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Role of alpha cluster over non alpha cluster projectile in low energy incomplete fusion reaction dynamics

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Continuous efforts are being made to comprehend the process of low energy incomplete fusion (ICF) reaction dynamics. The lack of proper theoretical model below 8 MeV/nucleon, which could reproduce the experimentally measured ICF data satisfactorily, makes it the topic of great interest. Another important motivation is to look for some systematic dependence of ICF on various entrance channel parameters. Keeping the aforementioned aspects into consideration, the experiment has been performed using ^{12}C ion beam on ^{165}Ho target by employing the stacked foil activation technique. The experimentally measured cross sections of the populated evaporation residues have been measured and compared with the complete fusion code PACE4. It has been observed that the measured cross sections for evaporation residues populated via xn and pxn emission channels are well reproduced by PACE4 code. However, in the α-emission channels (observed in the projectile break-up), the significant enhancement in the measured cross sections over PACE4 predictions is observed which is accredited to ICF process. In the present work, ICF dependence on the target deformation and the combined parameter $\mu * Z_P Z_T * (1-\beta_2)$has been studied. The ICF fraction has also been found sensitive to projectile Q_α- value.

Keywords: Complete and incomplete fusion, Incomplete fusion fraction, Target deformation, Projectile Q_α value

1 Introduction

The study of heavy ion (HI) fusion reactions is of great interest for both theoretical and experimental nuclear physicists. Depending upon the mass and energy of the interacting nuclei, such reactions may lead to the formation of super-heavy elements. The study of such nuclear reactions may also provide explicitly some important information related to nuclear astrophysics. In the energy region of ≈ 4-7 MeV/nucleon, various processes can take place for tightly bound projectile induced reactions with heavy mass targets[1]. The incident projectile may completely fuse with the target nucleus known as direct complete fusion (DCF). There is also a probability that projectile may break-up into fragments in the vicinity of target nuclear field and all the fragments may fuse with the target nucleus sequentially, known as sequential complete fusion (SCF). The third process is that one of the break-up fragments may fuse with the target nucleus known as break-up or incomplete fusion (ICF). The unfused fragment in incomplete fusion moves in the forward direction as a spectator with almost the incident beam velocity[2-4]. There is also a probability that none of the break-up fragments may fuse with the target nucleus, which is known as non capture break-up (NCBU) process. Figure 1 shows these different reaction processes that may take place with ^{12}C as projectile. Experimentally the SCF cannot be distinguished from the DCF[5] hence, CF cross section is the sum of SCF and DCF.

Many efforts are being made to comprehend the phenomenon of complete and incomplete fusion nuclear reaction dynamics. The current interest is to understand the dependence of incomplete fusion on (a) incident projectile energy, (b) projectile-target mass asymmetry, (c) coulomb effect, (d) target deformation, (e) projectile structure and to search some new entrance channel parameters on which incomplete fusion process may depend. Further, the lack of proper theoretical model, which could reproduce the experimentally measured incomplete fusion reaction cross sections appropriately, is also a

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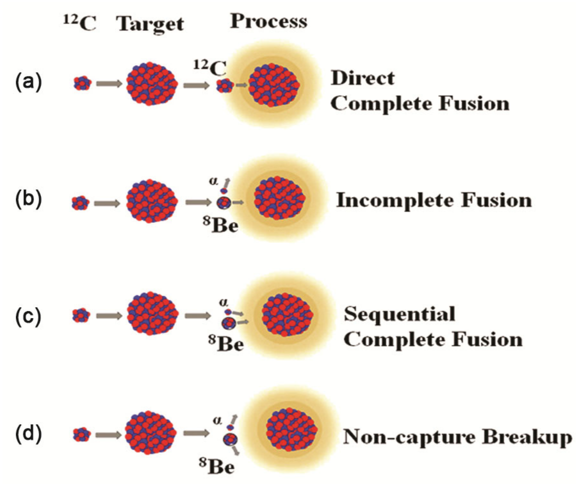

Fig. 1 – Diagram showing different reaction processes that may occur with ^{12}C as projectile.

motivation for the present study. Hence, keeping the above views into consideration the experiment was performed using ^{12}C (alpha cluster) as projectile and ^{165}Ho (deformed) as target.

