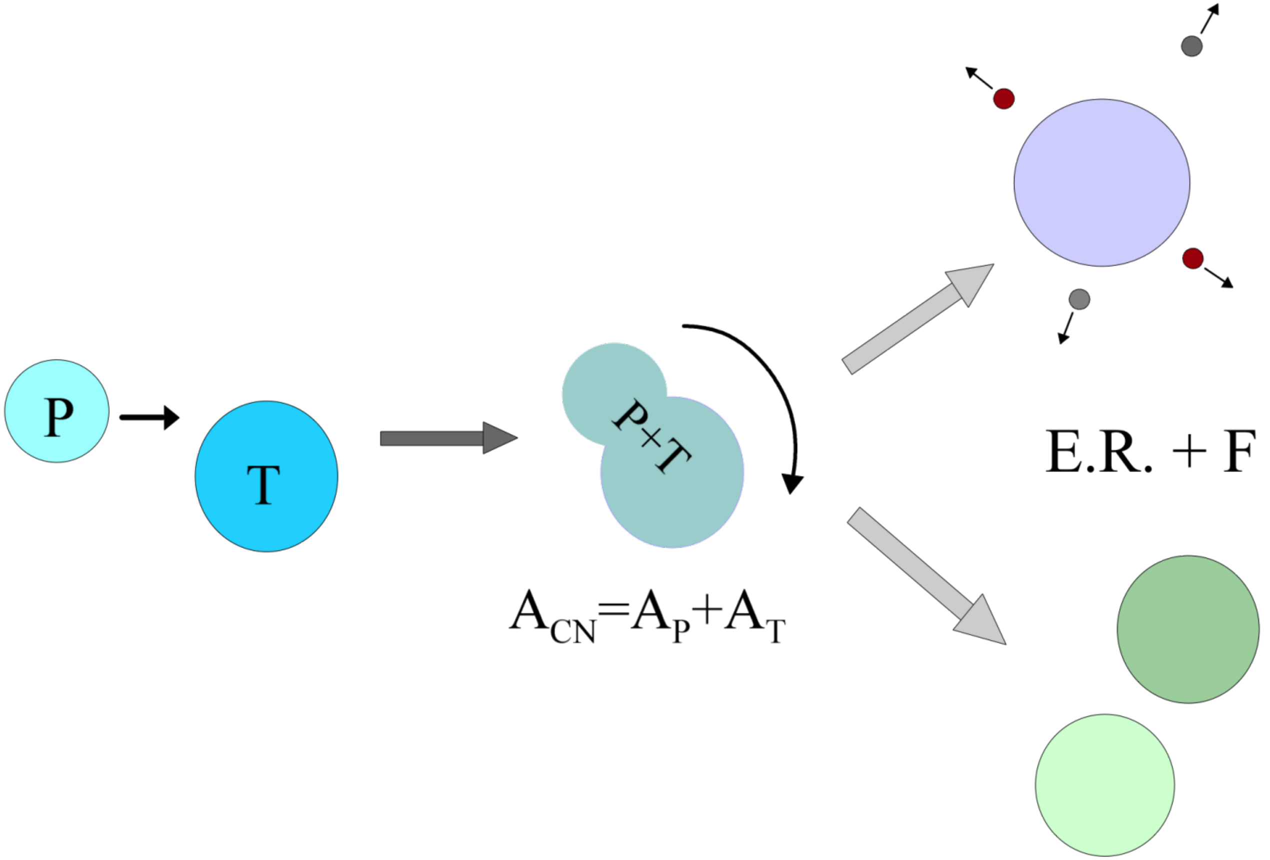
Heavy-ion reactions around the Coulomb barrier: *an overview*

Kouichi Hagino
Tohoku University, Sendai, Japan

1. *Introduction: why subbarrier fusion?*
2. *Role of nuclear structure in subbarrier fusion*
3. *Fusion of unstable nuclei*
4. *Pair transfer reactions*
5. *Fusion for superheavy elements*
6. *Summary*

Recent review:
K. Hagino and N. Takigawa,
Prog. Theo. Phys. 128 (2012) 1061

Fusion: compound nucleus formation



$A_{CN}=A_P+A_T$

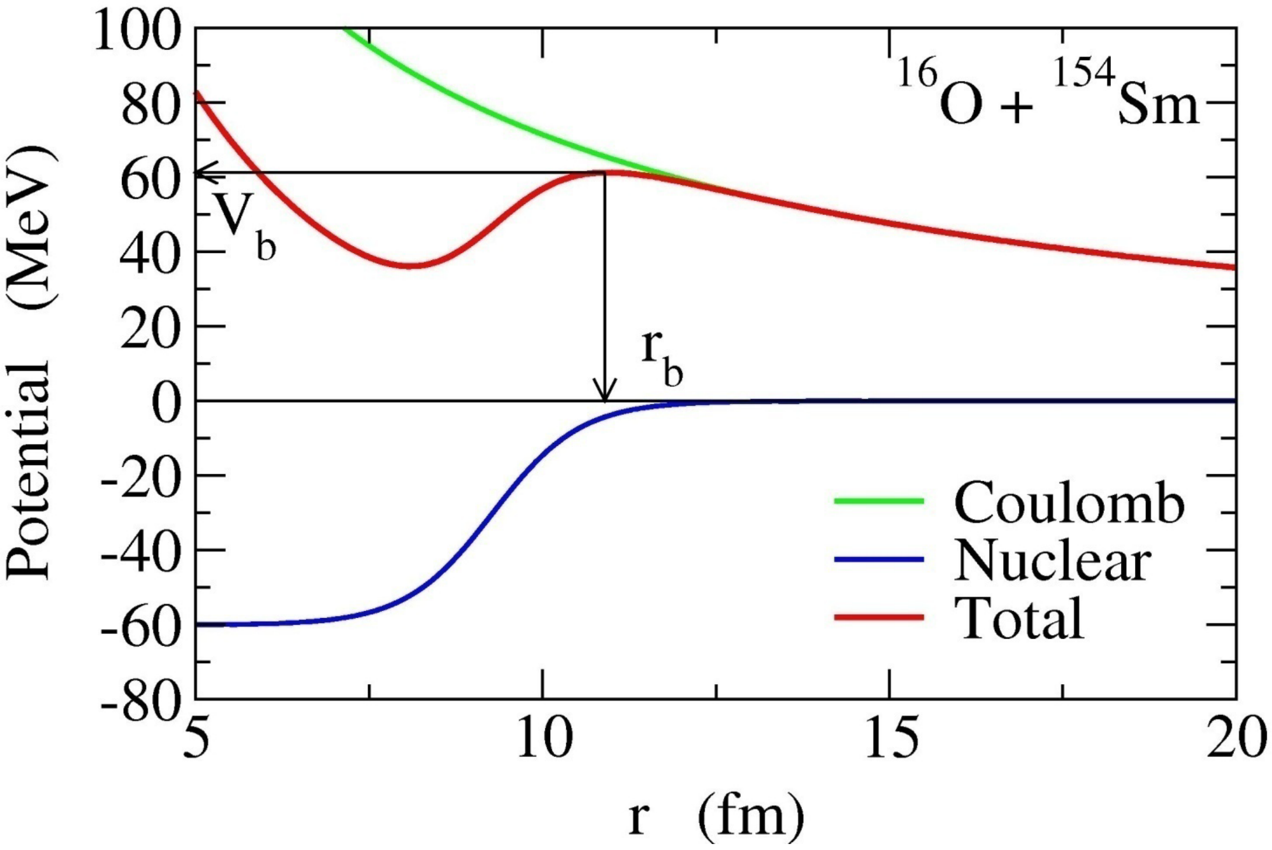
E.R. $\left(A_{CN} < 170\right)$

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

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

courtesy: Felipe Canto

Inter-nucleus potential



Two forces:

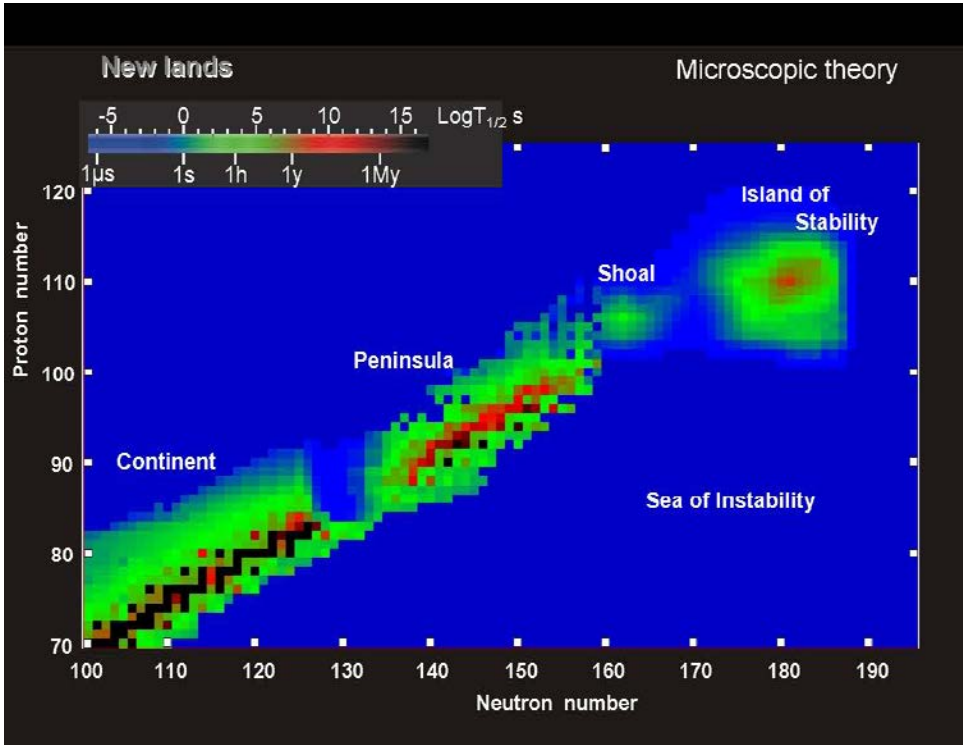
1. Coulomb force
   Long range, repulsive
2. Nuclear force
   Short range, attractive

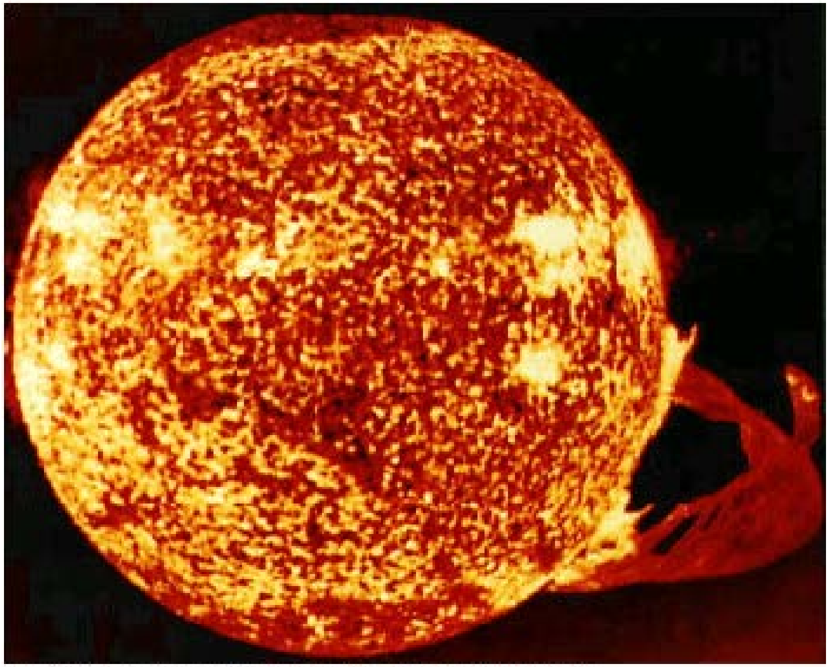
Potential barrier due to the compensation between the two (Coulomb barrier)

- 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)

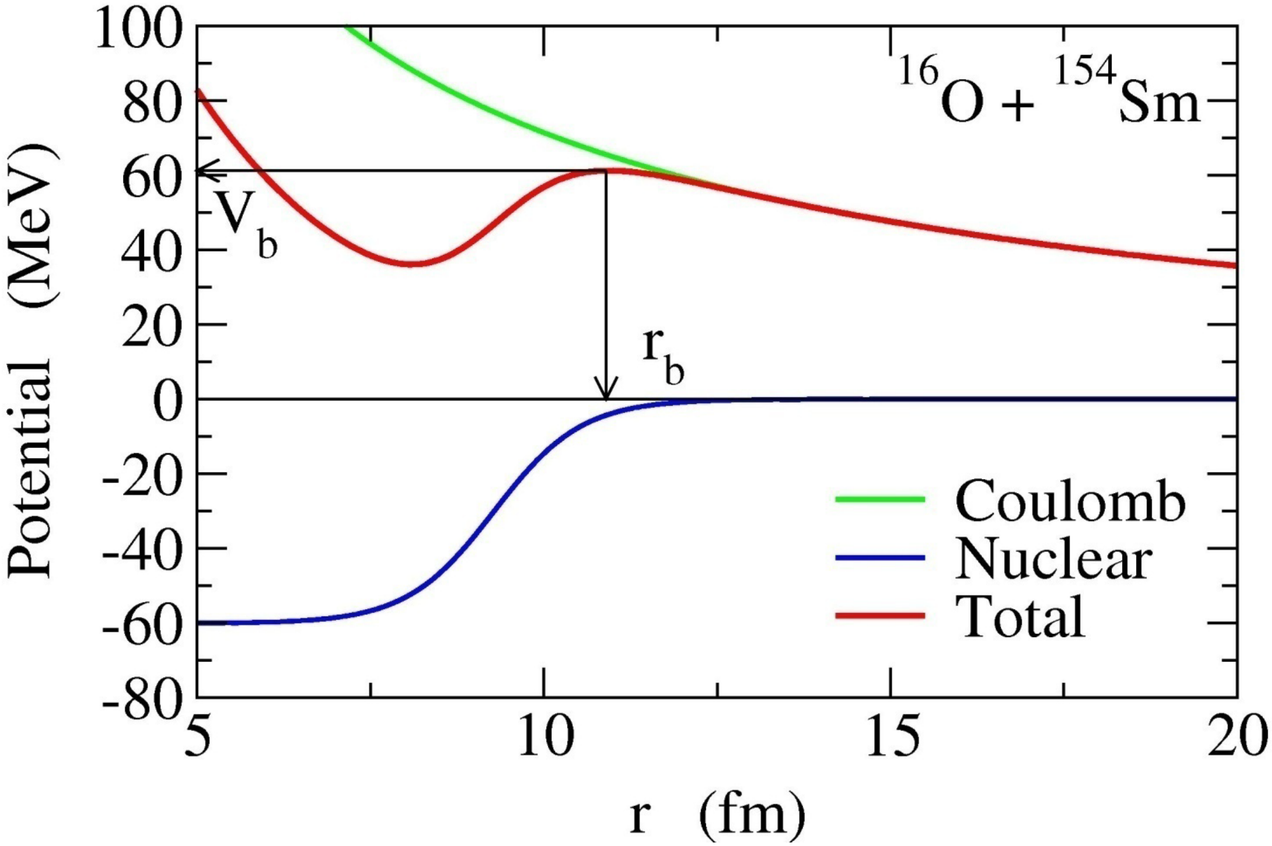
Why subbarrier fusion?

