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Systematic study of incomplete fusion reactions: Role of various entrance channel parameters

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The evaporation residues, populated through complete and incomplete fusion processes in the reaction of ^{18}O+ ^{165}Ho, have been analyzed via excitation function measurements at projectile energies ≈ 4-7 MeV/nucleon. The cross-sections measured experimentally have been compared with the predictions of the compound nucleus model code PACE-4 calculations which only considers complete fusion (CF) reaction cross-sections. The experimental cross-section of the reaction residues populated through xn and pxn channels matches well with the theoretical model code PACE-4 predictions. On the other hand, α-emitting channels show an enhancement in the measured cross-section over PACE-4 calculations which reveals the occurrence of incomplete fusion (ICF) at the studied energy range. The relative percentage of incomplete fusion has been calculated from the experimental data and its dependence on various entrance channel parameters like projectile energy, mass-asymmetry, α-Q value and Coulomb factor (Z_PZ_T) has been studied. The strength of incomplete fusion function obtained in the ^{18}O+ ^{165}Ho interaction has been compared with the previously studied systems. Results of the present study indicate that ^{18}O (two neutron excess) projectile shows more incomplete fusion contribution as compared to ^{12}C,^{13}C and ^{16}O projectiles due to its relatively small negative α-Q value.

Keywords: Incomplete fusion reactions, PACE-4, Foil activation technique, Excitation function

1 Introduction

Extensive efforts have been made experimentally and theoretically to understand the heavy-ion induced reaction dynamics at energies below 10 MeV/nucleon[1,2]. The incomplete fusion reaction dynamics was first observed by Britt and Quinton using ^{12}C, ^{14}N and ^{16}Oprojectiles for the bombardment of Au and Bi targets at energies ≈10.5 MeV[3]. Later on γ-ray multiplicity measurements performed by Inamura *et al.* provide ample information on ICF reaction dynamics[4]. At relatively low energies, similar observations have been reported by Kauffman and Wolfgang in which projectile like fragments (PLF’s) were identified in the forward cone[5]. Moreover, the origin of PLF’s from undamped non-central collisions was reported by Geoffroy *et al*. by correlating energies and angular distributions along with γ multiplicity into consideration[6]. Tserruya *et al*. also reported the ICF reaction dynamics by measuring the time of flight of evaporation residues[7]. Various theoretical models have been proposed and adapted to explain the mechanism of ICF reaction dynamics. The breakup fusion model (BUF) of Udgawa *et al*.[8] and the sum rule model by Wilczynski *et al*.[9] are the most widely used models to describe the ICF reaction dynamics. All the above-aforementioned models have been confined to explain the ICF reactions at energies ≥ 10 MeV/nucleon. Till now no reliable theoretical model is available which could reproduce experimental data at relatively low energies ≈ 4-7 MeV/nucleon and hence makes the investigation of ICF reaction dynamics still an active area of research. In the present work, excitation functions (EFs) of several reaction residues have been measured in the reaction of ^{18}O+^{165}Ho at projectile energies ≈ 4-7 MeV/nucleon. To understand the effect of neutron excess projectiles on low energy ICF reaction dynamics, present work has been taken into

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consideration. Also, a comparison of ICF fraction obtained in the present data with the data available in the literature helps to understand the ICF behavior from the non-α to α-cluster structure projectiles. The dependence of ICF reaction dynamics on entrance channel parameters like (a) Incident energy of the projectile, (b) mass-Asymmetry, (c) Coulomb factor ($Z_P Z_T$) and (e) α-Q value of the projectile is studied in the current work to reach on some definite conclusion.

2 Experimental Details

The experiment was performed at Inter-University Accelerator Center, New Delhi using the ^{18}O ion beam by employing the activation foil technique. The main advantage of the activation foil technique is that at different energies many target foils can be irradiated together in single irradiation through which more possible reactions can be studied. The rolling technique has been followed for the preparation of the targets of ^{165}Ho of thickness ~1.0-1.5 mg/cm^{2}and Al-foils of thickness~ 1.5-1.7 mg/cm^2. The thickness of the target and degrader foils has been determined by weighing as well as by the α-transmission method. Irradiation of two stacks, with three target-catcher assemblies in each, has been done separately by ^{18}O at energies 105 MeV and 88 MeV in the General purpose Scattering Chamber (GPSC). Considering the half-lives of interest, irradiation of each stack has been carried out for a duration of ≈ 10 hours. γ source (^{152}Eu) of known strength has been used for the calibration of the HPGe detector. The source was kept at different source-detector positions for determining the energy and geometry dependent efficiency of the detector. After irradiation, the off-line measurements of the target-catcher assemblies were performed. The pre-calibrated High Purity Germanium Detector (HPGe) has been used for counting the activities produced in the target-catcher assemblies individually coupled to a CAMAC based data acquisition system. Counting of γ-rays from the populated ERs has been carried out for a few days, at an interval ranging from 10 minutes to several hours.

3 Results and Discussion

In the interaction of ^{18}O+^{165}Ho, excitation functions (EFs) of eleven evaporation residues populated through the process of CF and/or ICF have been measured at E_{Lab} ≈ 88 MeV – 105 MeV. The EFs measured have been examined within the framework of the compound nucleus model code PACE-4[10] based on Hauser-Feshbach theory[11]. PACE-4 uses the BASS model to calculate the fusion cross sections[12]. The code PACE-4 involves the nuclear level density parameter a=A/K, where A represents the mass of the compound nucleus and K is an adjustable parameter, which may be varied to match the experimental data. It is observed in the present analysis that the experimental cross-sections of the reaction residues populated via xn/pxn channels match well with the predictions of PACE-4 at a= A/10 MeV^{-1} indicating that these residues are populated via CF process. An enhancement in cross-sections for αn and αxn channels over the theoretical cross-sections predicted by PACE-4 is observed at the same level density parameter a= A/10 MeV^{-1} indicating their population through the ICF process. The ICF fraction for the present system is calculated as F_{ICF} (%) = $(\sum\sigma_{ICF}/\sigma_{TF})$ * 100 where$\sigma_{TF} = \sum\sigma_{ICF} + \sum\sigma_{CF}$. In this work ICF dependence on the various entrance channel parameters has been investigated.

