Dynamics and Time-scales in Breakup and Fusion

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Abstract.
Nuclear reaction dynamics at energies near the fusion barrier is known to be dominated by quantum effects, such as tunneling, and quantum superpositions that give rise to channel couplings. The understanding of near-barrier reaction dynamics continues to evolve as improved experimental techniques reveal new facets of interaction dynamics. Recent coincidence measurements using weakly bound stable nuclei have not only provided a complete picture of the physical mechanisms triggering breakup, but have also shown how information on reaction dynamics occurring on time-scales of \( \sim \) zepto-seconds can be obtained experimentally. These new experimental findings demand major developments in quantum models of low energy nuclear reactions.

1. Introduction
Experimental advances in the last two decades that enabled precision measurements of fusion cross-sections \([1 - 5]\) have transformed our understanding of reaction dynamics at energies near the barrier. It is now well accepted that the collision dynamics is best described by a linear superposition of the quantum states of the two interacting nuclei \([6]\), which results in the single fusion barrier being effectively replaced by a distribution of barrier energies \([6, 7, 8]\). This affects collision outcomes such as elastic and inelastic scattering, transfer and fusion. The effect on fusion is seen most clearly at energies below the average fusion barrier, where the measured cross-sections are much larger than the expectations of calculations assuming a single fusion barrier. The clear indications of the effects of quantum superposition implies that near-barrier collisions can be used to investigate fundamental quantum effects \([9, 10]\). This goal links nuclear physics to other areas where understanding effects of quantum superposition and irreversible outcomes in complex quantum systems is a major research theme \([11, 12]\), such as in atomic physics, photonics and biophysics \([13]\). Indeed, the orientation dependence of fusion barrier energies seen in nuclear collisions \([1, 2]\) has close parallels with the recently observed phenomenon of orientation dependent interaction energies and hence reaction rates in collisions of ultracold dipolar molecules \([14]\).

The concepts described above have emerged from studies of well bound nuclei. For such nuclei the lifetimes of the low lying collective states are much longer than nuclear collision times of a few \(10^{-22}\) sec. The question is how the reaction dynamics changes when the lifetimes

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of low lying states are similar to or less than collision times? Answering this is topical due to the increasing opportunities worldwide to perform experiments with unstable nuclei. It is indisputable that collisions of such nuclei must be described by a superposition of quantum states mentioned previously. Understanding the role of low lying unbound states or short-lived resonances, which can lead to breakup of nuclei, is however a challenge [15, 16, 17]. This poses a hurdle to understanding the near-barrier reaction dynamics of weakly bound nuclei, where reaction outcomes are sensitive to both couplings effects and the effect of breakup [15, 16, 17]. Recent experiments with weakly bound stable nuclei have provided a complete picture of the physical mechanisms that trigger breakup [18, 19]. The background that led to these experiments is described in the next section. It is followed by a description of the experimental methods that led to identification of all the processes that cause breakup, and a discussion on how the measurements can give information on time-scales of breakup processes. The latter provides a potent tool to identify those breakup processes that are fast enough (∼10^{-22} s) to affect fusion.

2. Fusion of weakly bound stable nuclei
It was shown unambiguously [20, 21] that in reactions of weakly bound stable nuclei, the complete fusion cross-sections at above barrier energies are suppressed compared with those of well-bound nuclei. This conclusion resulted from the application of the concept of experimental fusion barrier distribution. The suppression of complete fusion has since been seen in many other reactions with weakly bound stable nuclei [22 - 30]. It was natural to assume that the suppression of complete fusion is caused by the direct breakup of the weakly bound nuclei into their cluster constituents, e.g., ^6Li breaking up into ^4He and ^2H nuclei, ^7Li breaking-up into ^4He and ^3H nuclei. Amongst the many measurements made [31 - 39], some appeared to support this idea, but many did not. It thus remained a perplexing question for more than a decade.

