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Reaction dynamics of weakly bound nuclei at near-barrier energies

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The above-barrier suppression of complete fusion in reactions with weakly bound stable nuclei displays a strong correlation with their breakup threshold. Simplistically, this observation suggests that suppression of complete fusion is due to the direct breakup of the weakly bound partner, prior to reaching the barrier. However, new measurements of breakup at energies below the fusion barrier show that breakup following transfer, rather than direct breakup, is the dominant mechanism. The insights into the physical mechanisms of breakup from these measurements, in conjunction with theoretical developments, are being used to obtain an understanding of the relationship between sub-barrier breakup and suppression of complete fusion.

1. INTRODUCTION

The differences in the reaction dynamics of well bound and weakly bound nuclei arise due to the presence of low-lying continuum- and short-lived resonance states in the latter [1]. The resulting low threshold against breakup for weakly bound nuclei leads to significant yields of reaction products where part of the fragment is captured by the target (referred to as incomplete fusion (ICF) in this paper). Quantum mechanical models such as the continuum discretized coupled channels model (CDCC), are unable to separate ICF from complete fusion (CF) of the projectile with the target. This has precluded a direct comparison of the experimental and theoretical results. However, experiments with weakly bound stable nuclei incident on heavy target nuclei have definitively demonstrated that the above-barrier fusion cross-sections are suppressed compared with the expectations for well-bound nuclei [2–7]. The next challenge is to obtain a complete quantitative understanding of the mechanism of breakup and its relationship with near-barrier fusion. This paper discusses the systematics of complete fusion at above barrier energies, recent ideas for correlating above-barrier CF suppression to sub-barrier breakup yields, and new breakup measurements which provide a complete picture of the breakup mechanism.

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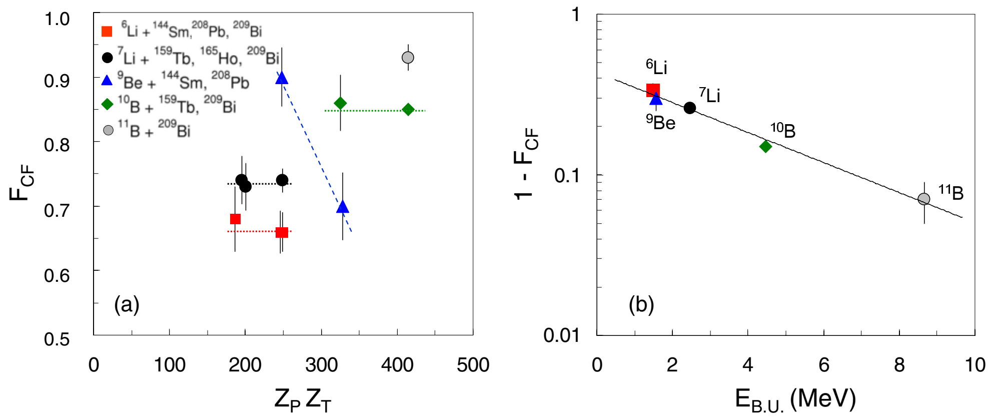

Figure 1. (a) The complete fusion suppression factor F_{CF} at above-barrier energies as a function of the charge product of projectile and target. (b) The quantity 1-F_{CF} as a function of the breakup threshold for reactions with targets of ^{208}Pb and ^{209}Bi. Data are from Refs. [2–9]. The lines guide the eye.

2. SYSTEMATICS OF SUPPRESSION OF COMPLETE FUSION

The first measurement [2] of above-barrier suppression of complete fusion for the reaction of ^{9}Be with ^{208}Pb, and subsequent works [3–9] using other weakly bound stable nuclei in various laboratories, now allow a systematic study [9] of CF suppression. The suppression, quantified by the ratio F_{CF} of the observed CF cross sections to those expected without breakup, is plotted in Fig. 1(a) as a function of the charge product of the target-projectile combination. The CF suppression for the reactions involving ^{6,7}Li and ^{10}B projectiles are almost independent of target mass, with the suppression being largest for reactions with a ^{6}Li projectile which has the lowest threshold against breakup (−1.473 MeV). The suppression for ^{9}Be + ^{144}Sm deviates from this observed near-constant behaviour of F_{CF} for reasons which are not entirely clear, but may be related to experimental issues. In Fig. 1(b) the quantity (1 - F_{CF}) is plotted against the lowest breakup threshold only for those reactions with the heavy target nuclei ^{208}Pb and ^{209}Bi, where identification of CF products is unambiguous due to the negligible α-evaporation from the compound nucleus. The suppression shows a remarkably consistent correlation with the breakup threshold [9]. Simplistically, this may suggest that breakup into the most energetically favourable partition is playing the dominant role in suppressing CF.

3. PREVIOUS EXPERIMENTS ON BREAKUP

Evidence from previously works, however, suggests that the concept of breakup into the most energetically favourable partition is too simple. Singles measurements with ^{6,7}Li on targets of ^{58}Ni and ^{118}Sn observed low numbers of d and t compared with α-particles [10], indicating that breakup is more complex than simply $^{6}\text{Li} \to \alpha + d$ and $^{7}\text{Li} \to \alpha + t$.

