DOI: 10.15415/jnp.2015.31007

Influence of Incomplete Fusion Reaction on Complete Fusion Below 10 Mev/ Nucleon Energies

HARISH KUMAR[1*], RAHBAR ALI[2], D. SINGH[3], NASEEF M. P. N.[1], M. AFZAL ANSARI[1**], K. S. GOLDA[4], S. MURALITHAR[4], RAKESH KUMAR[4], J. J. DAS[4], R. P. SINGH[4] AND R. K. BHOWMIK[4]

[1] Department of Physics, Aligarh Muslim University, Aligarh – 202002, INDIA

[2] Department of Physics, G. F. (P. G.) College, Shahjahanpur -242 001, INDIA

[3] Centre for Applied Physics, Central University of Jharkhand, Ranchi – 835 205, INDIA

[4] Inter-University Accelerator Centre, New Delhi – 110 067, INDIA

* **Email: amu.harish@gmail.com**

Received: May 23, 2015 | Revised: June 05, 2015 | Accepted: June 24, 2015

Published online: August 03, 2015
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Abstract: An attempt has been made in the present work to provide an ample opportunity to explore the information about the influence of incomplete fusion (ICF) reaction dynamics on complete fusion in heavy ion induced nuclear reactions. Excitation functions for several evaporation residues produced in the interaction of projectile ^{16}O with target ^{175}Lu have been measured over the wide projectile energy range ≈ 70-100 MeV. The recoil-catcher activation technique followed by the offline γ-ray spectroscopy has been used for the present measurements. In case of precursor decay, we have made use of Cavinato *et al.* formulation to calculate the independent cross-section of the identified residues. The measured EFs are compared with theoretical predictions of statistical model code PACE-2 and any enhancement in the measured cross-section from theoretical prediction may be due to ICF reaction process. An attempt has been made to estimate the ICF contribution of the cross-section from the measured excitation function data and the dependence of ICF cross-section on projectile energy.

Keywords: Heavy Ion Nuclear Reaction, Fusion, Excitation Function, Activation Technique, Break-up Probability

1. INTRODUCTION

In recent years, the study of heavy-ion (HI) induced nuclear reactions with heavier target nuclei has been the subject of renewed interest for the better understanding of reaction dynamics. It is now well established from the earlier

Journal of Nuclear Physics, Material Sciences, Radiation and Applications
Vol. 3, No. 1
August 2015
pp. 47–54

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studies that incomplete fusion (ICF) reactions start competing with the complete fusion (CF) reactions at projectile energies just above the Coulomb barrier. In CF processes, the entire projectile fuses with the target nucleus in the vicinity of target nuclear field and formation of an equilibrated compound nucleus comes into existence which may further decay by emitting the particles and/ or characteristics γ-rays. However, in case of ICF, the break-up of projectile may takes place into two fragments, near to the target nuclear field. One of the fragments fuses with the target while remnant moves as spectator in the forward direction with approximately beam velocity [2-4], [9], [11-15]. Incomplete fusion (ICF) or massive transfer reactions have been studied extensively at lower projectile energies below 10 MeV/nucleon in recent years. However, the study of ICF is still an active area of investigations due to complex nature of incomplete mass transfer mechanism and its ambiguous dependence on various entrance channel parameters. The ICF features first observed by Britt and Quinton [5] at lower projectile energies with the break-up of projectiles like ^{12}C, ^{14}N, and ^{16}O into α-clusters. Later on Inamura *et al.* [16] provided the additional but concrete information to understand the ICF reaction dynamics.

Several models have been proposed to explain the ICF reactions, such as Break-up fusion model [17] of Udagawa and Tamura, Sum-rule model of Wilczynski et al. [8] and promptly emitted particles (PEP) [7] etc. The existing models have been used to fit the experimental data above 10 MeV/nucleon energies. However, no theoretical model is yet available to explain ICF process data satisfactorily at energies less than 10 MeV/nucleon. Thereby, ICF reaction mechanism is still an active area of investigations. Most of the studies on ICF have been centered to medium mass target (A $\leq$ 100) around beam energies $\approx$ 4-7 MeV/nucleon. There are fewer studies with heavier targets (A $\geq$ 150) at lower projectile energies $\approx$ 4-7 MeV/nucleon. In case of heavier target nuclei, the evaporation of α-particle from the compound nucleus has the less probability due to the high Coulomb barrier, thereby, ICF fraction is observed to be dominating as that of CF fraction in α-particles emission products. In order to reach on some definite conclusions regarding various parameters on ICF nuclear reaction dynamics, more and more experimental data using α-cluster and non- α-cluster projectile on heavier target nuclei are needed at lower projectile energies.

