Comparing fusion data of weakly and tightly bound systems

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Work in collaboration with

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Weakly bound nuclei:

- Light stable nuclei: $^6,^7\text{Li}$, $^9\text{Be}$
- Unstable nuclei: $^6,^8\text{He}$, $^{11}\text{Li}$, $^{11,14}\text{Be}$, etc.

\[
B(A, Z) = a_v A - a_s A^{2/3} - a_a \frac{(N - Z)^2}{A} - a_c \frac{Z(Z - 1)}{A^{1/3}} + \ldots
\]

- ~ 300 stable nuclei
- ~ 4000 unstable
How is fusion affected by weak binding?

Static Effects:
Different densities ⇒ Lower barrier (thicker)
(halos, skins)

Dynamic Effects:
Low breakup threshold ⇒ Strong continuum coupling
Static effects:

Illustration: $^4,^6\text{He} + ^{238}\text{U} - \text{halo vs. no-halo}$

- $^6\text{He} + ^{238}\text{U}$ barriers - $\Delta V_B = 1.3$ MeV

- $^6\text{He} + ^{238}\text{U}$

- Enhancement of $\sigma_F$ at $E$ near and below $V_B$

halo leads to lower and thicker barrier
Theoretical predictions – dynamic effects:

CC equations $\Rightarrow$ Pol. pot. in elastic channel $V_{\text{pol}} = U_{\text{pol}} - iW_{\text{pol}}$

$U_{\text{pol}} \rightarrow$ changes the barrier,

$W_{\text{pol}} \rightarrow$ long range absorption

Couplings with bound channels leads to large enhancement of $\sigma_F$ at sub-barrier energies.

What about weakly bound systems?
additional channels in collisions of weakly bound projectiles

Question: how does breakup couplings affect CF?
Enhancement? Hindrance? (with respect to what?)

New fusion processes
CF (DCF, SCF), ICF
TF = CF + ICF
Two investigation methods:

1. Compare fusion data with theoretical predictions for the same system

2. Compare fusion data of the weakly bound systems with those of a similar tightly bound one
1. Experiment vs. theory

\[ \Delta \sigma_F \equiv \sigma_F^{\text{exp}} - \sigma_F^{\text{theo}} \Rightarrow \text{'ingredients' missing in the theory} \]

Theoretical possibilities:

a) Single channel - standard densities
   \[ \Delta \sigma_F \text{ arises from all static and dynamic effects} \]

b) Single channel - realistic densities
   \[ \Delta \sigma_F \text{ arises from couplings to all channels} \]

c) CC calculation with all relevant bound channels
   \[ \Delta \sigma_F \text{ arises from continuum couplings} \]

d) CDCC
   \[ \text{no deviation expected} \]
Example: $^6\text{He} + ^{209}\text{Bi}$

Shortcomings of the procedure:

- Choice of interaction plays fundamental role
- Does not allow comparisons of different systems
- Difficult to include continuum – no separate CF and ICF
2. Compare with data of a similar tightly bound system
(example: \(^6\text{He} + ^{238}\text{U}\) vs. \(^4\text{He} + ^{238}\text{U}\))

Differences due to static effects:

1. Gross dependence on size and charge:
   \(Z_P, Z_T, A_P, A_T\) – affects \(V_B\) and \(R_B\)
   \(V_B \sim Z_P Z_T e^2 / R_B; \quad \sigma_{\text{geo}} \sim \pi R_B^2, \quad R_B \propto A_P^{1/3} + A_T^{1/3}\)

2. Different barrier parameters due to diffuse densities
   (lower and thicker barriers)
Differences due to dynamic effects:

3. Couplings to bound channels
   (larger $\sigma_F$ at $E < V_B$)

4. Continuum couplings (breakup)  ?

To investigate 4, it is necessary
to eliminate effects 1, 2 and 3 !

Fusion data reduction required !
Comonly used reduction methods:

Example: $^{4,6}$He + $^{209}$Bi

No reduction

Large enhancement below $V_B$
Small enhancement above $V_B$

A and Z dependence eliminated

smaller enhancement below $V_B$
No enhancement above $V_B$

All static effects eliminated
(Realistic $V_B$ and $R_B$)

No enhancement below $V_B$
Hindrance above $V_B$

Method changes conclusions!!
Testing the method: reduction in optical model calculation

compare $^{16}$O + $^{209}$Bi with $^{40}$Ca + $^{209}$Bi

Reduced $\sigma_F$ should be the same!

