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Breakup mechanisms for ^{7}Li + ^{197}Au, ^{204}Pb systems at sub-barrier energies

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Abstract. Coincidence measurements of breakup fragments were carried out for the ^{7}Li + ^{197}Au and ^{204}Pb systems at sub-barrier energies. The mechanisms triggering breakup, and time-scales of each process, were identified through the reaction Q-values and the relative energy of the breakup fragments. Binary breakup of ^{7}Li were found to be predominantly triggered by nucleon transfer, with p-pickup leading to $^{8}\mathrm{Be} \rightarrow \alpha + \alpha$ decay being the preferred breakup mode. From the time-scales of each process, the coincidence yields were separated into prompt and delayed components, allowing the identification of breakup process important in the suppression of complete fusion of ^{7}Li at above-barrier energies.

1 Introduction

The discovery of halo nuclei [1, 2] ushered in the development of radioactive ion beams (RIBs). This called for better understanding of the interactions of their cousins, the weakly-bound but stable nuclei. Such understanding is essential in relating the internal nuclear structure, e.g. nucleon clustering and low threshold for cluster-breakup [3–6], to the reaction outcomes, e.g. fusion, nucleon transfer, and breakup [7]. Relating nuclear structure of weakly-bound and unstable nuclei to nuclear reaction outcomes within a coherent framework has became an important goal in reaction theory. With ^{6,7}Li and ^{9}Be being more accessible, while offering similar characteristics (namely nucleon clustering and low breakup threshold), studying the former presents a great opportunity to understand and predict the behaviour of the much less accessible RIBs.

Complete fusion (CF) of the weakly-bound nuclei ^{6,7}Li and ^{9}Be with high-Z targets, at above-barrier energies, are consistently observed [8–10] to be lower than theoretical expectation. The low threshold energies for breakup of Li and Be are widely associated with this suppression of CF [8–13], with breakup described as cluster decay from unbound states independent of the mechanism that populates it [14–20]. Qualitatively, coupling to channels leading to breakup was shown [21] to suppress CF at above-barrier energies. More realistic modelling of the interplay between breakup and CF requires the incorporation of the mechanisms for triggering breakup, the time-scales of breakup [22–24], and possible post-breakup capture of the fragments [7, 25]. To isolate breakup itself from the probability of fragment capture, sub-barrier coincidence measurements of breakup fragments of ^{7}Li with ^{197}Au and ^{204}Pb were performed. The mechanisms for breakup, and their time-scale, were identified through the reaction Q-values and the relative energy of the captured breakup fragments.

2 Experimental setup

Beams of ^{7}Li were provided by the 14UD electrostatic accelerator at the Australian National University. They were incident on a self-supporting ^{197}Au target, 150 μg cm^{-2} in thickness, and a 400 μg cm^{-2} thick ^{204}Pb target on a 20 μm cm^{-2} carbon backing. The beam energies and target combination are listed in Table 1, along with the centre-of-mass barrier energy V_{b} of each reaction.

Table 1. Beam energies at which measurements were made for the reactions of ^{6}Li with indicated targets. $E_{\mathrm{c.m.}}$ includes energy loss in the target.

Target	V_{b} (MeV)	E_{beam} (MeV)	$E_{\mathrm{c.m.}}$ (MeV)	E/V_{b}
^{197}Au	28.72†	28.0	27.00	0.94
		29.0	27.97	0.97
^{204}Pb	29.54†	27.5	26.54	0.90
		30.0	28.96	0.98

† Scaled barrier as described in Ref. [26].

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Charged breakup fragments from the reaction were captured in coincidence using BALiN [27], a detector array consisting of four large area double-sided silicon strip detectors (DSSD) arranged in a lamp-shade configuration with apex angle 45°. For the given detector thickness of 400 μm, only high-Z particles, α-particles, and low energy protons (<7.0 MeV), deuterons (<9.0 MeV) and tritons (<11.0 MeV) would fully deposit their energies in the DSSDs. The detector array was placed at backward angles, covering scattering angles from 117° to 167°. The pixel identification characteristics of the DSSDs does not allow position location within the pixel. However, to simplify subsequent event reconstruction, a position was assumed by randomisation, taking a uniform distribution of the position within the physical boundaries of the pixel.

