Fusion, break-up and scattering of stable weakly bound nuclei

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For a comprehensive review of this subject:

Fusion and breakup of weakly bound nuclei

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The break up of stable weakly bound nuclei

Suitable stable weakly bound nuclei

\[ ^6\text{Li} \rightarrow ^4\text{He} + d \quad S_a = 1.48 \text{ MeV} \]

\[ ^7\text{Li} \rightarrow ^4\text{He} + t \quad S_a = 2.45 \text{ MeV} \]

\[ ^9\text{Be} \rightarrow ^8\text{Be} + n \rightarrow ^4\text{He} + ^4\text{He} + n \quad S_n = 1.67 \text{ MeV} \]
The Fusion X Break-up problem

- The full understanding of the fusion and break-up processes induced by stable weakly bound nuclei is an important reference for the investigation of similar systems involving radioactive beams.
Motivation for the investigation of the break-up effect on the fusion cross section

• Study of correlations and couplings between reaction mechanisms in heavy ion collisions.
• Does the break-up coupling to fusion enhance its cross section or does the BU compete with fusion and suppress it?
• Important for astrophysical processes and production of super-heavy elements.
Fusion with tightly bound nuclei above the Coulomb barrier

As the energy increases, other reaction mechanisms compete with the fusion, that becomes limited or saturated.
Fusion with tightly bound nuclei below the Coulomb barrier

- Important nuclear structure effects.
- Usual enhancement of the cross section, when compared with predictions from one dimensional barrier penetration models.
Role of coupled channels in the sub-barrier fusion cross section enhancement

Is is well stablished that inelastic excited states and transfer channels enhance the sub-barrier fusion cross section.
Where is the fusion decided?

There is controversy whether the Coulomb barrier should be transposed \( r_f = 1.2 \text{ fm} \) or if the fusion is decided even before the barrier is reached \( r_f = 1.5 \text{ fm} \).
Threshold anomaly in the elastic scattering

- Optical Potential: \( U(E) = V_0 + ?V(E) + W(E) \)
  where \( W(E) = W_V(E) + W_S(E) \)

Tenreiro et al – PRC 53 (1996), 2870
Processes to be considered in reactions with weakly bound nuclei
Theoretical aspects to be considered

- **Static effects**: longer tail of the optical potential arising from the weakly bound nucleons.
- **Dynamical effects**: strong coupling between the elastic channel and the continuum states representing the break-up channel.
  - strong influence on reaction channels, particularly on fusion cross section.
- **Relative motion of the fragments and their interactions**: What are their trajectories following the BU? EBU, ICF, CF?
Usual questions

- Does the BU channel enhance or suppress the fusion cross section? Is the effect on $s_{CF}$ or $s_{TF=CF+ICF}$?

- What are the effects on different energy regimes and on different target mass regions?

- Different BU threshold energies should affect $\sigma_{BU}^{\text{elastic}}$ significantly. Is that true for $\sigma_{CF}$ or $\sigma_{CF+ICF}$?
Theoretical methods

- **Schematic models**: dynamical polarization potential; semiclassical trajectories, survival probabilities.

- **More realistic calculations**: CDCC (continuum discretized coupled channel) calculations: Bound-continuum states couplings, with or without resonance states, discretized continuum states, continuum-continuum couplings.
Schematic representation of bound and continuum states and their couplings in CDCC calculations

Full lines: Hagino 2000. Dashed lines: additional couplings by Diaz-Torres and Thompson 2002
Experimental aspects to be considered

• What is it measured? $s_{CF}$ or $s_{TF} = CF + ICF$?

• Can ICF be separated from transfer channels leading to the same compound nucleus?

