Mechanism of Breakup Reactions of Weakly-Bound Nuclei

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Abstract

Nuclear reactions occurring near the Coulomb barrier are an effective approach for investigating the interplay between nuclear structure and reaction dynamics. With the development of accelerators, an increasing number of exotic nuclei can be produced; therefore, it is crucial to further understand the influence of weak binding energy on reaction dynamics and fusion reactions. Currently, extensive experimental studies have shown that the complete fusion cross sections for stable weakly-bound nuclei such as 6,7Li and 9Be with heavy-mass target nuclei are approximately 30% lower compared to those calculated by existing theoretical models and those deduced from tightly-bound nuclear systems. To investigate the role of breakup of weakly-bound nuclei in suppressing complete fusion cross sections, studying the breakup effects and breakup mechanisms of weakly-bound nuclei has become a new focus area. This paper will review recent related work on breakup reactions of weakly-bound nuclei both domestically and internationally, including the work of our research group in this area.

Full Text

Study on the Breakup Mechanism of Weakly Bound Nuclei

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Abstract

Nuclear reactions occurring near the Coulomb barrier provide an effective pathway for investigating the interplay between nuclear structure and reaction dynamics. With the development of accelerator technology, an increasing number of exotic nuclei can be produced, making it crucial to understand how weak binding energies affect reaction dynamics and fusion processes. Numerous experiments have demonstrated that the complete fusion cross sections for stable weakly bound nuclei such as ^{6,7}Li and ^{9}Be reacting with heavy target nuclei are approximately 30% lower than those predicted by existing theoretical models and derived from tightly bound nuclear systems. To explore how breakup of weakly bound nuclei contributes to this suppression of complete fusion cross sections, studying the breakup effects and mechanisms of weakly bound nuclei has emerged as a new area of focus. This paper reviews recent domestic and international work on breakup reactions of weakly bound nuclei, including research conducted by our group.

Keywords: weakly bound nuclei; complete fusion cross section; suppression factor; breakup reaction

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In recent years, fusion reactions involving weakly bound nuclei such as ^{6,7}Li and ^{9}Be as projectiles have been a hot topic in both experimental and theoretical nuclear physics research [?]. Extensive studies have revealed that in these fusion reactions, complete fusion exhibits significant suppression above the Coulomb barrier and considerable enhancement below the barrier compared with theoretical calculations and tightly bound nuclear systems [?]. These effects of weakly bound nuclei on fusion have attracted increasing attention to understanding the underlying reasons and physical mechanisms.

When weakly bound nuclei participate as projectiles in nuclear reactions, their low breakup thresholds make them prone to dissociation into multiple fragments before fusing with the target nucleus. Additionally, transfer reactions can occur between the projectile and target, producing projectile-like and target-like nuclei, such as ^{208}Pb(^{7}Li,^{6}Li)^{209}Pb and ^{208}Pb(^{6}Li,^{5}Li)^{209}Pb [?], which can also undergo breakup reactions. Consequently, both direct breakup and transfer-induced breakup channels exist in weakly bound nucleus fusion reactions. The presence of these breakup channels reduces the probability of complete capture of the projectile or projectile-like nucleus by the target or target-like nucleus, thereby suppressing the complete fusion (CF) cross section and increasing the incomplete fusion (ICF) cross section. However, different breakup channels—such as neutron-transfer breakup, proton-transfer breakup, and direct breakup—occur with different probabilities and have different impacts on fusion cross sections. Therefore, further investigation into the mechanisms of various breakup channels in weakly bound nucleus fusion reactions is essential [?].

Numerous experiments on weakly bound nucleus breakup mechanisms have been conducted both domestically and internationally, primarily employing online charged-particle measurements to identify different breakup channels. Theoretical models [?] are then used to extrapolate the breakup probabilities for each channel from sub-barrier to above-barrier energy regions. This paper is organized as follows: Section 2 describes the main experimental measurement methods, Section 3 reviews recent research progress, Section 4 presents related work by our group, and Section 5 provides a summary and outlook.

