Coherence and Dissipation in Nuclear Fusion

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Inter-nuclear potential

Potential energy

Repulsive electrostatic

Barrier

Attractive nuclear

Many-body problem
- no exact solution
- phenomenological potential
Density of quantum states increases rapidly with excitation energy

\[ N \sim \exp(\sqrt{2aE^*}) \]
Identifying fusion in calculations

- Coupled channels - calculate tunnelling or (1-Reflected)
- Imaginary potential absorbs flux below some separation distance
  → identified with “fusion” (loss of K.E. to heat bath not modelled)
Scattering of identical nuclei

|f (θ)|² + |f(π – θ)|² + f*(θ) f(π – θ) f(θ) f*(π – θ)

Interference
3º. 

Villari et al., PRL 71, 2551 (1993)
Hinde et al., PRC 76, 014617 (2007)
Nuclear fusion – textbook treatment

Single fusion barrier

\[ \sigma_{\text{fusion}} \propto \exp \left[ k (E - B) \right] \]

\[ 1 - \frac{B}{E} \]

Single barrier model works well for fusion of light nuclei

\[ ^{40}\text{Ca} + ^{40}\text{Ca} \]
Fusion of heavy nuclei: experiment vs. expectations

\[ \sigma_{\text{fus}} \text{ (mb)} \]

- Fusion cross-section

- Single barrier

- 154\(^{Sm}\)

- 144\(^{Sm}\)

References:
- Wei et al, PRL, 67 (1991) 3368
- Morton et al, PRL, 72 (1994) 4074
Net cross-section smaller – opposite of what is seen

Not classical - excitation leads reduction in K.E. – reduced cross-sections

\[ \sigma = (1-P_n) \sigma(E) + P_n \sigma(E - \varepsilon_n) \]

Colliding nuclei in coherent superposition of (low energy) collective states (purely quantum effect) → Coupled channels model

Net cross-section smaller – opposite of what is seen
Two channels – approximation

\[
\begin{pmatrix}
-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + V(r) + \begin{pmatrix}
0 & F \\
F & \epsilon
\end{pmatrix}
\end{pmatrix}
\begin{pmatrix}
u_0(r) \\
u_1(r)
\end{pmatrix} = E
\begin{pmatrix}
u_0(r) \\
u_1(r)
\end{pmatrix}
\]

Eigenvalues of the coupling matrix: \( \lambda_{\pm} = \left( \epsilon \pm \sqrt{\epsilon^2 + 4F^2} \right) / 2 \)

Coherent superposition \( V \) splits into two eigen-barriers

\[
\sigma = w_+ \sigma(E, V+ \lambda_) + w_- \sigma(E, V- \lambda_)
\]

Dasso et al, Nucl. Phys. A 405, 221
• Fusion as a function of energy – eigen-barriers are like filters
• Fusion - snapshot of the eigen-channels of the quantum system at contact
• Scattering – asymptotic populations of the basis states
$^{16}\text{O} + ^{58}\text{Ni}$

Charge product = 224


$^{58}\text{Ni} + ^{60}\text{Ni}$

Charge product 784

M. Rodriguez, ANU PhD work (2009)
Heavy Ion Accelerator facility at the ANU

15 Million Volts
beam 0.1 c

experimental setup
Excellent energy definition → measurements in tunnelling regime

15 Million Volts

Beam velocity 0.1 c
Fusion measurements – the challenge

- Beam, fusion products, elastic scattering – all forward focused
- Stop direct beam ($10^{10} - 10^{11}$ nuclei/sec)
- $10^4 - 10^{12}$ elastics for every fusion product!
- Acceptance $\geq 80\%$
- $\approx 100\%$ detection efficiency
- Highest efficiency separator for fusion studies
- Fusion measurement, coincidence and implantation studies
Highly efficient fission detector array developed in-house
So where is the problem now?

Importance of channel couplings in fusion

\[ \sigma (\text{mb}) \]

\[ E - V_B \text{ (MeV)} \]

Dasgupta et al, PRL 99 (2007) 192701
So where is the problem now?

