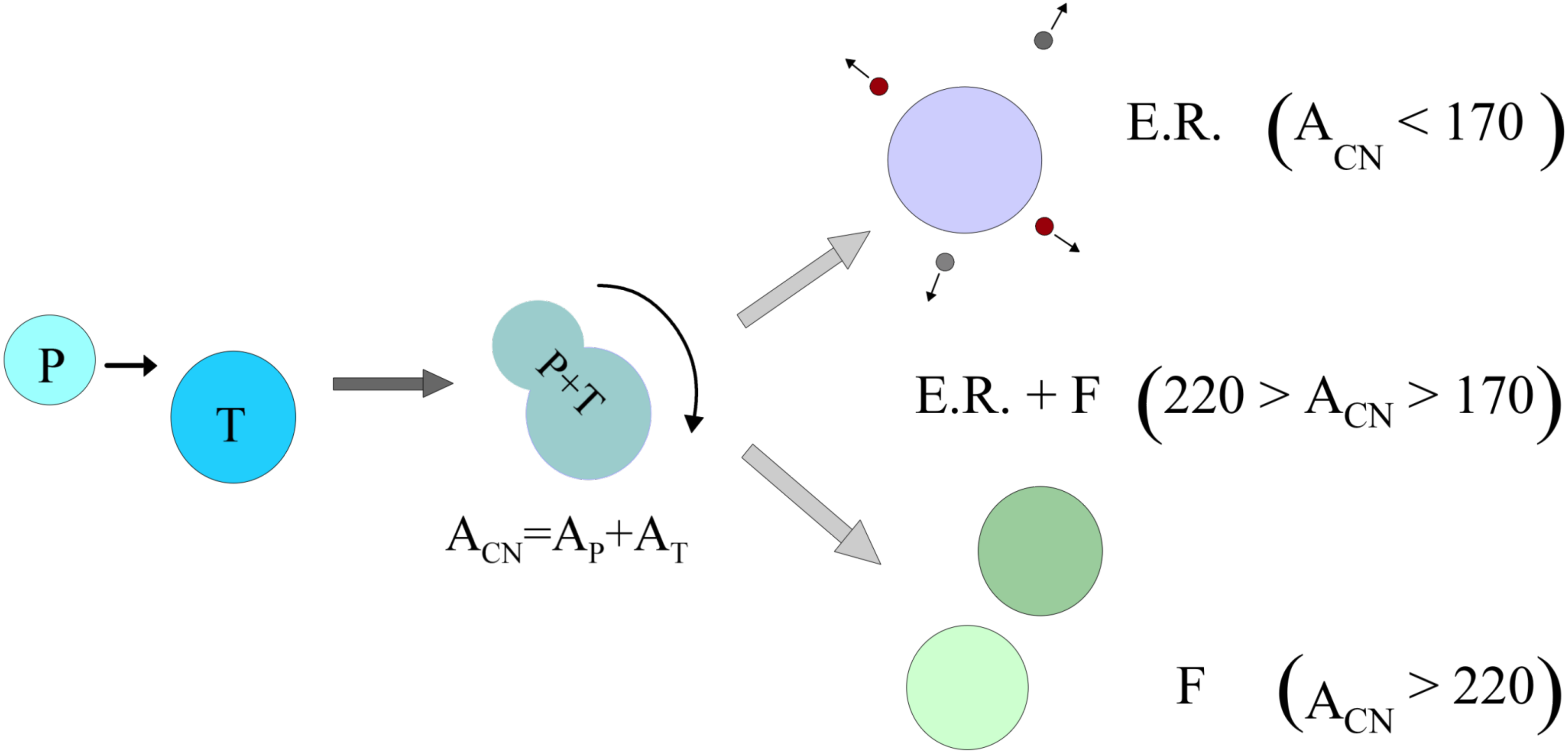
Heavy-ion reactions around the Coulomb barrier: *an overview*

Kouichi Hagino
Tohoku University, Sendai, Japan

1. *Introduction: why subbarrier fusion?*
2. *Role of nuclear structure in subbarrier fusion*
3. *Friction, dissipation, quantum decoherence?*
4. *Fusion of unstable nuclei*
5. *Pair transfer reactions*
6. *Summary*

Fusion: compound nucleus formation



$$A_{CN}=A_P+A_T$$

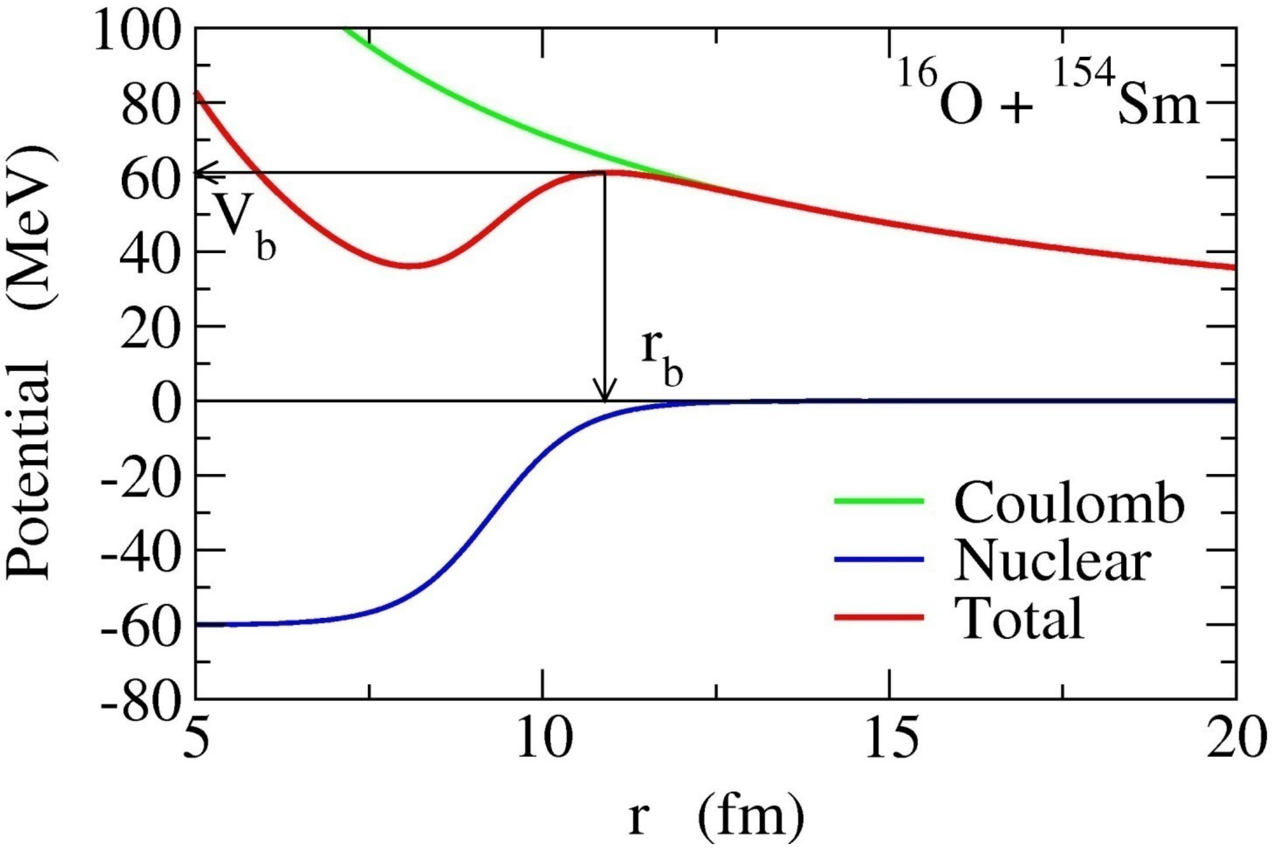
E.R. $\left(A_{CN} < 170\right)$

E.R. + F $\left(220 > A_{CN} > 170\right)$

F $\left(A_{CN} > 220\right)$

courtesy: Felipe Canto

Inter-nucleus potential



Two forces:

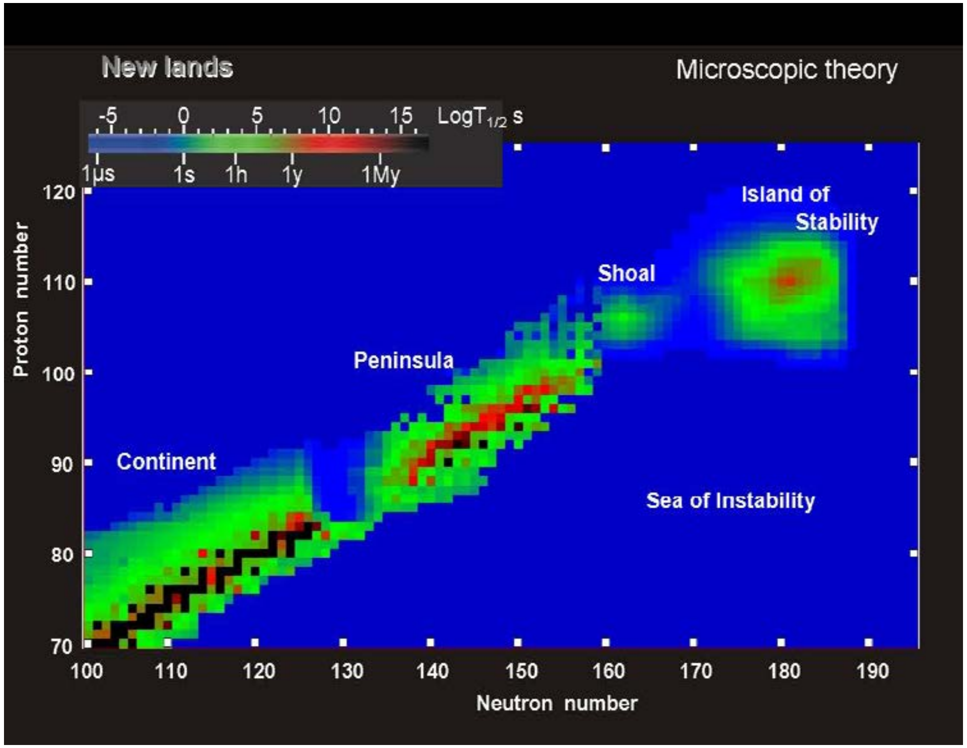
1. Coulomb force
   Long range, repulsive
2. Nuclear force
   Short range, attractive

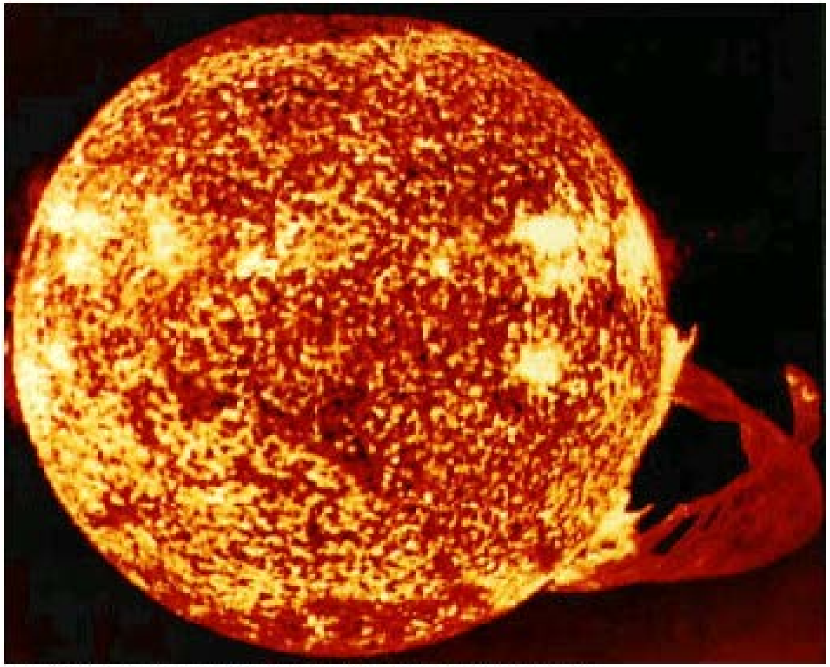
Potential barrier due to the compensation between the two (Coulomb barrier)

- above barrier
- sub-barrier
- deep subbarrier

Why subbarrier fusion?

