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A comprehensive analysis of incomplete fusion reactions in ^{16}O + ^{159}Tb System

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In the present work, three distinct and complementary experiments viz. (i) measurement of excitation functions, (ii) measurement of recoil range distributions, and (iii) spin distribution measurements using particle-gamma technique, have been carried out to understand the dynamics of complete fusion and incomplete fusion reactions at energies ≈ 4- 7 MeV/nucleon. The analysis done indicates significant ICF contribution in ^{16}O + ^{159}Tb system at these energies. The three complimentary experiments confirm the observation of ICF and the relative contributions obtained are found to agree within 5%.

KEYWORDS: Heavy-ion, Complete fusion, Incomplete fusion

1. Introduction

A comprehensive understanding of fusion reactions induced by heavy-ions (HI), has always been a topic of interests at energies ≈ 4 – 7 MeV/nucleon [1]. Generally at these energies, complete fusion (CF) reactions significantly contribute to the total fusion (TF) cross-section. However, recent experimental data [2] indicates notable signature of incomplete fusion (ICF) reactions at these energies, although CF is the dominating mode of reaction. On the basis of driving input angular momentum (ℓ), at $\ell \leq \ell_{crit}$, the HI reactions predominantly take place through the entire fusion of the projectile with the target nucleus i.e., via CF mode. However, for $\ell \geq \ell_{crit}$, the entire fusion of projectile with the target nucleus is hindered, unless a part of the projectile is emitted as a spectator to provide sustainable input angular momentum, and gives way to ICF. Several theoretical models [3] have been proposed to understand the reaction dynamics of ICF, which are reliable upto some extent at energies ≥ 10 MeV/nucleon, but these models are unable to explain the ICF data precisely at energies < 10 MeV/nucleon. In addition, the entrance channel parameters also play an important role in the dynamics of ICF reactions [3,4]. Hence in order to understand the relative contribution of CF and ICF reactions, three complementary measurements viz., (i) Excitation Functions (EFs) of evaporation residues [4], (ii) Recoil Range Distributions (RRDs) [4], and (iii) Spin Distributions (SD) [3] have been measured. Such comprehensive analysis for the same system is not available in the literature. A brief discussion on these measurements and analysis are given in the following sections.

2. Experimental details, data analysis and interpretation

The experiments have been performed at the ion beam facility of the Inter University Accelerator Centre (IUAC), New Delhi, India. A detailed explanation of experimental technique may be found elsewhere [3,4]. In the present work, 9 radionuclides viz., $^{175-x}$Ta(xn) where x = 3-5; $^{174-x}$Hf(pxn) where, x = 3,4; ^{171}Lu(2$p2n$); $^{171-x}$Lu(αxn) where x = 1-2; and ^{165}Tm($2\alpha2n$) have been identified. In EF measurements, the production cross-section of the radionuclides are analyzed within the framework of statistical model code PACE2 [5]. As a representative case, in Fig. 1(a), the experimentally measured and

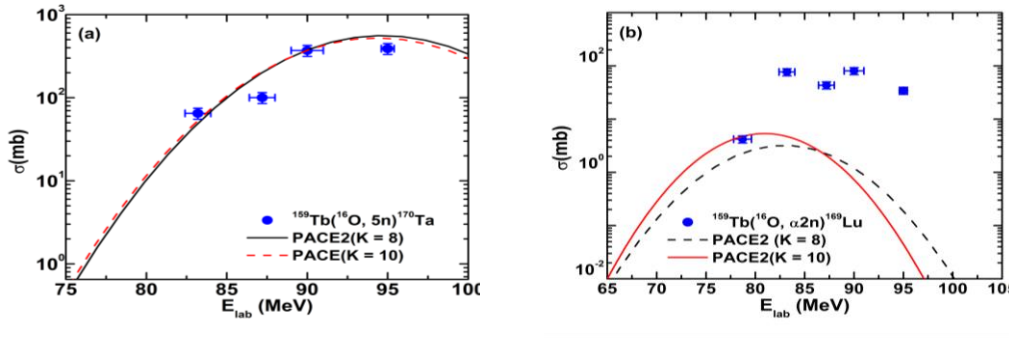

Fig. 1. (a-b) Measured EFs of ^{170}Ta and ^{169}Lu residues populated via $5n$ and $\alpha 2n$ channels compared with PACE2 calculations.

