EXPLORING ENTRANCE CHANNEL EFFECTS IN THE INTERACTION OF ^{16}O WITH ^{93}Nb*

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The excitation functions (EFs) of the number of evaporation residues have been measured in the interaction of a ^{16}O projectile with a ^{93}Nb target at energies $\approx$ 3.5–7 MeV$/A$ using a well established activation technique followed by off-line γ-ray spectroscopy. The measured excitation functions have been compared with theoretical predictions obtained using the statistical model code PACE4. The EFs of evaporation residues populated through α-emitting channels show an enhancement over theoretical predictions calculated using the fusion-based model code. Incomplete fusion dynamics is found to play an important role in heavy-ion-induced reactions at energies as low as 3.5–7 MeV$/A$. To have more exclusive information about ICF dynamics, the strength of ICF in terms of the incomplete-fusion fraction ($F_{\rm ICF}$) is also deduced and correlated with various entrance channel parameters. It is found that besides projectile energy, projectile structure and mass asymmetry strongly affect the ICF dynamics in the considered energy range.

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1. Introduction

The reactions of heavy-ion nuclei have been extensively investigated for several decades [1–4]. The heavy-ion reactions may broadly be classified in terms of degree of momentum transferred from a projectile to a target in first stage of collision. Three important classes of heavy-ion reactions are complete fusion (CF) reactions, incomplete fusion (ICF) reactions, and direct reactions. At higher incident energies above 10 MeV/A or more, pre-equilibrium reactions also become important. In the case of CF, the entire momentum of the projectile is transferred to the target nucleus forming an excited composite system from which emission of particles may take place, on the other hand, in the case of ICF, only a part of the projectile fuses with the target nucleus and the rest of it moves with almost the same velocity as that of the incident ion beam. Here only a fraction of momentum essentially equal to the fraction of mass that fuses is transferred to the target. Direct reactions involve a transfer of a single nucleon or cluster in grazing collision with very little momentum transfer. Though the distinction between incomplete fusion and direct reactions has been accepted in principle [5], but it has not always been clear for an individual reaction. In 1961, Kaufmann and Wolfgang [5] were the first who showed the existence of rather inelastic grazing collision processes in multinucleon transfer reactions of ^{12}C, ^{14}N, and ^{16}O in contrast to the direct tunneling process which dominates a single-nucleon transfer. A subsequent study using the recoil technique confirmed that the process intermediate between complete fusion and direct transfer is important in forming products somewhat heavier than the target. The first hint of incomplete momentum transfer for this type of reaction was reported by Alexander and Winsberg [6]. In the same year, Britt and Quinton [7] observed the existence of fast light particles emitted at the early stage of the reaction. However, consistent appreciation of the process which is now referred to as ICF only emerged with the pioneering work of Inamura *et al.* [8] from 1977 onwards using particle gamma coincidence measurements of the projectile-like fragments. Though a large number of theoretical models have been proposed, all these models have been used to fit the experimental data obtained using projectile energy above 10 MeV/A or so. However, some recent studies showed the onset of ICF just above the Coulomb barrier (CB) [3, 4]. The observation of ICF in heavy-ion-induced reactions at relatively low projectile energies has renewed the interest of the nuclear physics community to prove the ICF dynamics exclusively at energies in the vicinity of the Coulomb barrier. At low projectile energies, the ICF reactions are not well understood and need more and more investigations. Our research group has been actively involved in probing ICF dynamics in heavy-ion-induced reactions for two decades and several efforts have been made by our group to study the effects of various entrance channel parameters, such as projectile energy and its structure, angular momentum window for ICF, deformation of interacting nuclei, mass asymmetry, *etc.*, on the ICF process by the forward recoil range distribution technique/recoil-catcher activation technique [2–4]. In the present work, we report on the excitation functions of evaporation residue for the ^{16}O+^{93}Nb system in the energy range of 3.5–7 MeV/A. The ICF fraction has been deduced from the measured excitation functions. The present work also includes an exclusive study on the dependence of the ICF fraction on projectile energy and mass asymmetry of interacting partners.