2 Experimental Measurement Methods

Current studies on breakup mechanisms of weakly bound nuclei such as ^{6,7}Li and ^{9}Be primarily employ online charged-particle measurement techniques. Position-sensitive detectors (typically silicon strip detectors) are used to measure emitted charged particles during reactions, providing accurate scattering angle and energy information. Depending on experimental requirements, coincidence measurements can be performed, and two-body kinematics calculations are used to select true coincidence events. Various physical quantities can then be analyzed. For example, the Q-value for a breakup reaction channel can be calculated from the energies of two breakup fragments using the formula:

$$Q = E_1 + E_2 + E_{\text{recoil}} - E_{\text{lab}}$$

where E_1 and E_2 are the kinetic energies of the two breakup fragments, E_{recoil} is the recoil energy of the target nucleus (which may become a target-like nucleus through transfer reactions), and E_{lab} is the incident particle energy. The recoil energy E_{recoil} can be determined from momentum conservation. This allows calculation of Q-values for different breakup channels and reconstruction of Q-value spectra. When all particles before and after the reaction are in their ground states, the Q-value is commonly denoted as Q_{gg}, which is a known quantity. When particles are in excited states after the reaction with excitation energy E_x, the Q-value becomes:

$$Q = Q_{gg} - E_x$$

In addition to the target (or target-like) nucleus possibly being in an excited state, the projectile (or projectile-like) nucleus prior to breakup may also be excited. Since the lifetime of excited projectile-like nuclei is very short, direct detection is difficult, and identification is typically achieved through the relative energy of breakup fragments. In the breakup process of a projectile (or projectile-like) nucleus without external forces, the relative energy of fragments can be calculated as:

$$E_{\text{rel}} = \frac{m_1 E_2 + m_2 E_1 - 2\sqrt{m_1 E_1 m_2 E_2}\cos\theta_{12}}{m_1 + m_2}$$

where θ_{12} is the relative angle between the two breakup fragments in the laboratory frame, which can be calculated from their scattering and azimuthal angles. Through two-body kinematics calculations, we can also obtain physical information such as the emission angle of the projectile-like nucleus in the laboratory frame and the angle between the relative momentum directions of the two fragments in the projectile-like nucleus rest frame. Online charged-particle kinematic measurements thus provide valuable physical information, enabling charged-particle source analysis and breakup channel identification to help clarify the breakup reaction process [?].

[Figure 1: see original paper] (color online) Schematic diagram of projectile-like nucleus breakup into fragments

As shown in Figure 1, A represents the projectile, B the target, C the projectile-like nucleus, D the target-like nucleus, and e and f the two breakup fragments. The relative energy of breakup fragments can be expressed as $E_{\mathrm{rel}} = E_{1,c} + E_{2,c}$, where $E_{1,c}$ and $E_{2,c}$ are the energies of the two fragments in the projectile-like nucleus rest frame. Using known quantities and measured physical values, we can derive the fragment relative energy formula:

$$E_{\mathrm{rel}} = Q_{BU} + E_{P,x} + \Delta E_{T,C}$$

where Q_{BU} and $E_{P,x}$ are the breakup reaction energy and excitation energy of the projectile-like nucleus, respectively, and $\Delta E_{T,C}$ is a relative energy correction term related to the breakup location. When the projectile-like nucleus breaks up far from the target-like nucleus without Coulomb field influence, $\Delta E_{T,C}$ equals zero and E_{rel} exhibits a peak structure. When breakup occurs near the target-like nucleus, the Coulomb field affects fragment trajectories, making $\Delta E_{T,C}$ a continuous distribution and resulting in a broad E_{rel} distribution. Therefore, the relative energy spectrum of breakup fragments effectively describes the final state of the projectile-like nucleus, though final-state lifetime effects must be considered in this analysis.

