Near Barrier Reactions – many-body quantum dynamics in action

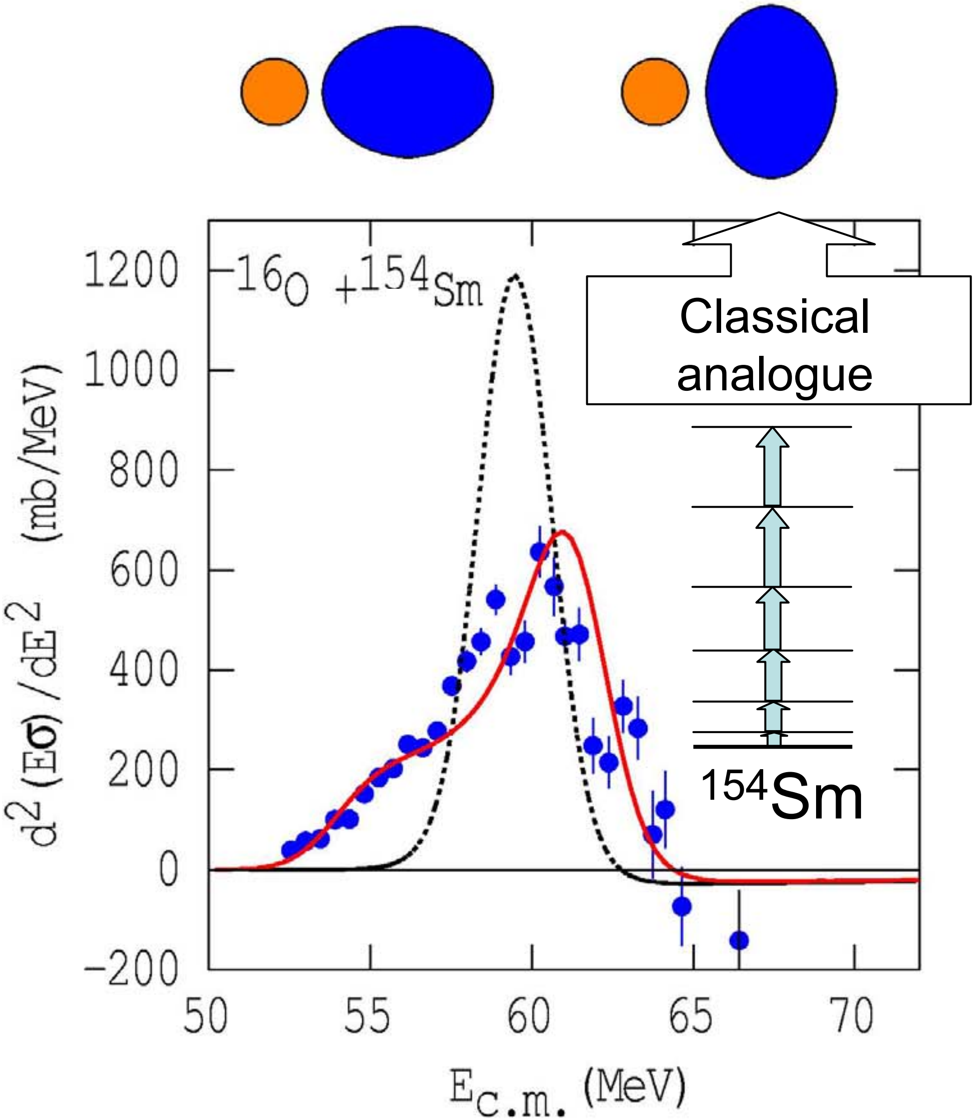
Part III – Fusion, Tunnelling, Weakly bound nuclei

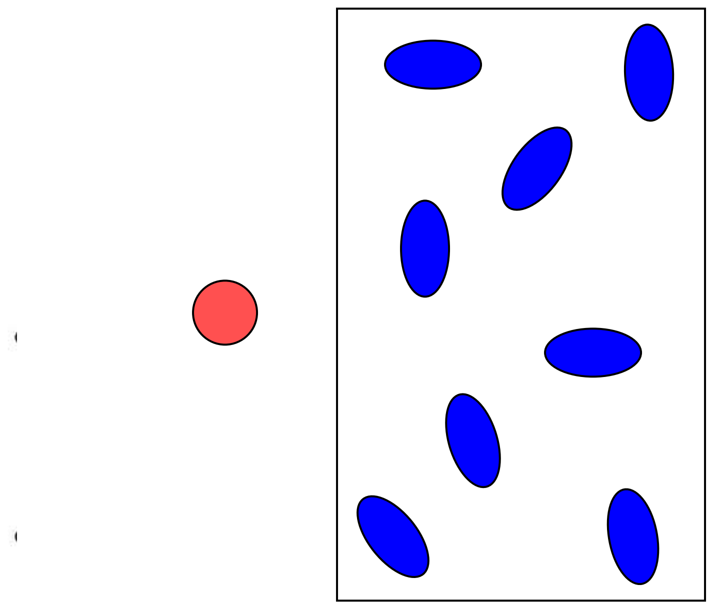
Mahananda Dasgupta

Department of Nuclear Physics

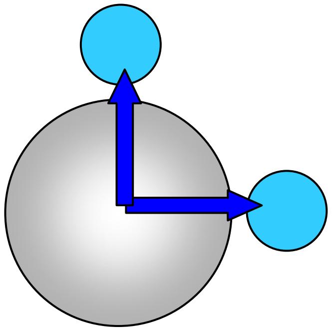
Australian National University, Canberra

Australian National University

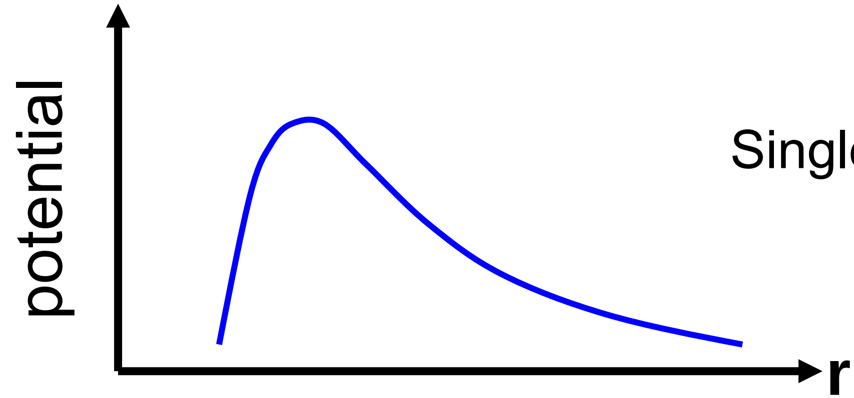

$^{16}O + ^{154}Sm$
$d^2(E\sigma)/dE^2$ (mb/MeV)
$E_{c.m.}$ (MeV)
1200
1000
800
600
400
200
0
-200
50
55
60
65
70
Classical analogue
^{154}Sm



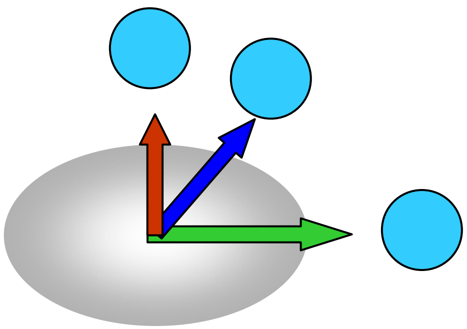
Structure effects in reactions – a classical demonstration



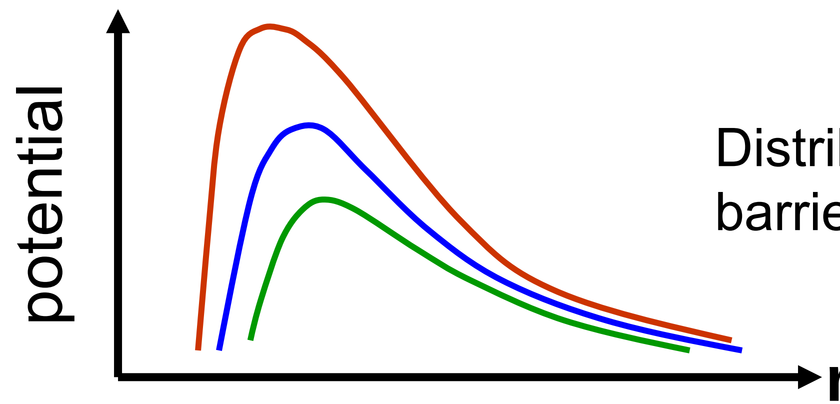
Distance between the two nuclei remains the same



