Spin-distribution measurement: A sensitive probe for incomplete fusion dynamics

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Spin distributions of various reaction products populated via complete and/or incomplete fusion of ^{16}O with ^{169}Tm have been measured at projectile energy ≈5.6 MeV/nucleon. Particle ($Z = 1, 2$) γ-coincidences have been employed to achieve the information about involved reaction modes on the basis of their entry state spin populations. The experimentally measured spin distributions for incomplete fusion products have been found to be distinctly different than those observed for complete fusion products. The driving input angular momenta associated with incomplete fusion products have been found to be relatively higher than complete fusion products, and increases with direct α-multiplicity. It has also been observed that incomplete fusion products are less fed and/or the population of lower spin states are strongly hindered, while complete fusion products indicating strong feeding over a broad spin range.

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Incomplete fusion (ICF) in heavy ion (HI) induced reactions has been a topic of renewed interest at energies near and/or above the fusion barrier (B_{fus}) [1–6]. Large-scale efforts have been in progress to understand the multitude of ICF processes at energies ≈5–7 MeV/nucleon, where only complete fusion (CF) is expected to be dominant [7–9]. Firstly, the ICF dynamics has been investigated by Britt and Quinton in their pioneering measurements on the production of energetic forward-peaked α-particles [10]. Similar studies were carried out by Galin *et al.* [11]. However, the advances in the understanding of ICF dynamics took place after the particle-γ-coincidence measurements by Inamura *et al.* [12] and Zolonowski *et al.* [22]. In addition, Geoffroy *et al.* [13], measured correlation of charged-particle energies and angles with γ-multiplicities, where ICF processes have been shown to originate from undamped peripheral collisions. It is now known that the CF occurs for the driving input angular momentum ℓ up to a limiting value, i.e., ℓ equal to ℓ_{crit} [14]. The probability of CF is assumed to be unity for ℓ equal to ℓ_{crit} and expected to be zero for $\ell > \ell_{\text{crit}}$ (as per sharp cut-off approximation) [15–17]. In case of CF, the attractive nuclear potential overcomes the sum of repulsive Coulomb and centrifugal potentials. Consequently, the target nucleus hugs the projectile with the involvement of all nucleonic degrees of freedom leading to the formation of fully equilibrated compound nucleus (CN). While, at relatively higher projectile energies and at finite values of impact parameters, CF gradually gives way to ICF, where the centrifugal potential increases for the higher values of impact parameters. Under the influence of the centrifugal force field, the attractive nuclear potential is not strong enough to capture the entire projectile. Therefore, an incompletely fused composite system (a part of projectile plus target nucleus) appears in the exit channel. In addition, if the input angular momentum exceeds the critical limit (ℓ_{crit}) for CF, no fusion can occur unless a part of the projectile is emitted to release excess driving input angular momenta. After emission of a part of the projectile, the remnant is now supposed to have resulting input angular momenta less than or equal to its own critical limit for fusion to occur [13,18,19]. Further, it has also been observed that both the processes contribute significantly below and above their input angular momentum limits [20]. Moreover, Gerschel [21] suggested that the localization of ℓ-window depends on the target deformation at energies ⩽10 MeV/nucleon. Where, in case of deformed targets peripheral collisions are observed with ℓ-values in the vicinity of ℓ_{crit} for CF, while for spherical targets, the ℓ-window is found to be centered around values $\leqslant 0.5\ell_{\text{crit}}$. The ICF dynamics has been extensively studied, nevertheless, no clear picture about the multiplicity of input angular momenta associated with different reaction channels has been drawn. A variety of dynamical models viz.; Break-Up Fusion (BUF) [23,24], SUMRULE [25], Promptly Emitted Particles (PEP's) [26], Fermi-jet [27,28], Hot Spot [29], Moving-Source [30], Exciton [31,32] models have been proposed to explain the characteristics of ICF dynamics. These models generally have been used to fit the experimental data obtained at energies ⩾10 MeV/nucleon. However, none of the proposed models is able to reproduce the experimental data obtained at energies as low as ≈4–7 MeV/nucleon. Recently, significant ICF contributions have been observed even at energies just above the B_{fus} [33–35], which has become the motivation to investigate ICF at relatively low bombarding energies. Apart from that, Dracoulis *et al.* [36], Lane *et al.* [37], and Mullins *et al.* [38] reported that ICF can selectively populate high spin states in final reaction products even at low bombarding energies, and can be used as a spectroscopic tool. However, a perfect modeling of the ICF processes is still lacking.