Two obvious reasons:





NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

discovering new elements
(SHE by cold fusion reactions)

nuclear astrophysics
(fusion in stars)

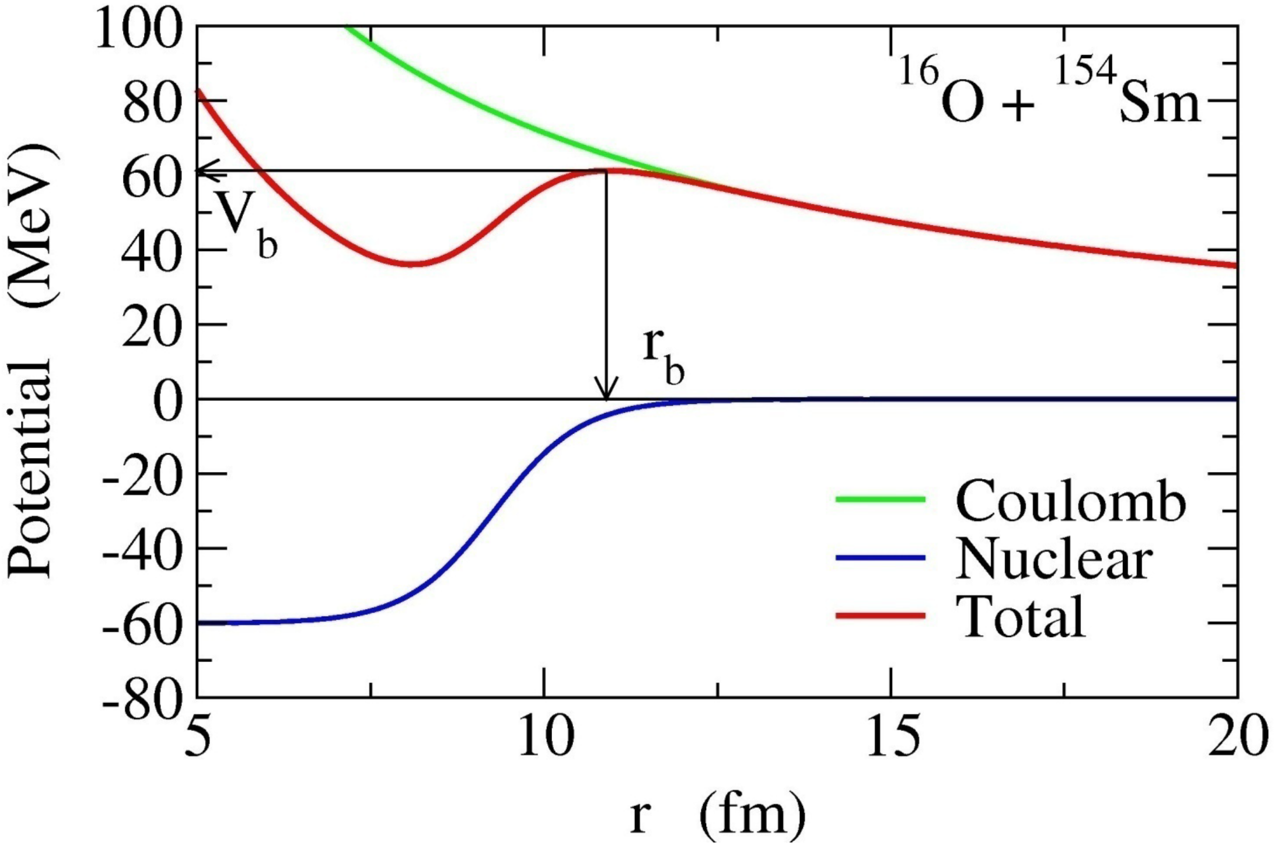
Why subbarrier fusion?

Two obvious reasons:

- ✓discovering new elements (SHE)
- ✓nuclear astrophysics (fusion in stars)

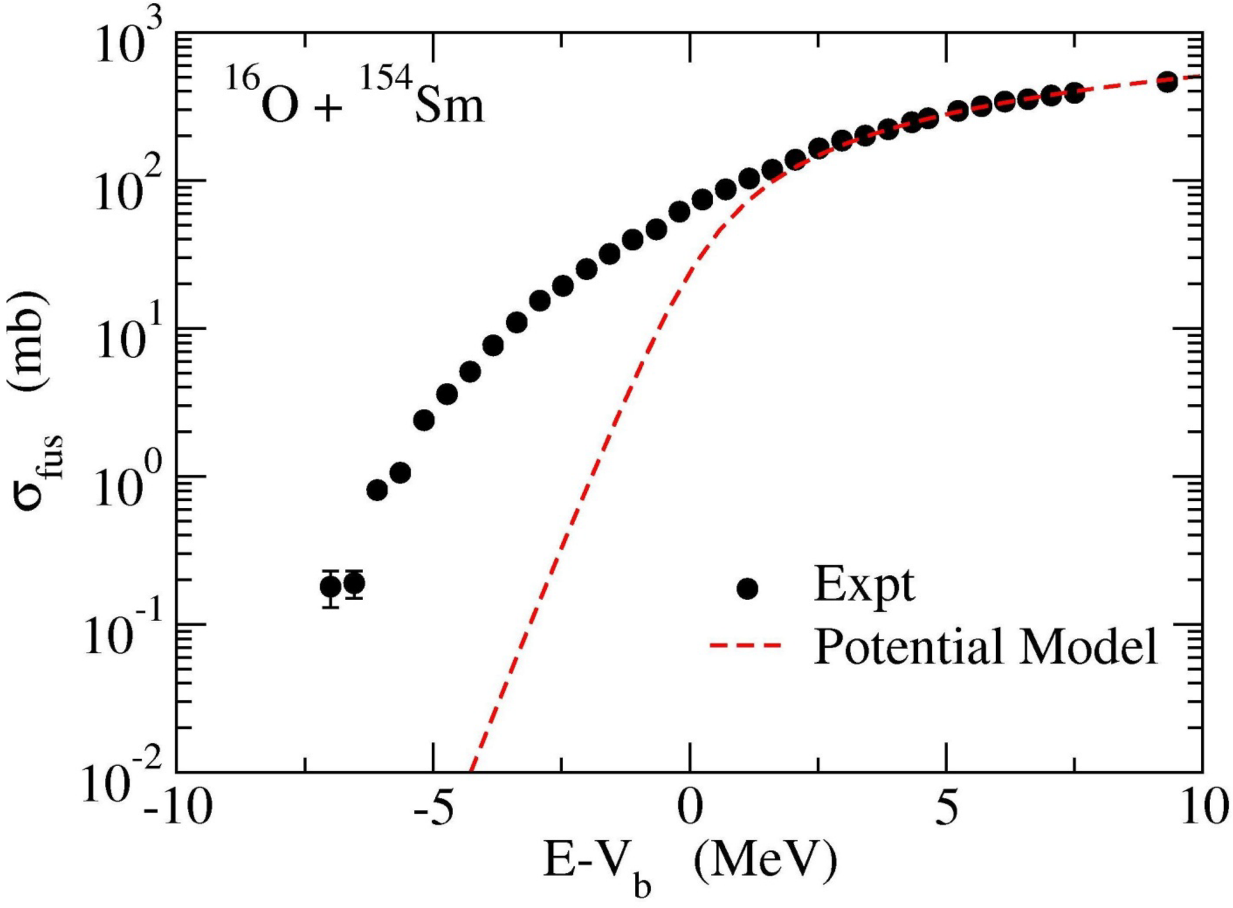
Other reasons:

- ✓reaction mechamism
  strong interplay between reaction and structure
  (channel coupling effects)
    cf. high *E* reactions: much simpler reaction mechanism
- ✓many-particle tunneling
  cf. alpha decay: fixed energy
    tunneling in atomic collision: less variety of intrinsic motions



the simplest approach to fusion cross sections: potential model

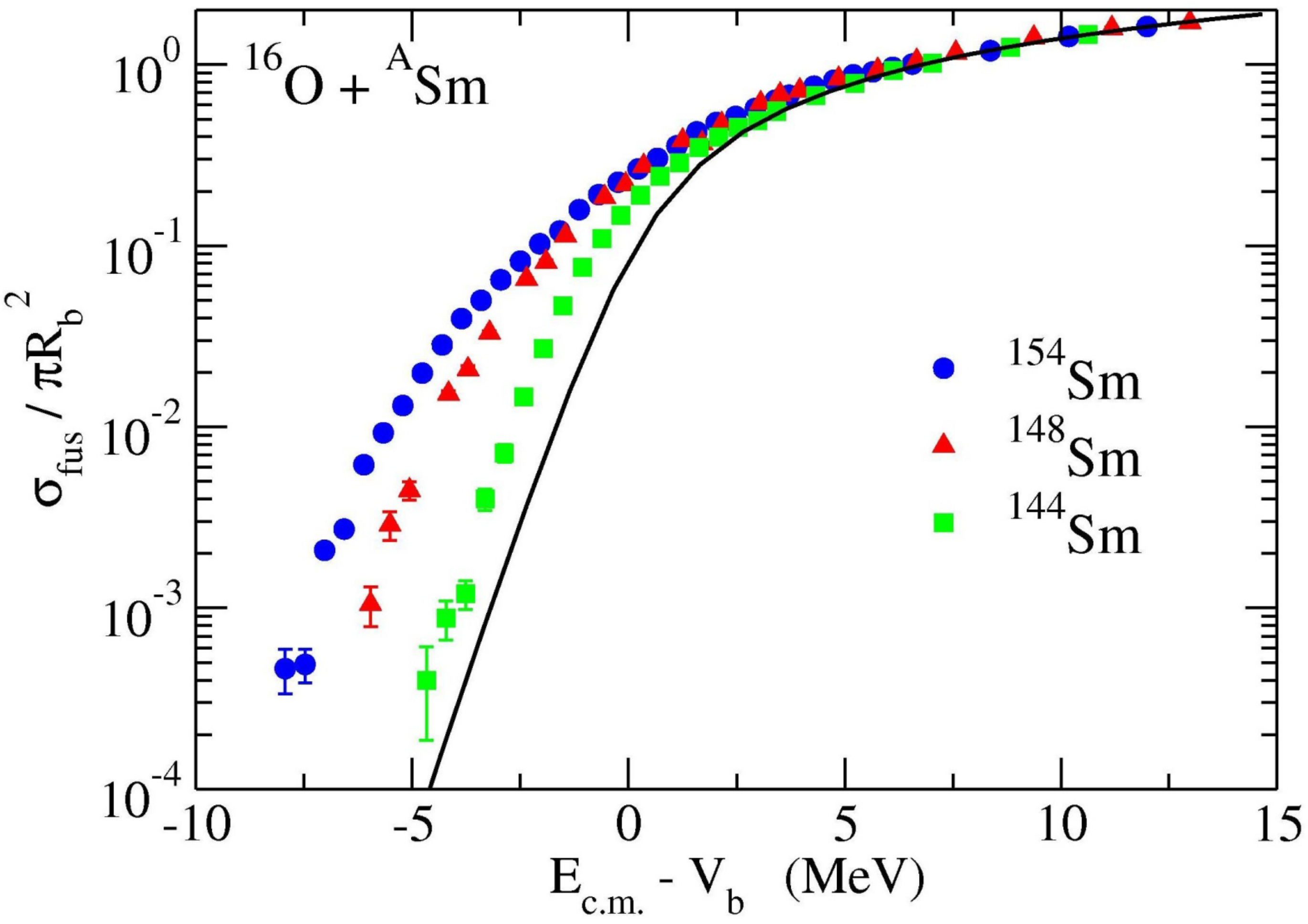
$$\sigma_{\text{fus}}(E) = \frac{\pi}{k^2}\sum_l (2l+1)P_l(E)$$



Potential model:
Reproduces the data reasonably well for
$E > V_b$

Underpredicts σ_{fus} for
$E < V_b$

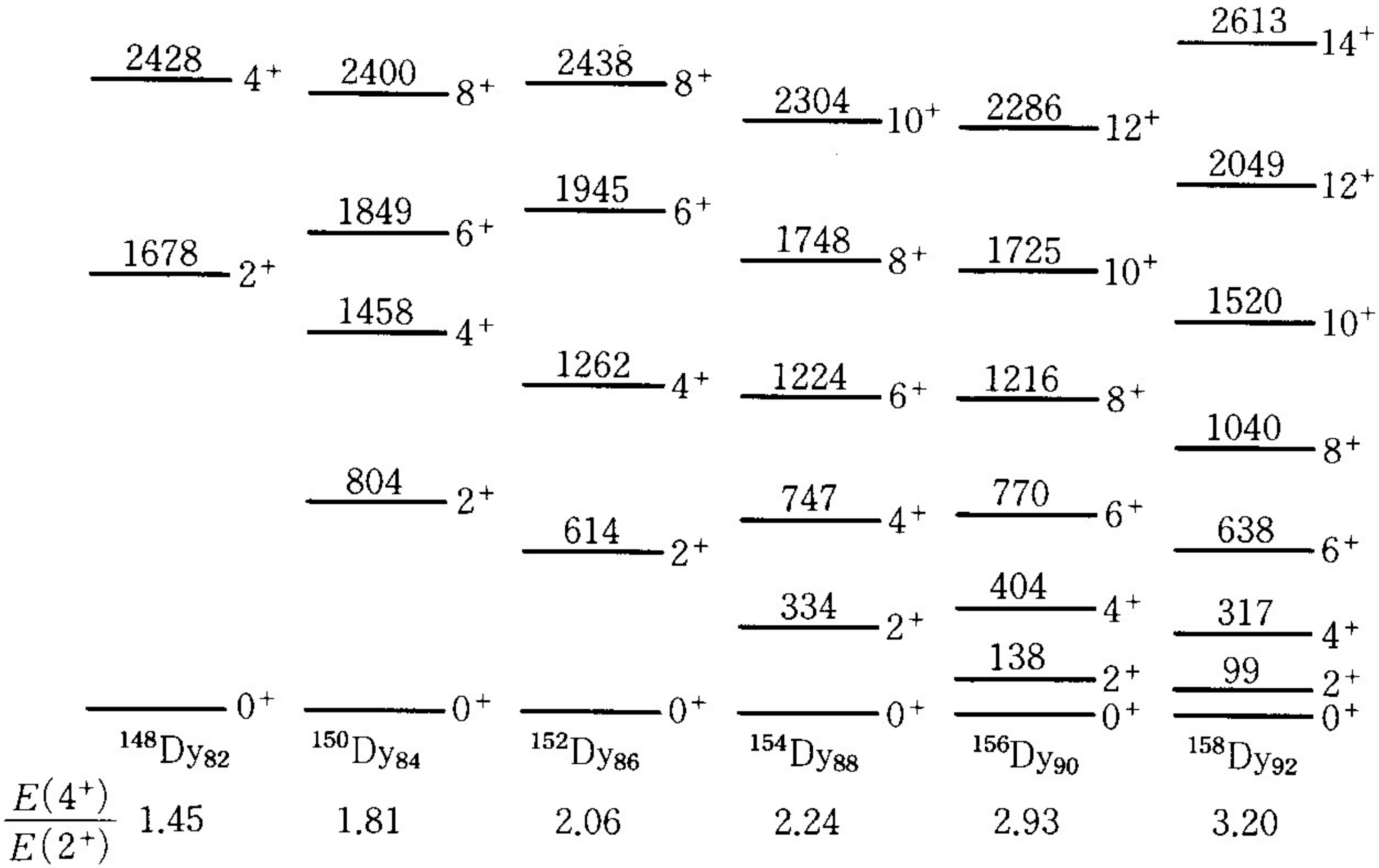
cf. seminal work:
R.G. Stokstad et al., PRL41('78)465
PRC21('80)2427



