Dynamics and Time-scales in Reactions with Weakly Bound Nuclei

Mahananda Dasgupta
Department of Nuclear Physics
Australian National University, Canberra
Not an elementary particle

Many body quantum system

Quantum states

0

Distribution of fusion barrier energies

Dasso et al., Nucl. Phys. A 405 (1983) 221
Fusion of heavy nuclei: experiment vs. expectations

\[ \frac{16\text{O} + 154\text{Sm}}{\text{Energy ÷ barrier energy}} \]

Discrepancy w.r.t single barrier – superposition of states (channel coupling)

Fundamentally changed long-held ideas of fusion

Led to theoretical advances in coupling enhanced tunnelling

Measurement of high precision fusion cross-sections

Review: Dasgupta et al., Annu. Rev. of Nucl. & Part. Sci. 48 (1998) 401
Well bound nuclei

$\tau \geq \text{ps}$

Quantum states

What if lifetime of states similar to collision times? (few $10^{-22}$ s)

→ Nuclei fragile against breakup into other nuclei

halos
Nuclei in a superposition of low-lying (collective) states
increased fusion at energies below the average barrier
(w.r.t. single barrier model)

Expect the same +
Effects specific to weakly bound nuclei

- Short-lived resonance states
  $ightarrow$ breakup

- Low lying continuum states
  $ightarrow$ coupling effects
  $ightarrow$ breakup
At $E_{cm} >$ barrier energy  $\sigma_{\text{fus}}(^{11}\text{Be}) > \sigma_{\text{fus}}(^{9}\text{Be})$

- Effect of n-halo?
- Why $\sigma_{\text{fus}}$ equal below the barrier?
Above-barrier suppression of complete fusion

- $^9\text{Be} + ^{208}\text{Pb}$ measurements
- Expt. Determination of average barrier
- Comparison with reaction with well-bound nuclei forming the same CN

Dasgupta et al., PRL 82 (1999) 1395

Dasgupta et al., PRC 70 (2004) 024606
• Increase in fusion due to couplings
  - dominates at energies below the barrier
• Decrease in fusion due to flux in excited states
  - clearly seen above the barrier

Schematic picture
- identifies CF with fusion in g.s.
Application of barrier distribution first quantitative understanding of fusion of fragile nuclei


What causes the reduction in fusion?

<table>
<thead>
<tr>
<th>E_{c.m.} (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>σ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

7Li + 209Bi

Complete fusion

Capture of full projectile Z

Signorini et. al., EPJ A5, 7 (1999)
Tripathi et al., PRL88,172701 (2002)
Wu et al., PRC68, 044605 (2003)
Dasgupta et al., PRC70 (2004) 024606
Mukherjee et al., PLB636, 91 (2006)

Gomes et al.,PRC73,064606 (2006)
Rath et al., PRC 79, 051601 (2009)
Gasques et al., PRC 79, 034605 (2009)
Dasgupta et al., PRC81, 024608 (2010)
RIB review: Keeley et al., Prog. Part.
Gasques et al., PRC 79, 034605 (2009)

All measurements at ANU

α - decay+fission

1 − F_{CF}

E_{B.U.} (MeV)

Is it this simple?
\[ ^{7}\text{Li} \rightarrow \alpha + t \ (Q = -2.467 \text{ MeV}) \]

- **Reaction models:** $\alpha$ core + valence (t)
  - Fortunato, Vitturi, EPJA26 (2005)33
  - Keeley et al, PRC66 (2002)044605

- **Experiments – not consistent with breakup into mainly $\alpha + t$**
  - Martinez Heimann et al., FUSION08, 275 (2008)
  - Pfeiffer et al., NP A206, 545 (1973)
  - A. Pakou et al., PRC76,054601 (2007)
  - Pradhan et al., PRC83,064606 (2011)
Breakup measurements at sub-barrier energies

- Eliminates fragment absorption → least confusion
- Large coverage (0.83 \( \pi \) sr)
- Detectors with high pixellation (512 pixels)