These methods do no work!
Fusion functions $F(x)$ (our reduction method)

$$E \rightarrow x = \frac{E - V_B}{\hbar \omega} \quad \text{and} \quad \sigma_F^{\exp} \rightarrow F^{\exp}(x) = \frac{2E}{\hbar \omega R_B^2} \sigma_F^{\exp}$$

Inspired in Wong’s approximation for $\sigma_F$:

$$\sigma_F^{W} = R_B^2 \frac{\hbar \omega}{2E} \ln \left[ 1 + \exp \left( \frac{2\pi(E - V_B)}{\hbar \omega} \right) \right]$$

If $\sigma_F^{\exp} \approx \sigma_F^{W} \quad \Rightarrow \quad F(x) \approx F_0(x) = \ln \left[ 1 + \exp(2\pi x) \right]$}

$$F_0(x) = \text{Universal Fusion Function (UFF)} \quad \text{system independent} !$$
Same test: $^{16}\text{O} + ^{209}\text{Bi}$ vs. $^{40}\text{Ca} + ^{209}\text{Bi}$

$\sigma_F$ from optical model calculations

Previous reduction methods

Fusion functions

Static effects fully eliminated !!
Shortcomings:

a) Wong approximation may not work

- O.K. for light systems only above $V_B$
- O.K. for heavy systems ($Z_p \ Z_T > 500$), even below $V_B$
b) Channel coupling channel effects

(a) CC: $2^+, 3^- (T); 3^- (P)$

(b) Wong is bad

(c) CC Rot. band (T); 3$^- (P)$

(d) CC $3^-, 5^- (T)$
Direct use of the reduction method

Compare \( F_{\text{exp}}(x) \) with UFF for \( x \) values where \( \sigma_F^{\text{opt}} \approx \sigma_F^W \)

Deviations are due to couplings with bound channels and breakup

Refining the method

Eliminate influence of couplings with bound channels

Renormalized fusion function

\[
F_{\text{exp}}(x) \rightarrow \overline{F}_{\text{exp}}(x) = \frac{F_{\text{exp}}(x)}{R(x)}, \quad \text{with} \quad R(x) = \frac{\sigma_F^{CC}}{\sigma_F^W} \approx \frac{\sigma_F^{CC}}{\sigma_F^{\text{opt}}}
\]

If CC calculation describes data \( \rightarrow \overline{F}_{\text{exp}} \approx \text{UFF} \)
Illustration:

If CC calculations are accurate:

for tightly bound systems
\( \bar{F}_{\text{exp}}(x) \approx \text{UFF} \)

for weakly bound systems
difference is due to breakup
Applications

• CF stable projectiles – heavy targets\(^1\)
• TF stable projectiles – heavy targets\(^1\)
• TF halo projectiles – heavy targets\(^1\)
• TF stable projectiles – light, very light and medium light targets\(^2\)

Other Applications

• Reaction Functions\(^3\) (J. Shorto’s seminar)
• Universal barrier distribution

3. Shorto, Gomes, Lubian, Canto, Mukherjee, Chamon, PLB 678 (2009)77
CF stable projectiles – heavy targets

- Suppression above the barrier (~ 30%)
- Enhancement below the barrier
TF stable projectiles – heavy targets

- No effect above the barrier
- Large enhancement below the barrier
TF stable projectiles – very light targets

- No effect above the barrier
- Almost no data below the barrier
TF stable projectiles – light targets

- No effect above the barrier
- No data below the barrier
TF halo projectiles – heavy targets

- Suppression above the barrier (~30%)
- Similar to CF in stable systems – ICF small
- Inconclusive below the barrier – more data needed
TF stable projectiles – medium-light targets

$\bar{F}_{\text{exp}}(x)$ very different from the UFF, at all energies! why?
New recent data of di Pietro et al.
Other data incompatible with systematic

(a) Fusion Function vs. $x$

(b) Fusion Function on a logarithmic scale vs. $x$
Conclusions

• New reduction method: $\sigma_F^{\text{exp}} \rightarrow \bar{F}_F^{\text{exp}}(x) \Rightarrow$ compare with UFF
  
  ○ Influence of static effects and of bound channels eliminated
  ○ Allows comparisons of very different systems in a single plot

• Several applications

  1) CF stable proj. - heavy targets:
     suppression (~ 30%) above $V_B$, slight enhancement below $V_B$
  2) TF stable proj. - heavy targets:
     no appreciable effect above $V_B$, enhancement below $V_B$
  3) TF halo proj. - heavy targets:
     similar to 1 (suppression ~ 30%) above $V_B$ (small ICF)
     inconclusive below $V_B$
4) TF stable proj. - very light and light targets (no CF data available): 
   No appreciable effect above $V_B$, very little data available below $V_B$

5) TF stable proj. - medium-light targets: 
   $E > V_B$: old data very different from the UFF, recent data very close. 
   no data available below $V_B$

- Useful to spot problems in experiments or new reaction mechanisms

- Extension to $\sigma_R$ and barrier distributions