Single barrier



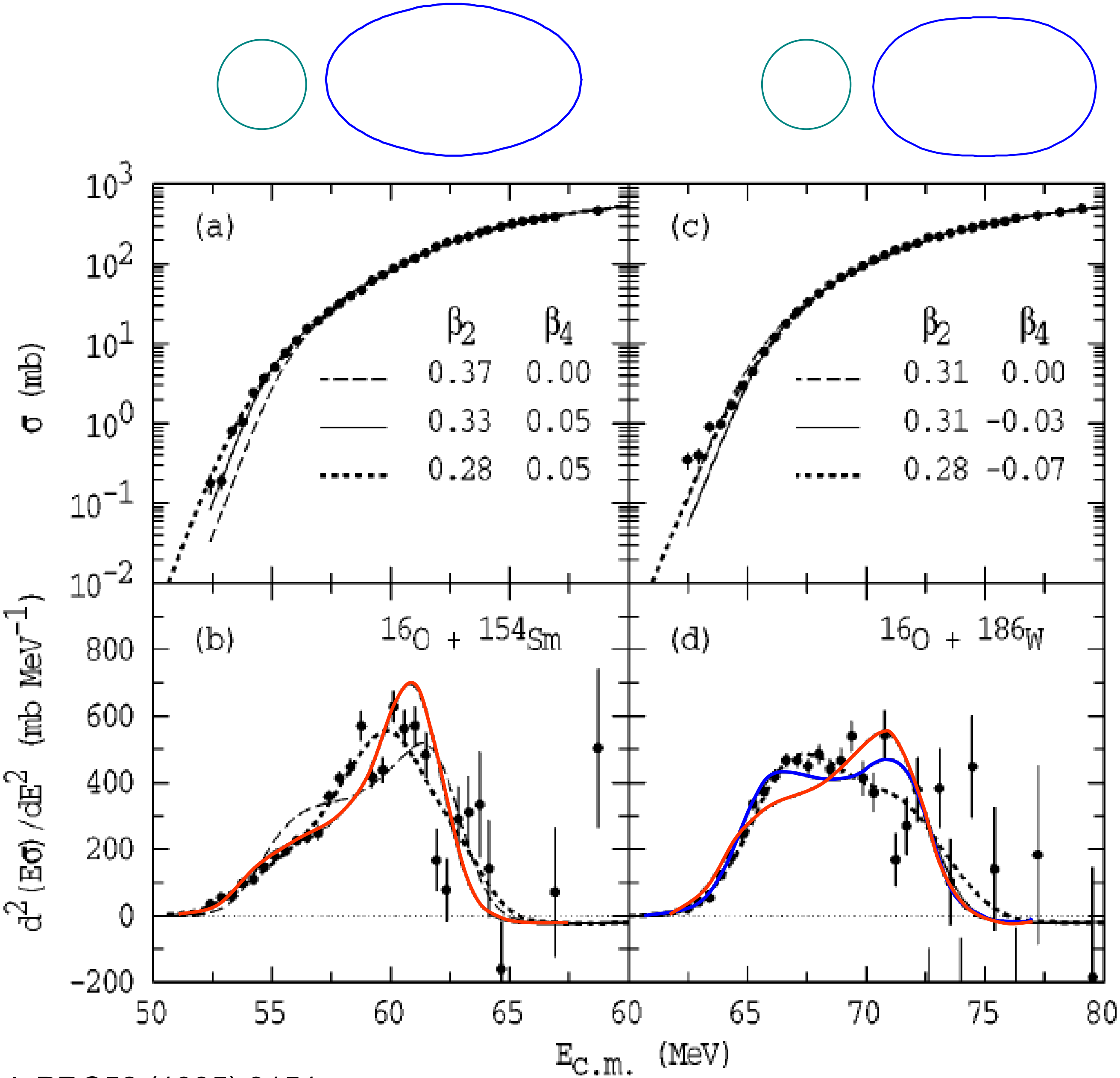
Distance between the two nuclei changes with angle



Distribution of barrier heights

Effect of coupling can be included in the entrance channel potential $V(r) \rightarrow V(r, \theta)$

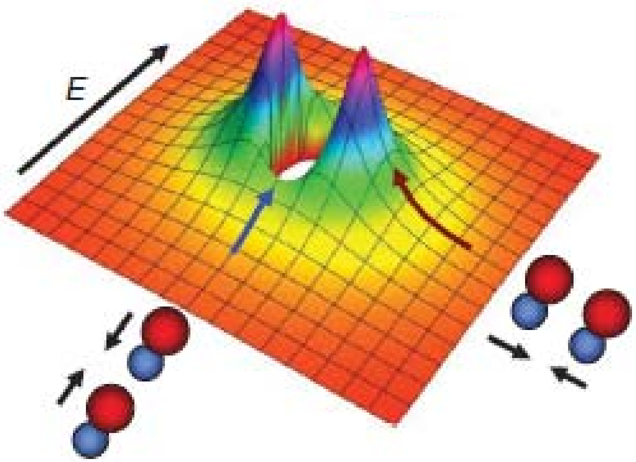
Affects subsequent evolution – elongated configuration prone to fission



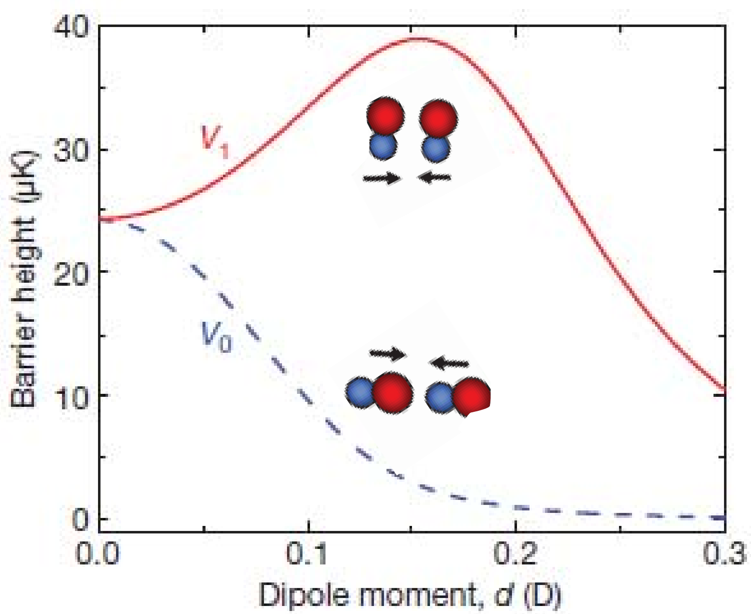
Leigh et al, PRC52 (1995) 3151

Lemmon et al, PLB316 (1993) 32

Dipolar collisions of polar molecules



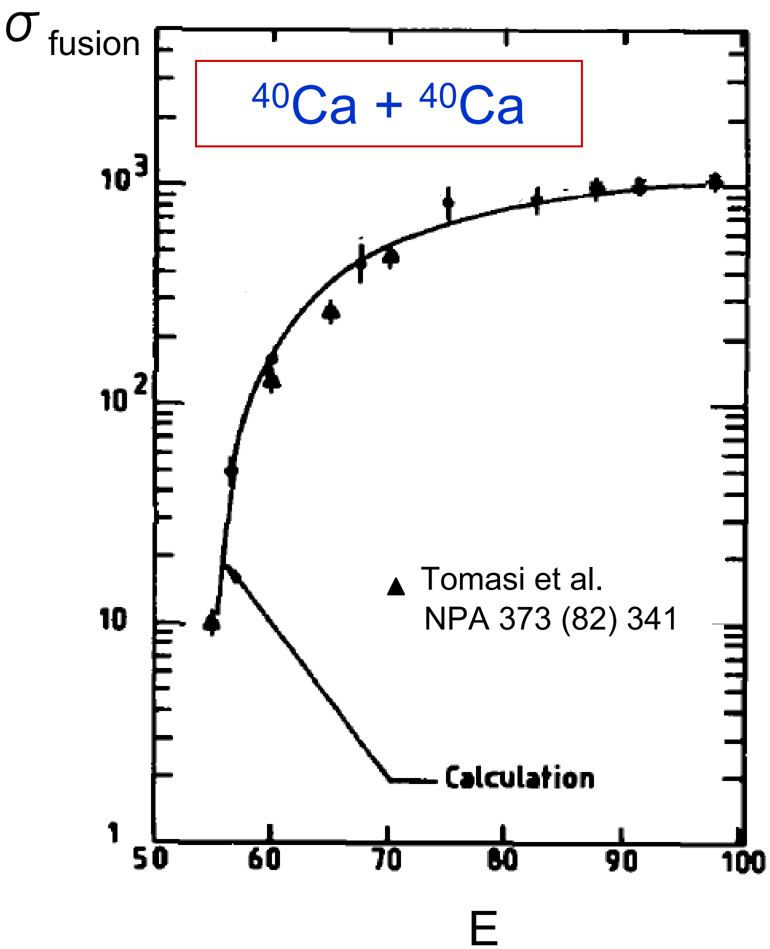
Collision of ultracold polar molecules ($^{40}K^{87}Rb$)