Two obvious reasons:

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

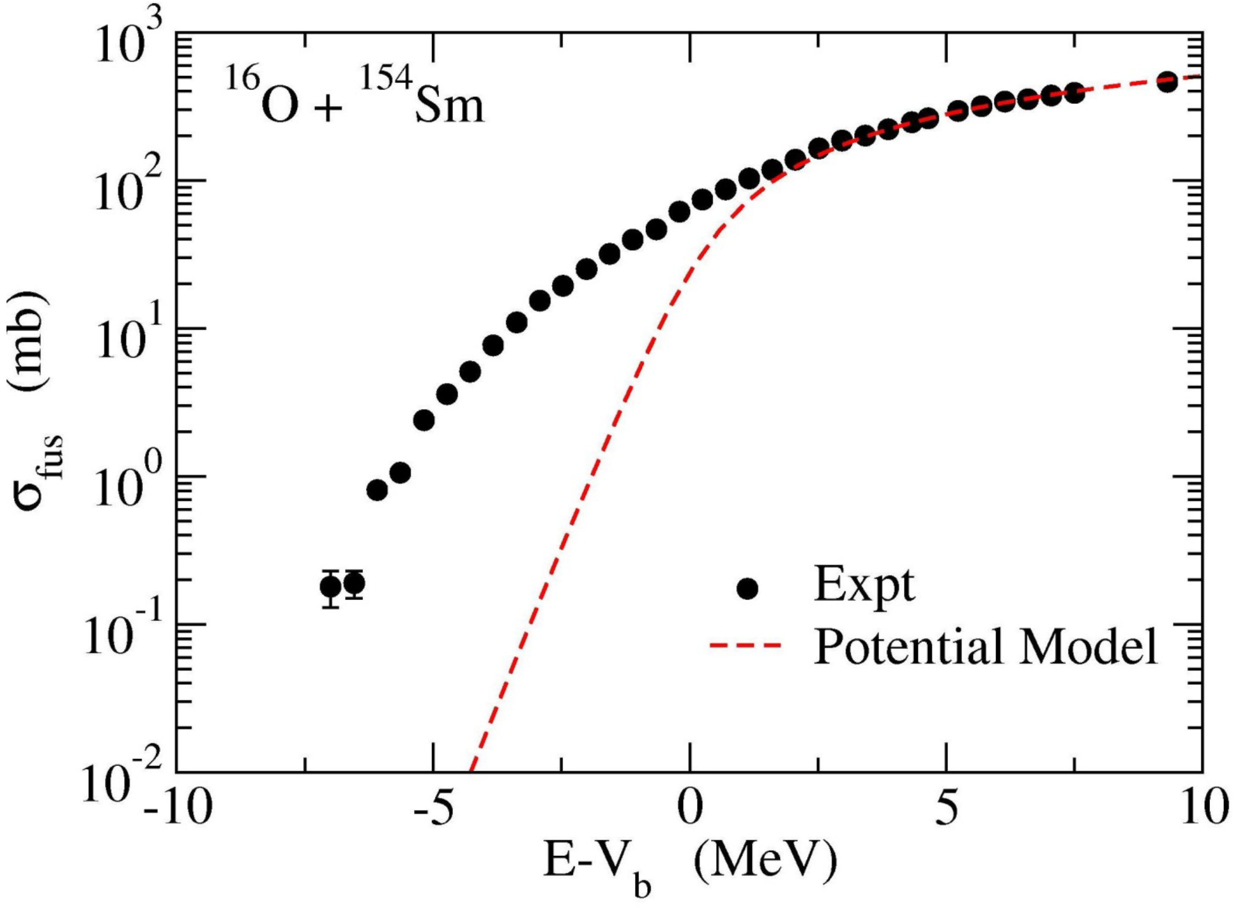
Other reasons:

- ✓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

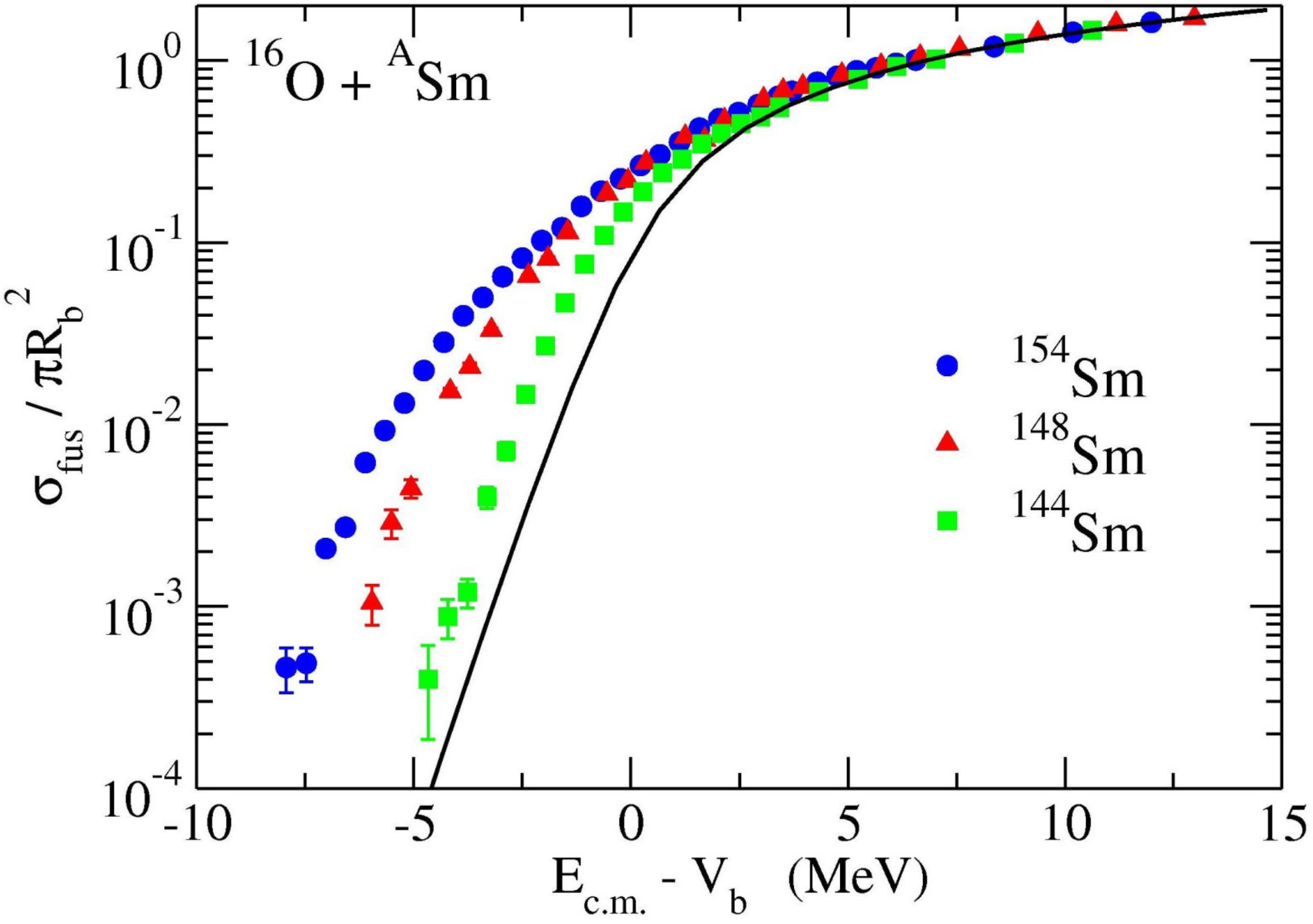
$$\sigma_{\mathsf{fus}}(E) = \frac{\pi}{k^2}\sum_{l}(2l+1)P_l(E)$$