2. Experimental details

The experiments were performed by utilizing the 15UD Pelletron National Accelerator Facility at the Inter-University Accelerator Center (IUAC) New Delhi (India). The well-established activation technique followed by off-line gamma-ray spectroscopy was used for the measurements. The stack of Nb foils each followed by Al catcher foils was irradiated in the General Purpose Scattering Chamber (GPSC) having a unique facility for in-vacuum transfer of targets. Keeping in mind the half-lives of evaporation residues of interest, the stack was irradiated for 7 hrs. During irradiation, the beam current was kept constant. After irradiation, the activities produced in the target catcher assembly followed employing a pre-calibrated HPGe detector and associated electronics coupled with 4K MCA. The experimental setup and data analysis techniques used in the present measurements are the same as those presented in our earlier publication. More details about the technique used in the present work can be found in Refs. [3, 4].

3. Results and discussions

The excitation functions (EFs) of seventeen evaporation residues populated in the interaction of ^{16}O+^{93}Nb system through the process of CF and/or ICF have been measured at $E_{\rm Lab} \approx 3.5$–7 MeV/A. The experimental EFs are analysed within the light of the statistical model code PACE4 [9]. The PACE4 code is based on the Hauser–Feshbach formalism which follows the correct procedure of angular momentum coupling at each stage of deexcitation of excited nuclei. In this code, the angular momentum conservation is explicitly taken into account and the CF cross section is calculated using the Bass formula. The level density parameter is $a = A/K$ MeV^{-1}, where A is the mass number of the residual nucleus and K is a free parameter. It is to be noted that any enhancement in the experimentally measured EF over the PACE4 prediction may be assigned to an incomplete fusion process. Figure 1 shows the experimentally measured and PACE4-calculated EF of the ER ^{105}Cd populated through the $p3n$ channel. As can be inferred from

Fig. 1, the experimentally measured excitation function of the ER ^{105}Cd is well reproduced by the statistical model code PACE4 for the level density parameter $K = 8$.

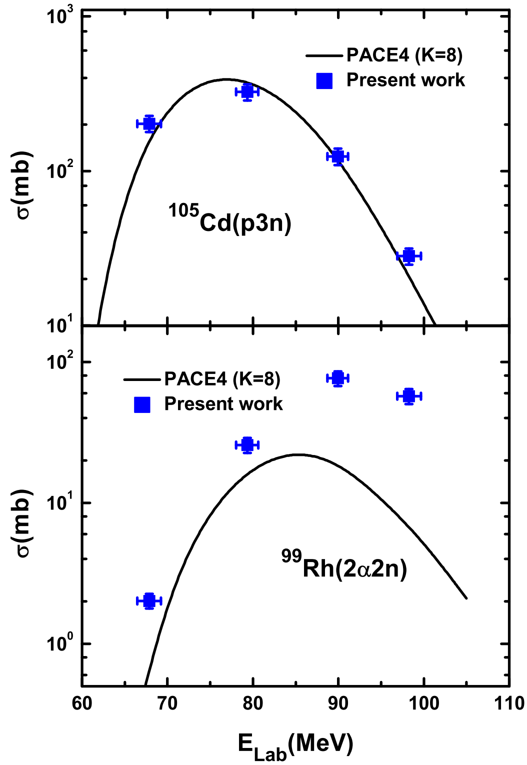

Fig. 1. Experimentally measured EFs of evaporation residues ^{105}Cd ($p3n$) and ^{99}Rh ($2\alpha 2n$), are compared with PACE4 predictions ($K = 8$).