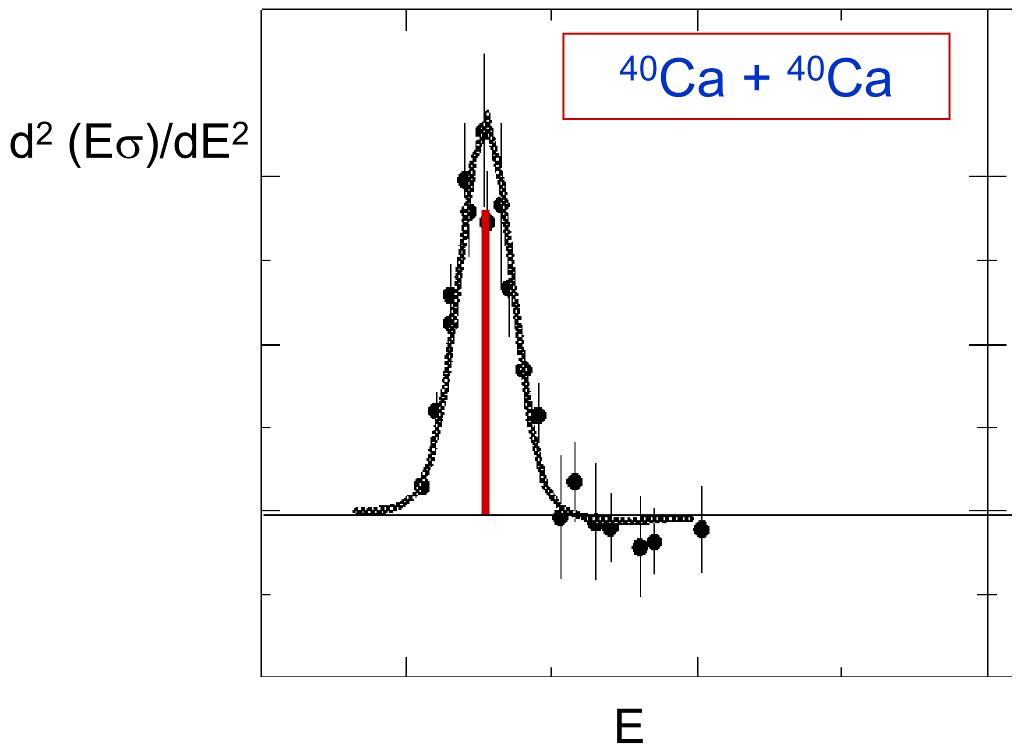


Barrier for head-to-tail collisions less than side-to-side collisions

Ni et al., Nature 464 (2010) 1324

Fusion of light nuclei: experiment vs. expectations





Single barrier model works well for fusion of light nuclei

Why don't we see the effect of coupling for lighter nuclei?

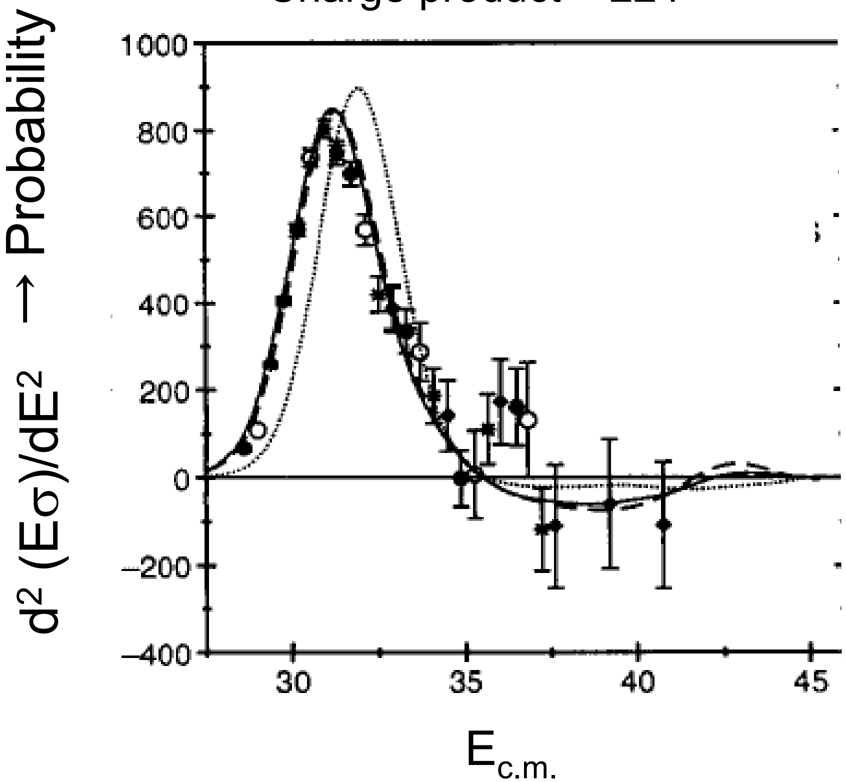
$$\mathrm{V}_{\mathrm{coupling}}(r,\xi) = f(r)\Gamma(\xi)$$