3 Recent Domestic and International Research Progress

This section reviews research over the past two decades on breakup reactions of weakly bound nuclei as projectiles. Experimental efforts have focused on using coincidence measurements to identify different breakup channels and investigate their contributions to fusion suppression. Two-body kinematics calculations provide physical information to determine final-state properties of projectile-like and target-like nuclei, extract near-target and resonant breakup cross sections, and further explore breakup mechanisms. Additionally, both incomplete fusion processes induced by breakup and transfer reactions may affect complete fusion cross sections [?], and experiments using other coincidence methods have addressed this issue.

In 2002, Hinde et al. reported breakup probabilities for various channels in ^{9}Be + natPb experiments [?], proposing that ^{8}Be breakup occurs via two mechanisms: prompt breakup and delayed breakup of long-lived ground-state ^{8}Be ($T_{1/2} \approx 10^{-16}$ s). They concluded that the above-barrier complete fusion suppression in weakly bound nucleus fusion reactions is caused by prompt breakup, and suggested that the suppression factor depends on target nuclear charge.

In 2010, R. Rafiei et al. reported similar measurements for ^{9}Be beams on targets including ^{209}Bi, ^{208}Pb, ^{196}Pt, ^{186}W, ^{168}Er, and ^{144}Sm [?]. Using two-body kinematics calculations, they reconstructed Q-values for coincident α particles and calculated relative energy spectra of breakup fragments. By correlating Q-value spectra with relative energy $E_{\rm rel}$ spectra, they identified different breakup channels. Figure 2 [Figure 2: see original paper] shows the Q-$E_{\rm rel}$ correlation spectra for ^{9}Be + ^{209}Bi at $E_{\rm cm}$ = 35.38 MeV and 26.73 MeV, with five regions corresponding to different breakup channels: Region 1 events originate from ground-state ^{8}Be breakup; Region 2 from excited-state ^{8}Be breakup; Region 3 from excited-state ^{9}Be breakup (producing an undetected neutron in addition to the observed α particles, via a two-step process of ^{9}Be* $\rightarrow$ ^{8}Be + n followed by ^{8}Be $\rightarrow \alpha + \alpha$); Region 4 from the $5/2^{-}$ resonant state of ^{9}Be; and Region 5 from excited-state ^{9}Be breakup. They identified Regions 2 and 5 as prompt breakup contributing to above-barrier complete fusion suppression, reaching the same conclusion as Hinde et al.

D. H. Luong et al. used charged-particle coincidence measurements in 2011 to obtain Q-value spectra and breakup fragment relative energy spectra for ^{6}Li + ^{208}Pb and ^{7}Li + ^{208}Pb systems [?]. They extracted excitation state information for target-like and projectile-like nuclei, determined the fraction of prompt breakup in each channel, and demonstrated that breakup of projectile-like nuclei produced via transfer reactions dominates. Their analysis introduced the concept of breakup timescales (Figure 3 [Figure 3: see original paper]), providing a new method to distinguish prompt and delayed breakup processes for further mechanism studies.

Building on 2011 work, D. H. Luong systematically compiled experimental results for ^{6,7}Li on ^{144}Sm, ^{207,208}Pb, and ^{209}Bi targets in 2013 [?]. Through coincidence measurements, they reconstructed Q-value and relative energy $E_{\rm rel}$ spectra for various systems, determining the fraction of prompt breakup in each reaction channel and identifying which channels most significantly affect fusion.