3 Mechanism for binary breakup

The Verification of the identities of the coincidence particles, and thus the reaction mechanism, requires the reconstruction of the three-body reaction Q-value. Consider a two-body collision with a projectile having initial and final kinetic energy $E_{\rm lab}$ and $E_{\rm f}$, respectively. The ground-state Q-value, $Q_{\rm gg}$, for any collision can be written as

$$Q_{\rm gg} = E_{\rm f} + E_{\rm ex,PL} + E_{\rm ex,TL} + E_{\rm rec} - E_{\rm lab}\,, \qquad (1)$$

where $E_{\rm f}$ is the kinetic energy of the projectile-like nuclei, $E_{\rm ex,PL}$ and $E_{\rm ex,TL}$ are the excitation energies of the projectile-like and target-like nuclei respectively, and $E_{\rm rec}$ is the recoil energy of the latter, all in the laboratory frame. For binary breakup of the projectile-like nucleus, its excitation energy is shared by the kinetic energies E_i of the fragments, $E_{\rm f} + E_{\rm ex,PL} = E_1 + E_2$, and the reaction Q-value can be determined from energy balance as

$$Q = E_1 + E_2 + E_{\rm rec} - E_{\rm lab}\,, \qquad (2)$$

where $E_{\rm lab}$ is derived from $E_{\rm beam}$ after correcting for energy lost in traversing the target. The recoil energy $E_{\rm rec}$ and mass of the target-like nucleus is determined through conservation of momentum from the momenta and masses of the two detected fragments [24, 28]. Since the excitation energy $E_{\rm ex,TL}$ of the target-like nucleus cannot be captured in our detector, the Q-spectra will show separate peaks for each state populated in the target-like nucleus.

Shown in Fig. 1 are the reconstructed Q-spectra, not corrected for coincidence detection efficiency, for the reactions of ^{7}Li with ^{197}Au and ^{204}Pb. The spectra show that almost all the yield contributes to sharp peaks in Q, meaning the breakup is indeed almost exclusively binary, with identified breakup modes of $\alpha+\alpha$ (green), $\alpha+t$ (blue), and $\alpha+d$ (magenta). The expected $Q_{\rm gg}$ for respective breakup modes are indicated by dashed lines.

Direct breakup of ^{7}Li into $\alpha+t$ can be seen to be less probable than breakup triggered by nucleon transfer, e.g. n-stripping of ^{7}Li leading to $^6{\rm Li}\rightarrow\alpha+d$, and p-pickup resulting $^8{\rm Be}\rightarrow\alpha+\alpha$. Peaks in the Q-spectra corresponding to $\alpha+\alpha$ breakup show that the target-like products ^{196}Pt and ^{203}Tl are populated mostly in their excited states. For