$$f(r) \sim \frac{dV}{dr}$$

$$\sim \mathrm{Z}_1\mathrm{Z}_2$$

$^{16}O + {}^{58}Ni$

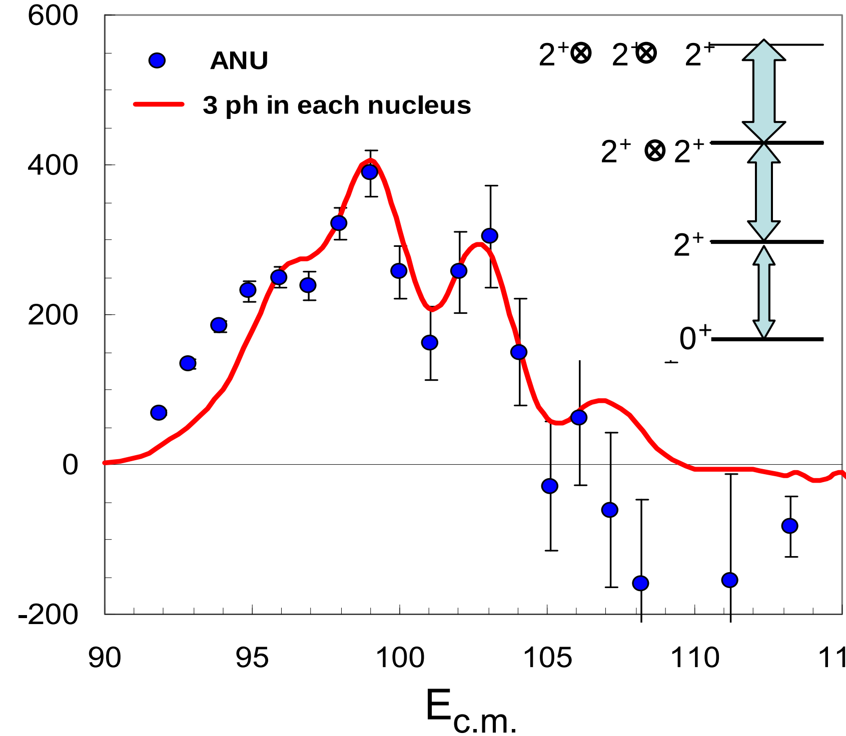
Charge product = 224



N. Keeley et al., Nucl. Phys. A628, 1 (1998)

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

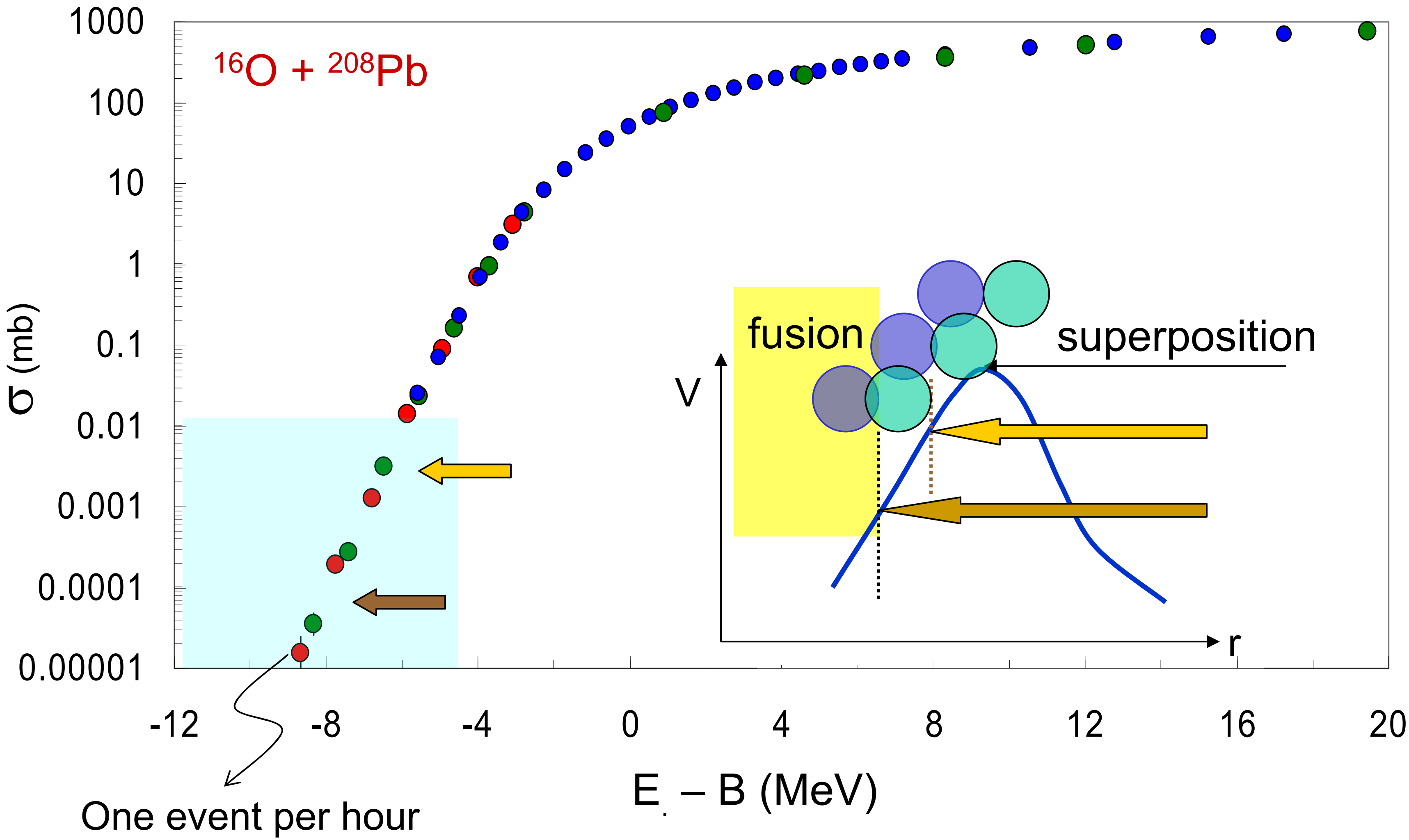
Charge product 784



M. Rodriguez, ANU PhD work (2009)

- Splitting of barriers ∝ coupling strength ∝ charge product of colliding nuclei

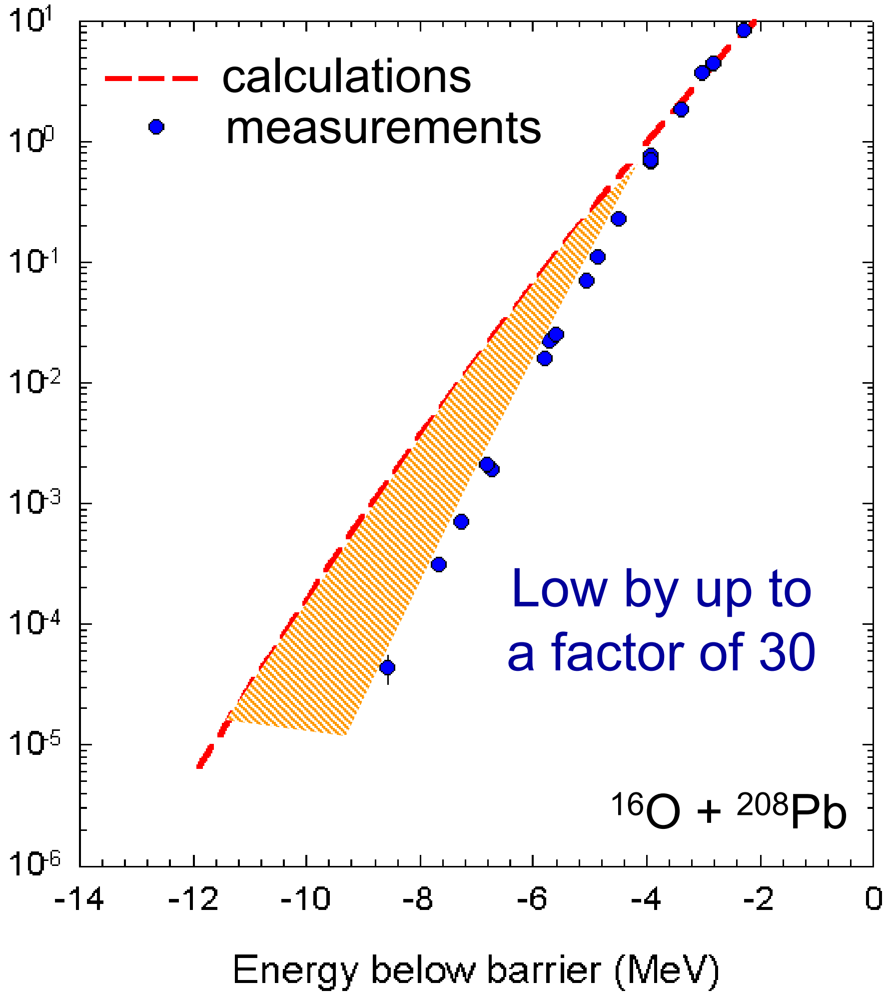
Advances – higher sensitivity – new opportunities



Probe dynamics of tunnelling of complex quantum system

increasing overlap of nuclear matter

Fusion cross-section (mb)



Dasgupta et al, PRL 99 (2007) 192701

Ni+Ni: C.L. Jiang et al., PRL 93 (2004) 012701

Jiang et al., PRC 81 (2010) 024611

Srivastava et al, PRL 103 (2009) 232702

Esbensen and Mişicu PRC76 (2007) 054609

Ichikawa, Hagino, Iwamoto, PRL103, 202701 (2009)

Composite systems tunnelling - effects of superposition appears to reduce irreversibility due to complex interactions as nuclei merge?

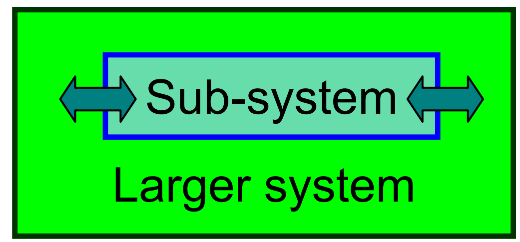
The Quantum to Classical transition - from coherent superposition to irreversibility

W.H. Zurek, Rev. Mod. Phys. 75 (2003) 715; Phys. Today 44 (1991) 36
M. Schlosshauer, Decoherence and the quantum to classical transition, Springer (2007)

Idealized isolated system

Superposition of basis states

Described by coherent Q.M.



System “entangled” with environment

Loss of coherence in smaller system

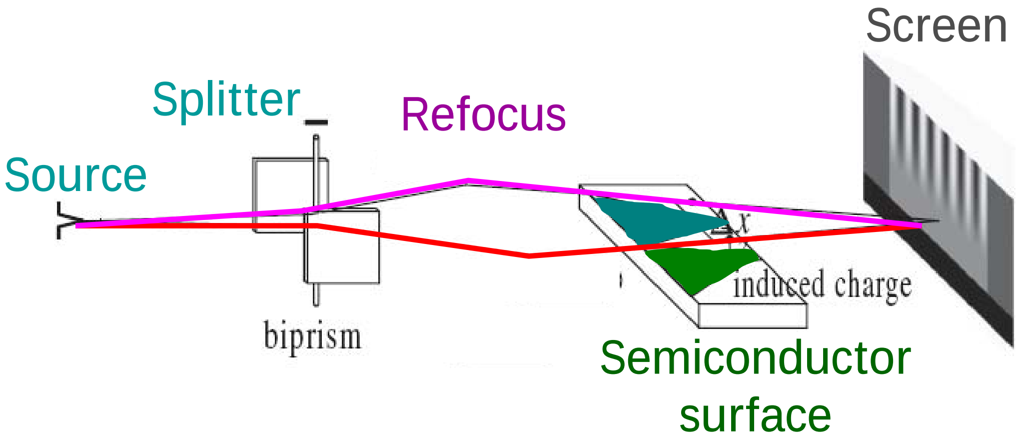
→ Irreversible outcome (classical)

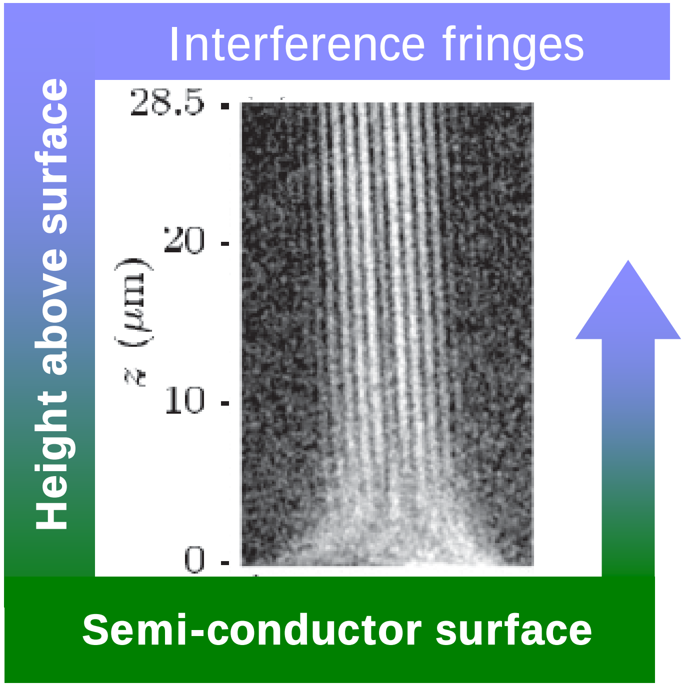
Can be described by density matrix (Q.M.)