⇒ Strong target dependence at $E < V_b$

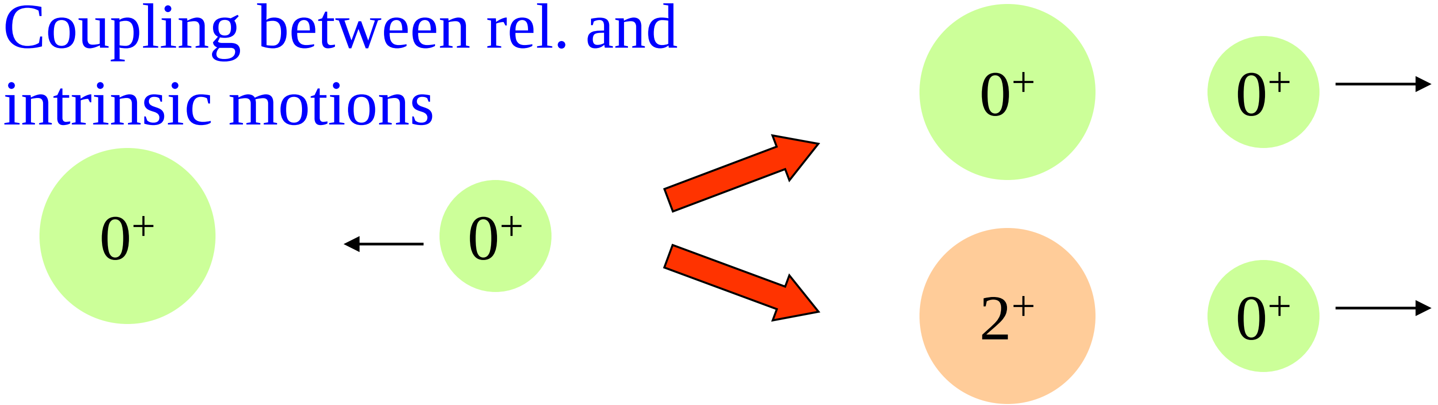
Low-lying collective excitations in atomic nuclei

Low-lying excited states in even-even nuclei are collective excitations, and strongly reflect the pairing correlation and shell strucuture



Coupled-Channels method

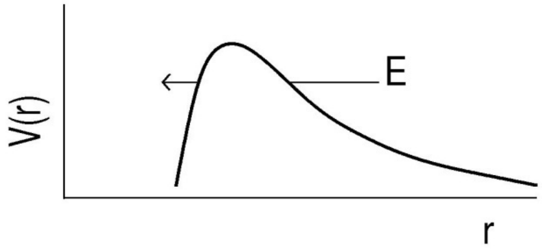
Coupling between rel. and intrinsic motions

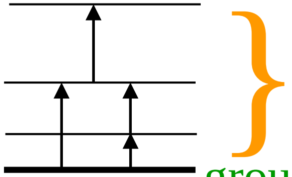


Entrance channel

Excited channel

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) + H_0(\xi) + V_{\rm coup}(\boldsymbol{r},\xi)$$





excited states

ground state

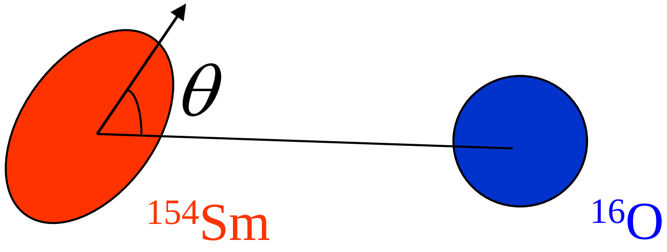
$$H_0(\xi)\phi_k(\xi) = \epsilon_k\,\phi_k(\xi)$$

$$\boxed{\Psi(\boldsymbol{r},\xi) = \sum_k \psi_k(\boldsymbol{r})\phi_k(\xi)}$$

→ coupled Schroedinger equations for $\psi_k(r)$

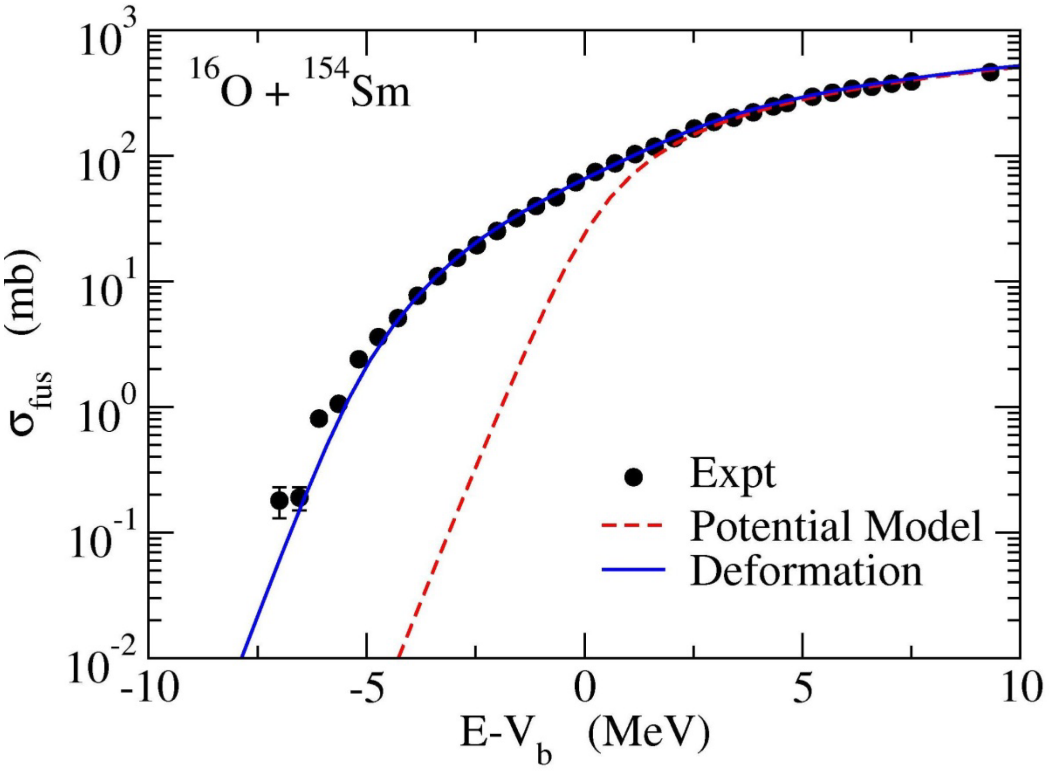
Subarrier fusion:

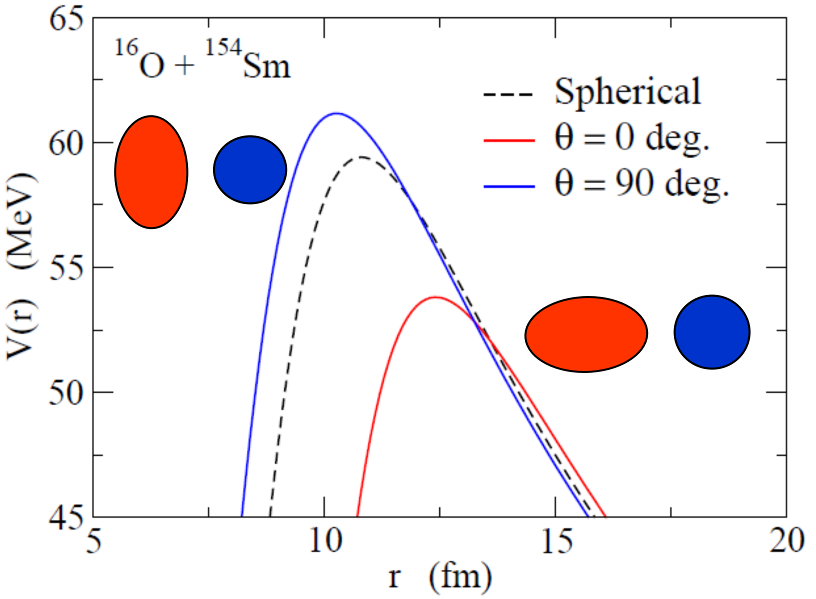
strong interplay between reaction and structure



coupled-channels equations

$$\boxed{\sigma_{\rm fus}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm fus}(E;\theta)}$$



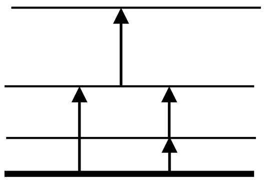


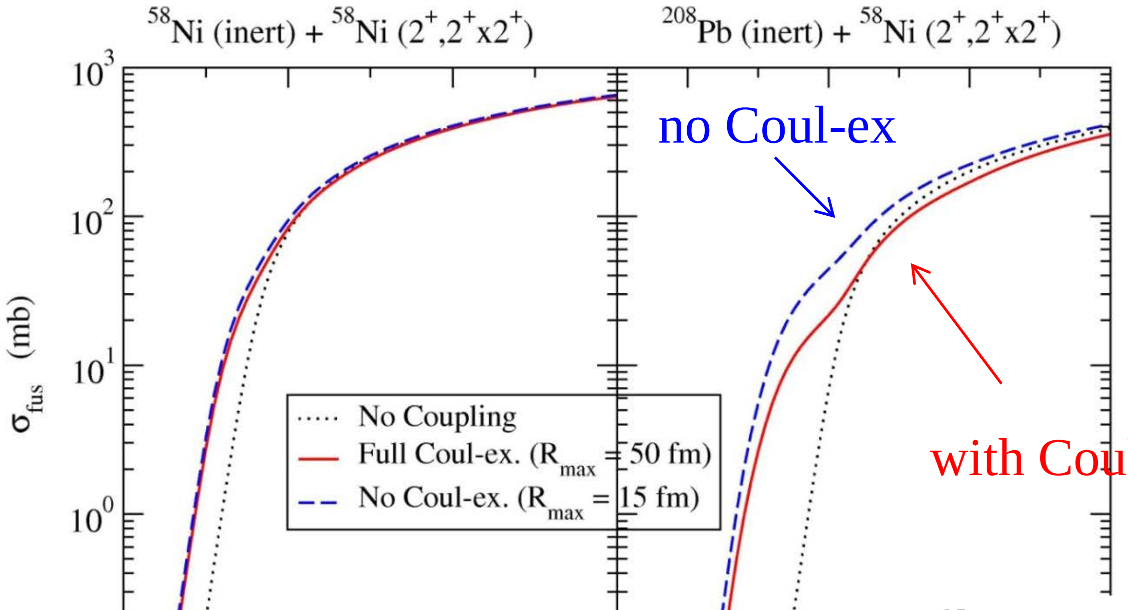
Def. Effect: enhances $\sigma_{\rm fus}$ by a factor of 10 ~ 100

Fusion: interesting probe for nuclear structure

Two effects of channel couplings

✓energy loss due to inelastic excitations



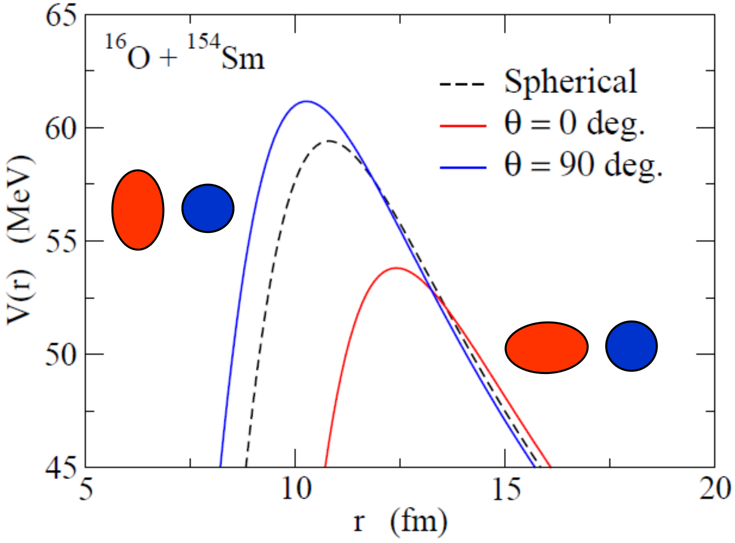


no Coul-ex

with Coul-ex

✓dynamical modification of the Coulomb barrier

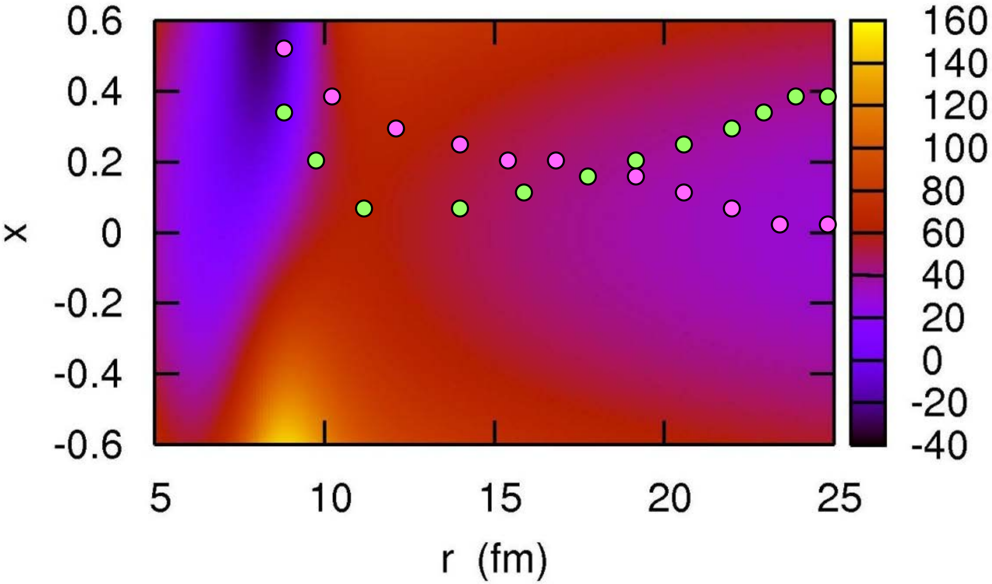
⟹ large enhancement of fusion cross sections