In the present work, we have measured and analyzed the excitation functions of evaporation residues produced in $^{16}O + {}^{175}Lu$ system at energies $4 - 7$ MeV/ nucleon. The experimentally measured EFs of various evaporation residues produced via CF and/or ICF have been compared with theoretical predictions based on statistical model code PACE-2 [1], which takes into account only the CF contribution.

2. EXPERIMENTAL PROCEDURE

For excitation functions (EFs) measurement, the experiment was carried out using the facilities of 15UD Pelletron accelerator at Inter-University Accelerator Centre (IUAC), New Delhi. Stacked foil activation technique has been used for EFs measurement. The main advantage of the activation technique is the possibility of measuring cross-section for the production of a large number of residues in a single irradiation. Self supporting target foils were prepared using the rolling machine. Keeping in view the half-lives of the interest, two stacks, each having four target foils have been backed by Al-catcher foils were irradiated by $^{16}O^{+7}$ beam with 20 nA current for about 6 hours in the General Purpose Scattering Chamber (GPSC) at energies $\sim$ 100 and $\sim$ 95 MeV. The GPSC has an in-vacuum transfer facility. The energy loss suffered by 5.49 MeV α- particle obtained from ^{241}Am source, was used to determine the thickness of target and Al-catcher foils. SRIM08 code [6] has been used for determining the thickness from the energy lost measurements. The sample was cut into the pieces and pasted on Al-holders of regular size having concentric holes of 10 mm diameter. The Al-holders were used for rapid heat dissipation produced during irradiation of target. The delay time between the stop of irradiation and the starting of counting may be minimized using the in-vacuum target transfer facility. The total charge collected in the Faraday cup, placed behind the target–catcher foils arrangement has been used to calculate the beam flux during the irradiation. In case of activation technique, a large number of residual nuclei may be produced and each radio- nuclide has a number of γ-rays, which provide a specific way for its identification. Therefore, in order to have the correct identification of the characteristic γ-rays of evaporation residues, a calibrated HPGe detector with high resolution is required. Also, for a given source-detector geometry the detector efficiency must be known. In the present measurements, the activities induced in each catcher foil of the stack were recorded separately using a high resolution ($\sim$ 2 keV for 1.33 MeV γ-ray of ^{60}Co) HPGe detector of 100 cm^3 active volume coupled to a PC through CAMAC based FREEDOM software at IUAC, New Delhi. The HPGe detector has been calibrated by using the standard ^{152}Eu γ- ray source of known strength. The ^{152}Eu source may decay by emission of various intense and well resolved γ-rays having the energy range from 120 keV to about 1410 keV.

The probability of occurrence of a particular nuclear reaction is generally described by the reaction cross-section. One may measure the cross-section of reaction products in order to get comprehensive information about the process of its formation. The expression [10] is extensively used to calculate the reaction cross-section $\sigma_r(E)$ at a given beam energy E;

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$$\sigma_r(E) = \frac{A\lambda \exp(\lambda t_2)}{N_0 \phi \varepsilon_G \theta K[1-\exp(-\lambda t_1)][1-\exp(-\lambda t_3)]} \quad (1)$$

where, A is the total number of counts recorded under the peak in time t_3, N_0 is the number of target nuclei, ϕ is the incident flux, t_1 is the irradiation time, t_2 is the time lapsed between stop and starting of irradiation, t_3 is the recording time, θ is the branching ratio, λ is the decay constant of the evaporation residue, ε_G is the geometry dependant efficiency of the detector, K is the self-absorption correction factor of the γ-ray in the target.

3. RESULTS AND DISCUSSION

EFs of various evaporation residues (ERs) produced via CF and/or ICF have been measured for the system $^{16}O + {}^{175}Lu$ at energies ranging from 4−7 MeV/nucleon. Special care has been taken to separated out the precursor decay contributions in the production of several evaporation residues to get the independent production cross-sections of the residues [11]. The measured EFs are then compared with the predictions of statistical model code PACE-2 [1], which gives only the CF contribution. So any enhancement in the measured cross-section from theoretical prediction may be due to ICF reaction process in addition to CF process. Independent cross-section for the production of daughter nucleus B in the sequential isobaric decay A→B is given by;

$$\sigma^B_{ind} = \sigma^A_{cum} - P_A \frac{T^B_{1/2}}{(T^B_{1/2} - T^A_{1/2})} \sigma^A_{ind} \quad (2)$$

where, $T^A_{1/2}$ and $T^B_{1/2}$ are the half-life of parent and daughter nuclei, P_A is the branching ratio, σ^B_{cum} is the cumulative cross-section of the daughter nucleus, σ^B_{ind} is the independent cross-section of the daughter nucleus and σ^A_{ind} is the independent cross-section of the parent nucleus. In case of two precursor isobars i.e. A→B→C with half-lives $T^A_{1/2}$, $T^B_{1/2}$ and $T^C_{1/2}$ and with branching ratios P_A and P_B, relation (2) takes the form;

$$\sigma^C_{ind} = \sigma^C_{cum} - P_B \frac{T^C_{1/2}}{(T^C_{1/2} - T^B_{1/2})} \sigma^B_{ind} - P_A P_B \frac{(T^C_{1/2})^2}{(T^C_{1/2} - T^B_{1/2})(T^C_{1/2} - T^A_{1/2})} \sigma^A_{ind} \quad (3)$$