(H.D. Zeh arXiv:quant-ph/0512078 v2) coherence shared with (lost in) environment

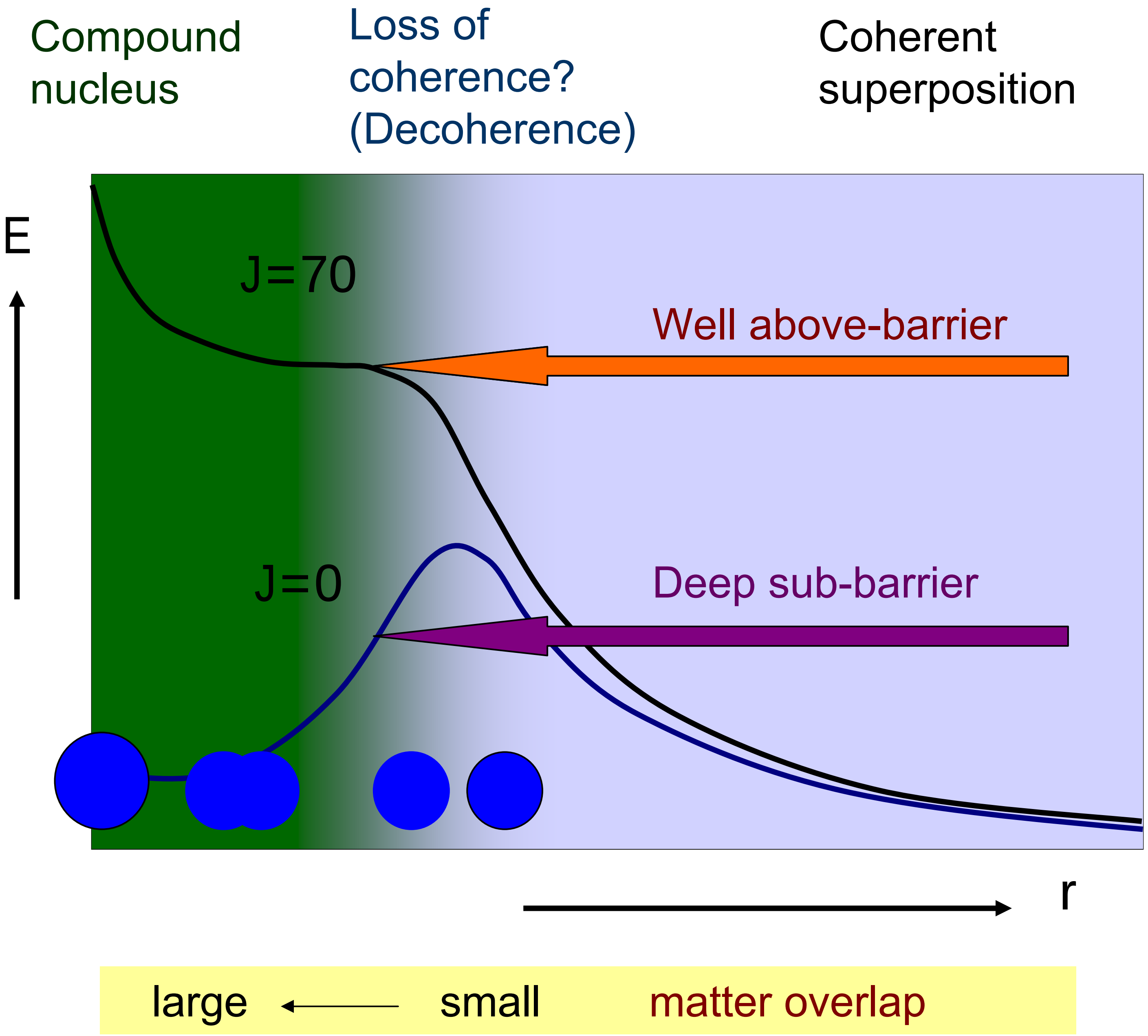
Example: Electron entanglement with a surface

Sonnentag, Hasselbach,
PRL 98, 200402 (2007)

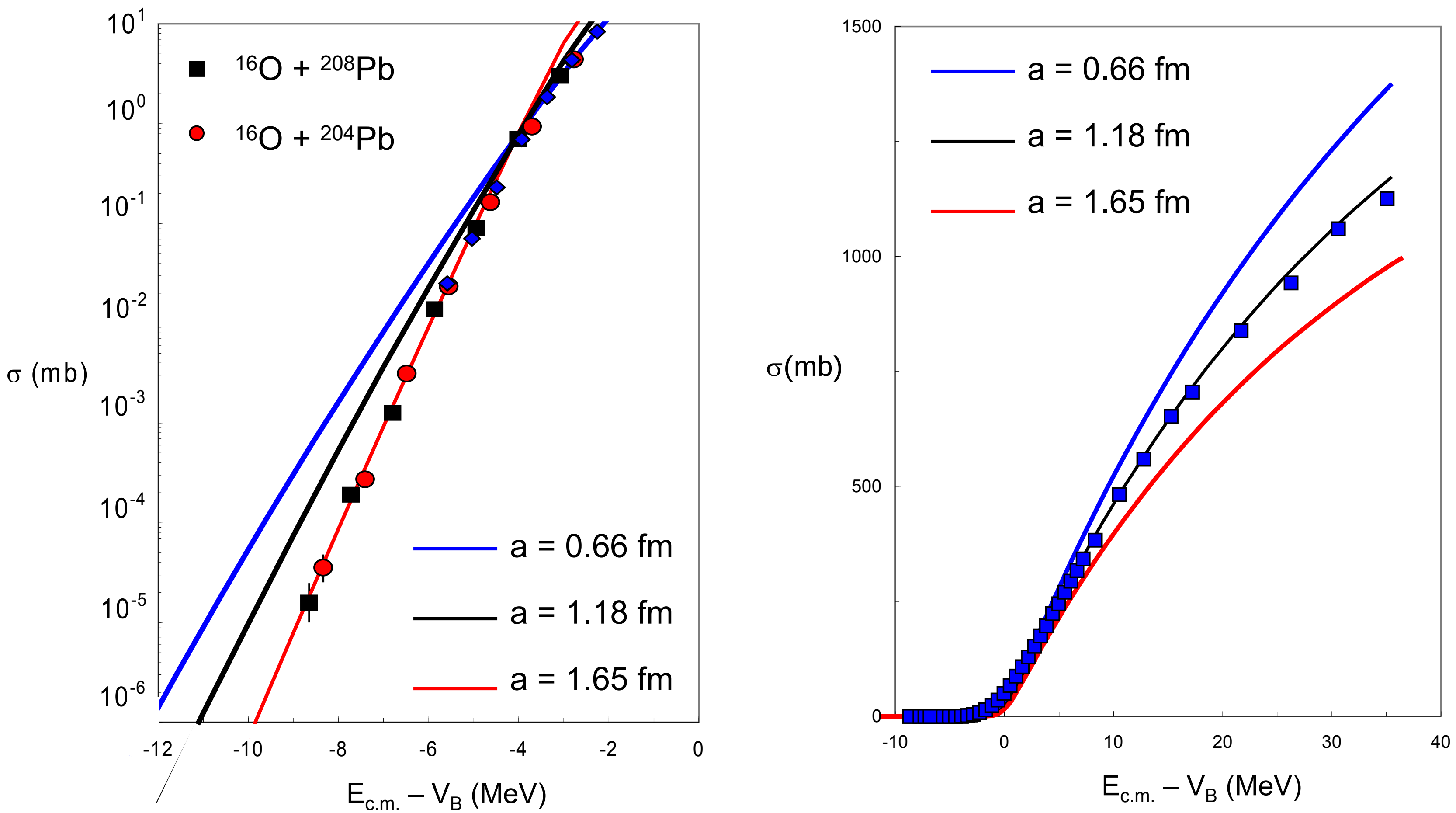




- Double-slit type experiment with single electrons



Compound nucleus
Loss of coherence? (Decoherence)
Coherent superposition
E
J=70
Well above-barrier
J=0
Deep sub-barrier
r
large
small
matter overlap

