INVESTIGATION OF α-TRANSFER AND BREAKUP REACTIONS FROM ^{7}Be +^{12} C*

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The α-transfer and breakup channels in ^{7}Be+^{12}C at 35 MeV are studied. The total cross sections from α-transfer, populating different states of ^{16}O are obtained. This work also presents the first exclusive breakup measurement of ^{7}Be. In contrast to earlier works, the results show a significant contribution of breakup.

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1. Introduction

Breakup and transfer reaction studies on weakly bound nuclei give valuable insights into nuclear structure and reaction dynamics [1]. The ^{7}Be nucleus is radioactive, has a low breakup threshold of 1.58 MeV, and exhibits comparable breakup and transfer reaction channels when incident on light targets. Earlier studies on the ^{7}Be+^{12}C reaction at 34 MeV indicated that α-transfer dominates over breakup from the observation of a few coincidence events [2]. For ^{7}Be+^{28}Si, the ^{3}He and ^{4}He production were mainly dominated by stripping [3]. Similar trends were observed for the medium-mass target ^{58}Ni at $E = 22$ MeV near the Coulomb barrier [4]. The analyses indicated that the ^{3}He and ^{4}He yields are governed predominantly by stripping and fusion–evaporation processes rather than breakup. The CDCC calculations suggest an overall breakup cross section of 10.8 mb [4]. In our recent work [5], the α-transfer reaction ^{12}C(^{7}Be,^{3}He)^{16}O data were analyzed in a DWBA framework. Here, we report a comparison of α-transfer and breakup channels, examining ^{3}He and α production. The exclusive breakup of ^{7}Be on ^{12}C is measured for the first time, allowing a clear identification of coincident ^{3}He–α events.

2. Experiment

The experiment was carried out at HIE-ISOLDE, CERN, using a 35 MeV ^{7}Be beam of intensity $\sim 5 \times 10^5$ pps [6]. Targets CD_2 and CH_2 of thickness 15 μm were used, and charged particles were detected using a compact silicon detector array. The array is in the shape of a pentagon and consists of Micron annular S3 and W1 DSSDs covering angles from 8° to 165°. The DSSDs are backed by unsegmented pads. Further experimental details are available in Ref. [6]. The relevant Monte Carlo simulations were carried out using NPTool [7].

3. Results

3.1. Inclusive cross section of α and ^{3}He

To get an idea about the contribution of transfer and breakup channels, angular distributions of the inclusive ^{3}He and α particles are plotted in the left panel of Fig. 1. A series of Legendre polynomials is used to fit the data

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}(\theta) = \sum_{\ell=0}^{\ell_{\max}} a_\ell \, P_\ell(\cos\theta)\,. \tag{3.1}$$

The dashed curves show the best-fit results adopting $\ell_{\max} = 3$. The integrated ^{3}He and α inclusive cross sections are obtained from the $4\pi a_0$ term, where a_0 is the zeroth-order coefficient of the Legendre polynomial expansion, summing up to about 37 mb and 157 mb, respectively. It is apparent that α particles are about four times more abundant than ^{3}He. While α production can be triggered by various reaction mechanisms, ^{3}He production is dominated by two main processes, namely, α-transfer ^{12}C(^{7}Be,^{3}He)^{16}O and breakup of ^{7}Be into α+^{3}He.

3.2. Transfer reaction $^{12}C(^7Be,^3He)^{16}O$

The angular distributions for the ^{12}C(^{7}Be,^{3}He)^{16}O reaction for several excited states of ^{16}O are given in Fig. 2 of Ref. [5]. The data were fitted using FRESCO [8]. The angle-integrated cross sections are shown here in the right panel of Fig. 1. The total cross section from this reaction summing over the excited states of ^{16}O is about 15 mb. Thus, we can see that the ^{12}C(^{7}Be,^{3}He)^{16}O reaction accounts for about 40% of the total ^{3}He yield. To understand the origin of the remaining ^{3}He, we proceed to study the breakup of ^{7}Be.