Importance of channel couplings in fusion

Dasgupta et al, PRL 99 (2007) 192701
Fusion well-below and well-above the barrier

For a given above barrier E – cross-section determined by the limiting \( l \rightarrow \) determined by high-\( l \) barrier, \( R \)

\( R_l \) at smaller separations than \( R_0 \)

Inner turning point for a below barrier E appears at same separation distance as the top of the high \( l \)-barrier

Two parts of fusion excitation function both probe smaller separations
• Coupled channels calculations
• Real Woods-saxon nuclear potential (diffuseness 0.65 fm)
• Incoming wave boundary condition/imaginary $W$ (mimic fusion)
simultaneous description of fusion well-above and well-below the barrier is not obtained

Some physical effect not being included → affects fusion in both energy regimes

Dasgupta et al, PRL 99 (2007) 192701
Nuclear incompressibility – shallower potential pocket (sudden potential)
Mişicu and Esbensen PRL96 (2006) 112701
Esbensen and Mişicu PRC76 (2007) 054609

Importance of energy and angular momentum dissipation above barrier

- Deep sub-barrier – cross-sections with IWBC (σ not hindered for imaginary pot.)
- Well-above barrier – no pot. pocket - need short range imaginary potential
Energy dependence of bare potential?

From experimental data (within the potential model)

Average barrier energy from barrier distribution

Average barrier from above barrier measurements (within 0.1 MeV)
Measurements for the $^{16}$O + $^{208}$Pb reaction

Transmitted flux:

- Fusion cross-sections
- Fusion mean square angular momentum - sensitive to angular momentum dependence of the barrier
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- Fusion cross-sections
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Measurements for the $^{16}$O + $^{208}$Pb reaction
The $^{16}$O + $^{208}$Pb reaction

Transmitted flux:
- Fusion cross-sections
- Fusion mean square angular momentum
  - sensitive to angular momentum dependence of the barrier

Reflected flux:
- High precision measurements of elastic scattering – near barrier
- Measurements of all quasi-elastic channels (inelastic, transfer)
- Inelastic scattering – octupole vibrational – coulomb nuclear interference
- neutron transfer, p, 2p transfer
$^{16}$O+$^{208}$Pb, $E_{\text{beam}} = 64$ MeV, $E/V_B = 0.80$

3$^{-}$ collective state, $^{208}$Pb

$^{16}$O+$^{208}$Pb, $E_{\text{beam}} = 74$ MeV, $E/V_B = 0.92$

$^{16}$O+$^{208}$Pb, $E_{\text{beam}} = 77$ MeV, $E/V_B = 0.96$
TOTAL QUASI-ELASTIC EXCITATION FUNCTION

Evers et al., PRC 81, 014602 (2010)
• Mean diffuseness for $^{16}$O induced reactions: 0.65 fm

confirms – shape of nuclear potential in the tail region
Identifying the components in the reflected flux

$^{16}\text{O} + ^{208}\text{Pb}$
Identifying the components in the reflected flux

\[ ^{16}O + ^{208}Pb \]
$^{16}\text{O} + ^{208}\text{Pb}, E_{\text{beam}} = 79 \text{ MeV}$

Best FRESCO calculation
Thompson et al.
NPA505,84(1989)
$^{16}\text{O} + ^{208}\text{Pb}, E_{\text{beam}} = 79 \text{ MeV}$

Best FRESCO calculation

Thompson et al.
NPA505,84(1989)

single $\alpha$ channel mocked up with broad width
Evers et al. (2010),
to be published
$^{16}\text{O}^{208}\text{Pb}$

$\Delta Z = 2$ transfer

Evers et al. (2010),
to be published
Described by single channel calculations

Inclusion of coherent superposition of distinct physical states of the separated nuclei

Multitude of excitations

Complete dissipation of the K.E. into internal excitations

Effect on dynamics?

Coupled-channels model
(low lying states)

Black hole

Coupled-channels model
(low lying states)