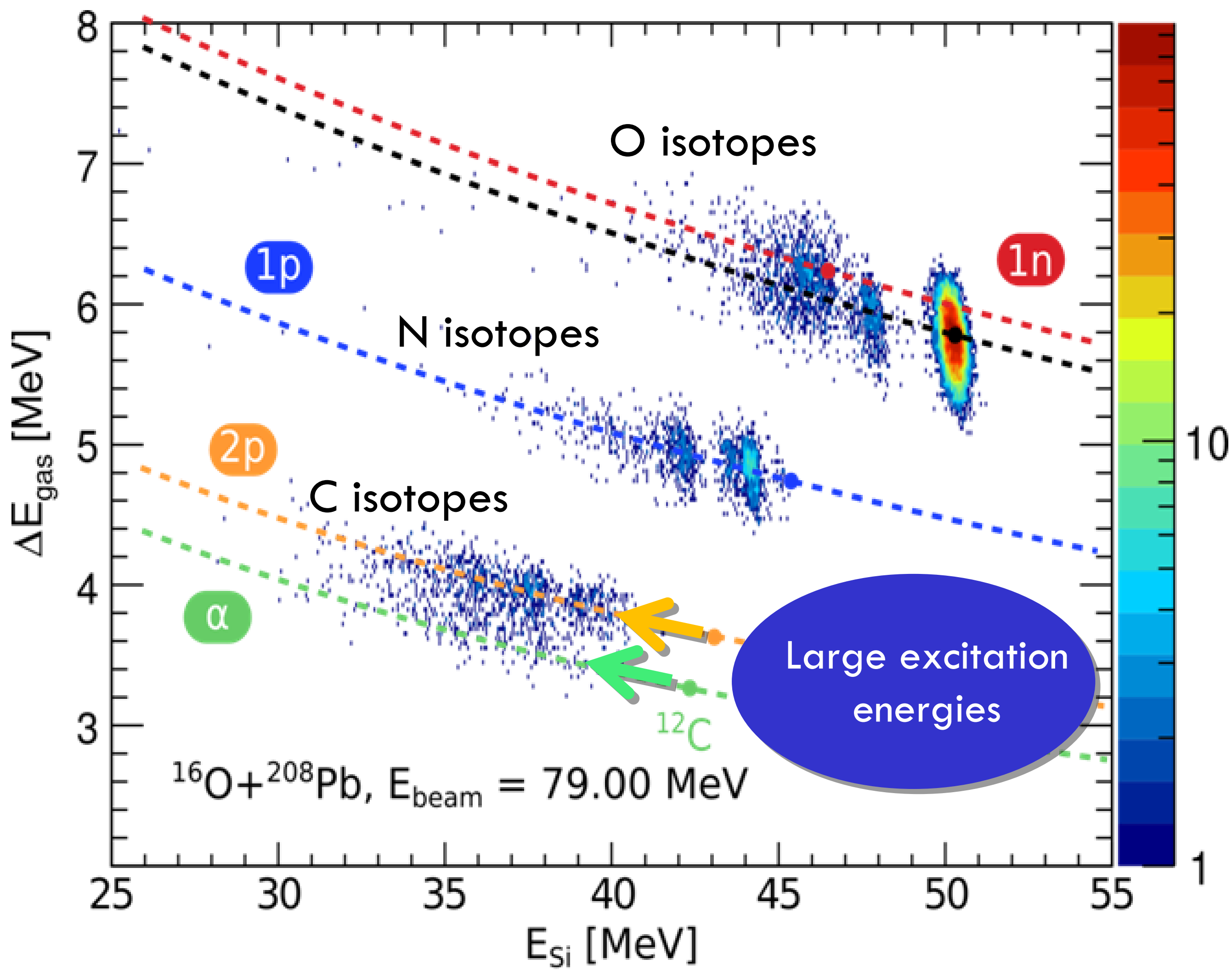


Fusion below and above the barrier inconsistent

- need to go beyond current models
- need to incorporate transition to irreversibility explicitly

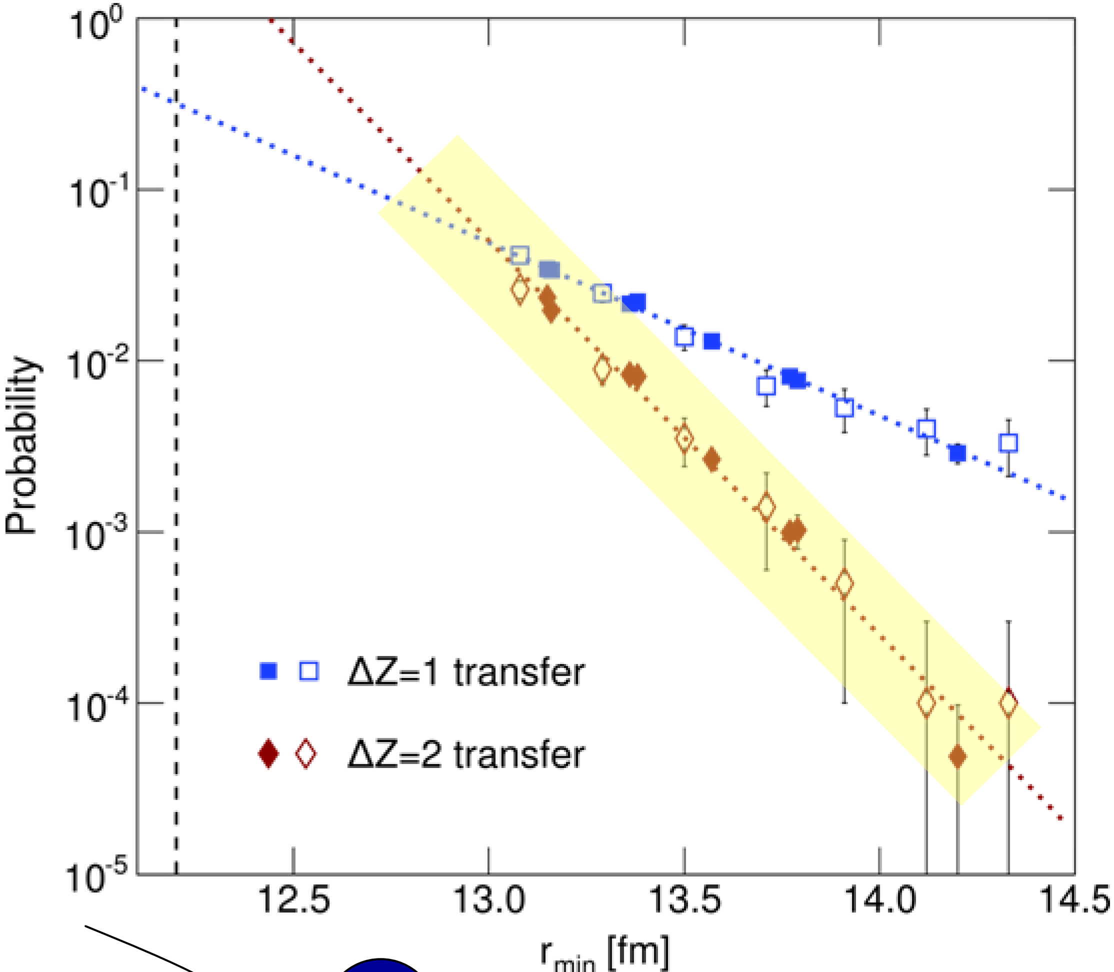
M. Dasgupta et al., PRL 99 (2007) 192701

Measurements of the back-scattered flux



Following cluster transfer the nuclei are “hot”

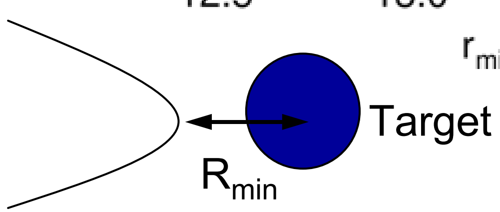
Radial dependence of transfer (→ "hot" nuclei)



- Steep radial dependence
- The first quantitative step towards theoretical developments

Evers, PhD work (2010)

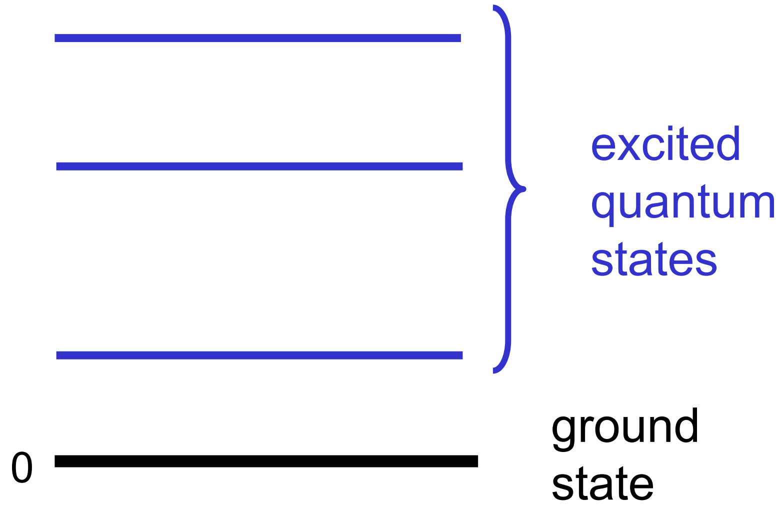
Accepted PRC (2011)



distance of closest approach

separation distance

probed by varying collision energy



Quantum states

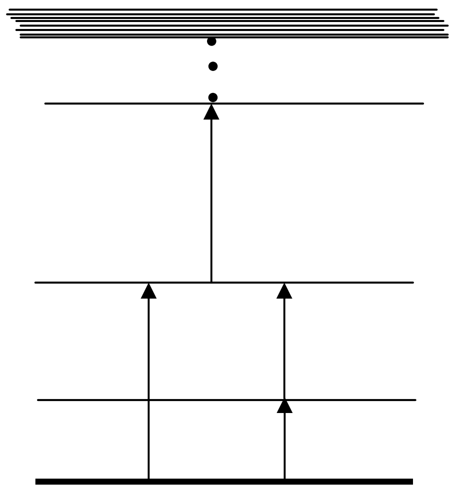
What if lifetime of states similar to collision times?