2 Experimental Details

The experiment was performed at Inter-University Accelerator Center (IUAC), New Delhi. The ^{165}Ho target foils and Al-catcher foils were prepared by using the rolling technique at the target fabrication laboratory, IUAC, New Delhi. The stacked foil activation technique[6] was implemented, so as to cover a wide range of energy in the less beam time. Stacks consisting of target foils and backed by Al-foils were irradiated by the ^{12}C ion beam to cover the energy above the Coulomb barrier and up to 87.4 MeV in the general purpose scattering chamber (GPSC). The schematic figure for EF measurements is shown in Fig. 2. After the irradiation, the target-catcher assembly was dismantled immediately from the GPSC and the γ-ray activities build up in the foils were recorded by keeping them in front of the high purity Germanium detector (HPGe). The HPGe detector was coupled to PC through CAMAC based data acquisition system CANDLE[7]. The HPGe detector was calibrated with the ^{152}Eu source at different source to detector distances. The dead time of the detector was kept less than 10%, throughout the counting of the irradiated samples. The cross section of the evaporation residues (ERs) populated in the interaction of ^{12}C + ^{165}Ho system at different energy points was calculated by using the same formula as used in our earlier work[2]. During the experiment proper care was taken while measuring the

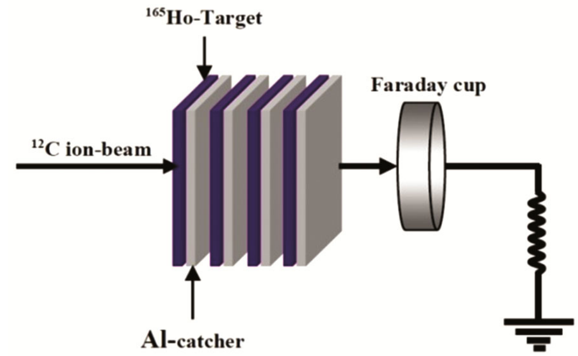

Fig. 2 – A schematic representation of stack arrangement used for the EF measurement of ^{12}C + ^{165}Ho system.

thickness of the target/catcher foils, incident beam flux, detector efficiency whose inaccurate measurements may add an error to the measured cross sections. Further the detailed experimental procedure is given in our earlier work[8].

3 Results and Discussion

When the incident projectile interacts with the target nucleus, the compound nucleus formed via complete fusion and/or incomplete fusion process is in the highly excited state and de-excites via emission of light nuclear particles and their characteristic gamma rays. In the present work, the EFs of several ERs populated via xn, pxn, αxn, αpxn and 2αxn were measured. The experimentally measured cross sections were compared with the statistical model code PACE4[9], which is based on Hauser-Feshbach theory[10] of compound nucleus (CN) decay. During the calculation, Gilbert and Cameron's[11] nuclear level density parameter $a = A/_K\ MeV^{-1}$ were used, where 'A' is the mass number of the nucleus and 'k' is the free parameter. In order to reproduce the measured cross sections, the value of free parameter can be varied within the physically justified limits[11]. The PACE4 code gives only the CF cross sections which are calculated by using the Bass model[12].

During the analysis, it was observed that the experimentally measured independent cross sections of the ERs populated via emission of xn and pxn channels were in good agreement with the PACE4 predictions at level density parameter $a = A/_{10}\ MeV^{-1}$, which employs that these ERs are populated via CF process. However, in case of αxn, αpxn and 2αxn emission channels the experimentally measured independent cross sections show a significant enhancement from the PACE4 predictions

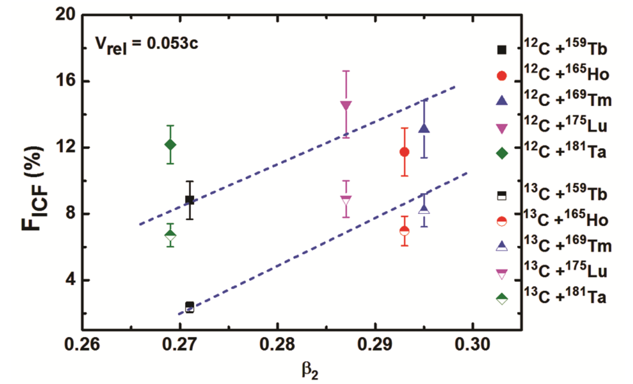

Fig. 3 – The deduced ICF fraction F_{ICF} (%) as a function of target deformation (β_2) at constant relative velocity (V_{rel} = 0.053 c), for $^{12,13}C$ projectile induced reactions with different targets. For references refer to text. The dotted lines are just to guide the eyes.

