A unified description of break-up fusion excitation functions at above barrier energies

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In recent years the intriguing occurrence of break up fusion (BUF) in heavy-ion collisions has been observed even at energies as low as near the Coulomb barrier [1]. The heavy ion (HI) reactions at the time of interaction may result in the emission of fast-forward-peaked α-particles in the exit channels. The emission of α-particle removes the excess angular momentum allowing the attractive pocket in the potential energy plot to be preserved, facilitating the occurrence of the BUF process. The recoil range distribution (RRD) measurements [2] provide undeniable evidence of projectile breakup in such reactions. Spin distribution (SD) measurements [3] further indicate the localization of angular momentum (ℓ) for BUF channels. Various theoretical models have been proposed to understand the dynamics of the BUF process. These models have been successful in explaining BUF data at energies above 10 MeV/A. However, they are unable to provide a complete explanation at lower energies (≈4-7 MeV/A). As a result, due unavailability of any reliable theoretical model, the dynamics of BUF reactions needs further exploration.

Therefore, in the present work an analytical framework for the breakup fusion contribution is proposed for the first time, based on the fundamental concept that as the angular momentum (ℓ) exceeds the critical value (ℓ_{crit}), breakup of the projectile is likely to occur [3]. This formalism aims to provide an understanding of the breakup fusion process in the absence of direct experimental measurements. The proposed formulation has been found to support the breakup fusion (BUF) contributions inferred from the comparison of measured excitation functions for alpha-emitting channels with those calculated using a statistical model approach. By appropriately scaling the incident heavy ion beam energy with the Coulomb barrier, it has been observed that the fusion cross-section generally exhibits a monotonic increase. However, the rate of increase and the magnitudes of the cross-sections differ for various projectiles, indicating their distinct characteristics and behaviors in fusion reactions. In the present work, we investigate the systems ^{12,13}C+^{159}Tb and ^{12,13}C+^{169}Tm within the energy range of ≈ 4-7 MeV/A.

The experiments to measure the excitation functions (EFs) for the residues populated via complete fusion and incomplete fusion for the ^{12,13}C+^{159}Tb and ^{12,13}C+^{169}Tm systems in the energy range of ≈ 4-7 MeV/A, employing stacked foil activation (SFA) technique were performed using the Pelletron accelerator facility at the Inter-University Accelerator Center (IUAC), New Delhi, India. Isotopically pure (99.99%) targets of ^{159}Tb and ^{169}Tm, (thickness ≈ 1.2-2.5 mg/cm^2), were prepared using a high-pressure rolling machine. Aluminum foils, serving as catcher foils and energy degraders (thickness ≈ 1.2–1.7 mg/cm^2), were also prepared. The thickness of each target and catcher foil was determined using the α-transmission method. The irradiations were conducted in the General-Purpose Scattering Chamber (GPSC), which has an in- vacuum transfer facility (IVTF). To measure the induced activities in the irradiated samples, each target-catcher foil assembly was

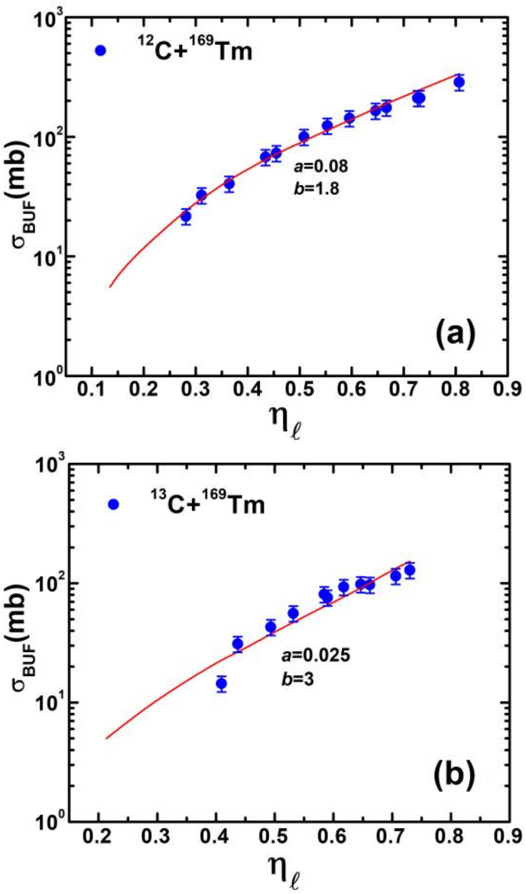

Fig.1: Comparison of the deduced BUF contribution with that obtained from analytical formulation

separately counted using a pre-calibrated HPGe γ-ray spectrometer setup. The energy and efficiency calibrations of the gamma-ray spectrometer were performed using standard gamma-ray sources. The resolution of HPGe spectrometer was 1.2 keV for the 1.33-MeV γ ray of ^{60}Co. Experimental EFs were obtained for a wide range of xn and pxn channels in the ^{12,13}C+^{159}Tb and ^{12,13}C+^{169}Tm systems. The measured EFs for the residues populated via xn and pxn channels were found to be in good agreement with the predictions of the statistical model PACE4 [4], confirming their production solely through CF processes. However, the observed enhancement in the α-emitting channels may be attributed to the involvement of BUF processes.

A comprehensive analysis was conducted by plotting the BUF cross section as a function of the angular momentum normalized to the critical angular momentum of the system, denoted as $\eta_\ell=\ell/\ell_{crit}$ and shown in Fig1(a-b) as a representative case for ^{12,13}C+^{169}Tm systems. The data points in this figure were fitted with two parameters homographic function. The best fit result, represented by the red full curve for each $\sigma_{BUF}(E,\ell)$ demonstrates an intriguing observation. Regardless of the selected fusion cross-section, used for predicting the BUF contribution, the best fit curve exhibits a clear dependence on normalized angular momentum. Moreover, there is a consistent and monotonic increase in $\sigma_{BUF}(E,\ell)$ as the normalized angular momentum increases. Remarkably, the results reveal a nearly linear behavior on a log scale, regardless of the specific systems studied in the present work. Considering the dependence of $\sigma_{BUF}(E,\ell)$ on both the incident energy and the angular momentum above ℓ_{crit} while assuming applicability of strong ℓ dependence in the first approximation, the deduced BUF cross-sections were subjected to a fitting procedure utilizing a functional form defined as;

$$\boldsymbol{\sigma_{BUF}(E,\ell) = a\left[\frac{\ell^2}{\mu E} + \sigma_{CF}(E) \times e^{b\eta_\ell^2}\right]}$$

Here, 'a' and 'b' are fitting parameters, while $\sigma_{BUF}(E,\ell)$ represents the functional relationship that captures the behavior of the BUF contribution as a function of the normalized angular momentum η_ℓ. This fitting function enables a quantitative as well as qualitative representation of the measured BUF cross-sections for all the systems studied, facilitating a deeper understanding of the interplay between energy, angular momentum, and the resulting BUF phenomena.

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