EFs of residues ^{186}Au(5n), ^{187}Pt(p3n), ^{186}Pt(p4n) and ^{184}Ir(α3n) are shown in Fig.1(a). The experimental values match well with theoretical predictions of statistical model code PACE-2 for level density parameter constant K = 10, which shows that these residues are populated through CF process as expected. Moreover, from the measured EF of ^{184}Ir(α3n) reveals that this residue is also formed by the complete fusion of projectile ^{16}O with target ^{175}Lu. The compound

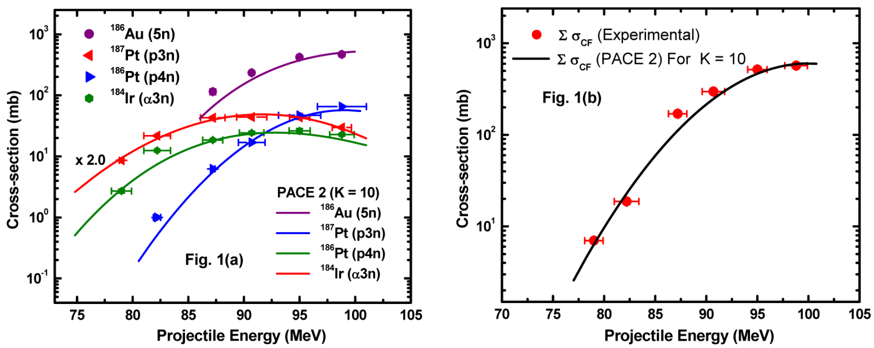

Figure 1: (a) Excitation functions of the evaporation residues ^{186}Au(5n), ^{187}Pt(p3n), ^{186}Pt(p4n) and ^{184}Ir(α3n) produced in the ^{16}O + ^{175}Lu system. Solid circles represent experimental data. The solid line represents the polynomial fit to the PACE-2 predictions and **(b)** the sum of cross-sections from all measured CF channels ($\sum \sigma_{CF}$) are plotted along with the sum of cross-sections for all CF channels obtained from PACE-2 as a function of projectile energy.

system ^{191}Au* may decay via statistical evaporation of one α-particle and three neutrons leaving behind the residue ^{184}Ir, which may be represented as:

$$^{16}O + {}^{175}Lu \Rightarrow {}^{191}Au^{*} \Rightarrow {}^{184}Ir + \alpha + 3n \tag{4}$$

It is noteworthy here that the EF of ^{184}Ir does not show any enhancement even ^{184}Ir is populated via the emission of α-channel. The absence of enhancement indicates that the excitation energy of the incompletely fused composite (IFC) system ^{187}Ir* (in the fusion of fragment ^{12}C with the target) is insufficient for emission of three neutrons. The sums of cross-sections for all measured CF channels ($\Sigma\sigma_{CF}$) are plotted along with the sum of cross-sections for all CF channels obtained from PACE-2 as a function of projectile energy. It may be pointed out that sum of cross-sections for measured CF channels matches with the sum of theoretical prediction as shown in Fig. 1(b). For the residue ^{183}Ir(α4n), as shown in Fig. 2(a), we have observed an enhancement from the theoretical predictions, which is the signature of contribution from ICF process along with the CF process, where the projectile breaks up into fragments [^{12}C + ^{4}He(α)], one of the fragment, 4He(α) moves forward with same angular momentum as that of the projectile and the other fragment fuses with the target ^{175}Lu, forming the excited compound system ^{187}Ir*, which decays by emitting four neutron to from ^{183}Ir. This can be represented as,

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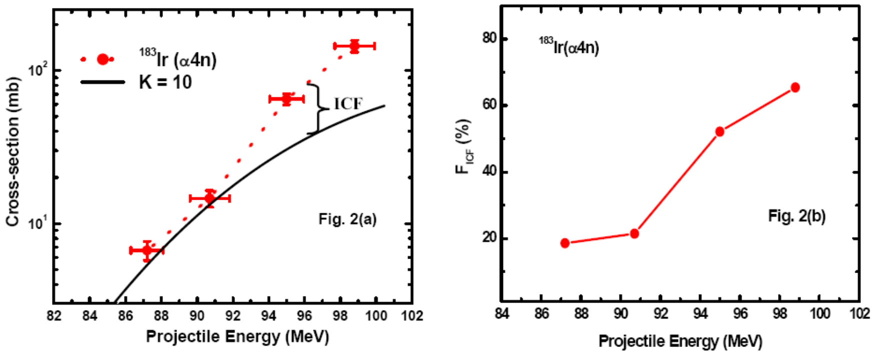