3. Experiments and kinematic reconstruction
Experiments measuring breakup, where all the breakup fragments are detected, can potentially help, provided none of the fragments are captured by the other (target) nucleus. An experiment was therefore designed [18, 19] to measure all breakup processes at energies below the barrier. Choosing below-barrier energies minimizes fragment absorption that can complicate both experimental and theoretical interpretations. The experiments were performed using beams of ^6,^7Li from the Heavy Ion Accelerator Facility of the Australian National University (ANU). Targets of ^209Bi, and isotopically enriched ^208Pb, ^207Pb and ^144Sm were used. An array of four 400μm thick double-sided silicon-strip detectors^3 (DSSDs), was used to measure the charged breakup fragments. Two of the DSSDs were placed back to back, forming a ΔE − E detector telescope for particle identification purposes [19]. The detectors were placed in a lamp-shade configuration in the backward hemisphere, as shown in Fig. 1. The front face of each DSSD is divided into 16 arcs and the back face is divided into 8 sectors. The intersection of each arc and sector defines the position(s) (θ, φ) of the detected particle(s) as shown schematically in Fig. 1.

The positions of the fragments and their measured energies are used to determine the energy of the recoiling target-like nucleus, and thus the reaction Q-value, through momentum conservation assuming three-body kinematics. The Q-value spectrum for breakup events show sharp peaks, demonstrating that the breakup is indeed almost exclusively binary, which validates the application of three-body kinematics in the reactions discussed here. Knowledge of the Q-values provides information about states populated in the target-like nucleus, but not about the states of the projectile-like nucleus. However, at breakup, the energy that is available for sharing between the breakup fragments is the sum of the breakup Q-value (Q_{BU}) and the excitation

^3 Manufactured by Micron Semiconductors Ltd., England
energy of the state from which breakup occurs ($E^*$). The information on the state of the projectile-like nucleus prior to breakup is thus contained in the relative energy ($E_{rel}$) of the two breakup fragments.

4. Characterizing breakup

The discussions in Sec. 3 show how the reaction $Q$-value together with the relative energy of the two breakup fragments completely characterizes the various breakup processes. Figure 2 shows a plot of $Q$-value against $E_{rel}$ for the reaction of $^7$Li with $^{207}$Pb. The $\alpha - t$ pairs result from breakup of $^7$Li; this observation matches the expectation that $^7$Li breaks-up into its cluster constituents. However, other breakup modes are very prominent. The $\alpha - \alpha$ pairs originate from breakup of the $^8$Be nucleus which is formed when $^7$Li picks up a proton from the closed proton-shell nucleus $^{207}$Pb. The $\alpha - d$ pairs are due to the breakup of $^6$Li formed in $n$-stripping reactions. The largest contribution to events that have large $E_{rel}$ values (i.e., events within dashed rectangles) is from breakup following $p$-pickup [19]. The significance of these events in affecting fusion will be discussed in the next sections. All the breakup modes identified in Fig. 2, are also observed in collisions of $^7$Li with $^{208}$Pb, $^{209}$Bi and $^{144}$Sm nuclei.

Considering now the reactions of $^6$Li with $^{208,209}$Bi, $^{208,207}$Pb and $^{144}$Sm nuclei, breakup of $^6$Li into $\alpha - d$ pairs is observed, as expected. However, as seen in Fig. 3, neutron transfer from $^6$Li to the target, forming $^5$Li which subsequently breaks into $\alpha - p$ is prominent in collisions with $^{208}$Pb, and indeed for all the other targets discussed here. This mechanism is a dominant contributor to events that have large $E_{rel}$ values (i.e., events within dashed rectangles). The $Q$-values corresponding to the different $\alpha - p$ bands identify the states of $^{209}$Pb that are populated following $n$-transfer; the band corresponding to the formation of $^{209}$Pb in its ground state is indicated.

As mentioned in Sec. 3, the combination of $Q$ and $E_{rel}$ is a powerful tool for obtaining detailed information about the states of both the projectile-like and the target-like nucleus.
Figure 2. (color online) The reaction Q-value plotted against the relative energy of the two fragments \((E_{\text{rel}})\) provides a complete picture of the breakup dynamics. Measurements are shown for a 29.0 MeV beam of \(^7\text{Li}\) incident on a \(^{207}\text{Pb}\) target. Coincidence pairs, \(\alpha-d\), \(\alpha-t\), and \(\alpha-\alpha\) result from breakup following \(n\)-stripping, inelastic excitations and \(p\)-pickup, respectively. The measured \(E_{\text{rel}}\) provides information on the state of the projectile-like nucleus prior to breakup and also gives information on breakup time-scales (see text). The dashed rectangles identify prompt breakup (\(\sim 10^{-22}\) s time-scale), whilst the peaks at small \(E_{\text{rel}}\) (marked by vertical dashed lines) are due to breakup from long-lived states in \(^6\text{Li}\) (first excited state at 2.186 MeV) and \(^8\text{Be}\) (ground state).

