Probing of Complete Fusion and Incomplete Fusion Dynamics in Heavy Ion Interactions at Energies above the Coulomb Barrier

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Introduction

The characteristics of α cluster states in heavy ions (HIs) are very important for understanding nuclear processes in stars. The details of the interaction between the cluster and regular states must be known for the deduction of such cross sections, since strong α cluster states can increase the α width to states that are closer to the region of astrophysical interest through configuration mixing [1]. It has proved to be far more difficult to study clustering phenomena in $N \neq Z$ nuclei because the "extra" nucleons introduce additional degrees of freedom [2, 3]. In the present work, an attempt has been made to study the presence α cluster states in the $N \neq Z$ projectile ^{19}F and possible role of the projectile structure on HI fusion reactions have been explored, in detailed way.

The present work has been carried out using five different experimental techniques namely; (i) excitation functions (EFs) of evaporation residues (ERs), (ii) forward recoil range distributions (FRRDs) of ERs, (iii) spin distributions (SDs) of ERs, (iv) excitation functions (EFs) of ERs using recoil mass spectrometers (RMS), and (v) quasi elastic (QE) excitation functions at back angle. These measurements have been carried out using 15 UD Pelletron accelerator at Inter University Accelerator Centre (IUAC), New Delhi, India.

The measurements of EFs of ERs populated in $^{14}N + ^{124}Sn$ and $^{19}F + ^{154}Sm$ systems, FRRDs of ERs populated in the system $^{19}F + ^{154}Sm$ were carried out using the general purpose scattering chamber (GPSC) facility of IUAC. The stacked foil activation technique followed by offline γ-spectrometry was employed in these measurements. Furthermore, the measurements of the SDs of different ERs produced in $^{19}F + ^{154}Sm$ system via CF and ICF channels were done through a charged particle-γ coincidence experiment. The experiment was carried out using the Gamma Detector Array (GDA) coupled with Charged Particle Detector Array (CPDA). Further, the ERs populated in $^{19}F + ^{191}Ir$ and $^{19}F + ^{193}Ir$ systems were detected using recoil mass separator Heavy Ion Reaction Analyzer (HIRA) and the back-scattered projectile like fragments were detected in the target chamber of HIRA. The targets used in these measurements were fabricated in the target lab of IUAC, New Delhi [4].

A comparison of the measured EFs for $^{14}N + ^{124}Sn$ and $^{19}F + ^{154}Sm$ systems with the statistical model predictions shows significant enhancement in the measured cross sections for the ERs produced via α emission channels. The measured results reveal significant ICF contributions for the projectiles ^{14}N (i.e. ^{14}N projectile breaks up into $\alpha + ^{10}B$, if ^{10}B fuses with the ^{124}Sn target, while α behaves as spectator), and ^{19}F (i.e. ^{19}F projectile breaks up into $\alpha + ^{15}N$ and/or $2\alpha + ^{11}B$, if ^{15}N and ^{11}B fuses with ^{154}Sm target, while α/2α behaves as spectator), with the targets ^{124}Sn and ^{154}Sm, respectively. A systematic comparison of the deduced ICF strength function (S_{ICF}) data for these systems with the literature data shows that the ICF probability increases with the entrance channel parameters namely; mass asymmetry, Coulomb factor (Z_PZ_T) and α- breakup threshold ($E^{\alpha}_{B.U.}$) of the projectile. Complete fusion functions extracted from measured complete fusion cross sections were compared with the universal fusion function (UFF) and found to be suppressed. This suppression disappears with the inclusion of ICF functions. These observations indicate that the $N \neq Z$ α clustered projectiles also have significant contributions of ICF on fusion cross sections at above barrier energies. However, the ICF probability for $N \neq Z$ α clustered projectile is lesser than the $N = Z$ α clustered projectile with similar $E^{\alpha}_{B.U.}$ values.

. The analysis of measured FRRDs inferred that the ERs populated through α emitting channels includes multiple component of linear momentum transfer from the ^{19}F projectile to the ^{154}Sm target. The FRRDs peaks of α emission channels at smaller distances clearly show an experimental signature of the breakup of the ^{19}F projectile into $\alpha + {}^{15}N$ and/ or $2\alpha + {}^{11}B$. Hence, the measured FRRDs clearly provide an evidence of the presence of α clustering in ^{19}F nuclei. In addition, the influence of the charge and mass asymmetry along with the deformations of projectile (β_2^P) and target (β_2^T), on the ICF contributions was investigated for different colliding nuclei. This analysis shows that the ICF contribution (S_{ICF}) will be governed by the deformations of both the projectile and target, along with the asymmetry parameters of the system. The present findings obtained from FRRDs measurements support the results from EFs measurements for the same system and projectile energy. These observations strongly suggests the presence of clustering in ^{14}N nuclei as α and ^{10}B (i. e. $^{14}N \rightarrow \alpha + {}^{10}B$), and ^{19}F nuclei as α and ^{15}N (i. e. $^{19}F \rightarrow \alpha + {}^{15}N$).

The measured SDs data shows different patterns for the ERs populated via CF and ICF dynamics. The SDs of α emission channels at forward angular zone clearly show the breakup of the ^{19}F projectile into $\alpha + {}^{15}N$ and/ or $2\alpha + {}^{11}B$. From the spin distributions of ERs, the feeding intensity pattern of ERs produced through CF and ICF process has also been investigated. Significant feeding of γ-transitions in CF channels has been observed over a broad spin range, while in the case of ICF channels, the population of low spin states are observed to be less fed and/or strongly hindered. In the present study, the mean input angular momentum for CF channels is found to be significantly lower as compared to ICF channels on a relative scale. A systematic study on the average input angular momenta values provides an experimental evidence of localization of CF and successive ICF channels in successive angular momentum windows as proposed in Sumrule model [5]. The present study establishes this picture for a wide range of systems and variable projectile and target deformations.

Further, the evaporation residue (ER) and quasi elastic (QE) excitation functions for the systems $^{19}F + {}^{191,193}Ir$ were measured. Coupled channel calculations were performed with the code CCFULL [6] for the interpretation of measured data. Fusion barrier distributions were also extracted from the QE cross sections. The present CCFULL calculations have been quite successful in reproducing both the fusion excitation function and the barrier distribution for the present systems. The comparison of the measured data with CCFULL calculations suggests the important role of the low-lying excitations due to nuclear-surface vibrations and collective rotations in the sub-barrier fusion. The experimental representation of fusion and QE excitation functions along with the barrier distributions for $^{19}F + {}^{191,193}Ir$ systems could not be explained by including inelastic couplings of the target in CCFULL calculations. They could only be explained by including inelastic couplings of the projectile ^{19}F also. It is also observed that the width of the barrier distribution remains similar for same $Z_P Z_T$. The present results suggest that other than the target structure effects, the projectile structure is also playing a role in the fusion process for $^{19}F + {}^{191,193}Ir$ systems.

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