Figure 2: (a) Excitation functions of the evaporation residue ^{183}Ir(α4n) produced in the ^{16}O + ^{175}Lu system. Solid circles represent experimental data. The solid line represents the polynomial fit to the PACE-2 predictions (*K* = 10) and (b) The deduced ICF Fraction (F_{ICF}) as a function of projectile energy for the residue ^{183}Ir(α4n).

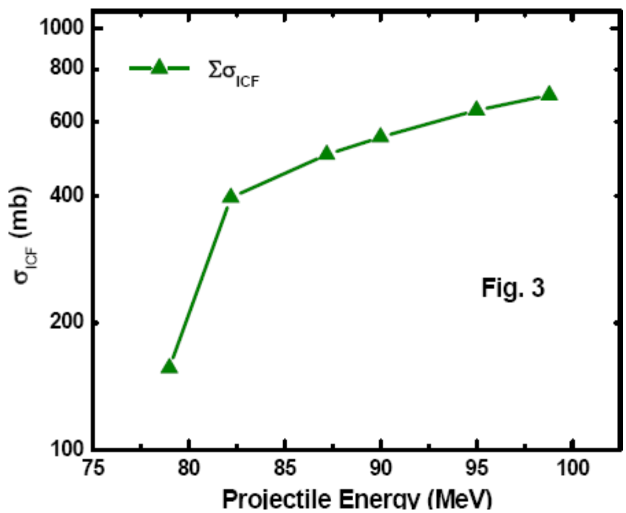

Figure. 3: Sum of incomplete fusion cross-sections ($\Sigma\sigma_{ICF}$) as a function of projectile energies for the ^{16}O + ^{175}Lu system.

$$^{16}O\left(^{12}C+\alpha\right)+{}^{175}Lu \rightarrow {}^{187}Ir^{*}+\alpha\,(spectator) \qquad (5)$$

$$^{187}Ir^{*} \rightarrow {}^{183}Ir+4n$$

Some other residues produced via αxn/2αxn channels like ^{187}Ir(α), ^{182}Re(2αn) etc. are expected to be populated either by CF and/or ICF processes; however, PACE-2 values for these residues are either very small or negligible. Thus, it may be concluded that these residues are populated by ICF process only and CF process does not contribute in the population of these residues. The ICF Fraction (FICF), $F_{ICF} = \left[\sigma_{ICF} / (\sigma_{ICF} + \sigma_{CF})\right]$ has been deduced for the residue ^{183}Ir(α4n) and plotted as a function of projectile energy and is shown in Fig. 2(b). It may be pointed out from this figure that FICF increases with projectile energy in case of ^{183}Ir(α4n). The ICF contribution of individual break-up α-emission channels (ICF products) for ^{16}O + ^{175}Lu system has been deduced by subtracting the theoretically calculated cross-section by PACE-2 from the experimentally measured cross-section at each projectile energy. The sum of cross-sections from all measured ICF channels $\left(\Sigma\sigma_{ICF}\right)$ has also been plotted against the projectile energy and shown in Fig. 3.

SUMMARY AND CONCLUSIONS

In the present work, the EFs of several evaporation residues produced via CF and/or ICF have been measured and analyzed in the framework of statistical model code PACE2 for the system ^{16}O + ^{175}Lu in the energy regime 4-7 MeV/ nucleon. The experimentally measured EFs of *xn/pxn* channels have been found to be reproduced reasonably well with the theoretical predictions based on statistical model code PACE2, indicating their population via CF only. On the other hand, a significant enhancement is observed in the measured cross-sections of α-emitting channels. It may be concluded that ICF contribution i.e. break-up probability of the projectile into α-clusters [i.e. break-up of ^{16}O into ^{12}C + ^{4}He and/or ^{8}Be + ^{8}Be and/or ^{4}He + ^{12}C] in general, increases with projectile energy.

ACKNOWLEDGEMENT

The authors are grateful to the Director, IUAC, New Delhi, for providing the necessary experimental facilities. One of the authors HK is grateful to UGC-DAE-CSR, Kolkata for awarding Fellowship under its Project. The authors are also thankful to the Chairman, Department of Physics, A.M.U., Aligarh for providing the necessary facilities related to this research work.

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