In view of the above motivations, an experiment has been performed at the Inter-University Accelerator Center (IUAC), New Delhi, INDIA, employing the particle-γ-coincidence

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technique. A spectroscopically pure, self-supporting natural ^{169}Tm (100%) target of thickness ≈0.93 mg/cm^2 prepared by the rolling technique has been bombarded with a 90 MeV $^{16}O^{+7}$ beam delivered from the 15UD-Pelletron Accelerator. The above projectile-target combination has been chosen because of the well-known prompt γ-transitions in the possible reaction products and also to supplement our earlier studies [33,39], where the information about ICF contribution has been obtained by the measurement and analysis of excitation functions and forward recoil ranges. The present work not only strengthens our earlier findings but also provides additional qualitative information on the driving input angular momenta associated with various CF and ICF channels. In this experiment, particle-γ-coincidence events have been recorded using the Gamma Detector Array (GDA) along with Charged Particle Detector Array (CPDA) setup. The GDA is an assembly of 12 Compton suppressed, high resolution HPGe γ-spectrometers at angles 45°, 99°, 153° with respect to the beam axis and there are four detectors at each of these angles. However, the CPDA is a set of 14-phoswich detectors housed in a 14 cm diameter scattering chamber, covering nearly 90% of total solid angle so that the angular distribution of charged particles ($Z = 1, 2$) in ≈4π-solid angle may be recorded. All 14 detectors of CPDA have been divided into the three angular rings: (i) forward angle (F) 10°–60°, (ii) sideways (S) 60°–120°, and (iii) backward angle (B) 120°–170°. In order to remove the scattered beam, CPDs have been covered by Al absorbers of appropriate thicknesses. In the present experiment, at ≈90 MeV projectile energy, the forward angles (F) CPD's 10°–60°, are expected to detect two α-components; i.e., (i) the fusion-evaporation (CF) α-particles of average energy $E_\alpha \approx 18$ MeV, and (ii) the ICF 'fast' α-particles of $E_{\text{direct-}\alpha} \approx 22.5$ MeV. As such, in order to record only 'fast' α-particles in forward cone (F), an Al absorber of appropriate thickness has been kept at forward angle (F) 10°–60° CPD's to cutoff low energy alpha component (i.e., E_α ≈18 MeV). All HPGe γ-detectors of GDA setup have been calibrated using various standard γ-sources of known strength. The efficiency of high-resolution HPGe γ-spectrometers have been determined by putting ^{152}Eu and ^{133}Ba γ-sources at the target position. The ^{241}Am-source has been used for CPDA gain matching. In-beam prompt γ-ray spectra have been recorded in multiparameter mode employing different gating conditions. Off-line data analysis has been performed by projecting α-backward (for CF products) and α-forward gates (for ICF products) on γ-spectra. Specific exit channels have been identified by looking into various α-gated spectra. The main reaction channels that were identified in the forward cone in coincidence with fast α-particle(s) have been ^{169}Tm(^{16}O,αxn)$^{181-x}$Re, ^{169}Tm(^{16}O,αpxn)$^{180-x}$W, ^{169}Tm(^{16}O,$2\alpha xn$)$^{177-x}$Ta, and ^{169}Tm(^{16}O,$2\alpha pxn$)$^{176-x}$Hf. However, the residues which have been identified in backward cone are ^{169}Tm(^{16}O,αxn)$^{181-x}$Re and ^{169}Tm(^{16}O,pxn)$^{184-x}$Os. The normal xn-channels ^{169}Tm(^{16}O,xn)$^{185-x}$Ir (CF products) have been identified from singles spectra and confirmed from decay γ-lines. Areas under the peaks of relevant γ-transitions have been used to obtain the relative production yield of different reaction products.

In the present work, different reaction modes have been identified on the basis of entry state spin population in a residual nucleus prior to its deexcitation [12], which are expected to be entirely different in CF and ICF reactions. The spin distributions [i.e., the yield (intensity) profile as a function of observed spin (J_{obs})] of residual nuclei have been measured for the given projectile-target combination at ≈5.6 MeV/nucleon. Experimentally measured spin distributions of evaporation residues have been fitted to a function of the following type adopted as the simplest analytical representation of data:

$$Y = Y_\circ/[1 + \exp(J - J_\circ)/\Delta], \tag{1}$$

where Δ is related to the width of input angular momentum ($J_\circ$) and $Y_\circ$ is the normalization constant. Here, $J_\circ$ is a sensitive parameter and provides the qualitative information about the mean driving input angular momenta associated with different reaction channels.