60° wedge detectors: Micron semiconductor Ltd., UK
Measurements - Fragment energy, positions → Kinematic reconstruction
Experimental Results: 2-D plots of coincidence fragments energies $E_1$ vs. $E_2$

- $^7\text{Li} + ^{208}\text{Pb} \quad \text{Ebeam} = 29.0\ \text{MeV}$
- Reaction Q-value:
  \[ Q = E_1 + E_2 + E_{\text{recoil}} - E_{\text{lab}} \]

- Identified $^2\text{H} + ^4\text{He}$
- Identified $^3\text{H} + ^4\text{He}$
- Identified $^4\text{He} + ^4\text{He}$
- Measured from momentum conservation
- Known reactions
Q-value spectrum

$^7\text{Li} + ^{208}\text{Pb}$  $E_{\text{Beam}} = 29.0$ MeV, $E/V_b = 0.95$

Luong et al., PRC 88, 034609 (2013)
• Q-value determination → information about states in target-like nucleus
  → no information on excited state of proj-like nucleus

• Relative energy of the fragments can provide this information

Relative energies of the breakup fragment → $Q + E^*_{\text{proj\_like}}$
Time difference
few $10^{-21}$ seconds!

$E_{\text{rel}}$ → time scale
- fragment energy
- angle between fragments
Breakup timescale: fragment relative energy $E_{\text{rel}}$ for $^{6}\text{Li} \rightarrow \alpha + d$

Diaz-Torres et al., PRL 98, 152701 (2007)
McIntosh et al., PRL 99, 132701 (2007)
Luong et al., PLB 695, 105 (2011)
Luong et al., PRC 88, 034609 (2013)
All processes that cause breakup

Luong, PhD work (2012)  

$^7$Li $+ ^{207}$Pb

$^4$He $\rightarrow$ $^3$H

$Q$ [MeV]  

$E_{rel}$ [MeV]
All processes that cause breakup

$^7\text{Li} + p$ pickup $\rightarrow ^8\text{Be}$

$^4\text{He}$ $\rightarrow$ $^4\text{He}$

Luong, PhD work (2012)

All processes that cause breakup

\[ E_{rel} = E^*(2.18 \text{ MeV}) + Q(-1.5 \text{ MeV}) \]

- \( \text{\^8Be} \rightarrow \text{\^4He} + \text{\^4He} \)

- n-transfer \( \rightarrow \)

- \( \text{\^6Li} \rightarrow \text{\^4He} + \text{\^2H} \) \( \tau = 3 \times 10^{-20} \text{ s} \)

- \( \text{\^208Pb}^{\text{gs}} \)

- \( \text{\^208Pb}^* \)

\( \alpha\)-d pairs - Q, \( E_{rel} \) consistent with n-transfer followed by breakup from \( \text{\^6Li} \) excited (2.18 MeV)
Key insights to develop predictive models

Prompt breakup – close to target

Transfer-triggered breakup

Breakup timescale

\[\text{Key insights to develop predictive models}\]
Q-projection of events excluding breakup from $^8$Be g.s.

- $^7\text{Li} + ^{207}\text{Pb}$
- $^7\text{Li} + ^{208}\text{Pb}$
- $^7\text{Li} + ^{209}\text{Bi}$

Large p-pickup probability

- $\alpha + d$
- $\alpha + t$
- $\alpha + p$
- $\alpha + \alpha$
Breakup of $^7\text{Li}$: Systematics across different targets

- $^p$-transfer leading to $^8\text{Be}$ dominates (driven by stability of $\alpha$; $Q \geq +9$ MeV)
- Breakup into constituent clusters decreases with decreasing target charge
- 1n stripping process target dependent ($Q_{gs} = -3.3, -0.4, +0.7$ MeV)
- 2n stripping also target dependent ($Q_{gs} = -3.8, +2.3, +6.1$ MeV)
Breakup Dynamics for $^7\text{Li} + ^{27}\text{Al}$