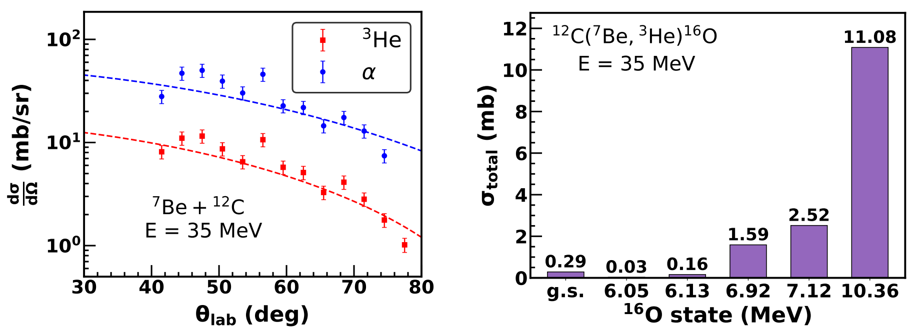

Fig. 1. Left panel: Experimental angular distributions for ^{3}He and α produced in the ^{7}Be+^{12}C reaction at 35 MeV. The dashed lines represent the best fits using the Legendre polynomials (see the text for details). Right panel: Total cross sections of different ^{16}O states populated via the ^{12}C(^{7}Be,^{3}He)^{16}O reaction at 35 MeV.

3.3. Breakup reaction $^{12}C(^7Be,\alpha^3He)^{12}C$

To study the breakup channel, two coincidence modes are considered. In W1–W1 mode, the coincidence of ^{3}He and α are carried out by putting two-dimensional gates on respective particle bands obtained from the ΔE–E spectrum in the pentagon W1 detectors. For the W1–S3 mode, one particle from the W1 detectors (α or ^{3}He) and another hit on the S3 detector (^{3}He or α) are taken in coincidence and the method of the Catania plot was applied [9]. This is a kinematic technique used to identify distinct reaction channels when one particle is not detected. Here, the recoil ^{12}C remains undetected. The energy and momentum of ^{12}C can be reconstructed using the conservation laws

$$\vec{P}_{^{12}\mathrm{C}} = \vec{P}_{\mathrm{beam}} - \vec{P}_{\alpha} - \vec{P}_{^{3}\mathrm{He}}\,, \tag{3.2}$$

$$E_{\mathrm{beam}} - E_{^{3}\mathrm{He}} - E_{\alpha} = \frac{P^2_{^{12}\mathrm{C}}}{2m_{^{12}\mathrm{C}}} - Q\,, \tag{3.3}$$

where E_i and $\vec{P}_i$ ($i = \alpha$, ^{3}He) are the energies and momenta of the detected particles, E_{beam} is the beam energy, $\vec{P}_{^{12}\mathrm{C}}$ and $m_{^{12}\mathrm{C}}$ are the momentum and mass of the undetected ^{12}C recoil, and Q is the reaction Q value.

The Catania plot of $(E_{\mathrm{beam}} - E_{\alpha} - E_{^{3}\mathrm{He}})$ *versus* $\frac{P^2_{^{12}\mathrm{C}}}{2}$ corresponds to a unique straight line in the plot which intercepts the y-axis at $y = -Q$ and has a slope of $\frac{1}{m_{^{12}\mathrm{C}}}$. Events from the other reaction channels lie elsewhere in the plot, as confirmed through Monte Carlo simulations. The Catania plot is shown in Fig. 2 and the dotted region, as obtained from NPTool simulations, encloses events from the ^{12}C(^{7}Be,α ^{3}He)^{12}C reaction. The inset shows the reconstructed mass spectrum of the ^{12}C recoil. The breakup reaction can proceed either directly or sequentially through resonance excited states in the continuum. The relative energy (E_{rel}) and opening angle (θ_{rel}) distributions between the breakup fragments provide signatures to distinguish the processes. The opening angle distribution [10] from Monte Carlo simulations

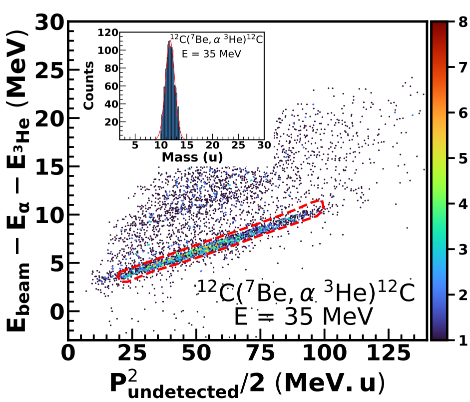

Fig. 2. The Catania plot with the dotted region enclosing events from the ^{12}C(^{7}Be,α ^{3}He)^{12}C reaction. The inset represents the reconstructed mass spectrum of ^{12}C.