theoretically calculated (PACE2) EF for ^{159}Tb(^{16}O, 5n)^{170}Ta reaction channel is shown. As can be seen, that the measured EF is well reproduced by the PACE2 code, indicating the production of this channel solely via CF process. Similarly, all the xn and pxn channels are found to be well reproduced by PACE2 code. However, in the case of α-emitting channels, significant enhancement over the PACE2 predictions has been observed. As a representative case in Fig. 1(b), the experimentally measured and theoretically calculated EF for the reaction channel $\alpha 2n$ is found to be significantly larger than PACE2 prediction. Since, the PACE2 does not take ICF into considerations, therefore, the observed enhancement in the cross-section, may be attributed to the ICF reactions over the entire range of energy. In order to ascertain the above fact, RRDs of reaction residues populated via CF and/or ICF in ^{16}O + ^{159}Tb system have been measured at 90 MeV beam energy [3]. In RRD measurements, the relative contribution of CF and ICF events are separated out on the basis of linear momentum transfer (LMT) from projectile to the target nucleus. The CF and ICF events are disentangled using the recoil catcher activation technique [3]. Fig. 2(a) shows the RRD of ^{171}Ta residues populated via

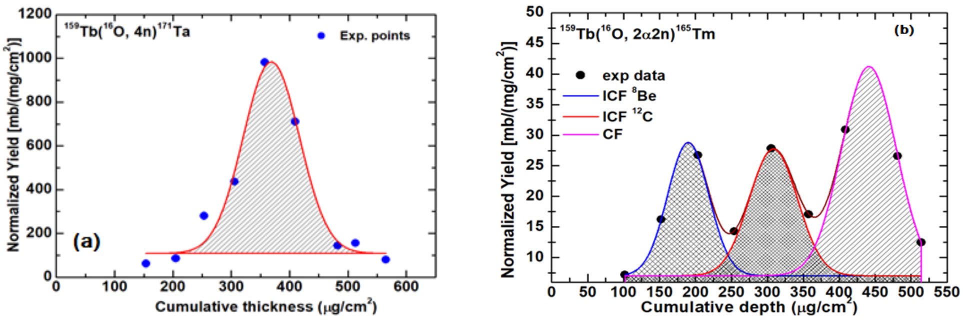

Fig. 2. (a-b) The recoil range distributions of ^{171}Ta and ^{165}Tm residues populated through *4n* and *2α2n* channels via CF and/or ICF in ^{16}O + ^{159}Tb system processes at energy 90 MeV.