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

Underpredicts σ_{fus} for
$E < V_b$

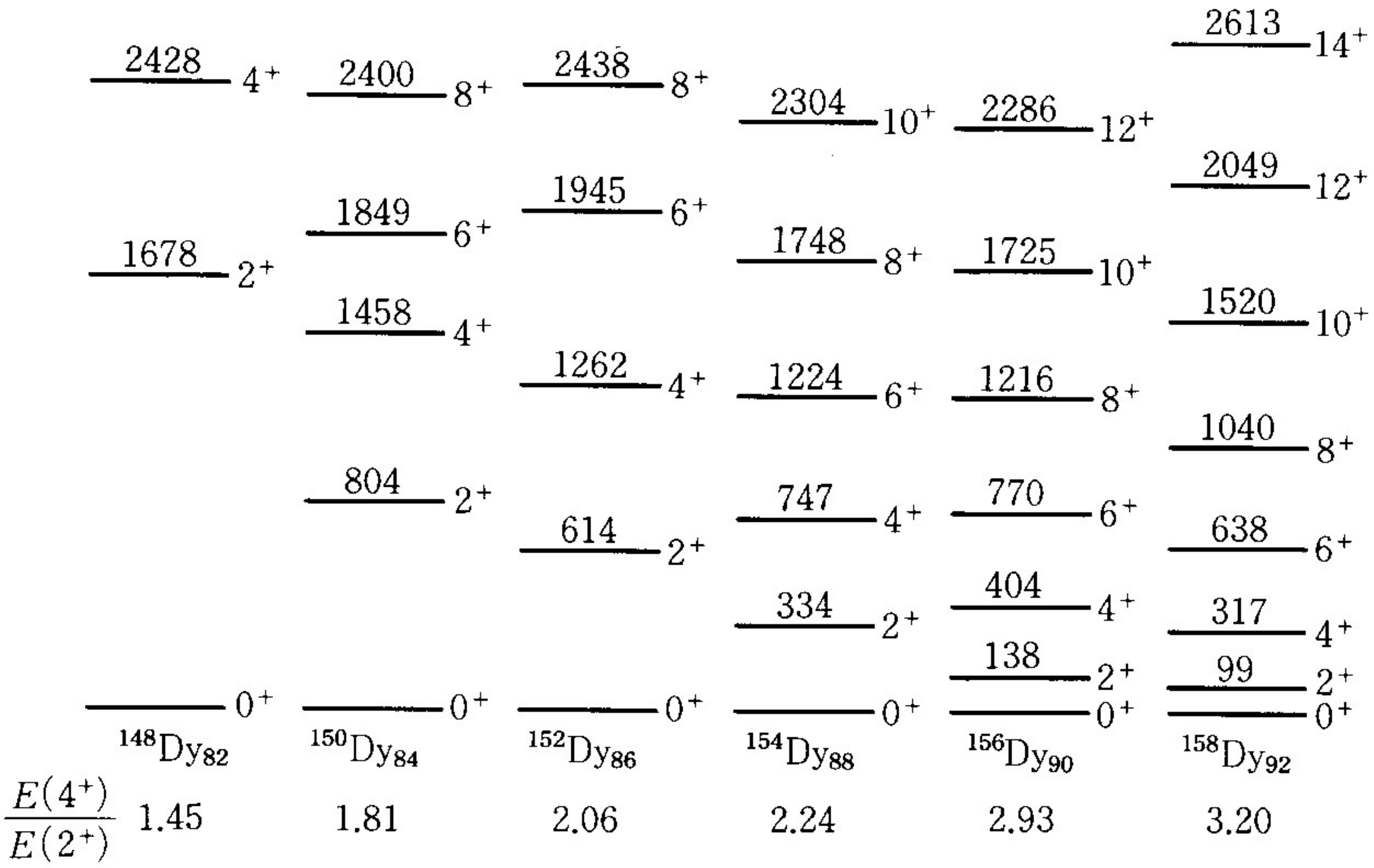
cf. seminal work:
R.G. Stokstad et al., PRL41(‘78)465
PRC21(‘80)2427



Strong target dependence at $E < V_b$

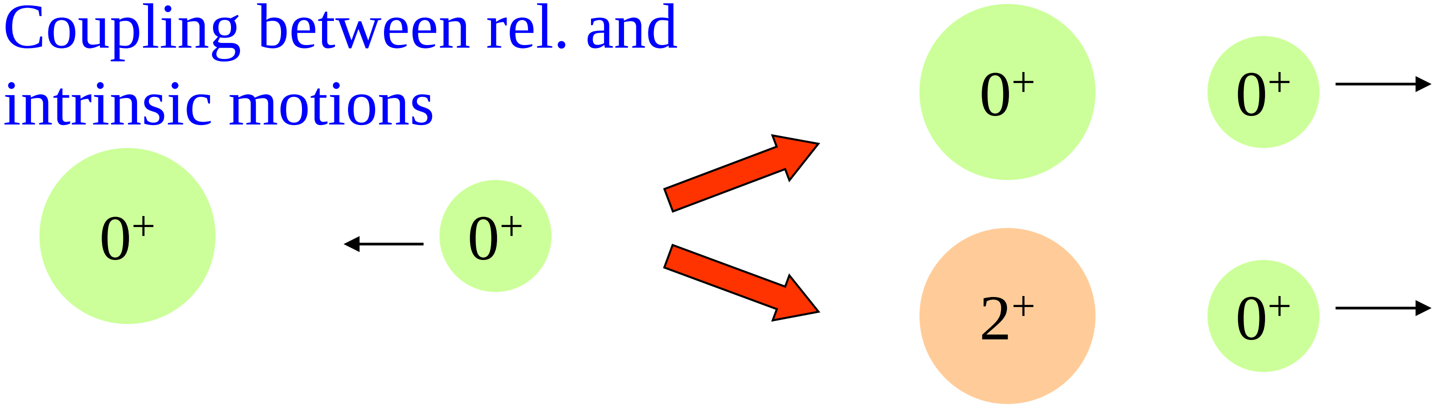
Low-lying collective excitations in atomic nuclei

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



Coupled-Channels method

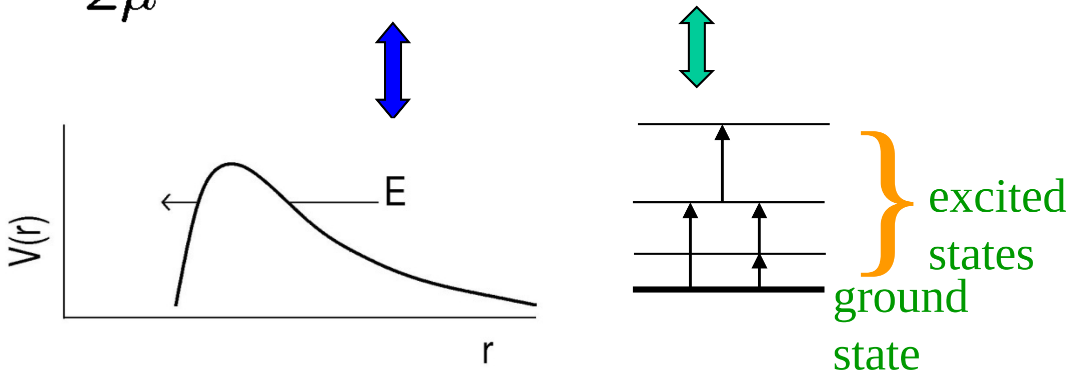
Coupling between rel. and intrinsic motions



Entrance channel

Excited channel

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



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

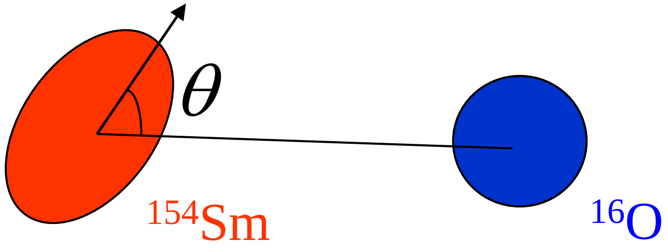
$$\boxed{\Psi(\boldsymbol{r},\xi) = \sum_k \psi_k(\boldsymbol{r})\phi_k(\xi)}$$

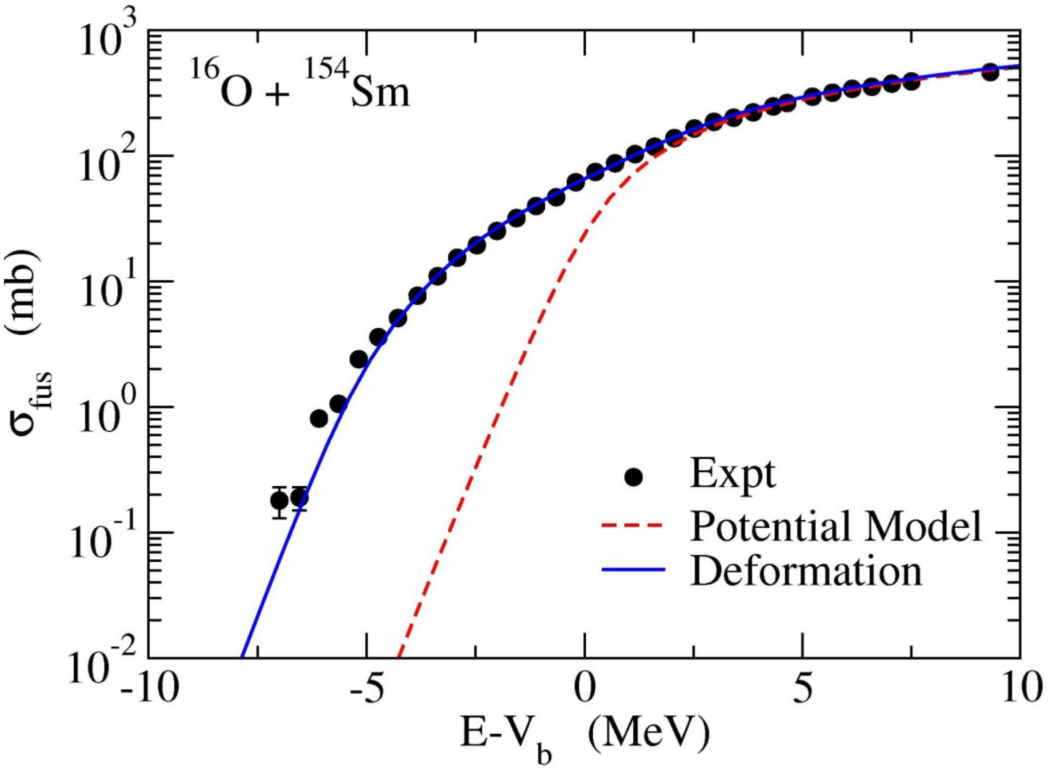
⇒ coupled Schroedinger equations for $\psi_k(r)$