K. Cook, PhD work (ANU), 2014

- Direct breakup negligible
- No one neutron transfer component ($Q_{gs} = -1$ MeV)

$^7\text{Li} + ^{27}\text{Al} \rightarrow ^8\text{Be} + ^{26}\text{Mg} \rightarrow 2\alpha + ^{26}\text{Mg}$

\textbf{p-transfer $\rightarrow ^8\text{Be}}$
\textbf{strong channel}
\textbf{$Q_{gs} = +9.1$ MeV}

$^7\text{Li} + ^{27}\text{Al} \rightarrow ^5\text{Li} + ^{29}\text{Al} \rightarrow \alpha + p + ^{29}\text{Al}$

\textbf{2n-stripping leading to $^5\text{Li}$}
\textbf{$Q_{gs} = +6.2$ MeV}

Preliminary
Breakup mechanism: comparison between $^6$Li, $^7$Li, $^9$Be

$^6$Li ($3^+$), $\tau = 3 \times 10^{-20}$ s

$^8$Be, $\tau = 10^{-16}$ s

$^7$Li + $^{208}$Pb
$E_{\text{Beam}} = 29.0$ MeV

$^9$Be + $^{208}$Pb
$E_{\text{Beam}} = 37.0$ MeV

Luong et al., PRC 88, 034609 (2013)
Luong et al., PLB 695, 105 (2011)

Rafiei et al., PRC 81, 024601 (2010)
Breakup following transfer of neutron to target

$^6\text{Li} + ^{208}\text{Pb}$
Breakup of $^6$Li: Systematics across different targets

$^6$Li + $^{208}$Pb

$E_{\text{Beam}} = 29.0$ MeV, $E/V_b = 0.95$

$^6$Li + $^{64}$Zn

$E_{\text{Beam}} = 12.2$ MeV, $E/V_b = 0.88$

Q.g.s. pn transfer $+9.65$ MeV $+5.64$ MeV

n-transfer $-1.73$ MeV $+2.32$ MeV

observed strength of n-transfer – correlated to Q-value
Breakup of $^9$Be: Systematics across different targets

- Breakup following $n$-transfer dominant (driven by 2-$\alpha$ clusters)

$Q_{g.s.}$: 2.3 MeV  
5.1 MeV  
6.3 MeV

$^9$Be + $^{208}$Pb  
$E_{\text{Beam}} = 37.0$ MeV, $E/V_b = 0.92$

$^9$Be + $^{144}$Sm  
$E_{\text{Beam}} = 34.0$ MeV, $E/V_b = 1.0$

$^9$Be + $^{64}$Zn  
$E_{\text{Beam}} = 17.7$ MeV, $E/V_b = 0.84$
- Breakup measurements made at a range of energies
- Probability as a function of distance of closest approach

Rafiei et al., PRC 81, 024601 (2010)
Diaz-Torres et al, PRL 98, 152701 (2007)

Prompt breakup probabilities at the fusion barrier

Relate to complete and incomplete fusion

Hinde et al., PRL 89 (2002) 272701
Diaz-Torres et al, PRL 98, 152701 (2007)

Experimental results demand advances in models
$^9$Be on various targets

Rafiee et al., PRC 81, 024601(2010)
What have we learnt and what is needed

- Sub-barrier measurements of coincident breakup fragments - highly efficient & high granularity detectors
  - Pin down reaction dynamics including time scales

- Direct breakup component decreases with decreasing target $Z$ - prompt (not delayed) breakup leads to incomplete fusion ($\rightarrow$ suppression of complete fusion)

- Breakup triggered by nucleon transfer (for high $Z_T \rightarrow$ low $Z_T$)
  - Ground state and excited state properties of neighbouring nuclei also important

- Complete picture of breakup modes + ability to “see” the dynamics at $10^{-21}$ second timescales
  - Results demand new model developments, stringent test of models
  - Important for prediction of complete fusion (measurements hard)