• When one talks about enhancement or suppression, is that in relation to what?
Measurements of $^{6,7}$Li + $^{209}$Bi and $^9$Be + $^{208}$Pb

ANU

$0.9 V_B \leq E \leq 1.7 V_B$

Yields of $\alpha$ particles (on-line and off-line)
$s_{CF}$, $s_{ICF}$ and barrier distributions

M. Dasgupta et al; PRL82 (1999),1395        PRC66 (2002),041602R
Measurements of $^{6,7}$Li, $^9$Be + $^{64}$Zn, $^{27}$Al
TANDAR
$E > V_B$
ToF and $E-\Delta E$

$I. Padron et al; PRC66 (2002), 044608$
$R.M. Anjos et al; PLB534 (2002), 45$
Measurement of the inverse reaction $^{12}\text{C} + ^{7}\text{Li}$

$\text{ANU}$

$E > V_B$

$E - ? E$ multi-anode

$S_{TF}$

A Mukherjee et al; PLB526 (2002), 295
Measurements of $^9$Be + $^{64}$Zn

USP
$E \geq V_B$

Gamma rays (on-line and off-line)
$s_{CF} \quad s_{ICF}$ was found to be negligible.

S.B. Moraes et al; PRC61 (2000),064608
Measurements of $^9$Be + $^{144}$Sm
Tandar
$0.8\text{VB} \leq E \leq 1.4\text{ VB}$
Detection of X-K rays (off-line)

$s_{\text{CF}}, s_{\text{ICF}}$

Gomes et al – BJP 35 (2005), 902
Heavy Targets
$^9$Be + $^{208}$Pb
complete fusion cross section

M. Dasgupta et al – PRL 82 (1999), 1395
\( ^{6,7}\text{Li} + ^{209}\text{Bi}, \ ^{9}\text{Be} + ^{208}\text{Pb} \)

Complete fusion cross section suppression factor as a function of the energy

M. Dasgupta et al – PRC 70 (2004), 024606
$^{6,7}$Li + $^{209}$Bi and $^9$Be + $^{208}$Pb
total fusion
(eventual transfer channels are included)
(for $^{6,7}$Li + $^{209}$Bi, the data are lower limits at the highest energies)

Those results agree with CCC and SBPM predictions

Gomes et al;
BJP 34 (2004), 737
$^9$Be + $^{144}$Sm : CF and ICF
Suppression factor: 0.90

Gomes et al – PLB 634(2006), 356
Conclusions for Heavy Targets

- The BU inhibits $s_{\text{CF}}$ at $E > V_B$
- There is a suppression factor for CF at this regime, but the BU threshold energy differences are not very much reflected in $s_{\text{CF}}$
- $s_{\text{TF}}$ is not affected by the BU at $E > V_B$
- $s_{\text{ICF}}$ is important in the whole energy range.
- At $E \leq V_B$, the situation is not so clear, as there is competition between enhancement of CF due to couplings and suppression due to the BU.
Care should be taken when comparing different systems.

How to “reduce”? 

Gomes et al – PRC 71 (2005), 017601
Care should be taken when comparing different systems. How to “reduce”?

$^{64}$Zn target

Gomes et al  – PRC 71 (2005), 017601
Different conclusions depending on

What is the potential to be used

How to perform CC calculations
Reliable potential: the double folding São Paulo potential

- It reproduces, without any free parameter, calculations obtained with potentials which match derived barrier distributions. *(Crema et al – PRC72 (2005) – 034610)*
\[ V(R) = V_{Fold}(R) e^{-4\frac{v^2}{c^2}} \]

\[ V_{Fold}(R) = \int \rho_1(\vec{r}_1) \rho(\vec{r}_2) v(\vec{R} - \vec{r}_1 + \vec{r}_2) d\vec{r}_1 d\vec{r}_2 \]

\[ v = \text{relative velocity between the nuclei} \]

\[ v^2 = \frac{2}{\mu} E_{\text{kinetic}} = \frac{2}{\mu} \left[ E - V_C(R) - V_{LE}(R) \right] \]

Finite-range approach \{ nucleon distributions for \( \rho \) \}

\[ v(\vec{r}) \rightarrow \text{M3Y – Reid or Paris} \]

\[ \rho \begin{cases} R_o = 1.31 A^{1/3} - 0.84 \text{ fm} \\ a = 0.50 \text{ fm} \end{cases} \]
Analysis of the $^{4,6}$He + $^{238}$U fusion by the São Paulo Potential

Crema et al, subm. PRL

$\text{SF} = 0.84$
Analysis of the $^6$He + $^{209}$Bi fusion by the São Paulo Potential

$\sigma_{\text{FUS}} (\text{mb})$

$^6$He + $^{209}$Bi

(a)

There is no sub-barrier fusion enhancement!!