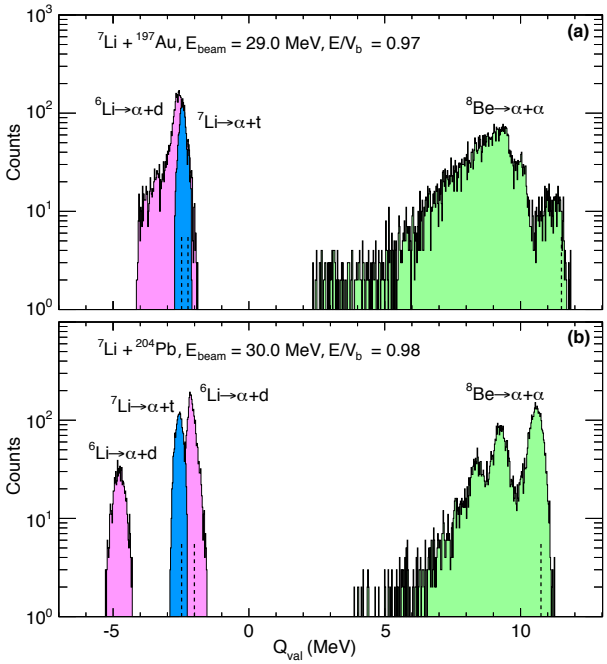

Figure 1. Q-spectra determined for the reactions of ^{7}Li with ^{197}Au and ^{204}Pb at indicated energies. Identified breakup modes consist $\alpha+d$ (magenta) and $\alpha+\alpha$ (green). Dashed lines indicate the expected $Q_{\rm gg}$ for each breakup mode. Peaks in the Q-spectra indicate breakup following the population of excited states of the target-like nuclei. (Contribution from $\alpha+p$ are not plotted due ot their insignificant yield.)

the n-stripping reaction of ^{7}Li with ^{204}Pb, the higher $E_{\rm beam}$ allowed population of ^{205}Pb at up to ≈2.7 MeV excitation.

The Q-value spectra give no clue to the relative population between the ground- and excited-states of ^{8}Be and ^{6}Li. However, the energy $E_{\rm ex,PL}$ of the excited states of the target-like nuclei appears in the kinetic energies $E_{1,2}$ of the breakup fragments, and have been shown [24] to be related to the time-scales of the process.

4 Time-scale of breakup and $E_{\rm rel}$

For binary breakup of the projectile-like nucleus on the outgoing trajectory, the relative energy $E_{\rm rel}$ of the fragments is the sum $Q_{\rm BU} + E_{\rm ex,PL}$, where $Q_{\rm BU}$ is the breakup Q-value. In terms of measured quantities

$$E_{\rm rel} = \frac{m_2E_1 + m_1E_2 - 2\sqrt{m_1E_1m_2E_2}\cos\theta_{12}}{m_1+m_2}\,, \qquad (3)$$

where θ_{12} is the angular separation between the fragments. For breakup close to the target nucleus, the breakup fragments particles will experience tidal effect [29] and $E_{\rm rel}$ no longer depends solely on the breakup energetics.

4.1 Relating fragment relative energy to time-scale of breakup

Using the three-body three dimensional model PLATYPUS [30–32], an illustrative calculation of the