Experimentally measured spin distributions for xn, αxn and $2\alpha xn$-channels are presented in Figs. 1 and 2. For a

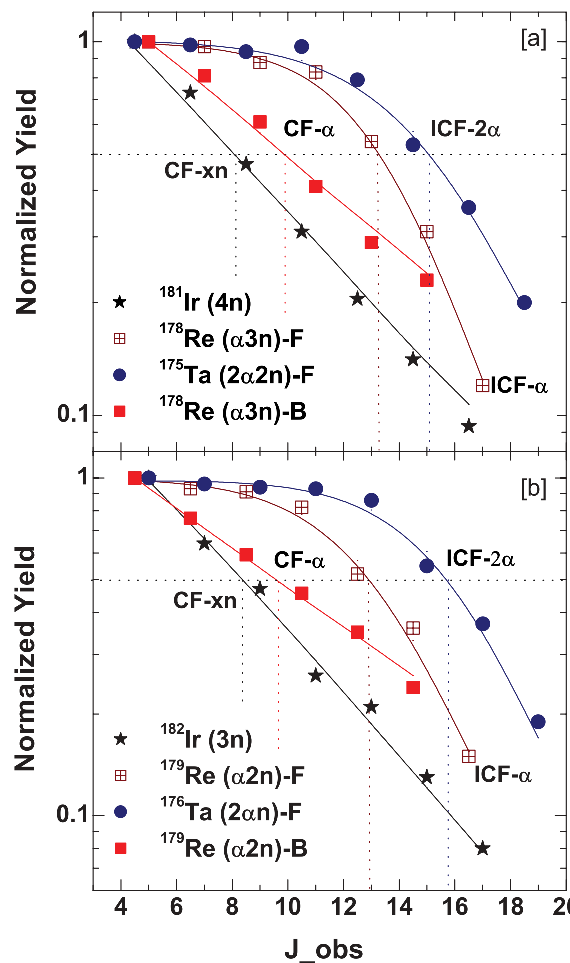

FIG. 1. (Color online) Experimentally measured spin distributions for different residues populated via xn (predominantly via CF) and αxn/$2\alpha xn$ (both CF and/or ICF) channels in ^{16}O+^{169}Tm system at ≈5.6 MeV/nucleon. Notations 'F' and 'B' represent the reaction products identified respectively from 'Forward' and 'Backward' α-gated spectra. The lines and curves through data points are the result of best fit procedure explained in the text.

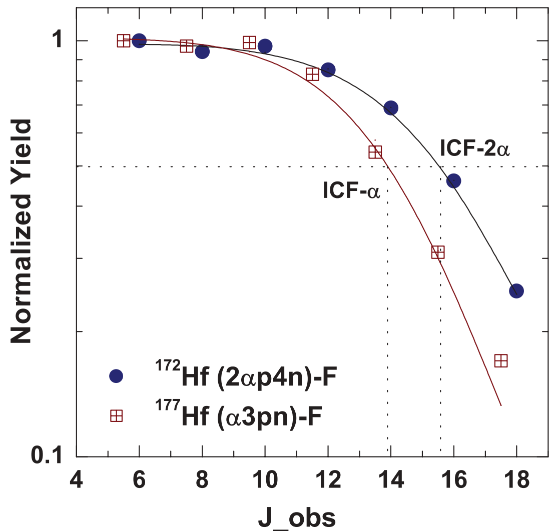

FIG. 2. (Color online) Explanation of the figure is same as Fig. 1.

better comparison of xn, αxn, and $2\alpha xn$ channels in a panel, relative yields of different CF and ICF products have been normalized to their own maximum observed yield values at lowest $J_{\rm obs}$. The errors have not been shown in these figures as they have been estimated to be $\leqslant 10\%$, and the inclusion of these errors is not likely to modify the present analysis. Reaction channels are labeled by self-explanatory notation of corresponding emission cascade. It can be observed from Figs. 1 and 2 that the experimentally measured spin distributions for ICF products are found to be distinctly different than that observed for CF products. The intensity of the xn-channels (predominantly populated via CF and identified from singles spectra) falls off rather quickly toward high spin states in the 'yrast' band, indicating strong feeding during the deexcitation of CN. This gradual monotonic increase in the intensity toward the band head is due to the fact that CF reactions lead to a CN of definite excitation energy (E^*), but with a broad spin distribution. In this case, the yrast states will be fed over a broad spin range. However, for αxn and/or $2\alpha xn$ channels identified from forward α-gated spectra (associated with ICF), the yield appears to be almost constant up to $J \approx 10\hbar$ for α-emitting channels, and $J \approx 12\hbar$ for 2α-emitting channels. Further, by comparison, CF and ICF spin distributions for ^{178,179}Re isotopes identified from backward-α-gated spectra (CF products) are found to be distinctly different than those observed from forward-α-gated (ICF products) spectra, Figs. 1(a, b). The yield of ^{178,179}Re isotopes identified from the backward cone is found to fall steeply with increasing spin, indicating strong feeding as expected for CF. The same characteristics of the spin distribution have also been observed in the case of ^{172,177}Hf isotopes populated via $2\alpha pxn$ and αxpn channels, Fig. 2. These results imply the absence of feeding to the lowest members of the 'yrast' band, or the population of low spin states are strongly hindered in direct α-emitting channels (ICF products). Moreover, the yield decreases above $J \approx 10$–$12\hbar$, indicating significant feeding at entry-state spin populations in the ICF processes. The observed trends likely reflect the fact that the entry-spin distribution for ICF reaction products is narrow and peaked at large ℓ-values. However, the dispute on this point has been discussed by Gerschel [21].