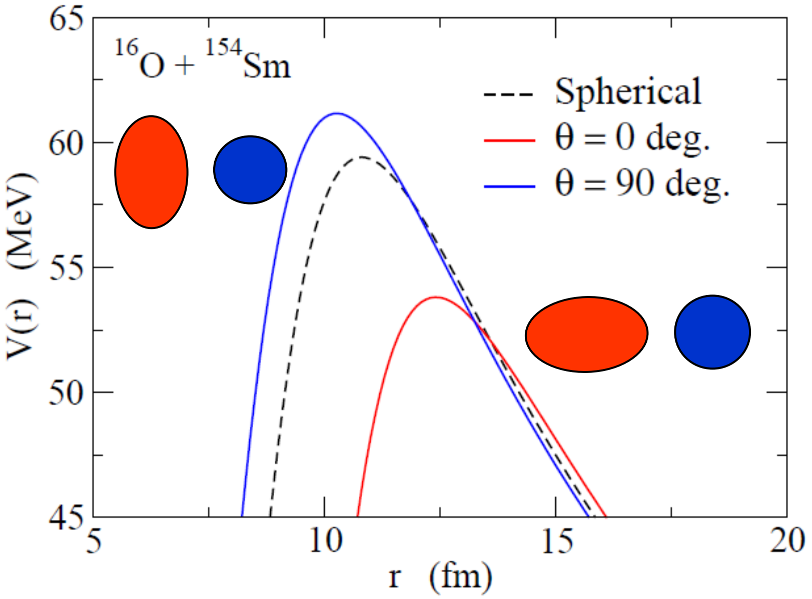
Subarrier fusion:
strong interplay between reaction and structure

coupled-channels equations

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



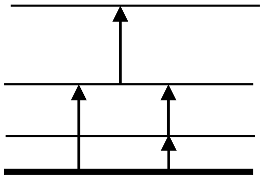




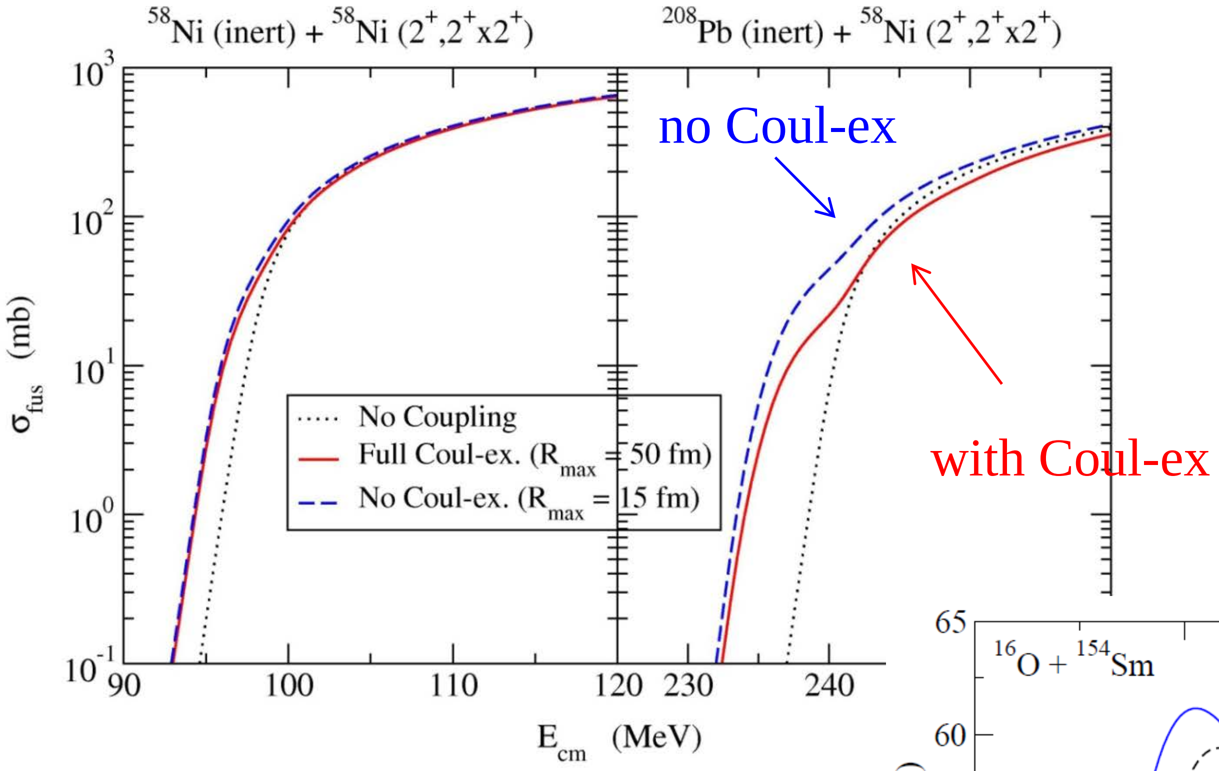
Def. Effect: enhances σ_{fus} by a factor of 10 ~ 100

Fusion: interesting probe for nuclear structure

Two effects of channel couplings

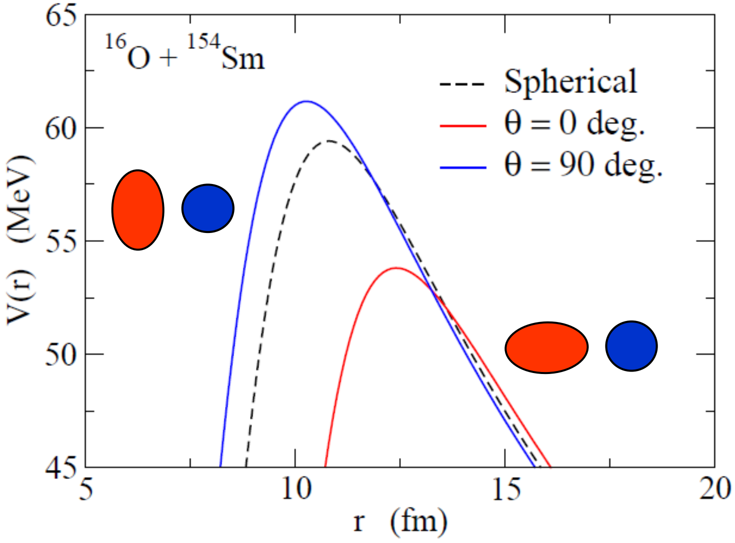


- ✓energy loss due to inelastic excitations



no Coul-ex

with Coul-ex



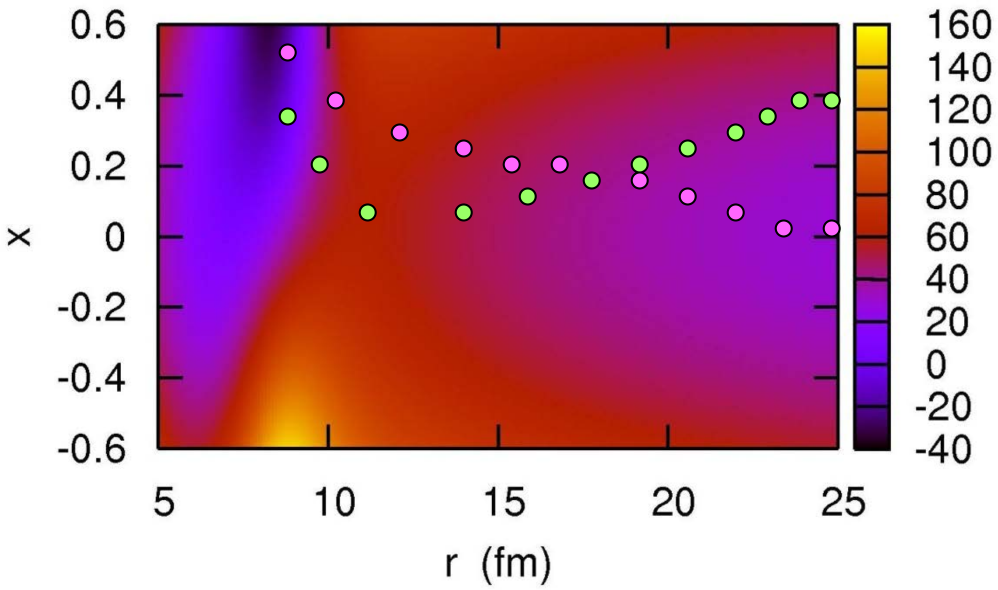
- ✓dynamical modification of the Coulomb barrier