cf. 2-level model: Dasso, Landowne, and Winther, NPA405(‘83)381

Coupling to excited states ⟶ distribution of potential barrier

multi-dimensional potential surface



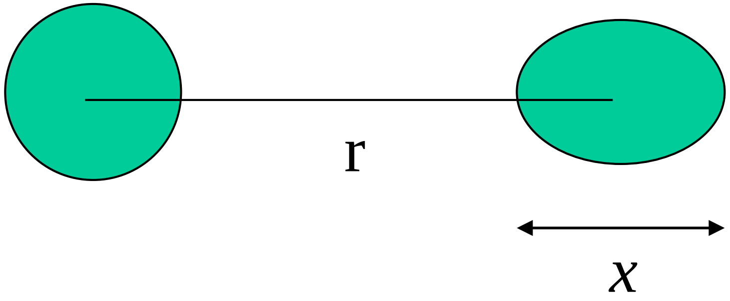
relative distance

single barrier

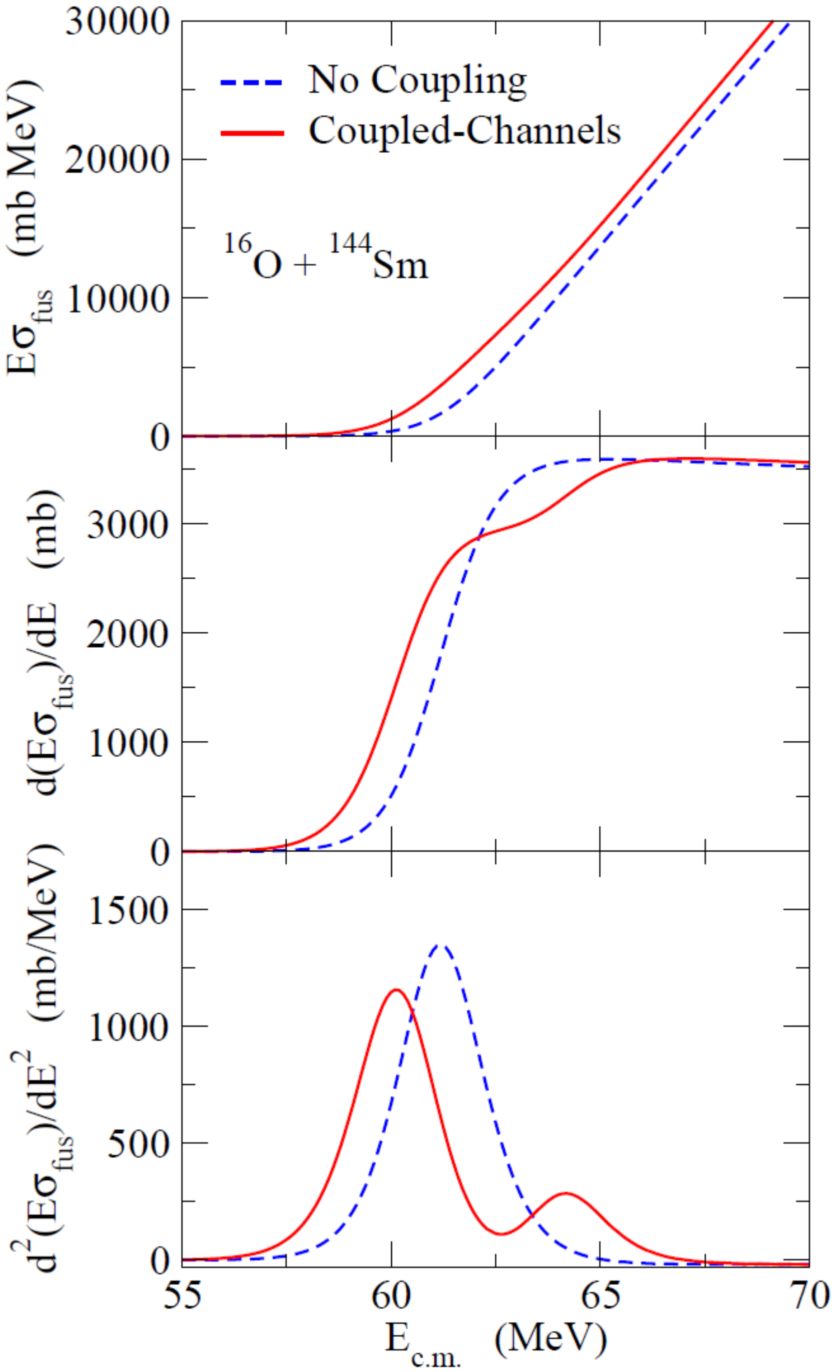
⟶ a collection of many barriers

$$P(E) = P[E, V(r)]$$

$$\rightarrow P(E) = \sum_{\alpha} w_{\alpha} P[E, V_{\alpha}(r)]$$



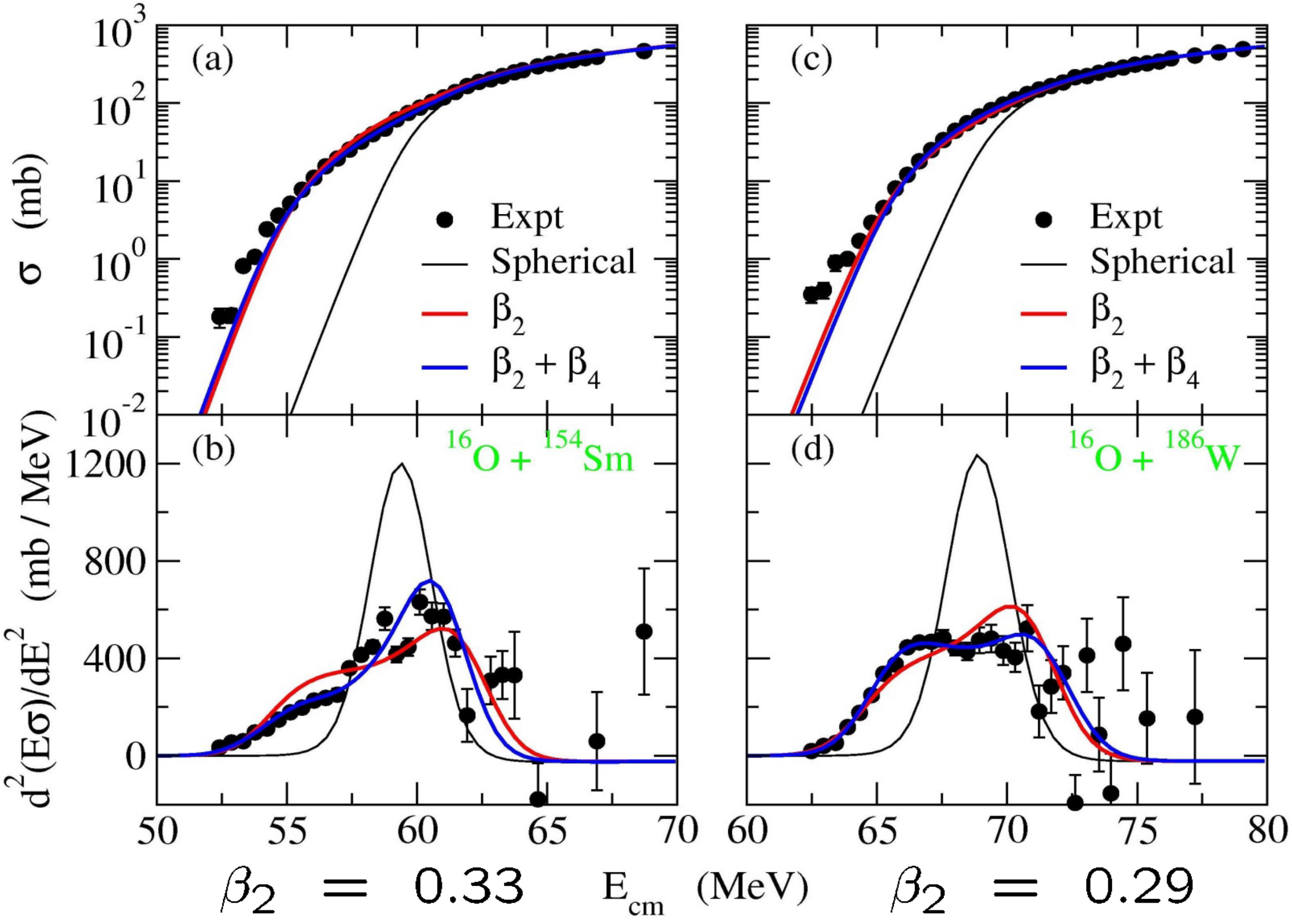
(intrinsic coordinate)



N. Rowley, G.R. Satchler,
P.H. Stelson, PLB254('91)25

$$\frac{d}{dE}[E\sigma_{\rm fus}(E)] \propto P(E)$$
$$\frac{d^2}{dE^2}[E\sigma_{\rm fus}(E)] \propto \frac{dP}{dE}$$

centered on $E = V_b$



$\beta_2 = 0.33$

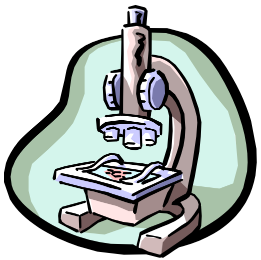
$\beta_4 = +0.05$

$\beta_2 = 0.29$

$\beta_4 = -0.03$

M. Dasgupta et al.,
Annu. Rev. Nucl. Part.
Sci. 48('98)401

Fusion barrier distribution:
sensitive to small effects such as β_4

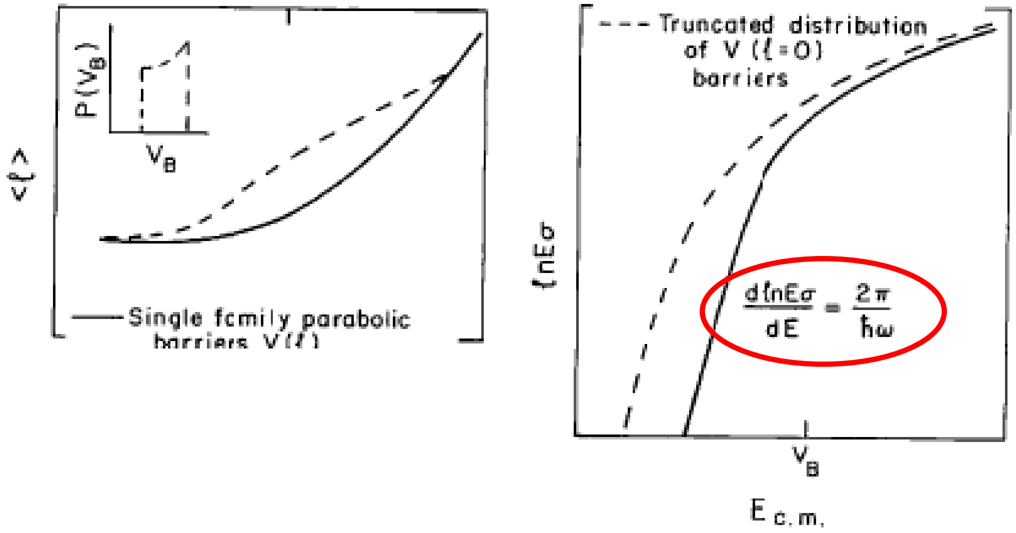


logarithmic derivative (~00's)

$$\sigma_{\rm fus}(E) \sim \frac{\hbar\Omega}{2E} R_b^2 \exp\left(\frac{2\pi}{\hbar\Omega}(E-V_b)\right) \qquad (E \ll V_b)$$

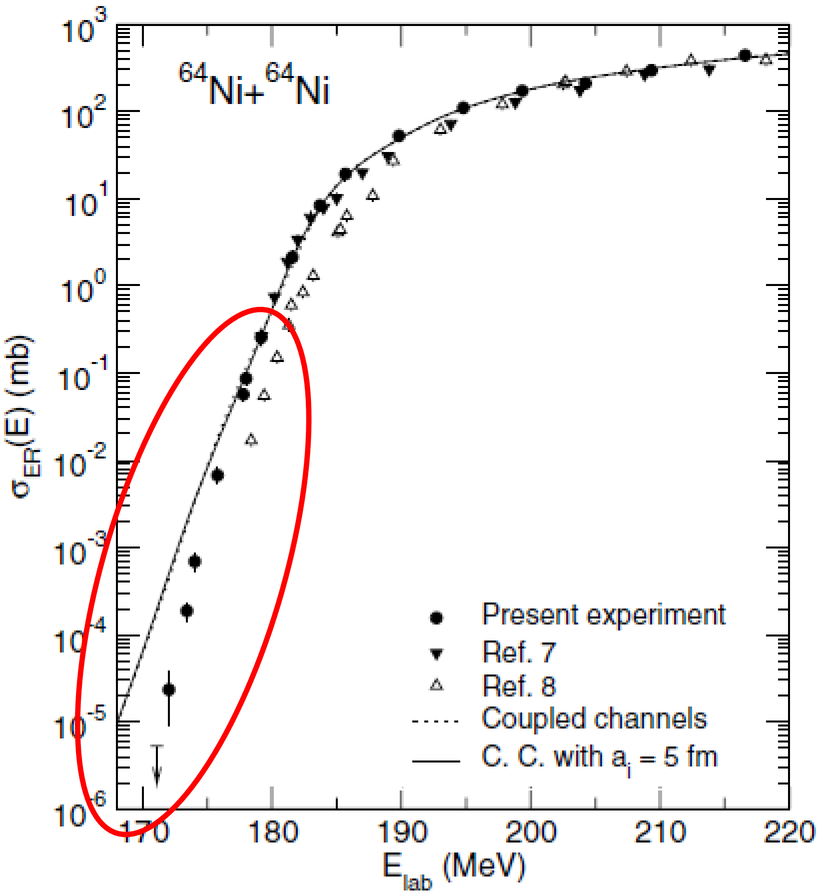
$$\boxed{\frac{d}{dE}\ln(E\sigma) = \frac{(E\sigma)'}{E\sigma} = \frac{2\pi}{\hbar\Omega}}$$

