrier height(E_x / V_b). The solid lines are eye guide to the graphical points.

found to vary with increasing values of projectile energy and clearly indicates the beam energy dependence of ICF. The present work for ^{12}C + ^{165}Ho system has been compared with ^{12}C + ^{169}Tm system [8] in Fig. 8. The variation of deduced ICF fraction for the two target projectile combinations has been studied as a function of excitation energy/barrier height (E_x/ V_b).As can be seen from Fig. 8, the percentage ICF fraction is found to decrease for more asymmetric system in this particular case.

4 Conclusions

In the present work, experimentally measured EFs for xn/pxn and αxn/2αxn channels populated in ^{12}C + ^{165}Ho system have been compared with theoretical EFs predicted by PACE4. For xn/pxn channels, experimental values have been found in good agreement with theoretical values of PACE4 with level density $\alpha = A/10$ MeV^{-1}, indicating their production via CF only. Whereas, for αxn/2αxn channels, comparison indicates the presence of ICF and the strength of ICF varies as projectile energy increases. Further, comparative study of ICF fraction variation with E_x / V_b for two almost similar mass systems ^{12}C + ^{165}Ho and ^{12}C + ^{169}Tm has been done. In the present study, it appears that the percentage ICF fraction decreases for slightly more asymmetric system. This may be due to the fact that some channels could not be measured because of experimental limitations[8]. Further investigations are required for many more systems for better understanding of systematics.

References

1 Shuaib M, Sharma V R, Yadav A, Thakur S, Sharma M, Majeed I, Kumar M, Singh P P, Singh D P, Kumar R, Singh R P, Muralithar S, Singh B P & Prasad R, *Phys Rev C*, 99 (2019) 024617.
2 Singh P P, Singh B P, Sharma M K, Gupta U, Kumar R, Singh D, Singh R P, Murlidhar S, Ansari M A, Prasad R & Bhowmik R K, *Phys Lett B*, 671 (2009) 20.
3 Lane G J, Dracoulis G D, Byrne A P, Poletti A R & McGoram T R, *Phys Rev C*, 60 (1999) 067301.
4 Dasgupta M, Hinde D J, Mukherjee A & Newton J O, *Nucl Phys A*, 787 (2007) 144.
5 Canto L F, Donangelo R, Mator Lia M, Hussein M S & Lotti P, *Phys Rev C*, 58 (1998) 1107.
6 Gupta S, Singh B P, Musthafa M M, Bhardwaj H D & Prasad R, *Phys Rev C*, 61 (2000) 064613.
7 Gavron A, *Phys Rev C*, 21 (1980) 230.
8 Chakrabarty S, Tomar B S, Goswami A, Gubbi G K, Manohar S B, Sharma A, Bindukumar B & Mukherjee S, *Nucl Phys A*, 678 (2000) 355.
9 Bass R, *Phys Rev Lett*, 39 (1997) 265.
10 Herman M, Capote R, Carlson B V, Obložinský P, Sin M, Trkov A, Wienke H & Zerkin V, *Nucl Data Sheet*, 108 (2007) 2655.