⇒ 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



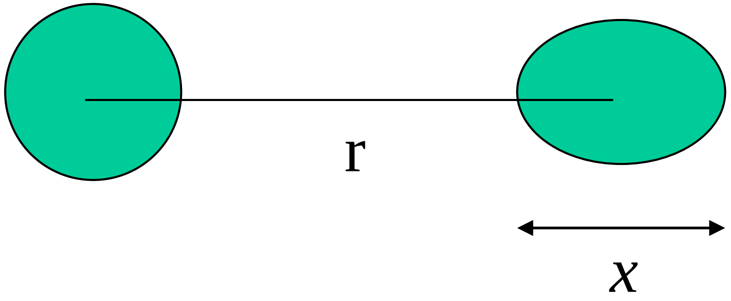
relative distance

single barrier

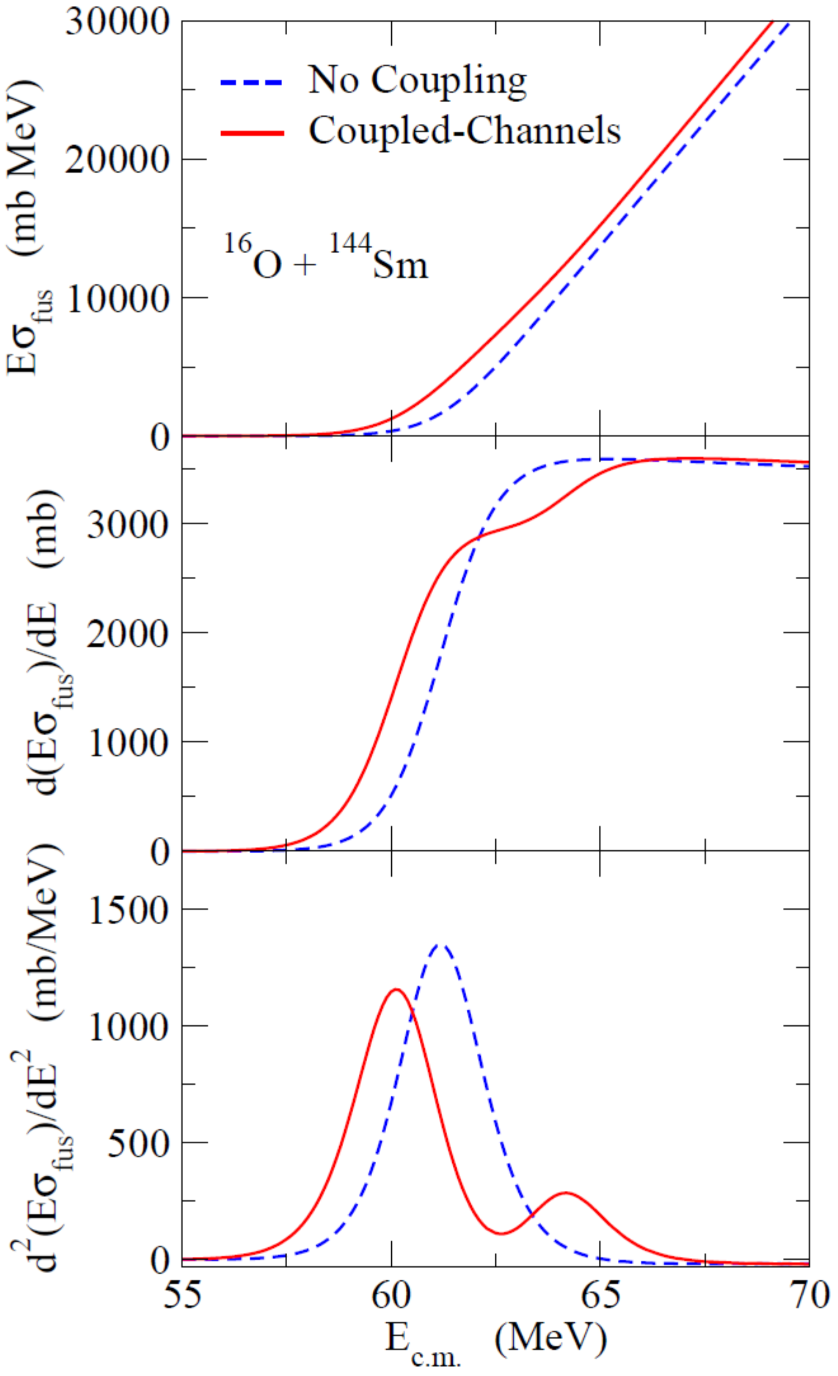
⟶ a collection of many barriers

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

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



(intrinsic coordinate)