Exclusive coincidence measurements of ^{7}Li incident on ^{65}Cu found α-d yields to be larger than α-t yields [11], and significant yields of breakup following n-transfer was measured more recently [12] for the reaction of ^{7}Li with ^{144}Sm. Therefore, the questions that need answering are (i) whether n-transfer is the dominant trigger for breakup and, (ii) how to relate observed breakup and CF. These questions are discussed in the following sections, with the latter discussed first.

4. RELATING BREAKUP AND FUSION

Quantum models of reaction dynamics cannot distinguish CF from ICF [13]. The CDCC method should, however, make reliable predictions if none of the breakup fragments are absorbed. Measurements of breakup at energies below the barrier, where the probability of fragment absorption is negligible, may therefore be understood within the framework of quantum models, thus facilitating an understanding of the relationship between breakup and CF. Evidence that such a relationship exists came from sub-barrier breakup measurement of ^{9}Be incident on Pb, which showed that the prompt breakup probability at the barrier is qualitatively consistent with the measured suppression of CF [14]. The breakup probabilities were found to vary exponentially with the distance of closest approach. This result led to the development of a three-dimensional classical dynamical reaction model [13], where the experimental breakup probabilities were used to predict the above-barrier CF and ICF yields. This model provided the first mapping from sub-barrier breakup to above-barrier suppression of CF, and provided a new impetus to perform breakup measurements at energies below the barrier for other reactions involving weakly bound nuclei.

5. BREAKUP DYNAMICS FROM SUB-BARRIER MEASUREMENTS

A highly pixellated double sided Si strip detector array, covering 0.84πsr in the backward hemisphere, has recently been commissioned at the Australian National University to make measurements of breakup fragments at energies below the barrier. Particle identification is obtained by arranging two detectors to give a ΔE$-$E detector telescope. The reaction Q-value is determined from the beam energy, energies of the breakup fragments and the recoiling target-like nucleus. The reaction Q-value gives information about the state of the target-like nucleus at breakup. However, it does not provide any knowledge about the state of the projectile-like nucleus ($E^{*}_{\mathrm{proj-like}}$), since this energy is recovered in the kinetic energy of the breakup fragments. Information on $E^{*}_{\mathrm{proj-like}}$ can however be obtained from the relative energy (E_{rel}) of the breakup fragments, which depends on the breakup Q-value and $E^{*}_{\mathrm{proj-like}}$. The reaction Q-value and E_{rel} taken together thus give a complete picture of the dynamics of breakup. The Q-projection of events, excluding breakup from the long-lived ^{8}Be ground state ($^{8}\mathrm{Be}_{\mathrm{g.s.}}$), is shown in Fig. 2 for the reaction of ^{7}Li + ^{209}Bi. Breakup from the $^{8}\mathrm{Be}_{\mathrm{g.s.}}$ has been excluded as its lifetime (10^{-16} s) is much longer than the typical reaction time scales of 10^{-21} s, and therefore $^{8}\mathrm{Be}_{\mathrm{g.s.}}$ is not expected [14] to play a role in the suppression of complete fusion. For the ^{7}Li + ^{209}Bi system, the breakup of $^{7}\mathrm{Li} \rightarrow \alpha + t$ is weaker than breakup triggered by p-pickup (leading to short-lived excited states of $^{8}\mathrm{Be} \rightarrow \alpha + \alpha$). Other channels such as n-stripping forming ^{6}Li, which subsequently breaks up into an α-d pair, and $2n$-stripping forming $^{5}\mathrm{Li} \rightarrow \alpha + p$,

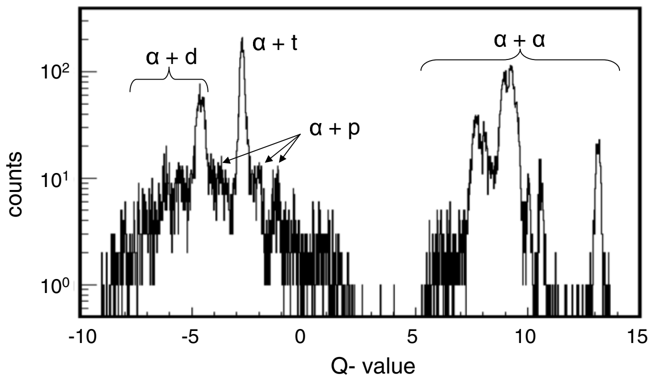

Figure 2. The reaction Q-value spectrum, excluding breakup from the ^{8}Be ground state (see text), for ^{7}Li + ^{209}Bi at an energy $\simeq$5% below the fusion barrier. Proton pickup leading to excited ^{8}Be, which breaks up into two α-particles, is a major channel.

are also present, but are weaker than the $p-$pickup channel. If instead of ^{7}Li the projectile ^{6}Li is used, then the dominant channel, by far, is n-stripping forming ^{5}Li, leading to breakup into an α-p pair. Further analysis of these extensive data sets is currently in progress to obtain quantitative yields for all the breakup partitions.

These measurements clearly demonstrate that breakup is mainly triggered by transfer, and whilst the CF suppressions for ^{6,7}Li + ^{209}Bi are similar, the transfer mechanism triggering breakup is different. These complete measurements of sub-barrier breakup, in conjunction with classical model calculations are expected to lead to a quantitative understanding of the breakup mechanism and its effects on fusion.

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