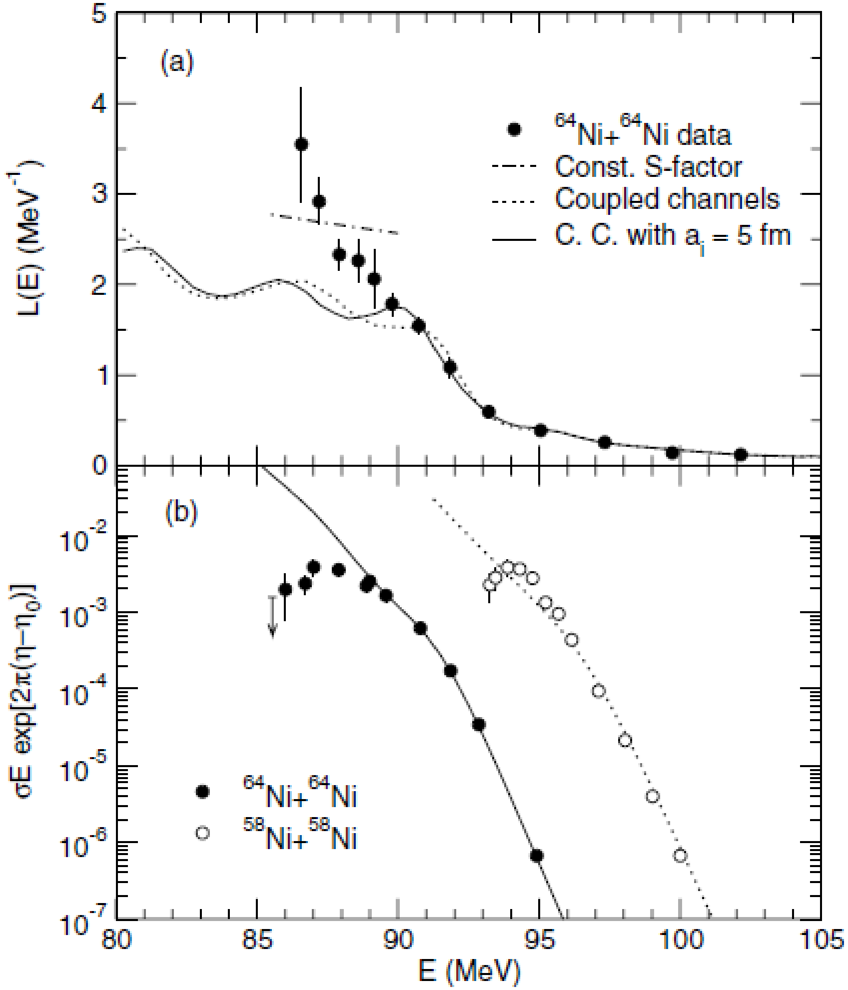
cf. $D_{\rm fus} = (E\sigma)''$



R. Vandenbosch,
Ann. Rev. Nucl. Part. Sci. 42('92)447

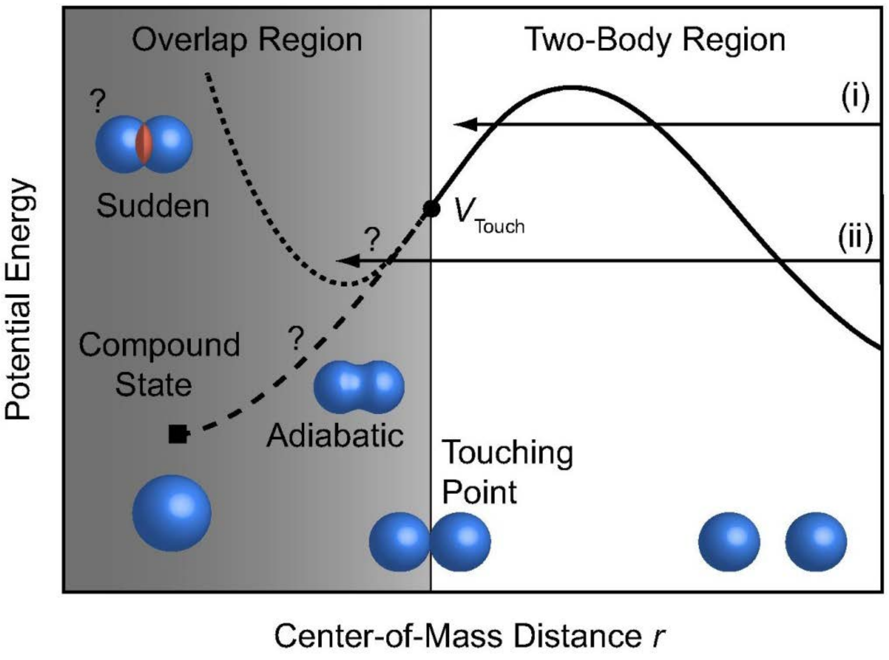
deep subbarrier hindrance of fusion cross sections

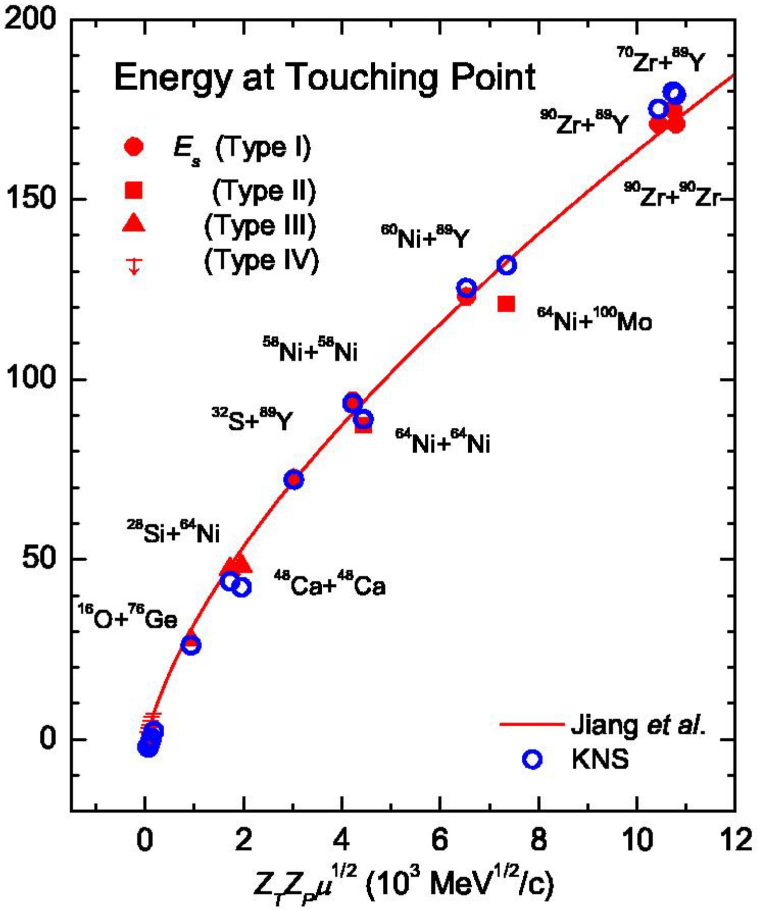




C.L. Jiang et al., PRL89(‘02)052701; PRL93(‘04)012701

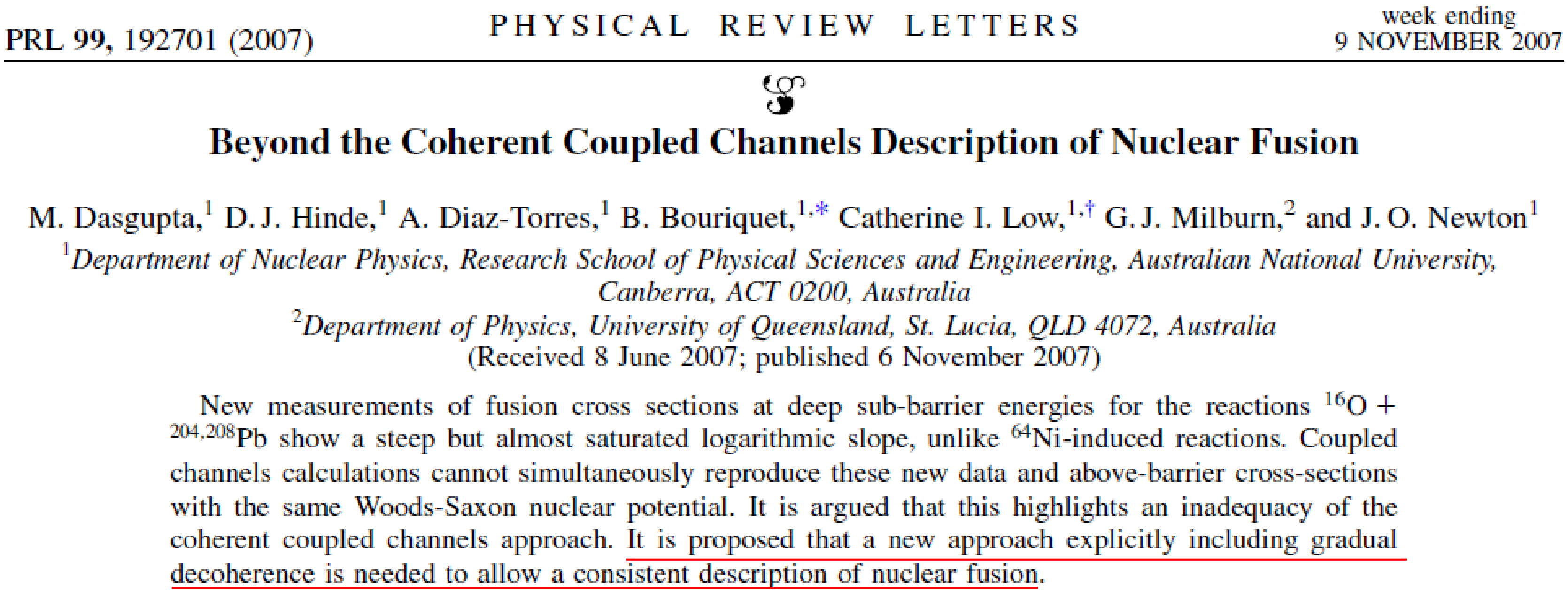
Systematics of the touching point energy and deep subbarrier hindrance





T. Ichikawa, K.H., A. Iwamoto,
PRC75('07) 064612 & 057603

Recent debates: quantum decoherence in deep subbarrier fusion?



PRL **99,** 192701 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2007

Beyond the Coherent Coupled Channels Description of Nuclear Fusion

M. Dasgupta,[1] D. J. Hinde,[1] A. Diaz-Torres,[1] B. Bouriquet,[1,*] Catherine I. Low,[1,†] G. J. Milburn,[2] and J. O. Newton[1]

[1]*Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia*

[2]*Department of Physics, University of Queensland, St. Lucia, QLD 4072, Australia*

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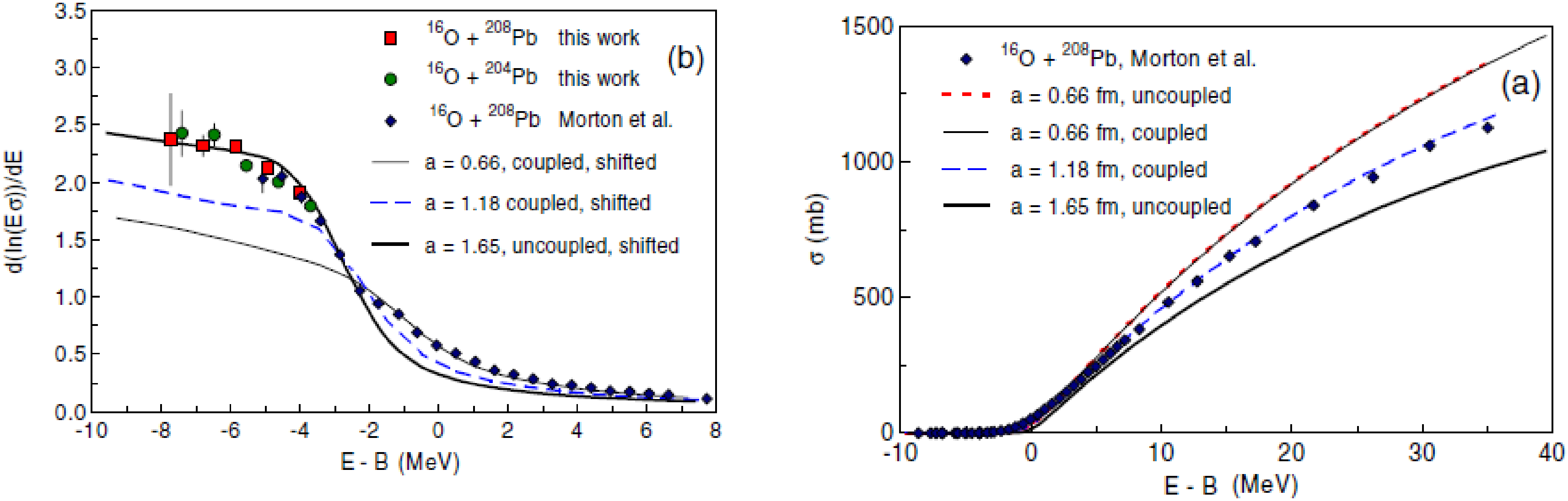
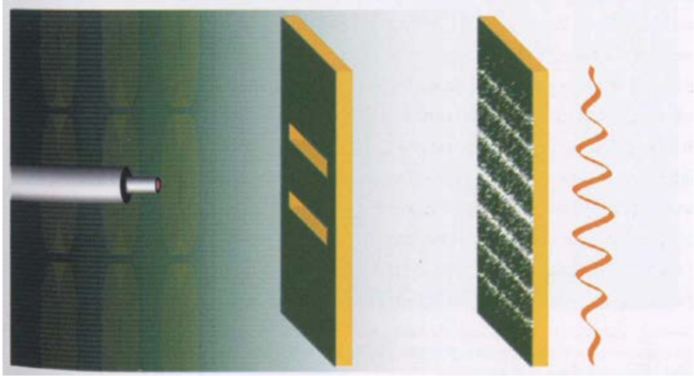
New measurements of fusion cross sections at deep sub-barrier energies for the reactions ^{16}O + ^{204,208}Pb show a steep but almost saturated logarithmic slope, unlike ^{64}Ni-induced reactions. Coupled channels calculations cannot simultaneously reproduce these new data and above-barrier cross-sections with the same Woods-Saxon nuclear potential. It is argued that this highlights an inadequacy of the coherent coupled channels approach. It is proposed that a new approach explicitly including gradual decoherence is needed to allow a consistent description of nuclear fusion.



