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Systematics for low energy incomplete fusion: Still a puzzle?

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Abstract

In order to have a better and clear picture of incomplete fusion reactions at energies ≈4-7MeV/nucleon, the excitation function measurements have been performed for ^{18}O+^{159}Tb system. The experimental data have been analyzed within the framework of compound nucleus decay. The cross-section for xn/pxn-channels are found to be well reproduced by PACE4 predictions, which suggest their production via complete fusion process. However, a significant enhancement in the excitation functions of α-emitting channels has been observed over the theoretical ones, which has been attributed due to the incomplete fusion processes. The incomplete fusion fractions have been deduced at each studied energy and compared with other nearby systems for better insight into the underlying dynamics. The incomplete fusion fraction has been found to be sensitive to the projectile's energy and α-Q-value.

1 Introduction

Fusion reactions, induced by heavy-ions (HIs), play an important role in nuclear physics since they enable to study the production & properties of nuclei away from the valley of stability [1]. For this reason the understanding of HI-reaction mechanism has always been an active area of study. During the last couple of decades, with the observation of incomplete fusion (ICF) reactions at energies in the vicinity of Coulomb barrier (V_b), considerable efforts are being employed by both experimental and theoretical physicists to understand the presence of ICF-reactions at such low energies, where complete fusion (CF) is supposed to be the sole contributor to the total fusion cross section [2–6]. The presence of ICF-reactions at such low energies triggered the resurgent interest to understand & find out the general systematics for low enery ICF reactions. It is not out of place to mention that, presently, no theoretical model is available which could reproduce the low energy ICF data satisfactorily.

The CF-reactions correspond to the complete amalgamation of interacting nuclei for input angular momentum $\ell < \ell_{crit}$, leading to the formation of completely fused excited composite system, which may decay via particle and/or γ-emission. However, in case of ICF-reactions, for partial waves $\ell > \ell_{crit}$ (as per sharp-cut off model), the projectile may break-up into its constituent to provide the sustainable input angular momentum. One of the fragments may fuse with the target nucleus forming the reduced excited composite system with relatively less mass, charge and excitation energy. While, the remnant flows in the forward direction with almost beam velocity. Since the observation of ICF reactions, several theoretical models/theories have been proposed to explain these reactions. In general, all the proposed models are found to fit the experimental data at projectile energies $\geq$ 10 MeV/nucleon to a large extent [6]. But, at low beam energies ($\approx$3-7 MeV/nucleon), the ICF-reactions are not well understood. In addition to this, the effect of various entrance channel parameters such as the beam energy [5], the angular momentum [7], the entrance channel mass asymmetry [8], the projectile structure in terms of alpha-Q-value and/or binding energy of the projectile [6] have been studied and contradicting dependence of ICF-reactions on these parameters have been reported [6]. Morgenstern *et al.* [9]correlated the ICF fraction with entrance channel mass asymmetry (μ_A). Recently, Singh *et al.* [5] introduced the importance of projectile structure in ProMass-systematics. Hence, in order to explore the low-energy incomplete fusion and to find a consistent general systematics for low energy ICF reactions, measurements of excitation function for $^{18}O+^{159}Tb$ system at energies ≈ 4-7MeV/A have been performed and compared with nearby systems.

2 Experiments

The experiments have been performed at the Inter-University Accelerator Center (IUAC), New Delhi to measure the excitation functions of radio-nuclides populated during $^{18}O+^{159}Tb$ interactions. Here, brief experimental details are given for the ready reference; however, the detailed description is given in ref [6]. Isotopically pure ^{159}Tb targets and Al-catcher/energy degrader foils, thicknesses ranging ≈ 1.5-2.5 mg/cm^2, were prepared using rolling technique. An *Al*-catcher foil of sufficient thickness has been placed behind each target foil so that the recoiling products during the irradiations may be trapped in the catcher foil thickness. The stacked-foil (to cover wide energy range in an irradiation) activation technique followed by off-line γ-ray spectroscopy has been used. The induced activities in the irradiated samples were recorded by counting each target-catcher foil assembly, using a pre-calibrated HPGe γ-ray spectrometer. A 50Hz pulser was used to determine the dead time of the detector. The efficiency calibration of the detector in the specified geometry was carried out using a standard ^{152}Eu source. The characteristic γ-lines have been used to identify the reaction products. Further, in order to make sure the identification of the reaction products, the decay curves of the identified reaction products have also been analyzed. Nuclear data of radio-nuclides, such as the characteristic gamma-lines, their abundances, half-lives, etc. were taken from ref [10]. After the identification and confirmation of the residues, the production cross sections of the reaction products have been determined using the standard formulation [5].

3 Results and discussion

In order to understand the formation mechanism of the residues produced during $^{18}O+^{159}Tb$ interactions, the experimentally measured excitation functions have been analyzed within the framework of statistical model code PACE4 [11], which is based on equilibrated CN-decay of Hauser-Feshbach theory. It may, however, be pointed out that the ICF and pre-equilibrium-emission (PEE) are not taken into consideration in this code. In this code, level density parameter (a=A/K) is an important input parameter which affects the CF cross-sections and where K may be varied to match the experimental cross-sections. As a representative case, in Fig.1 (a) the EFs for $3n$-channel have been compared with corresponding PACE4-predictions