Sunil Kalkal investigated light-mass targets ^{58}Ni and ^{64}Zn with ^{6,7}Li beams [?], performing angular and energy coincidence measurements of breakup fragments. Comparing relative energy spectra with heavy-target results revealed that ^{7}Li does not break up into α + t when colliding with light targets, while ^{6}Li breaking into α + d shows significant differences across target masses. Angular correlation analysis of breakup fragments clearly revealed substructures from delayed breakup of ^{6}Li (3^{+} state) and ^{7}Li ($7/2^{-}$ state), termed resonant breakup when occurring from projectile-like resonant states, and near-target breakup when occurring close to the target-like nucleus. These components are well separated in angular correlation spectra (Figure 4 [Figure 4: see original paper]), allowing experimental determination of resonant and near-target breakup fractions across different systems. The results indicate that direct breakup modes differ substantially for ^{6}Li reactions with different target masses, with resonant breakup playing a more significant role for light targets, and that direct breakup patterns differ between ^{6}Li and ^{7}Li reactions with heavy targets, possibly because ^{7}Li excited states have much higher excitation energies than direct breakup thresholds. Notably, near-target breakup constitutes a very small fraction of direct breakup for ^{6}Li + light targets, suggesting this channel does not affect fusion reactions.

S. Santra et al. performed coincidence measurements of emitted α and d particles in ^{6}Li + ^{209}Bi experiments [?], providing experimental angular distributions for sequential and direct breakup cross sections (described as Sequential and Direct breakup in their paper) of the ^{6}Li $\rightarrow \alpha$ + d channel (Figure 5 [Figure 5: see original paper]). CDCC (Continuum Discretized Coupled Channels) calculations indicated that resonant breakup from the 3^{+} state of ^{6}Li dominates this channel. Comparing resonant and near-target breakup cross sections with inclusive α cross sections suggested contributions from other breakup channels, warranting further mechanism studies.

D. Chattopadhyay's recent work on ^{6}Li + ^{112}Sn [?] observed coincident α and ^{3}He breakup fragments, identified a new breakup channel, and for the first time observed $7/2^{-}$ and $5/2^{-}$ excited states of ^{7}Be in relative energy spectra. They extracted angular distributions for near-target breakup and resonant breakup from these states, finding good agreement with theoretical calculations and providing a new explanation for the origin of inclusive α particles.

To further investigate breakup mechanisms, Shrivastava et al. employed charged-particle-γ coincidence measurements in ^{7}Li + ^{198}Pt experiments [?]. By gating on γ-rays and charged particles, they identified target-like nuclei and extracted relevant reaction channel cross sections, observing large cluster transfer of ^{5},^{6}He. Dynamical theoretical models validated the data and demonstrated the importance of different cluster structures of ^{7}Li in near-barrier dynamics calculations, providing a new experimental approach for studying weakly bound nucleus breakup mechanisms.

Cook's 2016 work [?] used dynamical models to simulate ^{9}Be breakup on various targets, incorporating breakup timescale effects and concluding that accounting for projectile-like nucleus excited-state lifetimes is crucial for reproducing breakup processes. Calculations indicated that breakup reactions contribute only 9% to the complete fusion cross section suppression factor, far below the theoretical 30%, suggesting that the main suppression arises from one-step transfer processes. To verify this, Cook et al. conducted ^{7}Li + ^{209}Bi experiments [?], using charged-particle coincidence measurements to obtain cross sections for all breakup channels where neither fragment was captured (No-Capture Breakup, NCBU) α particles, totaling 36 $\pm$ 1 mb. After subtracting delayed breakup components that do not suppress complete fusion, the remaining cross section was approximately 20 mb, only a small fraction of the existing incomplete fusion cross section of 302 ± 21 mb [?] for this system, indicating that other reaction channels contribute to incomplete fusion. They also obtained energy and angular distributions for α particles without coincident particles (Unaccompanied α), which showed higher energies and more forward angles compared to NCBU α distributions. Model calculations for α angular distributions when one breakup fragment is captured (Breakup Capture, BUC α) showed peaking at backward angles, distinctly different from Unaccompanied α distributions (Figure 6 [Figure 6: see original paper]). This discrepancy suggests different reaction mechanisms for α production. Further studies revealed that Po isotopes from incomplete fusion processes originate primarily from direct triton transfer rather than projectile breakup followed by fusion, concluding that complete fusion suppression is mainly due to cluster transfer effects rather than projectile breakup mechanisms.