Crema et al - subm to PRL

SF = 0.81
• What about elastic break-up cross sections?

• What about reaction cross sections?

• What about elastic scattering?
Measurements of elastic breakup cross sections

E.F. Aguilera et al; PRC63 (2001), 061603R

C. Signorini; NPA693 (2001), 190

C. Signorini; NPA693 (2001), 190

D.J. Hinde et al; PRL 89 (2002), 272701
$^9$Be + $^{144}$Sm : reaction, inelastic, CF and ICF

Gomes et al – PLB 634(2006), 356
$^9$Be + $^{144}$Sm: relative importance of different reaction mechanisms

Gomes et al – PLB 634(2006), 356
A new type of threshold anomaly: break-up threshold anomaly (BTA)

Gomes et al – J Phys G 31 (2005), S1669

The large BUelastic at low energies produces a repulsive polarization potential and suppress at $E < V_B$. 
$^{6}\text{Li} + ^{208}\text{Pb}$

$N_R$

$N_I$

$E_{\text{Lab}}$ (MeV)

Hussein et al – PRC (RC) – in press
Is the effect the same for medium and light mass targets?
Reaction, TF, CF, ICF and estimate of $B_U^{\text{elastic}}$ cross sections for $^9\text{Be} + ^{64}\text{Zn}$

Gomes et al, PLB 601 (2004), 20
Reaction, TF and estimate of BU\textsuperscript{elastic} cross sections for $^{6,7}\text{Li} + ^{64}\text{Zn}$

Gomes et al, PLB 601 (2004), 20
Reaction and TF cross sections for $^{16}$O, $^6$He + $^{64}$Zn

Gomes et al, PLB 601 (2004), 20
Di Pietro et al, EPL 64 (2003), 309;
PRC69 (2004), 044613
$^6$He, $^6,^7$Li, $^9$Be, $^{16}$O + $^{64}$Zn
Reduced reaction cross sections

Gomes et al, PLB 601 (2004), 20
Reaction, TF and estimate of $B_{U^{\text{elastic}}}$ cross sections for $^9\text{Be} + ^{27}\text{Al}$

Marti et al – PRC 71 (2005), 027602
Reduced reaction cross sections for $^{27}$Al target: here are the first experiments in the South Hemisphere with radioactive beams

Benjamin et al – subm PRL
Light target – there were controversies

$^{12}\text{C} + ^{7}\text{Li}$

Total Fusion

A. Mukherjee et al - PLB 526 (2002), 295
Is there break-up threshold anomaly (BTA) for light targets?

Figueira et al – unpubl.

Conclusions for light and medium mass targets

• No $s_{\text{CF}}$ suppression was measured, at high energies.
• The incomplete fusion is much less important than for heavy targets.
• Elastic break-up is still important, even with a weak Coulomb field.
• Reaction cross sections are increased by the break-up process.
• The break-up threshold anomaly is still present.
Perspectives

- Need of additional data at the sub-barrier energy regime.

- Need of more exclusive experiments on elastic break-up, elastic scattering, complete fusion and incomplete fusion, in order to obtain precise information for the calculations.

- Need of more data with radioactive beams.

- Need of development of theoretical models and calculations which take into account all relevant aspects.
Main Collaborators

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### Topics:

- Accelerator facilities
- Nuclear structure in nucleus-nucleus collisions and high spin physics
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- Superheavy elements
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- QCD, hadrons, and nuclear reactions with effective field theories
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