World-wide developments → accelerators for unstable nuclei

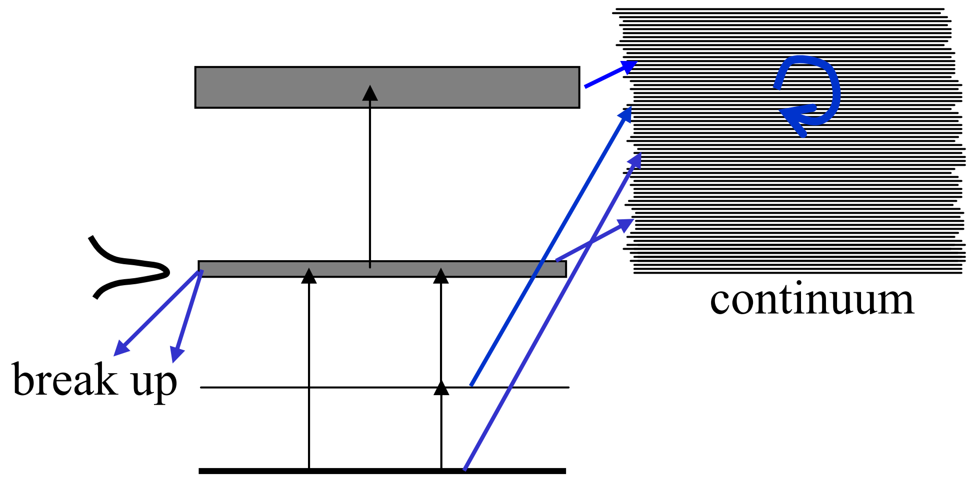
- Fundamental, applied nuclear physics
- Astrophysics
- Material science

⋮

Well bound nucleus



Weakly bound nucleus

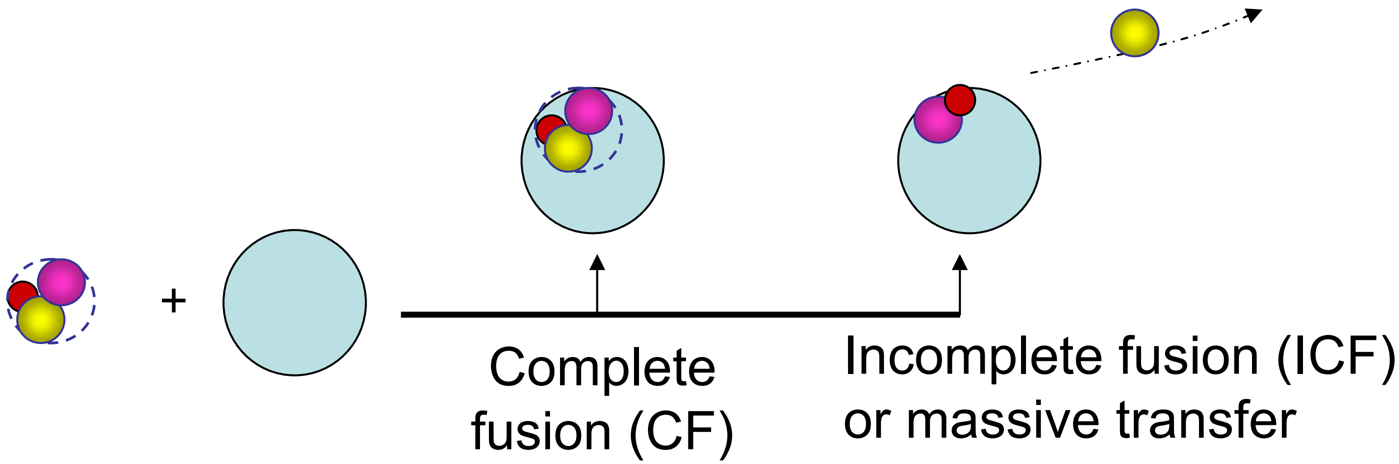


Couplings to internal states lead to increased fusion at energies below the average barrier (w.r.t. single barrier model)

Expect the same **+**

Effects specific to weakly bound nuclei

- Short-lived resonance states
  → breakup
- Low lying continuum states
  → coupling effects
  → breakup



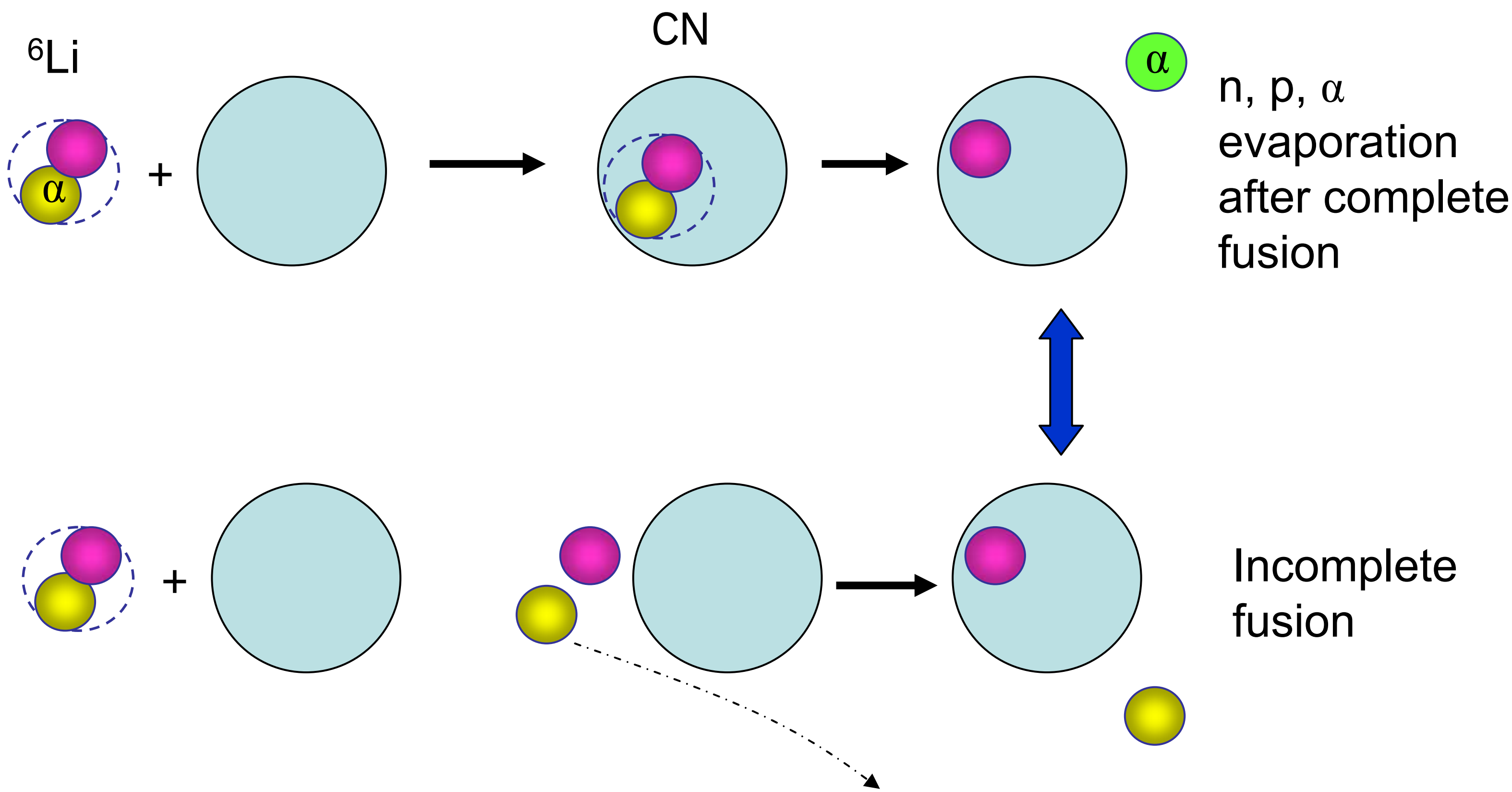
- **Theoretical predictions** - controversies related to:
  - (i) effect of couplings on fusion
  - (ii) effect of breakup on fusion

  } relative importance determines enhancement / suppression

  - (iii) coupled channels model (CDCC) unable to describe incomplete fusion, cannot separate it from complete fusion