Quantum decoherence



Coherent superposition

$$|\psi\rangle = \alpha|\psi_1\rangle + \beta|\psi_2\rangle$$

$\longrightarrow$ interference

In macroscopic systems, no superposition:

~~$|dead\rangle + |live\rangle$~~

Quantum decoherence theory

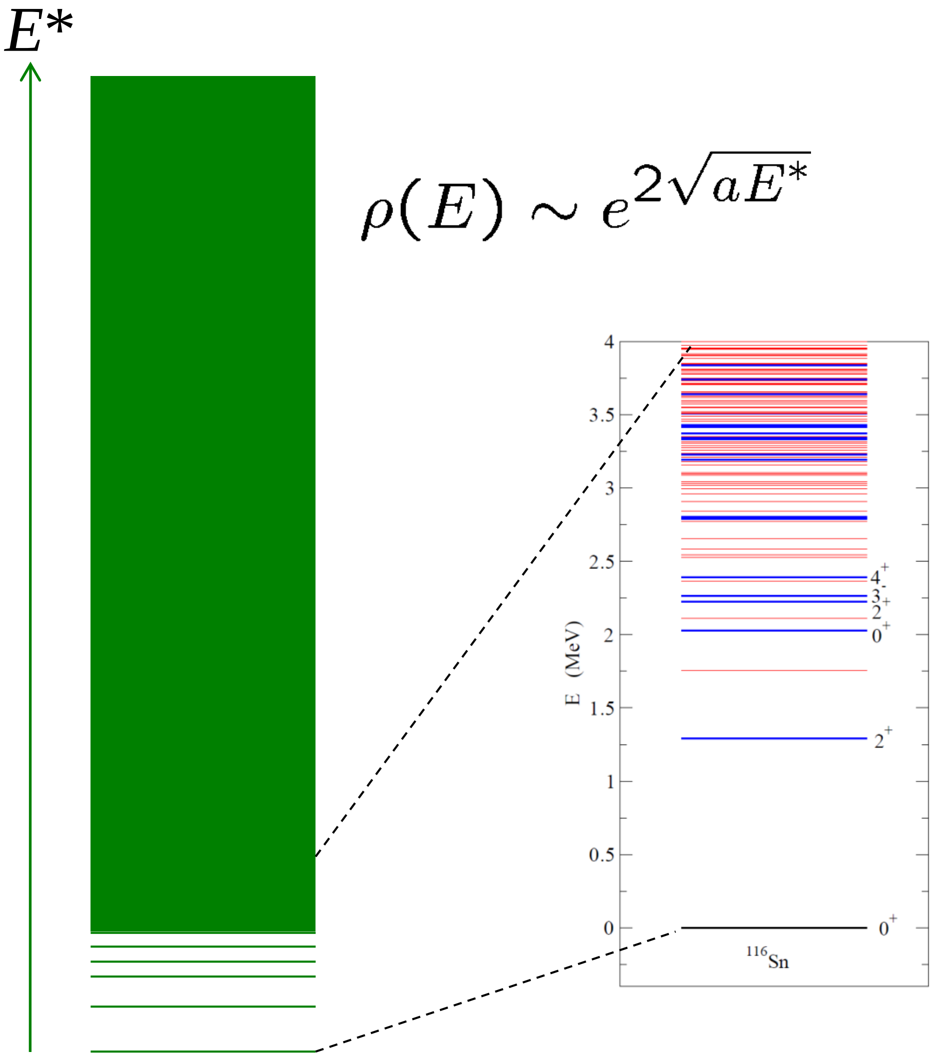
Couplings to environment

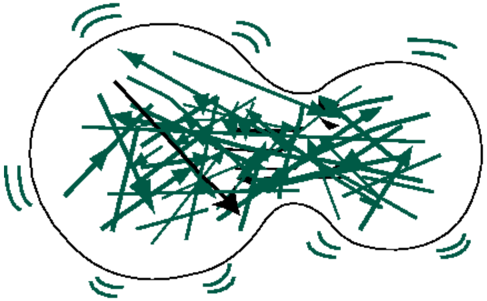
$\longrightarrow$ Quantum to classical transition

atomic nuclei: microscopic systems

→ little effect from *external* environment

$$\rho(E) \sim e^{2\sqrt{aE^*}}$$





These states are excited during nuclear reactions in a complicated way.

⇩

nuclear intrinsic d.o.f.
act as environment for
nuclear reaction processes

“*intrinsic* environment”

nuclear spectrum

Open questions

- Is quantum decoherence relevant to heavy-ion fusion?

  maybe yes, maybe no

- If yes, do we really have to care whether the system decoheres? or is it sufficient simply to take into account couplings to environments?

  clear demonstration of effects of decoherence: necessary
  (at this moment, it is just a conjecture)

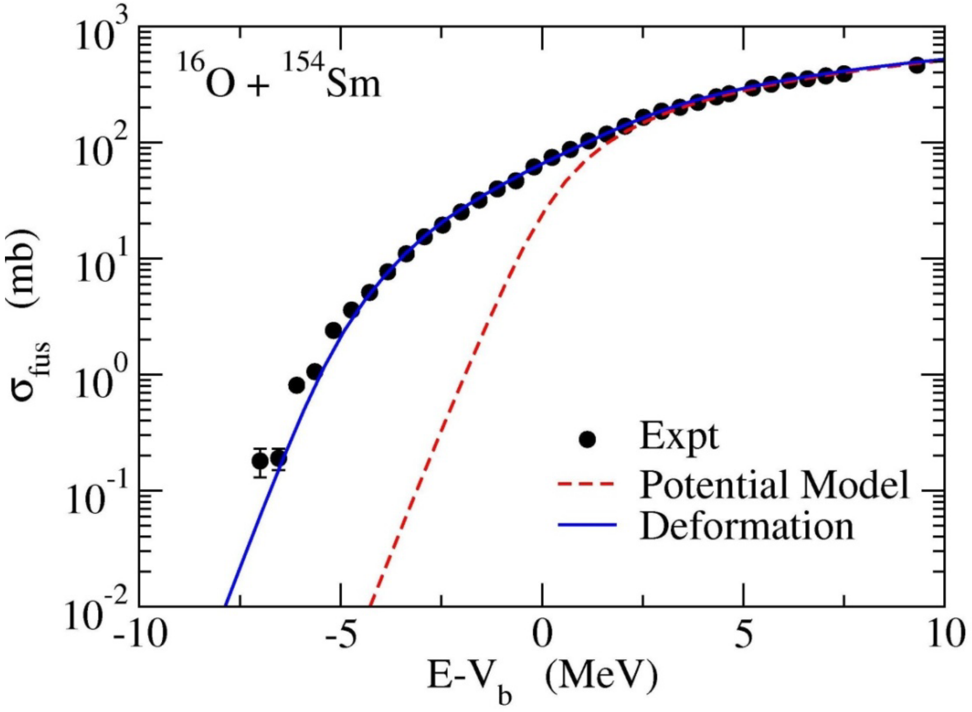
  cf. fusion cross sections: $\sigma_{\rm fus}(E)=\frac{\pi}{k^2}\sum_J(2J+1)\left(1-\sum_i|S_{i0}^{(J)}|^2\right)$

- How well can we describe effects of non-collective degrees of freedom (unified model between fusion and DIC)?

Fusion model ⟶ friction free: strong absorption inside the barrier

quantum mechanical model for Wall-Window friction?

Fusion of unstable nuclei



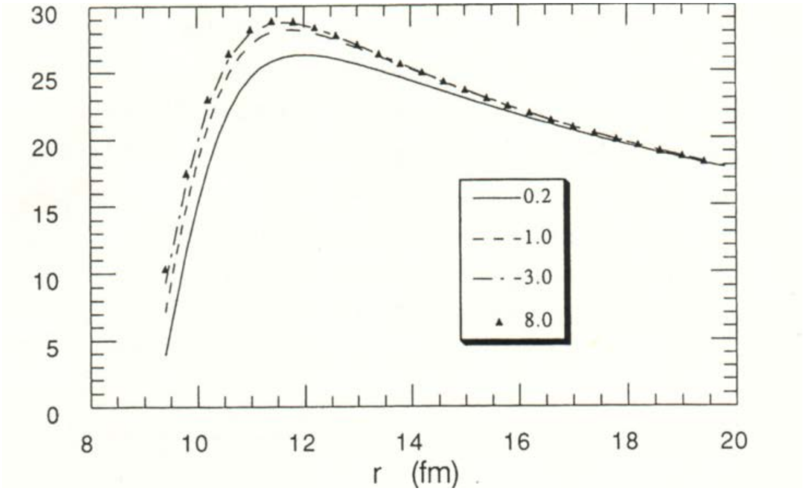
Fusion of stable nuclei: large enhancement of fusion cross sections

Fusion of unstable (weakly bound) nuclei?
fusion cross section: enhanced? hindered? no change?

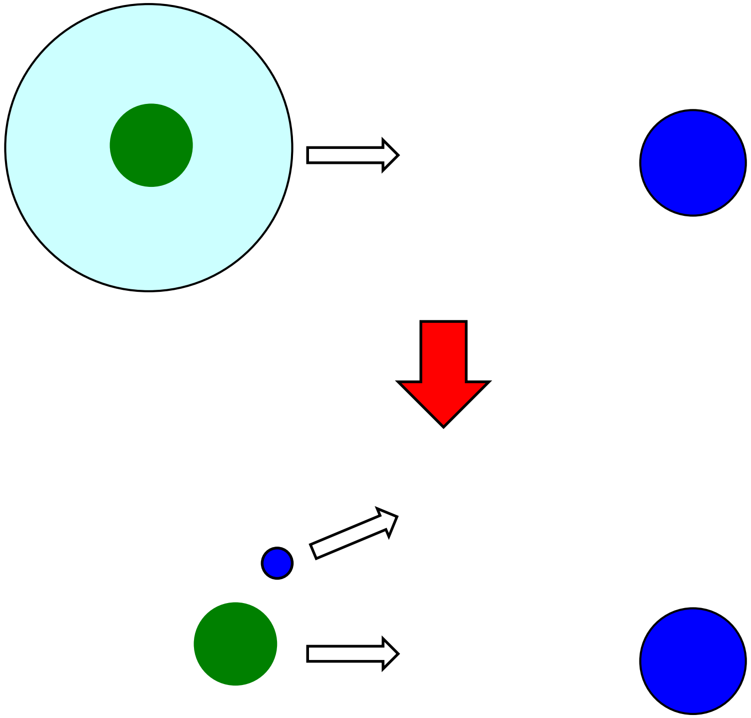
still not known completely

Two effets

1. Lowering of potential barrier
   due to a halo structure
   ⟶ enhancement
2. effect of breakup



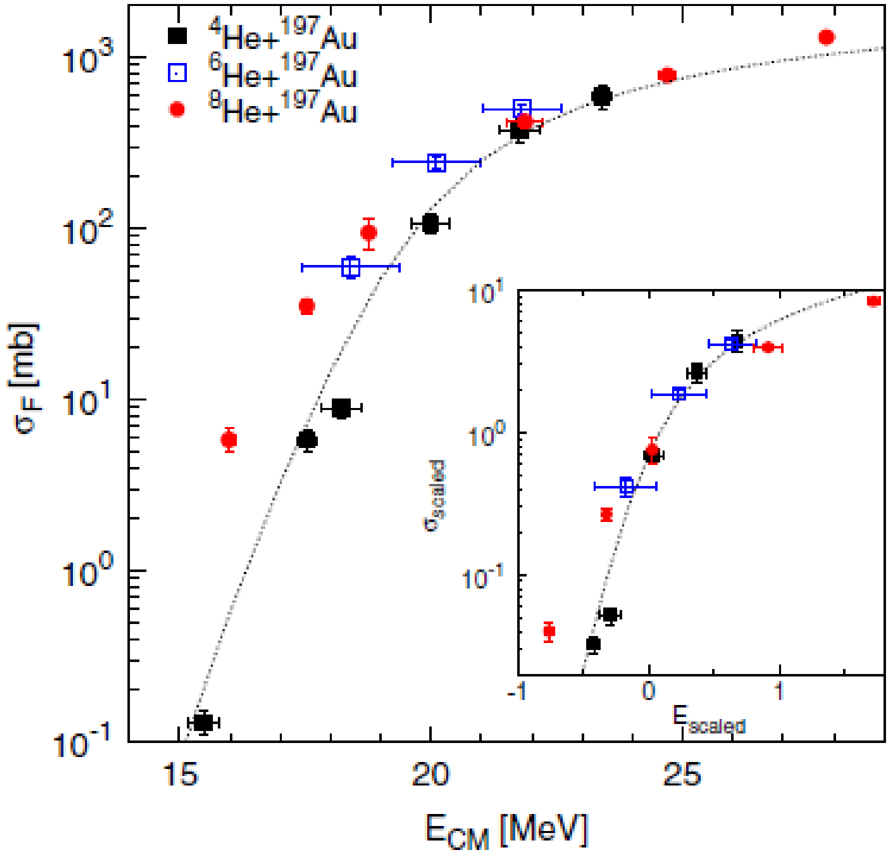
N. Takigawa and H. Sagawa, PLB265('91)23



- hindrance due to disappearance of barrier lowering after breakup?
- enhancement due to channel coupling effects as in stable nuclei?
- some more complicated dynamical effect?