formed following any interaction that leads to breakup. For example, \(n\)-transfer from \(^7\text{Li}\) to \(^{207}\text{Pb}\) resulting in the formation of \(^{208}\text{Pb}\) in its ground state (narrow block arrow) and excited states (wide arrow) can be identified in Fig. 2. Corresponding information about the projectile-like partner can be obtained from the \(E_{\text{rel}}\) spectrum. The vertical dashed arrow in Fig. 2 marks the \(E_{\text{rel}}\) value of the majority of the \(\alpha-d\) events, and corresponds to \(E^* = 2.186\) MeV [40] which matches the energy of the first excited state of \(^6\text{Li}\). The width of this state is \(24 \pm 2\) keV [40], corresponding to a mean life of \(3 \times 10^{-20}\) s. This mean life is much longer than the collision time and thus breakup of \(^6\text{Li}\) from the 2.186 MeV state is expected to occur well after the \(^6\text{Li}\) reaches its point of closest approach to the target, and thus well-beyond the range of the nuclear-attraction between the colliding nuclei. The breakup of this state is thus too slow to result in incomplete fusion (capture of either breakup fragments \(\alpha\) or \(d\) by the target-like nucleus). The breakup processes that can result in incomplete fusion (and thus reduce complete fusion) thus must necessarily occur from states with much shorter lifetimes, which breakup prior to reaching the fusion barrier. Information on breakup time-scales is thus crucial in understanding the reaction dynamics.
Figure 3. (color online) The reaction Q-value plotted against the relative energy of the two fragments ($E_{\text{rel}}$) provides a complete picture of the breakup dynamics. Measurements are shown for a 29.0 MeV beam of $^6\text{Li}$ incident on a $^{208}\text{Pb}$ target. Coincidence pairs, $\alpha - p$, $\alpha - d$, and $\alpha - \alpha$, result from breakup following $n$-stripping, inelastic excitations and pickup of a deuteron from the target, respectively. The measured $E_{\text{rel}}$ provides information on the state of the projectile-like nucleus prior to breakup and also gives information on breakup time-scales (see text). The dashed rectangles identify prompt breakup ($\sim 10^{-22}$ s time-scale), whilst the peaks at small $E_{\text{rel}}$ (marked by vertical dashed lines) are due to breakup from long-lived states in $^6\text{Li}$ (first excited state at 2.186 MeV) and $^8\text{Be}$ (ground state).

5. Obtaining information on breakup time-scales
The principle of obtaining breakup time-scales can be understood from a simple classical picture of the collision, shown schematically in the left panels of Fig. 4. Collisions at energies below the fusion barrier are considered so that capture of the projectile or the breakup fragments is negligible. The projectile, represented by the unfilled circle in Fig. 4 (a,b), is shown to be incident on the heavy target nucleus (dark circle); the light shading around the target nucleus represents the region where nucleon transfer can occur. If following inelastic scattering or transfer, the projectile-like nucleus is excited to a short-lived state then its breakup will follow soon after, while the projectile-like nucleus is still close to the target-like nucleus (Fig. 4(a)). Being close to the target-like nucleus, the two positively charged breakup fragments (small circles marked with ‘$+$’) can feel a strong Coulomb repulsion in different directions. This results in the two fragments getting a large relative velocity and thus a large $E_{\text{rel}}$. If, on the other hand, the projectile-like nucleus is excited to a long-lived state then breakup does not occur until the projectile is far from the target-like nucleus (Fig. 4(b)) where the effect of its Coulomb field is much reduced. The two fragments are now repelled from each other only by the Coulomb
interaction between them, which results in a small $E_{\text{rel}}$, corresponding to the energy released in breakup. The relative energy of the fragments therefore provides a measure of whether breakup of the projectile-like nucleus occurs close to the target-like nucleus or much further away. Indeed, the measured spectra presented in Figs. 2 and 3 show breakup events that have narrow peaks at low $E_{\text{rel}}$ values (indicated by the vertical lines) which must correspond to breakup far from the target-like nucleus (as in Fig. 4(b)) and those that extend to high $E_{\text{rel}}$ values (events within dashed rectangles) which are associated with breakup close to the target-like nucleus as depicted in Fig. 4(a).