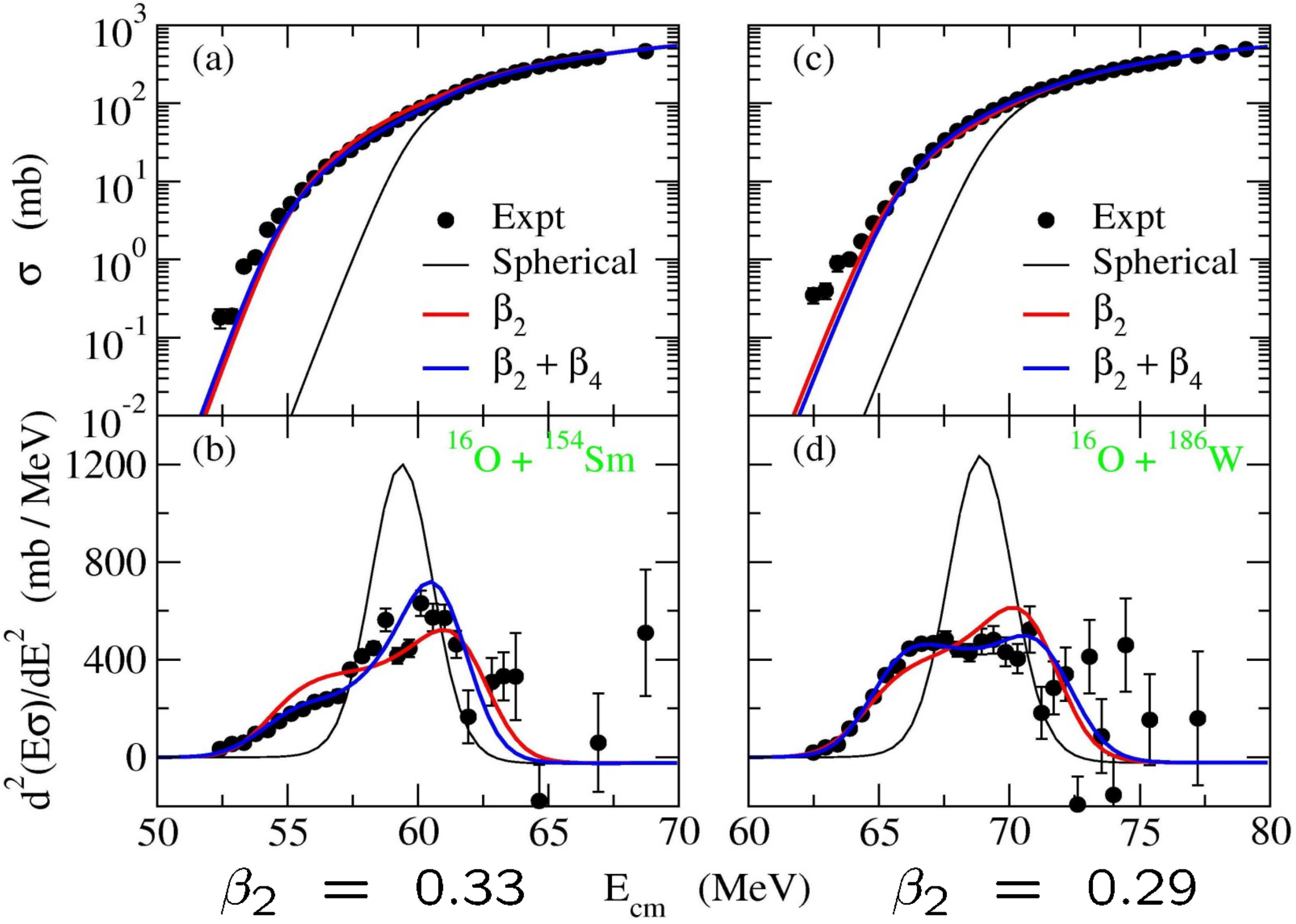


N. Rowley, G.R. Satchler,
P.H. Stelson, PLB254('91)25

$$\frac{d}{dE}[E\sigma_{\text{fus}}(E)] \propto P(E)$$

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

centered on $E = V_b$

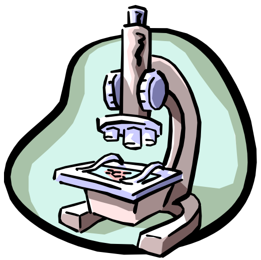


$\beta_2 = 0.33$ $\beta_2 = 0.29$

$\beta_4 = +0.05$ $\beta_4 = -0.03$

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

Fusion barrier distribution:
sensitive to small effects such as β_4

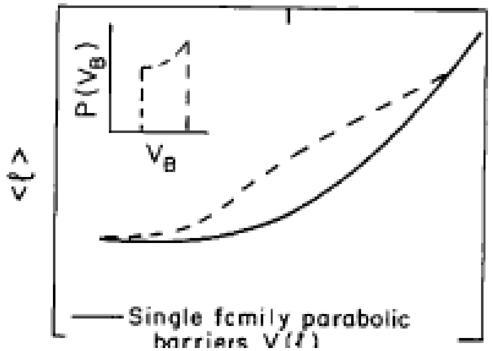


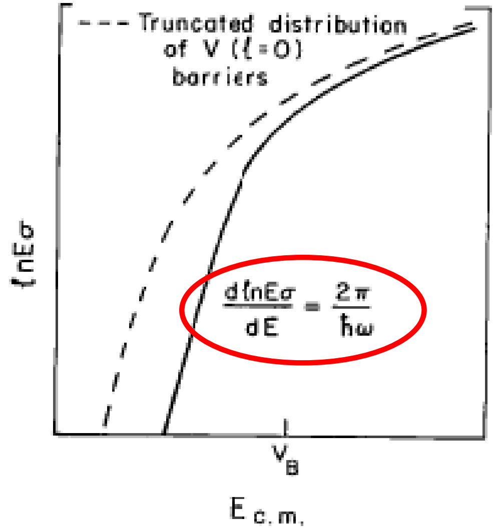
logarithmic derivative (~00's)