Experimental data

^{4,6,8}He + ^{197}Au



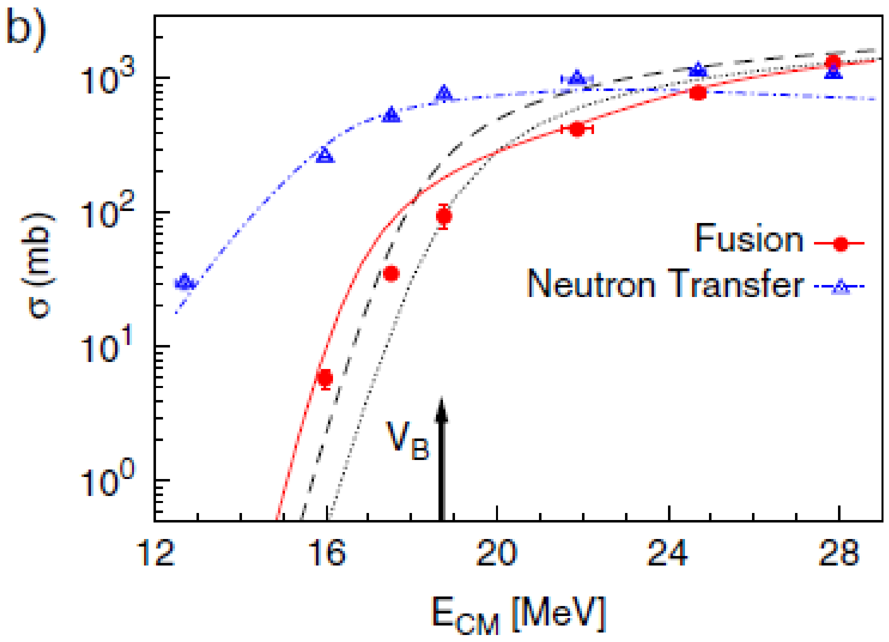
- ➢some enhancement compared to ^{4}He
- ➢similar behaviour between ^{6}He and ^{8}He (can we understand this?)

- ➢no huge effects of breakup/transfer!?

A. Lemasson et al., PRL103('09)232701

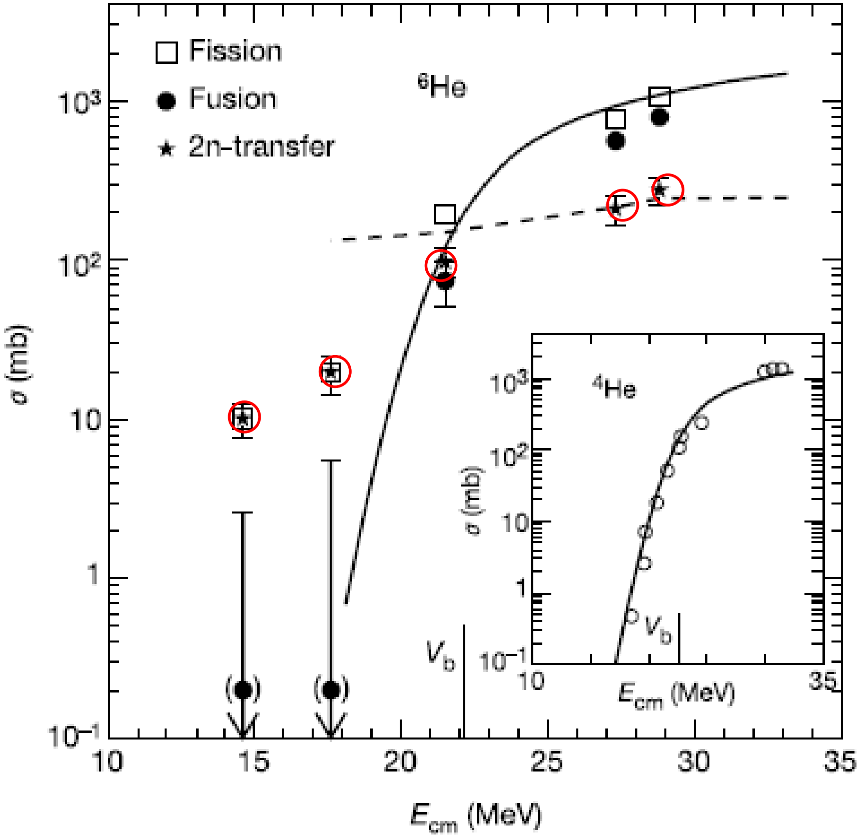
➢large transfer cross sections

$^{8}\mathrm{He} + {}^{197}\mathrm{Au}$

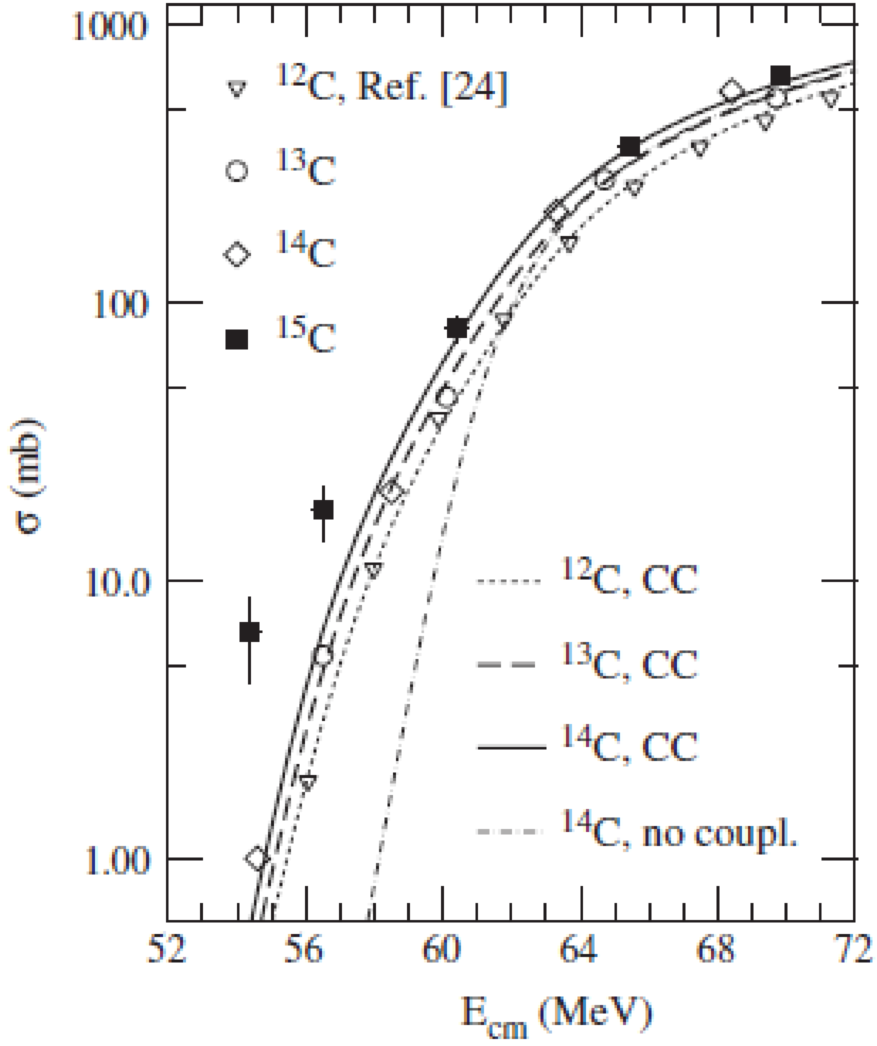


A. Lemasson et al.,
PRL103(‘09)232701

$^{6}\mathrm{He} + {}^{238}\mathrm{U}$



R. Raabe et al.,
Nature 431 (‘04)823



Very recent data for
$^{12,13,14,15}C + ^{232}Th$

M. Alcorta et al.,
PRL106('11)172701

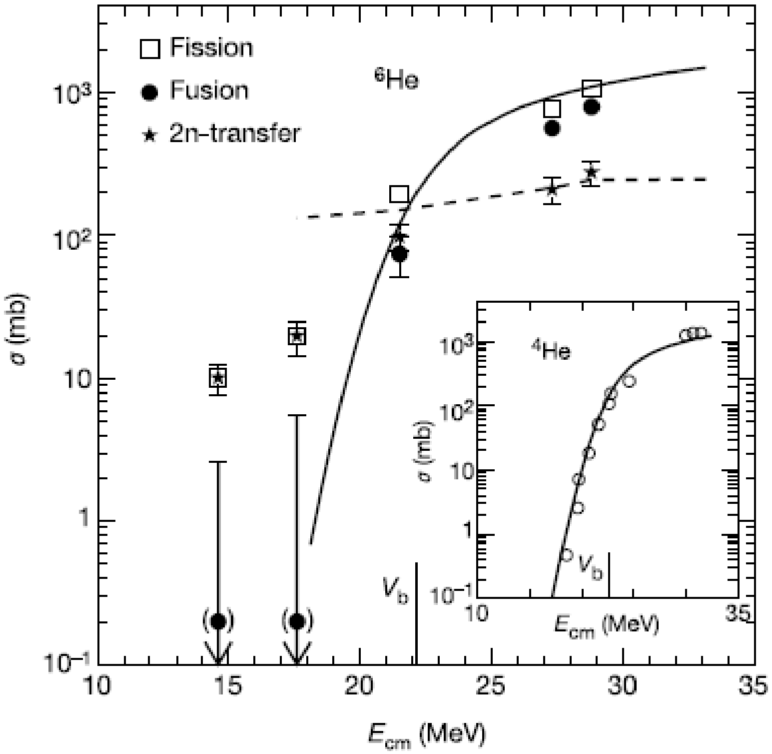
^{15}C: 1*n* halo nucleus

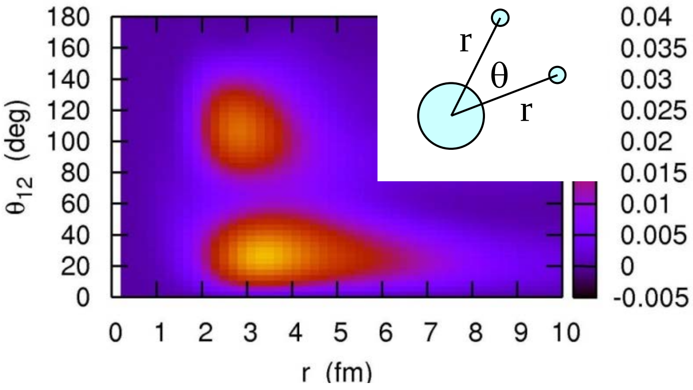
⟶ enhanced fusion cross sections

Pair Transfer

Calculations: need to include breakup and transfer in a consistent way

^{6}He + ^{238}U



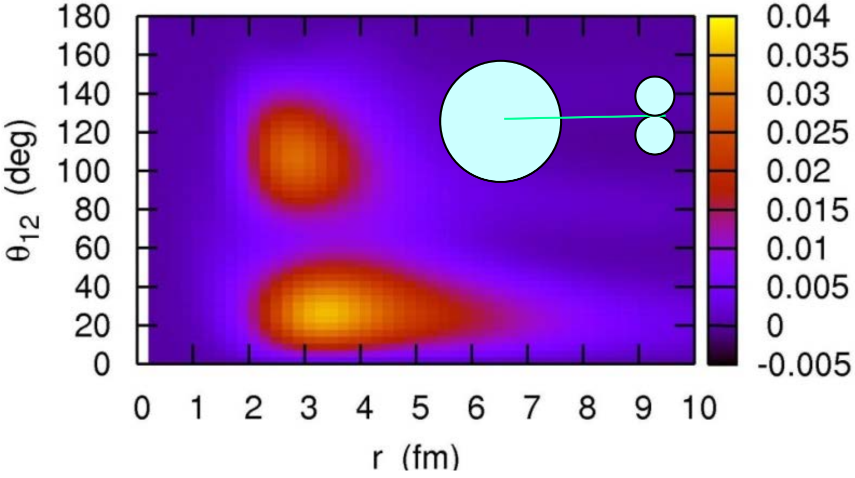


large (2n) transfer cross sections

pair transfer (in addition to breakup)
is one the important processes
in reactions of unstable nuclei

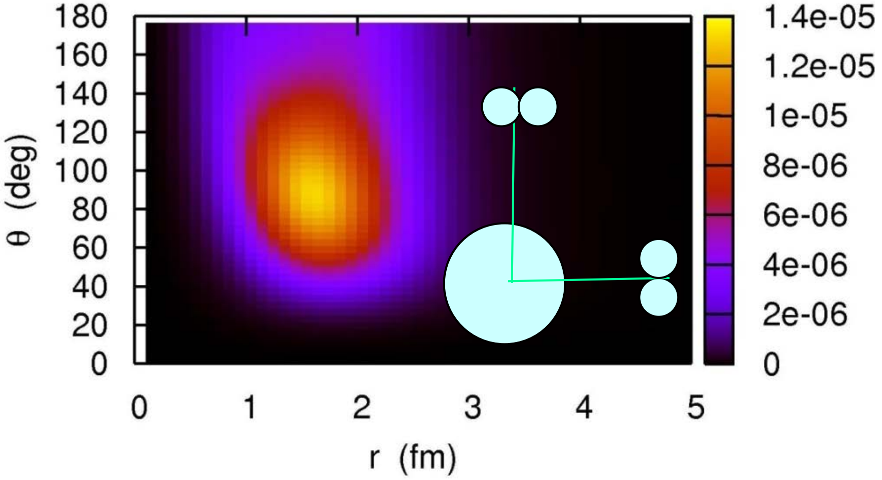
role of dineutron correlation?

