Nuclear reactions in a three body model(ii)

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Exclusive measurement

• Take $^6\text{Li}$ as example
Inclusive measurement

- Take $^6$Li as example

- Elastic Breakup (EBU) ("diffraction")
- Inelastic Breakup
- Incomplete Fusion & Transfer

CDCC/Faddeev 😃
Experimental examples

$^6\text{Li}(d+\alpha)$ induced reaction

Surrogate reaction

- **Knockout reaction**
- **Study the Spectroscopic factor**
- **Current theory based on eikonal approximation (semi-classical)**
- **Fully quantum model is needed**

Theoretical models for inclusive (nonelastic) breakup

• Requires inclusion of all possible processes through which the breakup fragment can interact with the target. Impractical in most cases.

In 1980s

• Ichimura, Austern, and Vincent developed a spectator-participant model (post-form)  

• Udagawa and Tamura suggested a breakup-fusion model (prior-form)  

• Hussein and McVoy adopted a spectator model with the Feshbach projection method  

• Three different approaches with different predictions

Goals

• Find a suitable model for inclusive breakup

• Explore relations between these models

Challenges

• Numerically difficult

• No numerical implementation in 1980s-2000s even for Finite Range DWBA
The Ichimura, Austern, Vincent (IAV) model

- Inclusive breakup:
  - \( a + A \rightarrow b + \text{anything} \rightarrow (x+A)^* \)

- Any possible states between \( x \) and \( A \) (including all nucleons degree of freedom)

- Project all degrees of freedom into three body model space

\[
\frac{d^2\sigma}{dE_b d\Omega_b} \bigg|_{\text{NEB}} = -\frac{2}{\hbar \nu_a} \rho_b(E_b) \langle \phi_x(\vec{k}_b) | W_x | \phi_x(\vec{k}_b) \rangle
\]

Imaginary part of \( x-A \) effective interaction
Apply to inclusive deuteron breakup

- $d \rightarrow (n + p), S_p=2.224\ \text{MeV}$
- Only proton is detected
- EBU: CDCC (FRESCO)
- NEB: IAV model
- Total Breakup (TBU) = EBU + NEB
- Dominated by NEB
- EBU has large contributions at small angles
- Supports IAV model

Apply to inclusive $A(^6\text{Li},\alpha X)$

- Dominated by NEB
- Supports IAV model

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We also studied the relations between different inclusive models
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Breakup and fusion

- From the barrier penetration picture

- Complete fusion: total charge of the projectile is absorbed by the target
- Incomplete fusion: part of the projectile is absorbed by the target

- Complete Fusion is suppressed due to weak binding of the projectile

Challenges

- To correctly understand fusion suppression (not only from semi-classical picture) and simultaneously predict the complete fusion cross section
- To study incomplete fusion is breakup-fusion (two-step) or transfer to continuum (one-step)
Study the fusion cross section through a three body model

- Take $^6$Li+A as an example

$$\sigma_R \approx \sigma_{\text{CF}} + \sigma_{\text{EBU}} + \sigma^{(b)}_{\text{NEB}} + \sigma^{(x)}_{\text{NEB}}$$
Study the fusion cross section through a three body model

\[ \sigma_{CF} \approx \sigma_R - \sigma_{EBU} - \sigma_{(b)}^{NEB} - \sigma_{(x)}^{NEB} \]

- Apply the above relation to \(^{6,7}\text{Li+209Bi}\) reaction around the Coulomb barrier
- Compare calculated fusion cross section with experiment

**CF**: complete fusion

**NEB**: nonelastic breakup

**EBU**: elastic breakup

- EBU mechanism plays a minor role
- Dominant breakup mechanism in both reactions is alpha production due to \((^{6,7}\text{Li,}\alpha X)\) NEB.


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Unraveling the mechanisms leading to fusion suppression

- Use a toy model to study effects of separation energy
  - vary the binding energy of $^7\text{Li}(\alpha+t)$ and $^6\text{Li}(\alpha+d)$ in the projectile.

- When the binding energy becomes larger, the calculated cross section approaches the barrier penetration model (BPM)

Exploring the reaction path for incomplete fusion

Incomplete fusion: part of the projectile absorbed by the target

Two-step: projectile is inelastically excited into its continuum and then fuses with the target

One-step: fragment fuses with the target directly from its ground state

Resolve this puzzle by studying nonelastic breakup (incomplete fusion is a part)

Use CDCC wave-function in the IAV model:

\[ \psi_{x}(k, r_{x}) = \int G_{x}(r_{x}, r_{x}^{\prime}) \langle r_{x}^{\prime} | V_{\text{post}} | \psi_{\text{CDCC}(+)} \rangle dr_{x}^{\prime} \]

\[ \psi_{\text{CDCC}(+)}(r_{a}, r_{bx}) = \sum_{b} \phi_{a}^{b}(r_{bx}) \chi_{a}^{b(+)}(r_{a}) + \int d k \phi_{a}^{k}(r_{bx}) \chi_{a}^{k(+)}(r_{a}) \]

- Continuum and ground states are separated
- Allows to study continuum effects on the NEB
- Test validity of DWBA
Apply to deuteron and $^6$Li induced reaction

**deuteron case**

- $d + ^{93}$Nb@25.5 MeV
- $E_{p}^{c.m.} = 14$ MeV

**$^6$Li case**

- DWBA is a good approximation compared to CDCC
- Nonelastic breakup (incomplete fusion) is mixture of one-step (>90%) and two-step (<10%) processes