4 Related Work by Our Research Group

Our group recently conducted experiments at the tandem accelerator of the China Institute of Atomic Energy, bombarding a 210 g/cm^2 ^{209}Bi target with ^{6},^{7}Li beams at 30 MeV, 40 MeV, and 47 MeV [?]. A large-solid-angle silicon detector array enabled charged-particle coincidence measurements. A telescope detector system provided clear particle identification, and kinematic coincidence calculations (Figure 7 [Figure 7: see original paper]) successfully identified four breakup channels—α + α, α + t, α + d, and α + p—in near-barrier and above-barrier regions, with their relative contributions to total breakup events. Notably, in the 30 MeV ^{6}Li + ^{209}Bi data, we newly observed α + t breakup coincidence events, demonstrating that the 1n pickup process for ^{6}Li cannot be ignored near the barrier. Our group has also recently identified the α + ^{3}He breakup channel in ^{6}Li + ^{209}Bi data, further verifying ^{7}Be production and providing experimental evidence for 1p pickup in this system.

Using reconstructed breakup Q-value spectra, we can determine final-state information for target-like nuclei such as ^{210}Bi, ^{208}Bi, and ^{208}Pb. Figure 8 [Figure 8: see original paper] shows Q-value spectra reconstructed from α + α coincidence events in ^{7}Li + ^{209}Bi at three energies, with Q_{gg} = 13.57 MeV. Different excited states of ^{208}Pb are observed, providing new insights for analyzing single-nucleon transfer mechanisms. Latest work is ongoing.

From two-body kinematics calculations, we can construct angular correlation plots of breakup fragments (Figure 9 [Figure 9: see original paper]), where θ_{12} is the relative angle between fragments in the laboratory frame and β is the angle between fragment relative momentum directions in the projectile-like nucleus rest frame (see Figure 1). Clear structures corresponding to the ground and first excited states of ^{8}Be are observed in ^{6}Li + ^{209}Bi. Combined with relative energy spectra, prompt and delayed breakup components can be distinguished and cross sections extracted. Notably, we observed for the first time the first excited state of ^{8}Be in 30 MeV ^{6}Li + ^{209}Bi data. The fractions of prompt and delayed breakup in the ^{8}Be breakup channel vary with incident energy, possibly due to changes in interaction times and breakup locations of excited projectile-like nuclei, which are closely related to their excited-state lifetimes. Further analysis is underway.

5 Summary and Outlook

This paper has introduced measurement methods for studying breakup mechanisms of weakly bound nuclei and reviewed relevant experimental research. Due to their low binding energies, weakly bound nuclei as projectiles in heavy-ion fusion reactions involve multiple mechanisms. Current experimental studies primarily use coincidence measurements to identify various breakup processes during fusion, explaining the origin of inclusive α particles and clarifying how different breakup processes affect fusion suppression. However, most data focus on sub-barrier or near-barrier energies, with limited data for above-barrier breakup mechanisms. Q-value spectra from breakup reactions, combined with charged-particle-γ coincidence measurements, effectively describe final states of target-like nuclei after breakup, providing new perspectives for studying single-nucleon transfer mechanisms. Final-state information of projectile-like nuclei can be extracted from relative energy spectra, and prompt versus delayed breakup components can be identified using lifetime information to further explain fusion cross section suppression and explore underlying breakup mechanisms.

Since both incomplete fusion processes induced by breakup and transfer reactions may affect complete fusion cross sections [?], identifying and extracting cross sections for these two processes would greatly aid understanding of their respective contributions. However, experimental identification of incomplete fusion and transfer reaction products remains challenging, requiring improvements in experimental apparatus and measurement methods. In future work, our group will further employ charged-particle-γ coincidence measurements to investigate nuclear reaction mechanisms.

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Note: Figure translations are in progress. See original paper for figures.