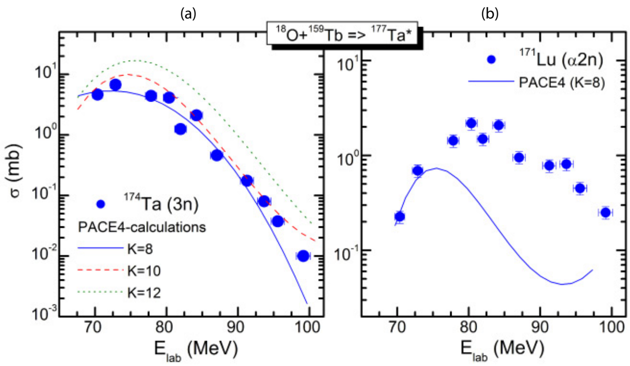

Figure 1: (Color online) Experimental EFs of ^{174}Ta($3n$) (a), ^{171}Lu($\alpha 2n$) (b) have been compared with that predicted by PACE4 for different values of level density parameter (a = A/K MeV^{-1}, where K = 812).

for three different values of level density parameter and "K=8" has been found to reproduce satisfactorily the experimental data, which shows the production of this residue via CF process. Similar observations have been observed for other xn & pxn-channels, showing their production via CF processes. The same set of parameters has been used to check the production mechanism of α-emitting channels, also. As shown in Fig.1 (b), the measured cross-sections for ^{171}Lu ($\alpha 2n$) residue are found to be significantly enhanced than theoretical predictions. It has already been mentioned that PACE4 do not take ICF, PEE into account and hence, this enhancement may be attributed as the contribution due to ICF-reaction mechanism.

It is evident from the analysis that ICF-reactions contribute significantly to the production cross-section of α-emitting channels at studied energy range. Further, the ICF-contribution for individual channels has been deduced by subtracting CF cross-sections (σ_{CF}) from the experimentally measured total fusion cross sections (σ_{TF}) at each studied energy and plotted in Fig.2(a). As can be seen from Fig.2(a) that the ICF contribution is increasing with beam energy. It is not out of place to mention that the σ_{TF} has been corrected for the missing channels (which could not be measured experimentally) by their PACE4 values. Hence, the σ_{ICF} may be taken at least as the lower limit of ICF-contribution.

3.1 α-Q-value systematics

In order to understand the effect of projectile on ICF-reactions, the F_{ICF}, the fraction of ICF to total fusion, have been deduced for ^{18,16}O+^{159}Tb systems and plotted in Fig.2(b). This comparison of F_{ICF} for different projectiles on same target reveals a strong projectile dependence of low-energy ICF

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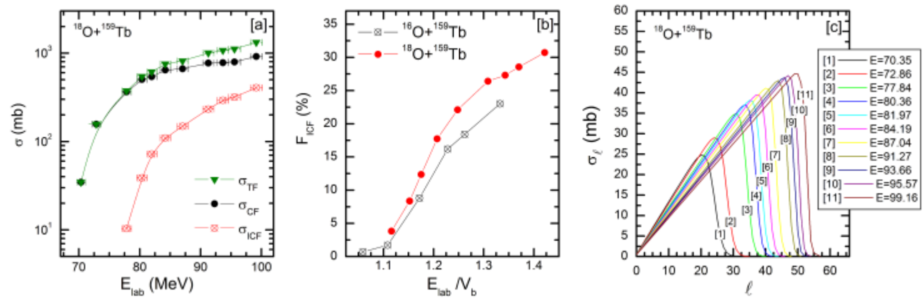

Figure 2: (color online) (a) The incomplete fusion cross-section along with total and complete fusion cross-section. (b) The comparison of F_{ICF} for ^{18,16}O projectiles on same target. (c) The fusion ℓ-distribution to understand the population of ℓ-bin at each studied energy.

reactions. It is clear from this figure, that the F_{ICF} is larger for ^{18}O than ^{16}O as projectile on the same target ^{159}Tb, which can be understood by recently proposed alpha-Q-value systematics [5]. The more-negative Q_{α}-value for ^{16}O translates into the smaller breakup probability into constituent α clusters, resulting in a smaller ICF-fraction than for ^{18}O induced reactions. The present work strengthens the recently observed alpha-Q-value systematics [5] for strongly bound projectiles.

3.2 Observation of ICF at $\ell < \ell_{crit}$

In order to study the diffuseness in ℓ-distribution, the critical angular momentum ℓ_{crit} for the present system at which the pocket in the entrance channel potential vanishes has been calculated [12]. The calculations give ℓ_{crit} as 63$\hbar$. The fusion ℓ-distributions for ^{18}O+^{159}Tb interactions over a broad energy range $\approx$ 70-99 MeV have been calculated using the code CCFULL [13], and are plotted in Fig.2(c). The values of ℓ_{max} at studied energies, are less than the ℓ_{crit} (63$\hbar$) for fusion for this system, in general. It is evident from this figure that there is no significant cross-section above ℓ_{crit}, even at the highest beam energy, and hence, suggest that a significant number of ℓ-bins below ℓ_{crit} may contribute to the ICF. The present observations clearly indicate a diffused boundary for ℓ-values, contrary to the sharp cut-off model, that may penetrate close to the barrier.

3.3 Remark on general systematics for low energy ICF

The mass-asymmetry systematics proposed by Morgentern *et al* [9] states that ICF contribution increases with mass-asymmetry of the interacting partners (but at some what higher energies > 10MeV/nucleon). Later, Singh *et al.* [5]introduced the importance of projectile structure on ICF reactions at low energies in his ProMass systematics. Recently, the α-Q-value systematics [6] for strongly bound projectiles has been proposed, which gives α-Q-value as a parameter to understand the projectile strucute effect on low energy ICF reactions. Further, no systematics is available which can include both the effect of projectile and target into account. Hence, some general systematics for low energy ICF reactions, which can deal both projectile-target effect into account, is still lacking and some more conclusive measurements are required.

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