Unraveling the Effects of Sequential Breakups on ^{12}C Fragmentation at Intermediate Energies

Arunima Dev T V,* Anagha P.K, Midhun C.V, M.M Musthafa,
Vafiya Thaslim T.T, Nicemon Thomas, S. Ganesan, and Antony Joseph
Dept. of Physics, University of Calicut,
Calicut University P.O Kerala, 673635 India and
Formerly Raja Rammanna Fellow of the DAE,
Bhabha Atomic Research Center, Mumbai, 400085, India

Introduction

Carbon ion therapy is highly valued for its physical and radiobiological benefits, but the secondary charged particle production from nuclear reactions in tissue remains a concern. This requires precise data sets on differential and double-differential cross sections for each fragment produced at therapeutic energies, making comprehensive radiation transport analysis critical.

Models like Fermi breakup, statistical multifragmentation, QCD, and antisymmetrized molecular dynamics etc., included in Geant4 QBBC_ABLA model successfully replicate proton data at forward angles [3]. But discrepancies remain for α particle cross sections due to internal α clustering in ^{12}C. Here, the transfer-induced breakups at intermediate energies affect angular distributions and energy spectra of emitted α particles. However, data mostly cover angular measurements, with no studies on particle coincidences or relative energy measurements to identify breakup states.

The present work aims to elucidate the processes involved in α production by analyzing Compound Nuclear, Pre-equilibrium, Knockout emissions, through the comprehensive Quantum Chromodynamics approach, and breakup modes, through the CDCC-CRC approach. This analysis serves to benchmark the evaluation procedure for fragmentation data in radiotherapy and space applications.

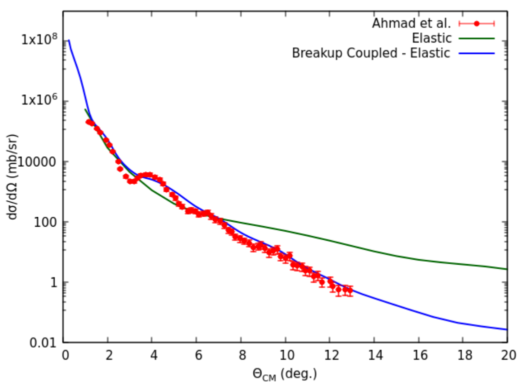

FIG. 1: Elastic scattering angular distribution of ^{12}C-^{12}C with and without transfer couplings at 120.75 MeV/u. compared with the data from Ahmad et al., [2]

Materials and Methods

In the case of ^{12}C beam at intermediate energies, the breakup pathway often involves the transfer of an α cluster between the projectile and target, leading to the formation of ^{8}Be in its ground or resonant states. This process, categorized as a finite-range transfer, results in ^{8}Be decaying into two α particles through sequential breakups. The population of excited states in ^{8}Be and ^{16}O, including breakup continuum states, was analyzed using the CDCC-CRC approach in the FRESCO code. Elastic angular distributions for ^{12}C-^{12}C scattering at 120.75 MeV/u, compared with experimental data from Ahmad et al., validated the inclusion of transfer couplings. HFB spectroscopic factors were added to the reconstructed α particle angular distributions, with QBBC_ABLA models incor-

*Electronic address: arunimadevtv29@gmail.com

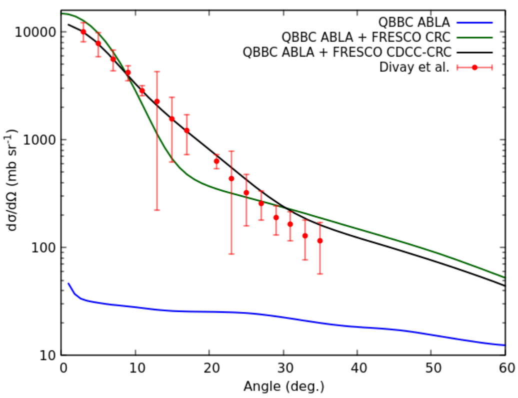

FIG. 2: Differential cross-section of α through transfer induced breakup calculated using FRESCO CDCC-CRC along with QBBC_ABLA, compared with Divay et al.,[1] data

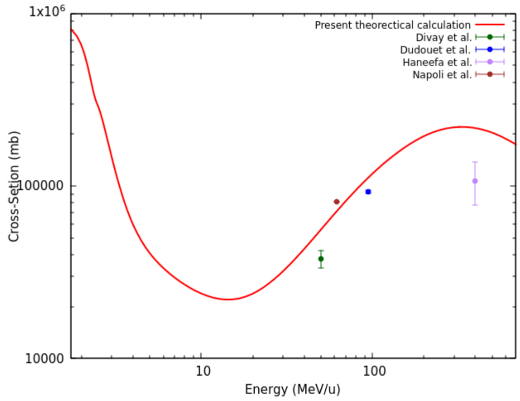

FIG. 3: The excitation function for $^{12}C(^{12}C, x\alpha)$ combining QBBC_ABLA and FRESCO CDCC-CRC with cross section from Divay et al.[1], Napoli et al.[4], Dudouet et al.[5] and Kummali et al.[3] are compared.

porating transfer, compound reactions, and knockout processes.

Using optimized potentials, states, couplings, and spectroscopic factors, the excitation function for ^{12}C(^{12}C, xα) was calculated. Contributions from compound reactions, pre-equilibrium processes, and hadron interactions were modeled with QBBC_ABLA, while breakups were computed via FRESCO CDCC-CRC. Results up to 500 MeV/u were compared with experimental data from Divay et al. [1], Napoli et al. [4], Dudouet et al. [5], and Kummali et al. [3].

Results and Discussion

Figure 1 shows that including transfer couplings via CDCC-CRC improves the accuracy of elastic angular distributions for ^{12}C-^{12}C scattering. The model accounts for discretized breakup continuum and CRC state couplings, effectively reproducing elastic scattering cross sections and highlighting the importance of transfer-induced breakups.

Figure 2 shows that the angular distribution from Divay et al. is successfully reproduced by integrating α transfer-induced breakups into the QBBC_ABLA model. However, QBBC_ABLA fails to fully reproduce the data due to its exclusion of certain partial waves and sequential breakups. The transfer-induced breakup significantly contributes to α production, with forward-focused distributions from low-lying states and broader distributions at mid-angles from CDCC and CRC overlap. This novel approach of incorporating sequential breakup into former QBBC_ABLA model, successfully explains the total fragmented α production. Figure 3 shows that the theoretical excitation function, with inclusive α production, reproduces the experimental data satisfactorily, demonstrating the model's consistency in effectively integrating statistical and breakup processes across the energy range. The study underscores the importance of employing physics-driven models rather than phenomenological methods for simulations in specific applications.

References

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