The concepts outlined above can be put on firmer ground by making calculations of the most likely range of relative energies for the different breakup distances on the incoming and
outgoing trajectories. The calculations were done using a three-body, three-dimensional classical trajectory model [41], which was developed to relate breakup and fusion. It has been applied successfully to explain the relationship between breakup and fusion of $^9$Be on various heavy targets [18], and also in understanding the angular momentum distributions measured using isomer ratios [42] in incomplete fusion products following reactions of $^6,^7$Li with $^{208}$Pb and $^9$Be with $^{209}$Bi. The model calculations in Fig. 4(c) show a strong variation of $E_{rel}$ around the distance of closest approach ($R_0$). The calculations verify the expectation that relative energy of the breakup fragments is a very sensitive measure of the breakup time-scales. Experimentally measured $E_{rel}$ can be thus be used to distinguish breakup from the two scenarios shown in Fig. 4(a) and (b), which have a time difference of a few $10^{-21}$ s.

6. Importance of time-scale information in understanding reaction dynamics

If breakup of a nucleus occurs from a state with a life time greater than $\sim$ zepto-seconds, then breakup cannot affect fusion. Such breakup events are easily identified experimentally due to their narrow spread in $E_{rel}$. Many works focussed on breakup from long-lived states. Although this can be a significant process, it cannot suppress complete fusion. The work presented here shows that the focus must be on prompt breakup processes, particularly for understanding the effect of breakup on fusion. For both the $^6$Li and $^7$Li induced reactions, prompt breakup following transfer (see Figs. 2 and 3) is more likely than prompt direct breakup into the projectile cluster constituents. The transfer mechanism that triggers prompt breakup of $^6$Li is $n$-stripping, whilst for $^7$Li it is $p$-pickup. If prompt breakup occurs following transfer, then the lifetime of states of the projectile, and also of neighboring nuclei that are populated following transfer, are important. This is a key insight for model developments.

It is clear that getting an experimental measure of time-scales is important in understanding processes that can affect capture. In reactions of low-$Z$ nuclei, such as those discussed until now, capture of the projectile by the target invariably leads to fusion. However for collisions of heavier nuclei, like those used in forming heavy elements, capture does not necessarily lead to fusion, as the di-nuclear system formed following capture can break apart due to the large Coulomb energy. The di-nucleus can break apart in less than $10^{-20}$ sec. An experimental measure of sticking time is useful for understanding the evolution of the di-nuclear system. The experimental method used for obtaining information on sticking times has been discussed in the contribution by Hinde et. al. in these proceedings. The measurements can distinguish between systems where mean sticking times varies by few $10^{-21}$ sec, which is ideal for probing fast dynamical processes such as quasi-fission.

7. Summary and outlook

Nuclear collisions at near barrier energies, being gentle, reveal fascinating aspects of quantum mechanics that have a significance and appeal beyond the field of nuclear physics. Precision measurements and innovative experiments have played a major role in revealing these aspects. Recent experimental ideas provide us with tools to completely characterize all processes that lead to breakup of weakly bound light nuclei into charged fragments. Crucially these experiments show that information on breakup time-scales can be obtained experimentally. This represents a major step forward in understanding reaction dynamics, since breakup processes that occur in $\leq 10^{-22}$ s can affect fusion very significantly. Measurements demonstrate that prompt breakup of $^6$Li and $^7$Li following transfer is more likely than prompt direct breakup into the projectile cluster constituents. The dominance of breakup following transfer means that the reaction outcomes involving weakly bound nuclei depend not only on the properties of the two colliding nuclei, but also on the ground state and excited state properties of their neighbors. This is a key insight to develop predictive models that can be used at the accelerator facilities for unstable nuclei and their applications. The experimental findings discussed here are a major challenge for
the quantum models of low energy nuclear reactions, as new technical developments are required to calculate experimental quantities relevant to breakup following transfer.

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