Moreover, in general, the value of $J_\circ$ is found to be $\approx 8\hbar$ for xn-channels, while for forward-αxn and $2\alpha xn$-channels $J_\circ$ is found to be $\approx 13\hbar$ and $\approx 16\hbar$, respectively. Again, it is interesting to note that, the $J_\circ$ value for α-emitting channels (^{178,179}Re isotopes) identified from backward α-gated spectra is found to be $\approx 10\hbar$, which indicates the involvement of significantly less input angular momenta as compared to ^{178,179}Re isotopes populated via direct-α-emitting channels. It may also be seen from the deduced values of $J_\circ$ that the multiplicity of direct α-particles increases with the driving input angular momenta, which shows the variation of ℓ-bins with different values of impact parameters at a given projectile energy. As such, it may be inferred that the lower ℓ-values do not contribute to the ICF, significantly.

In order to check the accuracy and self-consistency of the presently measured spin distributions, an attempt has been made to estimate the relative production yield of each reaction product from spin-distribution data. The experimentally measured relative yield of the individual reaction product has been extrapolated up to $J = 0\hbar$, and the yield value at $J = 0\hbar$ ($Y^{J=0}$) has been normalized with the total yield (sum of all fusion-evaporation channels) to estimate the relative yield value of each reaction product. In the same way the relative production yield of individual reaction products, calculated using theoretical model code PACE4, have been normalized with the total yield of fusion-evaporation channels.The ratio of experimentally measured and theoretically calculated relative yields ($Y_{\rm EXP}/Y_{\rm PACE4}$) for all fusion-evaporation channels has been plotted in Fig. 3. As shown in this figure, both the experimental and theoretical data agree reasonably well within the experimental uncertainties, strengthens/gives confidence in the measured spin distributions.

On the basis of results presented in this paper, it may be concluded that the low ℓ-values are strongly hindered and/or

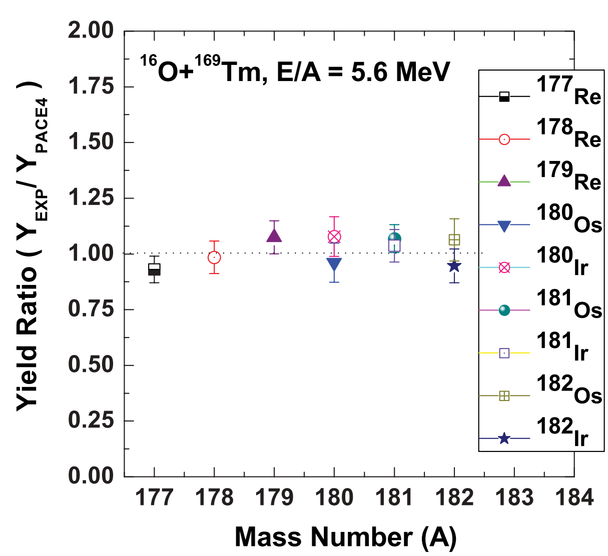

FIG. 3. (Color online) The yield ratio $Y_{\rm EXP}/Y_{\rm PACE4}$ of different residues produced only via CF of ^{16}O with ^{169}Tm at projectile energy $\approx$5.6 MeV/nucleon.

less fed in ICF. This confirms the fact that ICF reactions predominantly occur due to large input angular momenta coming from higher values of impact parameters. It may further be pointed out that the competition from successively opened ICF-channels (direct-α multiplicity) increases with driving input angular momenta. Each ℓ-value above ℓ_{crit} for normal fusion (CF) is expected to contribute to the direct-α emitting channels. As such, ICF seems to be a natural extension of the fusion processes for those interaction trajectories for which the driving input angular momentum does not allow CF. The extension of the present work at different energies would be interesting, and helpful for the refinement of the present findings. As such, it has been proposed to extend the above measurement for different projectile energies to generate some systematics.

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