and the experimental data are shown in the left panel of Fig. 3 with good agreement. The event-by-event Q-value distribution was obtained from the following equation:

$$Q + E_{\mathrm{beam}} = E_{\alpha} + E_{^{3}\mathrm{He}} + E_{\mathrm{recoil}}\,. \tag{3.4}$$

The Q *versus* E_{rel} plot (right panel of Fig. 3) reflects the projectile and/or target excitation [11]. The contributions of direct and sequential breakup

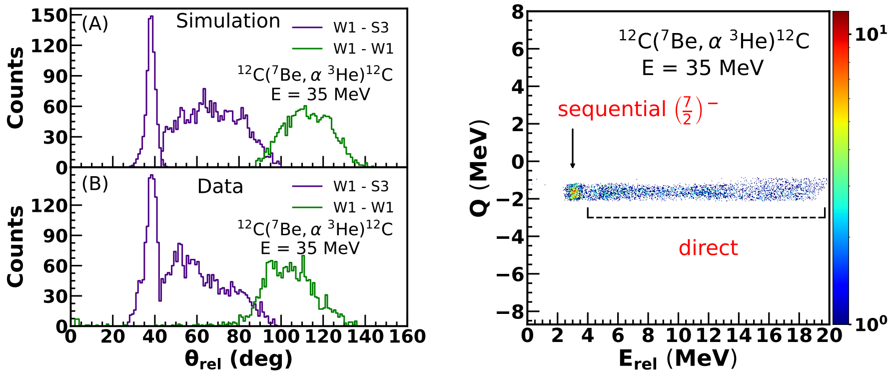

Fig. 3. (Color online) Left panel: The opening angle distribution of coincident ^3He and α from the breakup of ^7Be on ^{12}C at 35 MeV for W1–S3 (black/violet) and W1–W1 (gray/green) coincidences. The results from (A) Monte Carlo simulations and (B) experimental data are seen to be in good agreement. Right panel: The Q *versus* $E_{\rm rel}$ spectrum from the breakup of ^7Be on ^{12}C, showing projectile and/or target excitations. Events associated with direct breakup as well as sequential breakup processes are distinctly identified. The recoil ^{12}C remains in its ground state.

from the 4.57 MeV excited state of ^7Be are clearly seen. The target nucleus ^{12}C is in its ground state corresponding to elastic breakup events. To obtain true coincidence yields in exclusive measurements, accurate determination of the detection efficiency of breakup fragments is crucial. Monte Carlo simulations were carried out assuming isotropic emission of breakup fragments ^3He and α in the rest frame of ^7Be. Coincidence events within the geometrical acceptance of the detector array were used to compute the efficiency as

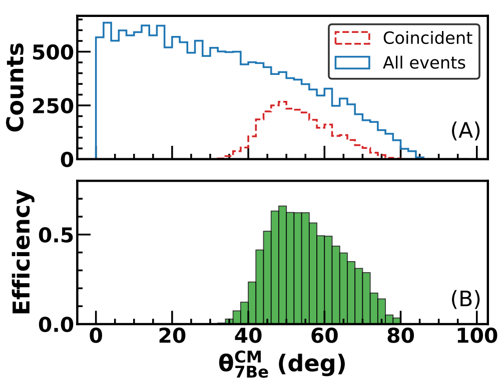

Fig. 4. The α-^3He coincidence detection efficiency of the detector setup for sequential breakup of ^7Be from the 4.57 MeV excited state.

a function of the reconstructed center-of-mass angle of ^{7}Be. Fig. 4 shows (A) the number of total simulated events and detected coincidence events, and (B) the resulting efficiency for sequential breakup of ^{7}Be from the 4.57 MeV excited state. This efficiency was incorporated into the experimental results.

4. Summary

We have studied the α-transfer and breakup reactions of ^{7}Be on ^{12}C at 35 MeV. The total cross section of the α-transfer reaction populating ^{16}O states have been obtained. The inclusive ^{3}He and α spectra demonstrate the dominance of α particle production. The present work shows a significant contribution from breakup reactions, in contrast to earlier studies. This work reports the first measurement of exclusive breakup of ^{7}Be on ^{12}C. The direct and sequential breakup processes of ^{7}Be have been separated and studied.

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