- **Experiments and interpretation** – controversies relating to:
  - (i) Identification of complete fusion products – need to separate from ICF
  - (ii) Uncertainties in potential parameters – affects reference calculations

Some processes are practically indistinguishable



e.g. reaction of ^{6}Li with light target nuclei (α evaporation)

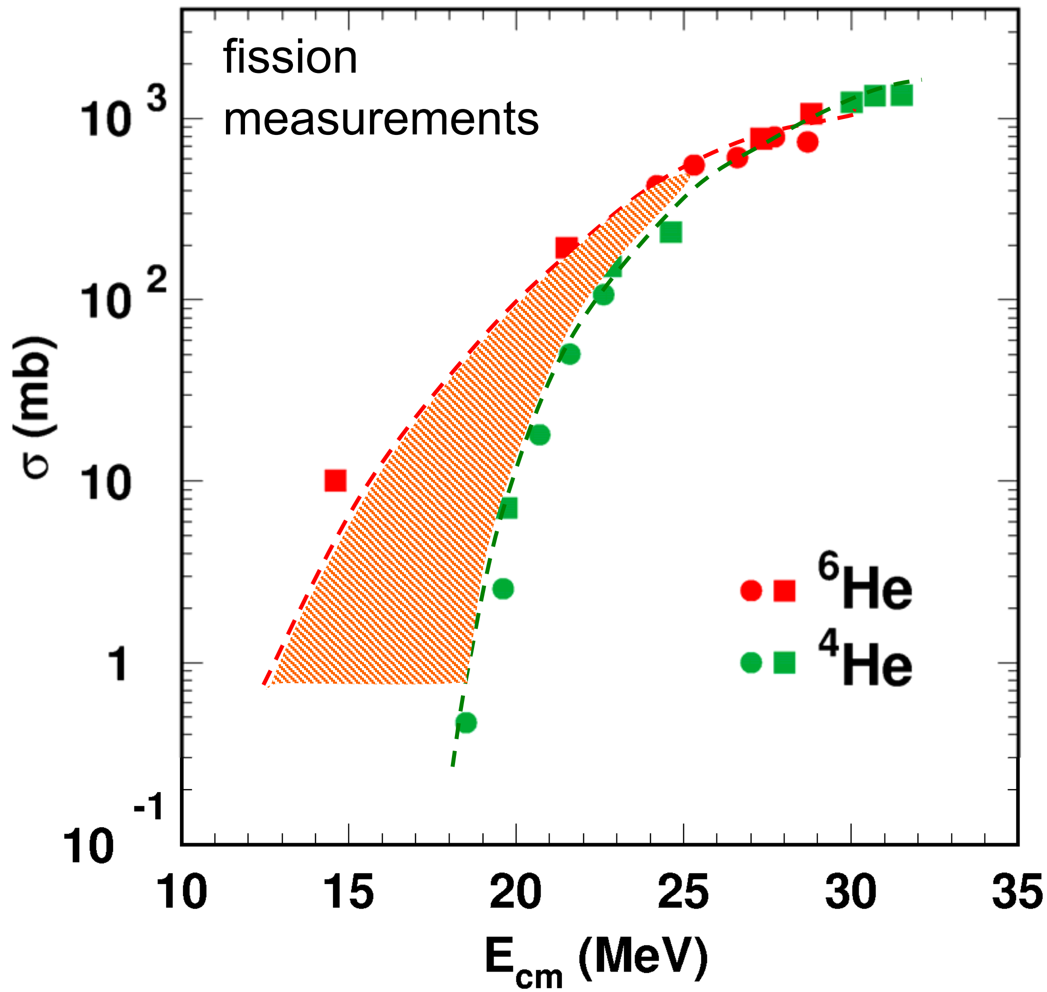
^{9}Be reactions – incomplete fusion of ^{8}Be

Careful of other reactions that lead to fusion-like products

$^{6}He + ^{238}U \rightarrow$ fused nuclei $\rightarrow$ fission

2n halo

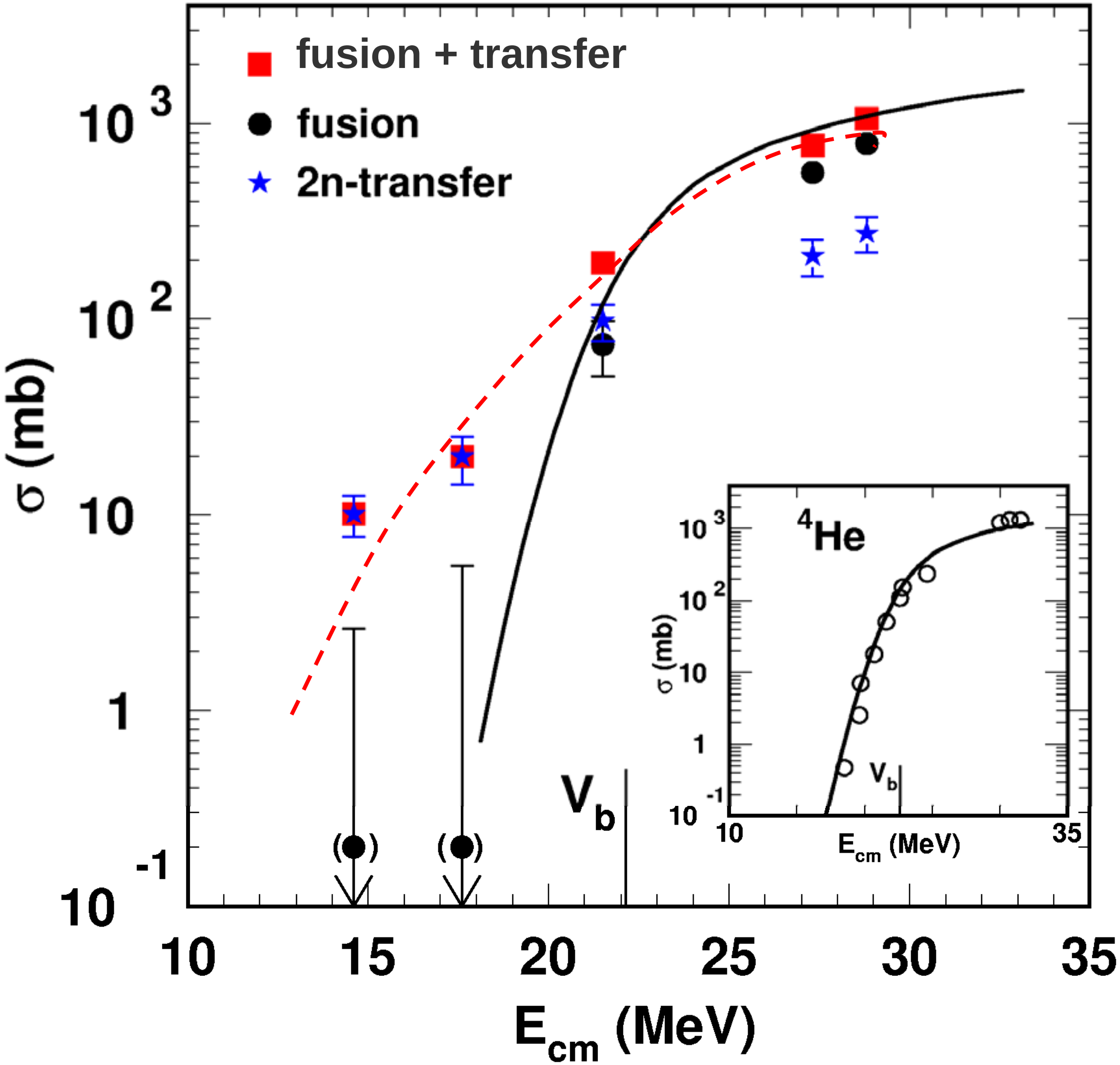
bound by
0.97 MeV



Trotta et al.
Phys. Rev. Lett.
84 (2000) 2342

Increased fusion due to halo?

Fusion of ^{6}He with ^{238}U



Raabe et al., Nature 431 (2004) 823

Fusion cross-sections for ^{6}He, similar to ^{4}He

Hinde and Dasgupta, Nature 431, 748 (2004)

Main messages

- Experimental fusion (capture) barrier distributions – “camera” to understand the dynamics at the point of capture

- Tunnelling well below the (lowest) barrier – an open problem

  - strong links to other areas of physics

- Clear identification of complete fusion products essential to get physics right

If we have a barrier lower than average barrier and a barrier higher than average barrier

Why we get cross-section enhancement below the average barrier?

Do the two channel problem that was given:

$$\sigma = w_{+}\, \sigma(E, V+ \lambda_{+}) + w_{-}\, \sigma(E, V + \lambda_{-})$$

K. Hagino – today's lecture.

come and talk with me

For $E< V_B$

$$\sigma(E,V_B) \approx \frac{\hbar\omega}{2E_{cm}} R_B^2 \exp\left\{\frac{2\pi}{\hbar\omega}(E_{cm} - V_B)\right\}$$