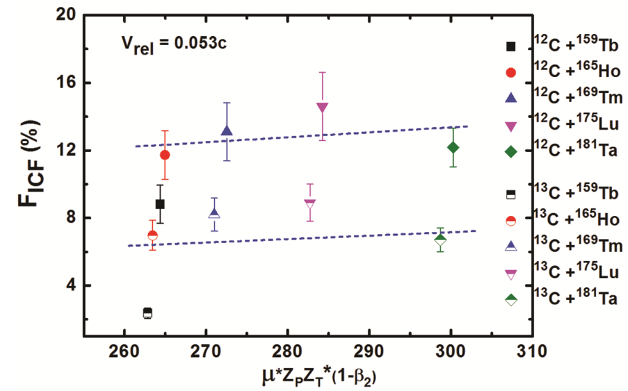

Fig. 4 – The deduced ICF fraction F_{ICF} (%) as a function of $\mu * Z_P Z_T * (1-\beta_2)$ at constant relative velocity (V_{rel} = 0.053 c), for $^{12,13}C$ projectile induced reactions with different targets. For references refer to text. The dotted lines are just to guide the eyes.

for the same level density parameter $a = {}^{A}/_{10}\ MeV^{-1}$, which is attributed to the ICF process. The ICF fraction, which is defined as strength of ICF relative to total fusion, i.e., $F_{ICF}(\%) = \left(\sum {}^{\sigma_{ICF}}/_{\sigma_{TF}}\right) \times 100$, $\sigma_{TF} = \sum\sigma_{CF} + \sum\sigma_{ICF}$ was obtained. In order to understand the dependence of ICF on target deformation 'β_2', the F_{ICF}(%) deduced for the present system $^{12}C + {}^{165}Ho$ is plotted in Fig. 3 along with the earlier studied systems $^{12}C + {}^{159}Tb$[13], $^{12}C + {}^{169}Tm$[14], $^{12}C + {}^{175}Lu$[8], $^{12}C + {}^{181}Ta$[15], $^{13}C + {}^{159}Tb$[16], $^{13}C + {}^{169}Tm$[17], $^{13}C + {}^{175}Lu$[8], $^{13}C + {}^{181}Ta$[15], at constant relative velocity (V_{rel} = 0.053 c) for various projectile-target combinations. The β_2 values are taken from literature[18]. It may be seen from Fig. 3, that as the value of target deformation increases, the F_{ICF} (%) increases, but increases differently for ^{12}C (α-clustered) and ^{13}C(non α-clustered) projectile induced reactions with the same targets. However, a regular trend is not observed. Moreover an attempt has been made to explore the dependence of ICF dynamics on the combination of entrance channel parameters $\mu * Z_P Z_T * (1-\beta_2)$, where 'μ' is the mass asymmetry, 'Z_PZ_T' is the Coulomb effect and 'β_2' is the target deformation. Hence, keeping this under view, in Fig. 4 the F_{ICF} (%) is plotted against $\mu * Z_P Z_T * (1-\beta_2)$. It is important to mention that the systems and their symbols are the same as in Fig. 3. From this graph, it is clear that F_{ICF} (%) increases almost linearly but for ^{12}C projectile induced reactions F_{ICF} (%) is more compared to ^{13}C induced reactions with the same targets. This difference may be explained on the basis of projectile Q_α value, which is simply defined as the amount of energy required to liberate an alpha particle from the incident projectile. As the projectile Q_α value for ^{12}C (-7.37 MeV) is less compared to ^{13}C (-10.65 MeV) hence, the reactions involving ^{12}C as projectile shows more F_{ICF} (%) compared to ^{13}C projectile induced reactions. Moreover, the value of ICF fraction for both $^{12,13}C + {}^{159}Tb$ is less and is away from the linear trend, this is probably due to the less mass asymmetry of these systems compared to others.

4 Conclusions

Various evaporation residues were populated in the interaction of $^{12}C + {}^{165}Ho$ system in the energy region of ≈4-7 MeV/nucleon. It is observed that ICF fraction almost increases with target deformation but the rate of rise does not follow any systematic trend. In order to better understand the ICF dynamics, an attempt is made to investigate the ICF dependence on the combination of entrance channel parameters $\mu * Z_P Z_T * (1-\beta_2)$. From which, it is observed that ICF increases almost linearly with target deformation but distinctly for alpha cluster (^{12}C) and non alpha cluster (^{13}C) projectile induced reactions with the same targets. Further, projectile Q_α value also seems to be an important entrance channel parameter on which ICF depends. More experiments are required to be performed in this energy region, with different projectile-target combinations to reach on some definite conclusions regarding complete and incomplete fusion dynamics.

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