4n channel measured at energy 90 MeV. As can be seen from this figure, the measured RRD show only one Gaussian peak, that corresponds to the entire LMT of projectile to the target nucleus indicating population of these residues via CF process. However, in Fig. 2(b), the RRD of ^{165}Tm residues populated via *2α2n* channel may be de-convoluted into three peaks. The peak at higher cumulative depth corresponds to the entire LMT from projectile to the target nucleus, while the peaks at lower cumulative depth correspond to the fusion of ^{12}C and ^{8}Be (if ^{16}O is assumed to break-up into either ^{12}C + α and ^{8}Be + 2α) with ^{159}Tb target. Hence from the results obtained from RRD data, it can be safely inferred that the ICF reactions are significantly contributing alongwith CF reactions at the energy range of interest. In order to understand the role of input angular momentum (ℓ), that actually drives the fusion processes (i.e., both CF and ICF), spin distributions (SDs) of reaction residues populated in ^{16}O + ^{159}Tb system [4] have been measured at four distinct energies using the particle-γ coincidence technique. In ICF, the projectile like fragments (PLFs) are likely to be observed in forward cone and may be detected by the forward particle detectors, and it is one of the most direct proof to study the ICF reactions. The experiments have been performed at four energies i.e., 83.5, 88.5, 93.5 and 97.6 MeV using the Charged Particle Detector Array (CPDA) and Gamma Detector Array (GDA) setup of IUAC, New Delhi. The details of experiments and analysis may be found elsewhere [4]. Fig.3 (a-b), shows the spin distribution of ^{168}Lu residues identified at four energies and expected to be populated through *α3n* channel via both processes i.e., CF and/or ICF. It may be remarked that the same residues ^{168}Lu populated via *α3n* channel are identified from the backward (B)-α-gated γ-spectra (associated with CF), and as well as from the forward (F)-α-gated γ-spectra (associated with ICF) [4] and are shown in Fig. 3(a-b). As can be seen from Fig. 3(a-b), the trend of SDs for *α3n* channel identified from the forward (F)-α-gated γ-spectra is found to be distinctly different from that of CF product ^{168}Lu(*α3n*) identified from the backward (B)-α-gated γ-spectra, as expected. This may be due to the fact that the intensity of the residues ^{165}Lu(*α3n*) identified from the backward (B) α-gated spectra falls off quickly towards the high spin states in the yrast band indicating strong feeding during the de-excitation of CN. This gradual monotonic increase in the intensity towards the band head is due to the fact that the CF reactions lead to a CN of definite excitation energy (E^*), but with a broad spin distribution. Hence, the yrast states will be fed over a broad spin range. However, the same residues ^{165}Lu(*α3n*) identified from the forward (F) α-gated spectra (associated with ICF), the yield appears to be almost constant upto 8$\hbar$ (see Fig. 3(b)). This indicates the absence of feeding to the lowest members of the yrast band or the population of low spin states is hindered in the direct α-emitting channels (ICF products). The observed trend reflects the fact that the entry-spin distribution for ICF reaction products is narrow and peaked at larger ℓ-values associated with ICF reactions [6].

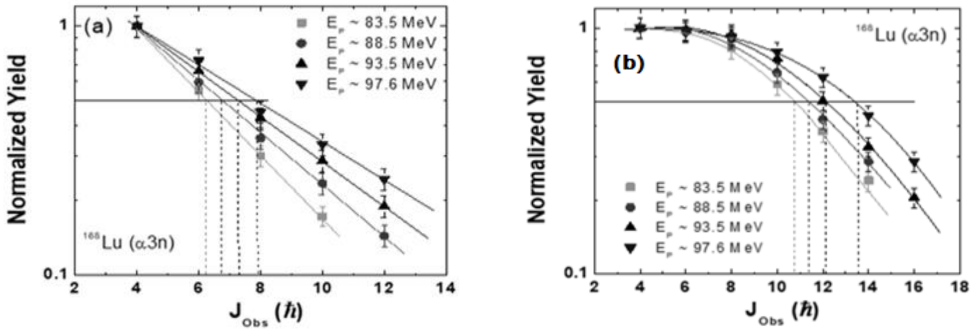

Fig. 3. Experimentally measured SDs for (a) CF- α3n-B channel and (b) ICF- α3n-Fchannel measured in ^{16}O + ^{159}Tb system.

3. Summary

In the present work, a comprehensive investigation on the reaction dynamics of ICF processes in ^{16}O + ^{159}Tb interactions at low energies has been studied using three complimentary measurements viz., (i) measurements of EFs (ii) measurements of RRDs, and (iii) measurements of SDs. In EFs measurement, significant contribution of ICF reactions has been observed in all α-emitting channels. Similarly, the deduced probability of ICF from the EF and RRD data nearly gives the same ICF fraction within the 5 % of experimental uncertainty. In SD measurements, the de-excitation pattern of α-emitting residues populated via both CF and ICF processes are found to be distinctly different, as expected. Hence, the results obtained from the analysis of three complementary experiments confirmed the presence of ICF reactions in ^{16}O + ^{159}Tb system at the energy range of interest.

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