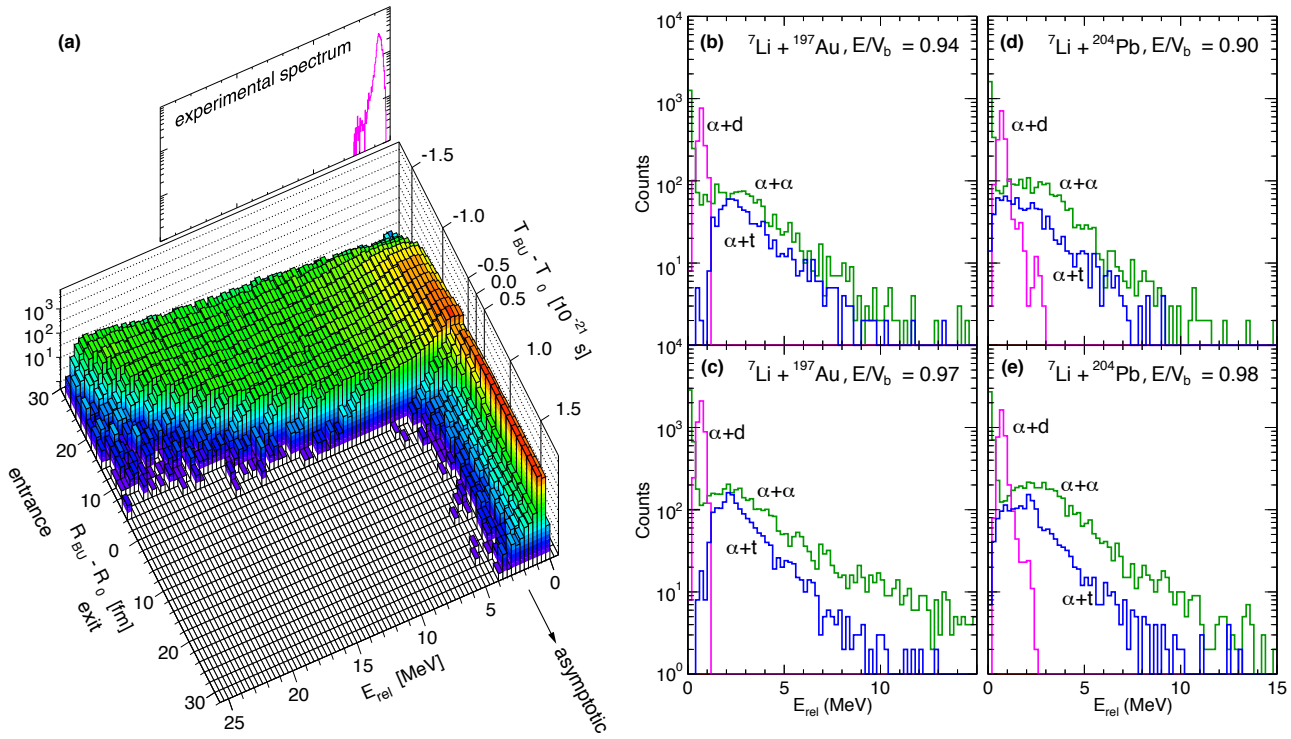

Figure 2. (a) Landscapes of the classically calculated $E_{\rm rel}$ versus the nuclear separation (left axis) or time (right axis) at which breakup occurs, relative to the point of closest approach (R_0, T_0), for ^{6}Li $\rightarrow \alpha + d$ breakup in the field of a ^{207}Pb nucleus. The spread in $E_{\rm rel}$ arises from the different impact parameters and fragments orientations at the moment of breakup. Breakup prior to reflection, $(T_{\rm BU} - T_0) < 0$ results in higher $E_{\rm rel}$ values than breakup after reflection $(T_{\rm BU} - T_0) > 0$. Impact parameters corresponding to angular momenta up to $49\hbar$ were considered. (b–e) Experimental $E_{\rm rel}$ spectra for identified $\alpha + \alpha$ (green), $\alpha + t$ (blue), and $\alpha + d$ (magenta) breakup modes for the indicated reactions. These spectra have neither been corrected for events with incomplete energy deposition, nor for coincidence detection efficiency.

dependence of $E_{\rm rel}$ on the projectile-target separation at which breakup occurs ($R_{\rm BU}$) was performed for breakup of ^{6}Li from the 3^+ (2.186 MeV) state. The distance $R_{\rm BU}$ was *uniformly* sampled along the trajectory of the ^{6}Li projectile with energy $E_{\rm beam} = 29.0$ MeV. The orientations of the $\alpha + d$ fragments at $R_{\rm BU}$, relative to the target nucleus, were also randomly sampled with an isotropic distribution. Shown in Fig. 2 is the result of this calculation. Since this is a classical calculation, the time of breakup $T_{\rm BU}$ relative to that of the closest approach (T_0) could be exactly evaluated, and is also shown. For comparison, the one-dimensional experimental $E_{\rm rel}$ spectra for $\alpha + d$ coincidences, from breakup of ^{6}Li on ^{205}Pb following n-stripping of ^{7}Li at $E_{\rm beam} = 30.0$ MeV, is shown above in magenta.