3.1 Responsivity of ICF to the α-Q value of the projectile

To understand the effect of α-Q value of the projectile on ICF reaction dynamics, we have compared the present data (α-Q value of ^{18}O =-6.228) with that given in the literature (α-Qvalues of ^{16}O[13], ^{12}C [14] and ^{13}C [15] are -7.161, -7.367 and -10.648 respectively). From Fig. 1 it is clear that the projectiles carrying less negative α-Q value show more ICF contribution than those having more negative α-Q values. Thus, it is worth to mention that ^{18}O is less bound and therefore has a larger probability to break-up into clusters in the nearby nuclear field of the target nucleus as compared to

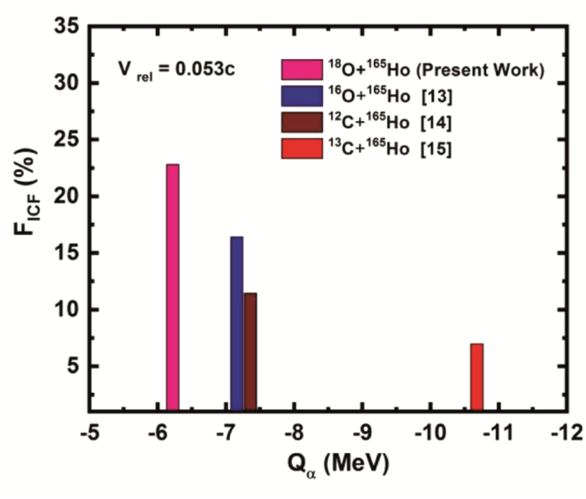

Fig. 1 — Comparison of the F_{ICF} values extracted for ^{18}O+^{165}Ho system along with the previously studied systems as a function of α-Q value of the projectile.

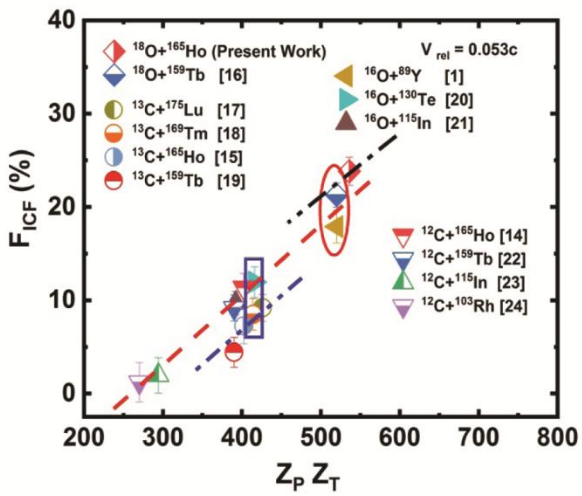

Fig. 2 — Comparison of the F_{ICF} values extracted for $^{18}O+^{165}Ho$ system along with the previously studied systems as a function of Z_PZ_T

other projectiles ^{16}O, ^{13}C and ^{12}C. Hence it may be figured out that α-Q value is one of the important entrance channel parameters to understand the ICF reaction dynamics.

3.2 Responsivity of Z_PZ_T on ICF

In order to check how does the Coulomb factor (Z_PZ_T) affect ICF reaction dynamics, the ICF strength function deduced in the present data has been compared with other earlier studied systems[1,13-24] available in the literature at constant value of V_{rel} = 0.053c.

It can be seen from Fig. 2 that the probability of ICF increases with Z_PZ_T implying that as the projectile approaches the nuclear field of the target nucleus, the breakup probability of projectile increases due to the enhancement of Coulomb interaction with an increase in Z_PZ_T. Also F_{ICF} follows linear systematics. Again as shown in Fig. 2 some projectile-target combinations possess the same value of Z_PZ_T but their ICF contributions are different. It arises due to the different α-Q values of the projectiles. Hence it is pertinent to mention that the Coulomb factor (Z_PZ_T) alone is not enough to explain low energy ICF reaction dynamics but the α- Q value of the projectile must be taken into account to understand the ICF reaction dynamics. Therefore, sufficient data is needed to understand the ICF reaction dynamics at energies 4-7 MeV/ nucleon.

4 Conclusions

Excitation functions of various evaporation residues in the interaction of $^{18}O+^{165}Ho$ have been measured to understand the reaction mechanism involved in their production. It has also been observed that the ICF dynamics is not affected by a single entrance channel parameter but it is also affected by several parameters like α-Q value and Z_PZ_T etc. Furthermore, it has been observed that the breakup probability of the projectile increases as the value of Z_PZ_T increases. In addition, it has been found that some projectile- target combinations have the same value of Z_PZ_T but possess a different value of ICF strength fraction which is due to different α-Q value of the projectiles. Moreover, α-Q value of the projectile is observed to be an important entrance parameter on which ICF depends. In order to reach on some definite conclusions regarding CF and ICF dynamics more experiments are required to be performed in the energy regime of 4-7 MeV.

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