^{6}He = ^{4}He + "dineutron"

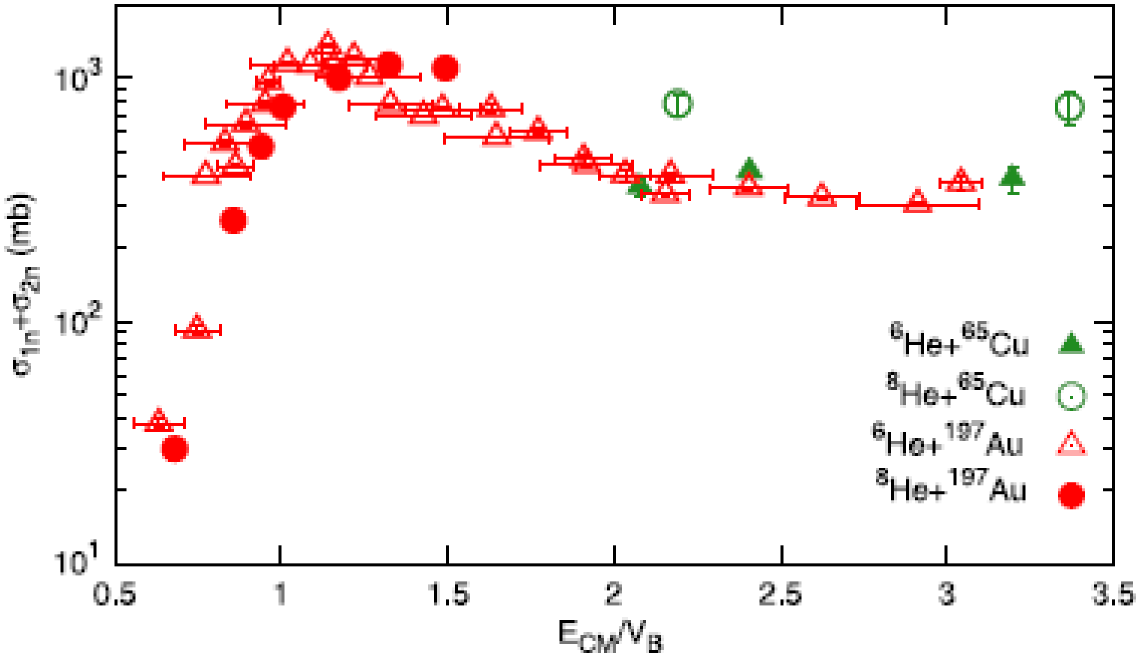


K.H. and H. Sagawa, PRC72('05)044321

^{8}He = ^{4}He + two "dineutrons"



K.H., N. Takahashi, and H. Sagawa, PRC77('08)054317.



increased transfer cross sections going from ^{6}He to ^{8}He

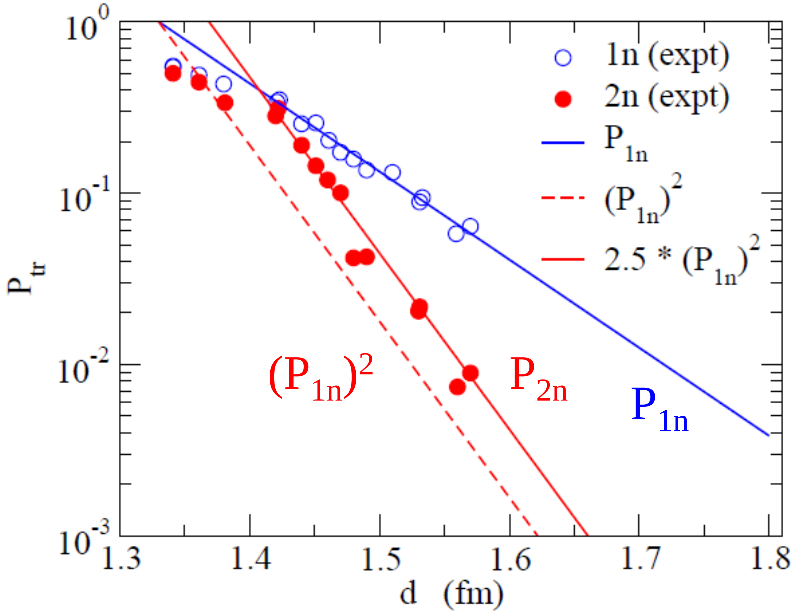
A. Lemasson et al., PLB697('11)454

Pair correlation and pair transfer

pair transfer probability strongly reflects the pairing correlation

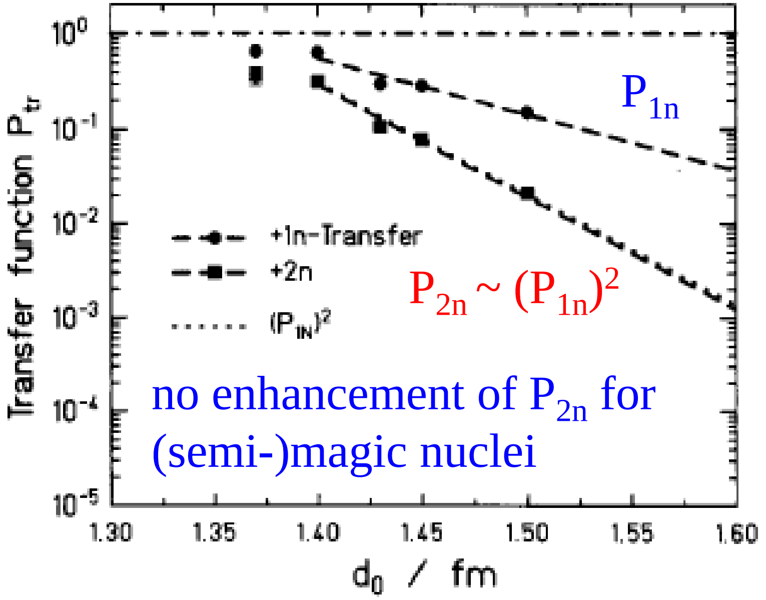
pair transfer probability: $P_{\mathrm{tr}} \sim \dfrac{d\sigma_{\mathrm{tr}}}{d\sigma_R}$

^{112}Sn + ^{120}Sn



W. von Oertzen et al., Z. Phys. A326('87)463

^{144}Sm + ^{208}Pb



no enhancement of P_{2n} for (semi-)magic nuclei

J. Speer et al., PLB259('91)422

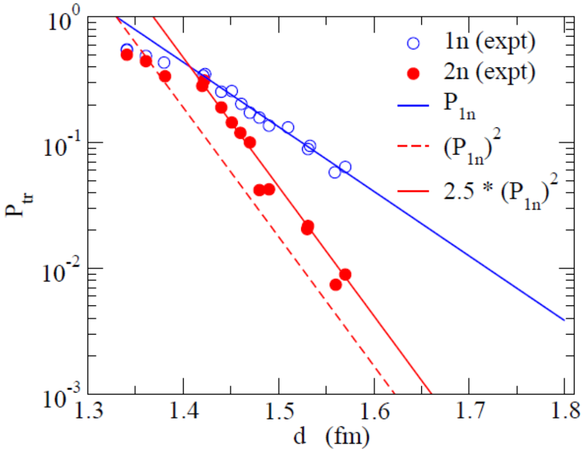
$$R_{\mathrm{min}} = d\,(A_P^{1/3} + A_T^{1/3})$$

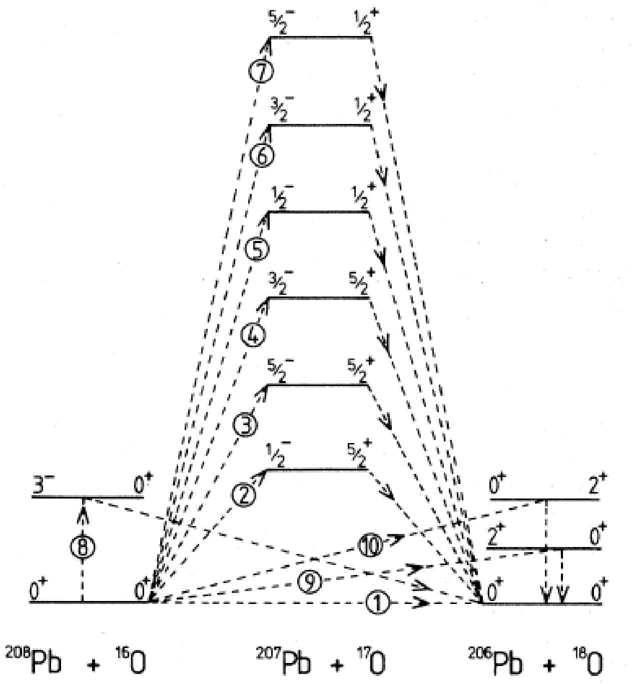
: the distance of the closest approach

Pair transfer:

- ✓**Reaction mechanism?**
  - sequential vs simultaneous
  - Q-value, angular momentum matchings
- ✓Role of dineutron correlation (on the surface)?
- ✓Influence to other reaction processes (e.g., subbarrier fusion)?

have not yet been fully clarified

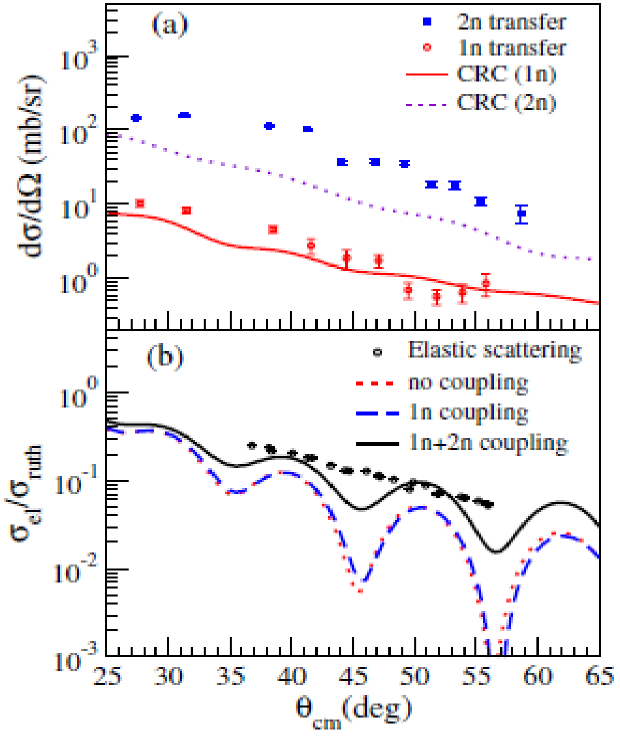




how is the reaction mechanism modified
if most of intermediate states are unbound?

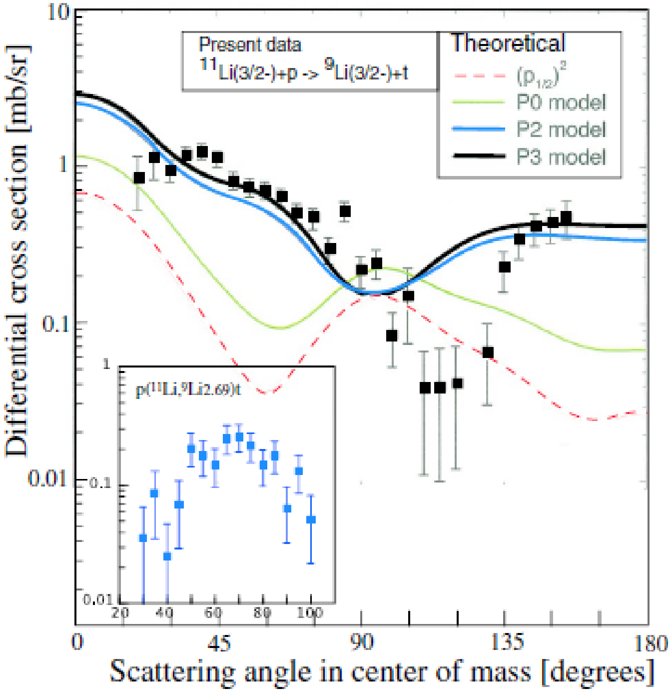
Recent experiments for transfer reaction of neutron-rich nuclei

^{6}He + ^{65}Cu



A. Chatterjee et al., PRL101('08)032701

^{1}H(^{11}Li,^{9}Li)^{3}H



I. Tanihata et al., PRL100('08)192502

It is timely to construct:

a new theory of pair transfer with dineutron correlation.

⟶ need a deep understanding of reaction dynamics

➡ influence on subbarrier fusion? (open question)

Summary

Heavy-ion subbarrier fusion reactions

✓strong interplay between reaction and structure
✓quantum tunneling with several kinds of environment

Open questions

✓how do we understand many-particle tunneling?
  - related topics: fission, alpha decays, two-proton radioactivities
    Large amplitude collective motions
✓role of dissipative environment?
  - dissipation, friction, quantum decoherence?
✓microscopic understanding of subbarrier fusion?

✓fusion of unstable nuclei?
  - breakup, (multi-nucleon) transfer

(Big) open question:

- Construction of microscopic nuclear reaction model applicable at low energies?

  → many-particle tunneling

cf. nuclear structure calculations

- 2-body nn interaction → mean-field → RPA
  ↘ residual interaction ↗ TDHF

advantage: non-empirical
disadvantage: difficult to control a mean-field

↓ guiding principle ↔ complementary ↑ deep understanding of results

- mean-field pot. → residual interaction → RPA
  ↘ TDHF

Microscopic nuclear reaction theories

TDHF, QMD, AMD → not applicable to low-energy fusion
(classical?)

Cluster approach (RGM)

→ only for light systems

H.O. wave function (separation of
cm motion)

Double Folding approach

→ surface region: OK, but inside?
role of antisymmetrization?
validity of frozen density approximation?

Full microscopic theory: ATDHF, GCM, ASCC ?
imaginary-time TDHF?

how to understand quantum tunneling from many-particle point of view?