Unveiling Cluster Transfer-Induced Fragmentation Mechanism in ^{12}C-^{12}C Collisions

Anagha P K[1],* Arunima Dev T V[1], Midhun C.V[1], M.M Musthafa[1], Antony Joseph[1], Vafiya T.T[1], Nicemon Thomas[1], and S. Ganesan[2]

[1] *Nuclear and Radiation Physics Group, Department of Physics, University of Calicut-673635, India and*

[2] *Formarly Raja Rammanna Fellow of the DAE, Bhabha Atomic Research Center, Mumbai, 400085, India*

Introduction

Understanding accurate nuclear reaction mechanisms, particularly fragmentation, is essential for accurately modeling the underlying physics, with significant implications for hadron therapy and space radiation protection. Current models often struggle to capture the complexity of these reactions, as evident from discrepancies between theoretical predictions and experimental data, particularly in residue cross sections, angular distributions, and energy spectra. These gaps point to the need for more precise investigation into the mechanisms driving fragment formation, especially through broader angular measurements and improved modeling techniques.

Inelastic and transfer-induced breakup modes become prominent at higher interaction energies, and the coupling between resonant and continuum breakups plays a critical role in determining the angular distribution and energy spectra of emitted alpha particles. However, existing experiments primarily focus on angular distribution alone, lacking the relative energy measurements necessary to differentiate contributions from various breakup states. This lack of data creates a significant gap in understanding the full scope of these nuclear processes. The present work aims to address this gap by introducing breakup couplings Continuum Discretized Coupled Channel (CDCC) and Coupled Reaction Channel (CRC) methods, adapting experimental data from Dudouet et al.

*Electronic address: anagha3315@gmail.com

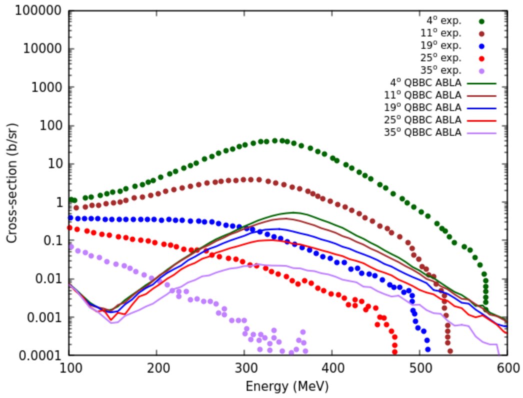

FIG. 1: The QBBC ABLA model-calculated alpha spectrum at various angles for 95 MeV/u ^{12}C, compared with experimental data from Dudouet et al. [1]

Materials and Methods

The ^{12}C-^{12}C nuclear reaction was simulated using the QBBC_ABLA PhysicsList in Geant4 [2]. The theoretical results were validated against experimental data for the ^{12}C(^{12}C,xp) and ^{12}C(^{12}C,xα) reactions. A ^{12}C ion beam at 95 MeV/u bombarded a thin graphite target, simulating 10^9 events to minimize statistical uncertainties. The energy, angle, and type of first-generation fragments (protons and alpha particles) were analyzed, converted to cross-sections, and compared with experimental data from Dudouet et al., [1](EXFOR Entry: 02170).

The QBBC_ABLA model calculations were done for proton and α-particle angular distributions. The proton distribution aligns well at mid-angles but diverges at forward

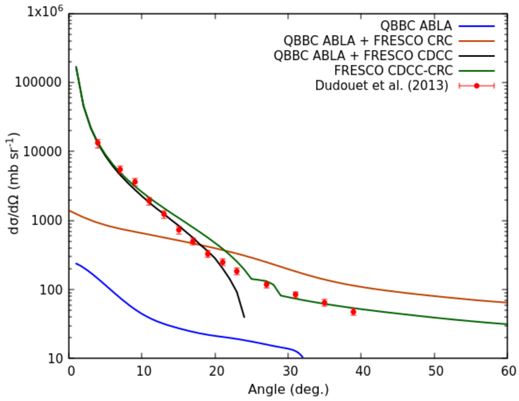

FIG. 2: Differential cross-sections for inelastic breakup and alpha transfer-induced breakup at 95 MeV/u ^{12}C, calculated using FRESCO CDCC-CRC along with QBBC_ABLA models, compared with experimental values from Dudouet et al. [1]

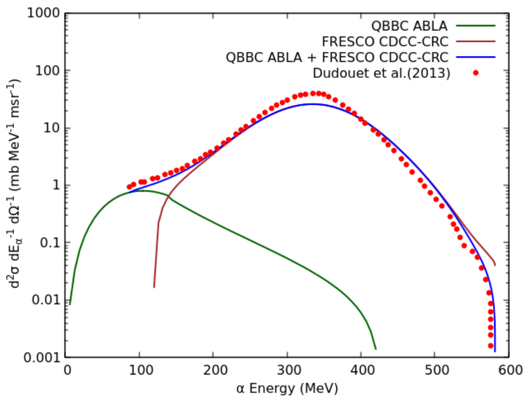

FIG. 3: Double differential cross-section (α spectrum) at 4° calculated using CDCC-CRC + QBBC_ABLA, showing direct and compound nuclear components, compared with Dudouet et al., [1] experimental measurements

angles, while the α-particle distribution fails to reproduce the available experimental data [3]. Figure 1 highlights these discrepancies in spectra across angles, for 95 MeV/u. The QBBC_ABLA PhysicsList's limitations are evident as it neglects sequential breakup mechanisms. To address this, the FRESCO code was integrated, incorporating Continuum Discretized Coupled Channels (CDCC) and Coupled Reaction Channels (CRC), with parameters adapted from evaluations and HFB spectroscopy factors.

Results and Discussion

The incorporation of α transfer-induced breakups and inelastic breakup modes, combined with the statistical QBBC_ABLA calculations, effectively reproduce both the particle angular distributions and spectra measured by Dudouet et al., [1]. Figure 2 illustrates the calculation of $\frac{d\sigma}{d\Omega}$, showing that at 95 MeV/u, inelastic coupling to breakup states, $\langle \alpha + ^8\mathrm{Be} | ^{12}\mathrm{C} \rangle$, is pivotal to the reaction mechanism. Specifically, transfer-induced breakup, where α transfer between the projectile and target generates unbound ^{8}Be, enhances α production. At this energy, inelastic coupling results in the emission of three α particles in the forward direction. These breakups cause pre-compound flux loss, reducing compound nucleus formation and lowering proton and α particle yields at higher angles.

This approach accounts for both inelastic and transfer-induced breakup processes, populating each unbound state and coherently summing them to determine overall α production. Figure 3 shows the double differential cross-section of α at 4° for 95 MeV/u, where experimental data is accurately reproduced by incorporating CDCC-CRC calculations with QBBC_ABLA, underscoring the importance of breakup processes. At intermediate energies, transfer-induced mechanisms predominantly drive α emission in ^{12}C-^{12}C collisions, while at higher energies, both α transfer-induced and inelastic breakups play significant roles. This emphasizes the necessity of comprehensive physics-driven models over phenomenological approaches.

References

[1] Dudouet et al., Phys. Rev. C. 88, 024606(2013)

[2] Allison et al., j. nima. 2016. 06. 125(2016)

[3] Arunima, Anagha, Midhun et al., arXiv:2409.07090(2024)