The variation of $E_{\rm rel}$ as a function of $R_{\rm BU} - R_0$ is indicative of the dependence of the former on the latter. The wide spread of $E_{\rm rel}$ from breakup before reaching R_0 is due to post-breakup acceleration of the fragments in the Coulomb field of the target nucleus. For breakup after the projectile-like nucleus has travelled past R_0, $E_{\rm rel}$ converges to ≈ 0.7 MeV, the energy available at breakup. The mapping of radius $R_{\rm BU}$ to the breakup time $T_{\rm BU}$ allows correlation of the time-scale for breakup to the measured $E_{\rm rel}$. Given that transfer occurs on time-scales of $\sim 10^{-22}$s [24], information on $T_{\rm BU}$ allows the classification of breakup into *prompt* ($T_{\rm BU} \lessapprox 10^{-22}$s), or *delayed* breakup. Prompt breakup results in breakup of the projectile or projectile-like nuclei in the entrance trajectory, and thus reduces the flux of intact nuclei available for fusion at the distance of closest approach R_0. On the other hand, delayed breakup happens on the exit trajectory, in the asymptotic region. These nuclei have survived breakup at R_0, and thus would have been able to participate in fusion if the beam energy was above the barrier.

4.2 Separation of prompt and delayed breakup

From the established relationship between the $E_{\rm rel}$ spectrum and the time-scale of breakup (Fig. 2(a)), the experimental $E_{\rm rel}$ spectra shown in Fig. 2(b–e) thus give information on the breakup time-scale, allowing a degree of separation between *prompt* and *delayed* breakup. For the direct ^{7}Li $\rightarrow \alpha + t$ breakup, the broad distribution to high $E_{\rm rel}$ shows its prompt nature, and would possibly play a role in the suppression of CF at above-barrier energies. For breakup at higher $E_{\rm beam}$, there is a slight peak at $E_{\rm rel} \sim 2.1$ MeV, perhaps denoting a tiny fraction of breakup from the $\frac{7}{2}^-$ (4.65 MeV) state of ^{7}Li whose lifetime of $\sim 9 \times 10^{-21}$ s might just be long enough to see the projectile breakup in the asymptotic region.

For transfer-triggered breakup, the breakup of ^{6}Li $\rightarrow \alpha + d$ following n-stripping have mostly high concentration of events with $E_{\rm rel} = 0.7$ MeV. This indicates breakup in the asymptotic region, and would have little impact in the CF of ^{7}Li at above-barrier energies. As for the ^{8}Be $\rightarrow \alpha + \alpha$ breakup following p-pickup, the high intensity of events with $E_{\rm rel} \approx 0.1$ MeV and broad tails comprising high $E_{\rm rel}$ events follows qualitatively the behaviour of asymptotic and prompt breakup, respectively, as expected from the classical model (Fig. 2(a)). Even when the asymptotic (low $E_{\rm rel}$) component is excluded, prompt $\alpha + \alpha$ breakup is still the most probable binary breakup channel for ^{7}Li. This reaction channel would thus play a major role in the suppression of CF, at above-barrier energies, in ^{7}Li-induced reactions.

5 Conclusion

The measurements presented in this work carry the most complete information on breakup in the reactions of ^{7}Li with high-Z targets. Binary breakup of ^{7}Li projectile is found to be triggered predominantly by nucleon transfer, both n-stripping leading to the $\alpha + d$ breakup of ^{6}Li, and p-pickup triggering the ^{8}Be $\rightarrow \alpha + \alpha$ decay. The dominance of transfer-initiated breakup is a stark contrast to the expected α + *triton* cluster breakup of ^{7}Li. This will provide a major challenge for the quantum theory of low energy nuclear reactions. From the relative energy $E_{\rm rel}$ of the binary breakup fragments, information on the breakup timescales allows the separation of prompt and asymptotic breakup components. By incorporating the breakup timescale into classical model calculations like PLATYPUS, more quantitative understanding of the breakup mechanism and its effects on fusion are expected.

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