Figure 1 (lower panel) also shows the EF of the ER ^{99}Rh expected to be populated through the $4p6n$ CF channel, $\alpha 2p4n$ ICF channel or $2\alpha 2n$ ICF channel. As can be seen, the experimentally measured EF of the ER ^{99}Rh shows an enhancement over the PACE4 prediction for the entire energy range. ER ^{99}Rh was found to get populated through the 2α emitting channel and is likely to have contributions arising from the CF, ICF$^{\alpha}$, as well as ICF$^{2\alpha}$ processes. Since the PACE4 calculations do not take ICF into account, the observed enhancement in the experimentally measured EF over the PACE4 prediction may be assigned to the contributions arising from the ICF$^{\alpha}$ and ICF$^{2\alpha}$ processes. For better insight into the onset and strength of ICF, the ICF strength function (*i.e.* the percentage fraction of ICF ($F_{\rm ICF}(\%)$) has been deduced for the present ^{16}O+^{93}Nb system along with the ^{18}O+^{93}Nb [1] system and is plotted in Fig. 2 with normalized energy. The ICF strength function defines the empirical probability of ICF at different projectile energies. It can be seen from Fig. 2 that the ICF probability increases with energy more for the ^{18}O projectile as compared to ^{16}O. Morgenstern *et al.* [10] proposed that the ICF fraction increases with the mass asymmetry of interacting partners. The incomplete fusion for the present ^{16}O+^{93}Nb system has been compared with some earliest measurements [11–13] at a constant relative velocity of 0.053c as a function of mass asymmetry and is shown in Fig. 2 (lower panel). This figure shows that the ICF fraction increases with their mass asymmetry, separately for each projectile. The present results are in contrast to the fact that ICF depends on the degree of mass asymmetry of the entrance channel as suggested by Morgenstern *et al.* [10]. Furthermore, the present results clearly show that the structure of the projectile along with the mass asymmetry affects the ICF dynamics at these energies.

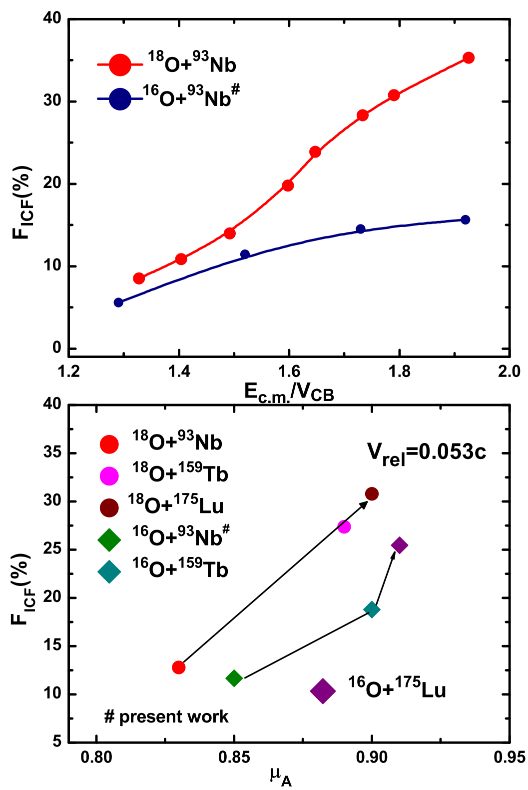

Fig. 2. The comparison of deduced $F_{\rm ICF}$ (%) as a function of normalized projectile energy for ^{16}O and ^{18}O projectiles with the same target ^{93}Nb and comparison of deduced $F_{\rm ICF}$ (%) in terms of mass asymmetry at constant relative velocity ($V_{\rm rel} = 0.053$c). For references and details, see the text.

4. Conclusions

The excitation functions of evaporation residues for the ^{16}O+^{93}Nb system have been measured in the energy range of 3.5–7 MeV/A . The measured excitation functions for the evaporation residues populated via xn/pxn emission channels were found to be in good agreement with those derived employing statistical model calculations using the PACE4 code. A significant enhancement in the measured excitation functions over their theoretical predictions as obtained by PACE4 is observed for the all evaporation residues populated through α-particle(s) emitting channels. This enhancement in cross-section values may be assigned to the occurrence of an incomplete fusion process. Furthermore, in order to achieve a better understanding of the ICF processes, an attempt has been made to deduce the ICF strength function and compared it with various entrance channel parameters. On the basis of the present results, it may be concluded that the ICF strongly depends on projectile energy and mass asymmetry of interacting partners.

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