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

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

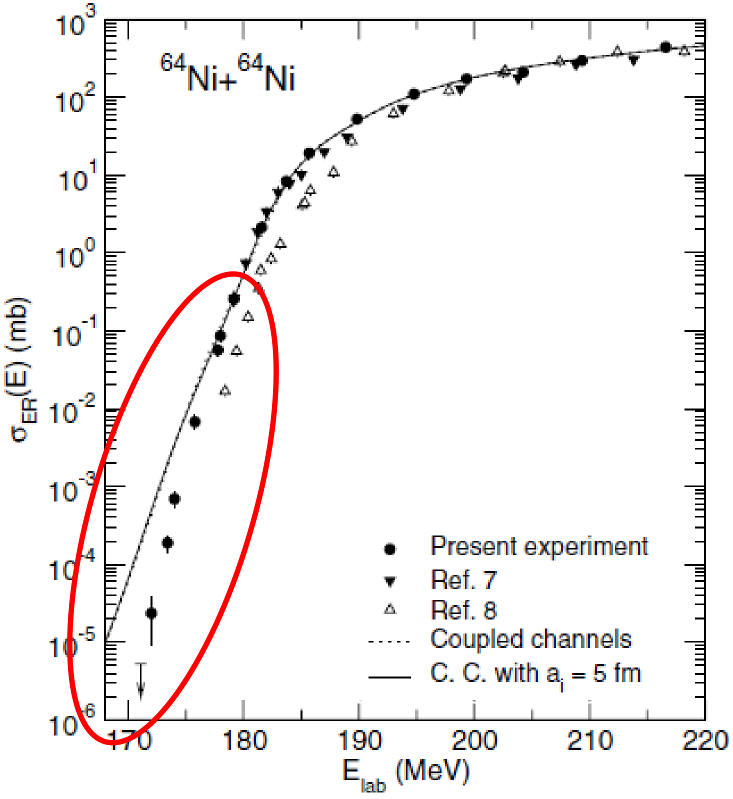
cf. $D_{\text{fus}} = (E\sigma)''$



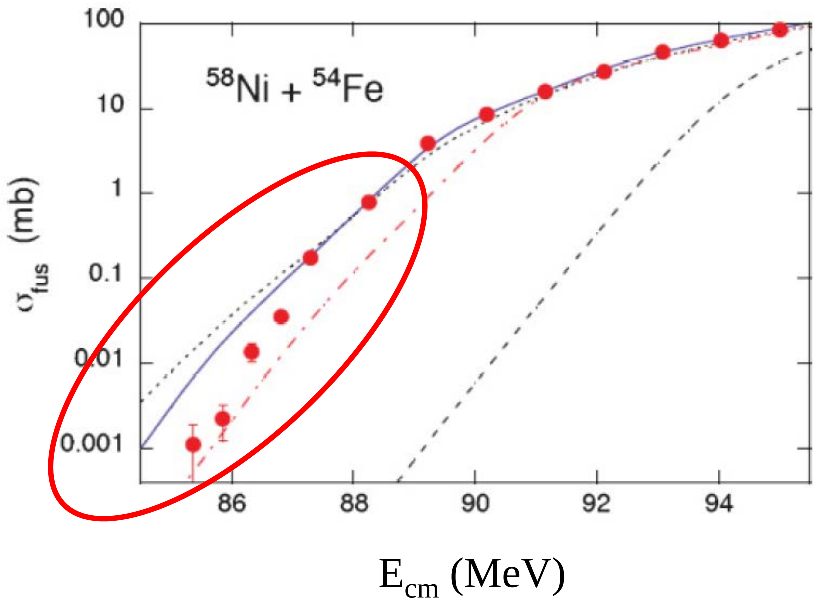


R. Vandenbosch,
Ann. Rev. Nucl. Part. Sci. 42('92)447

deep subbarrier hindrance of fusion cross sections



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

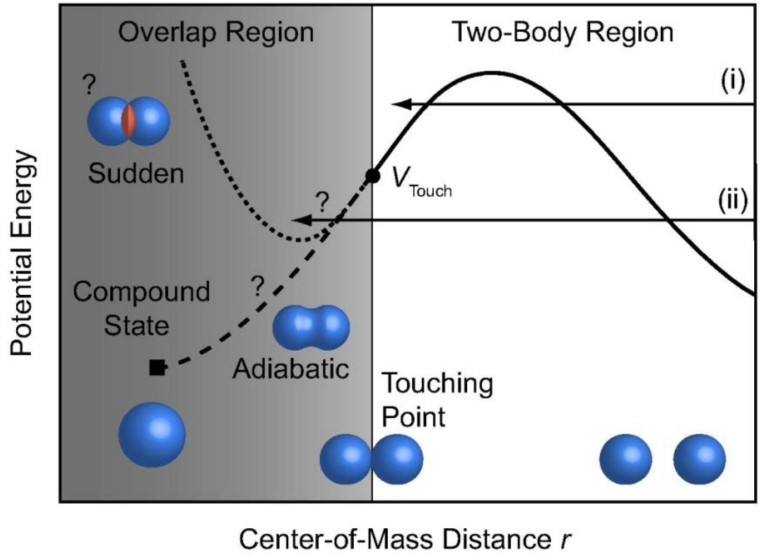


A.M. Stefanini et al., PRC82(‘10)014614

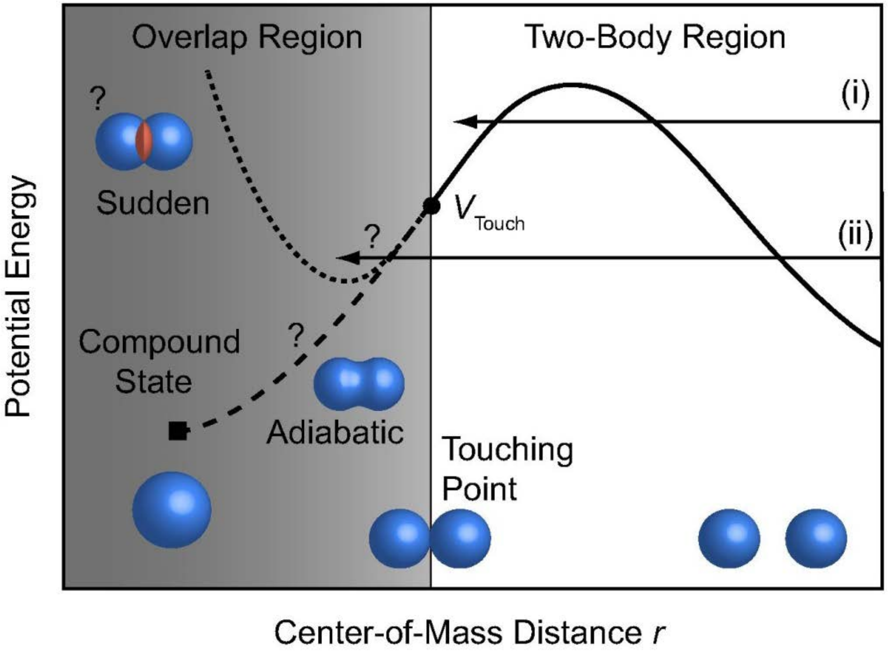
Theory:

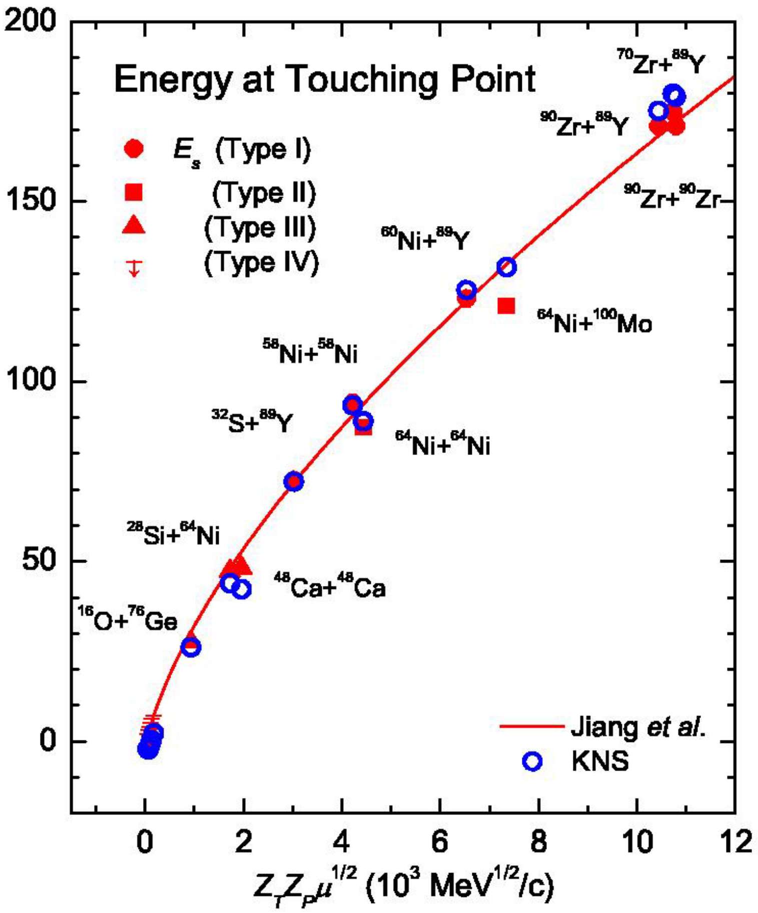
✓S. Misicu and H. Esbensen, PRL96(‘06)112701

✓T. Ichikawa, K.H., and A. Iwamoto,
PRL103(‘09)202701



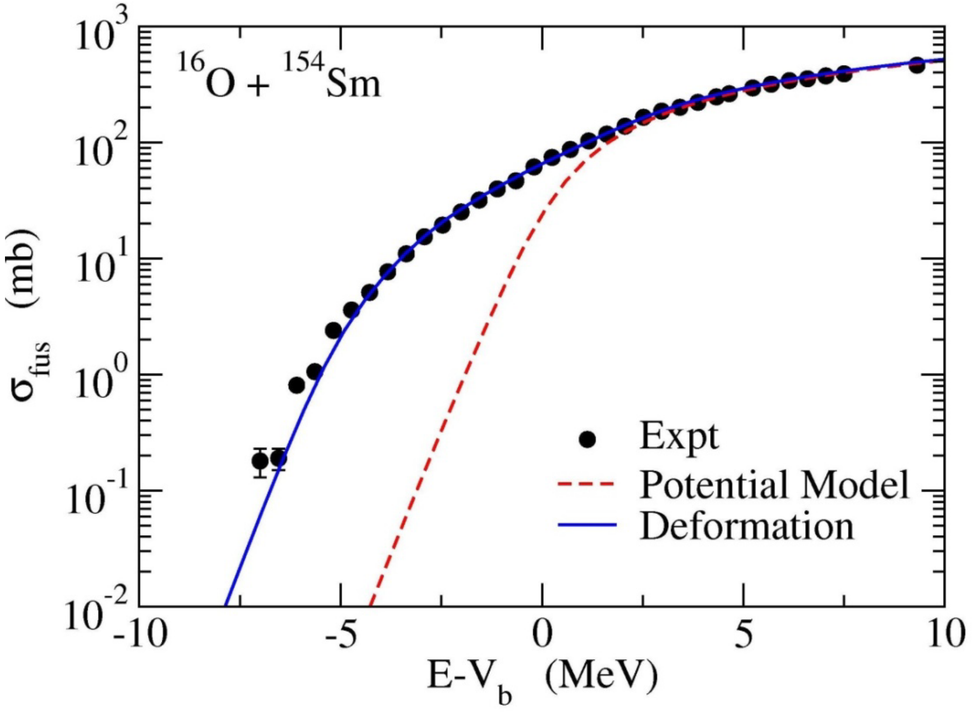
Systematics of the touching point energy and deep subbarrier hindrance





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

Fusion of unstable nuclei



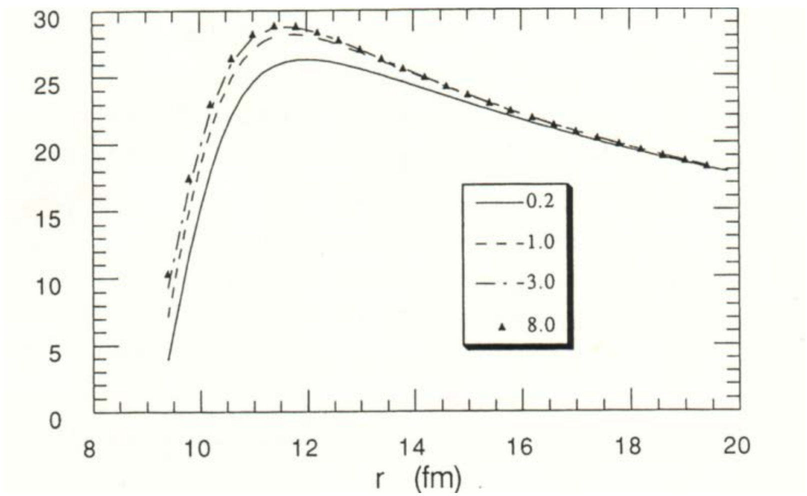
Fusion of stable nuclei: large enhancement of fusion cross sections

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

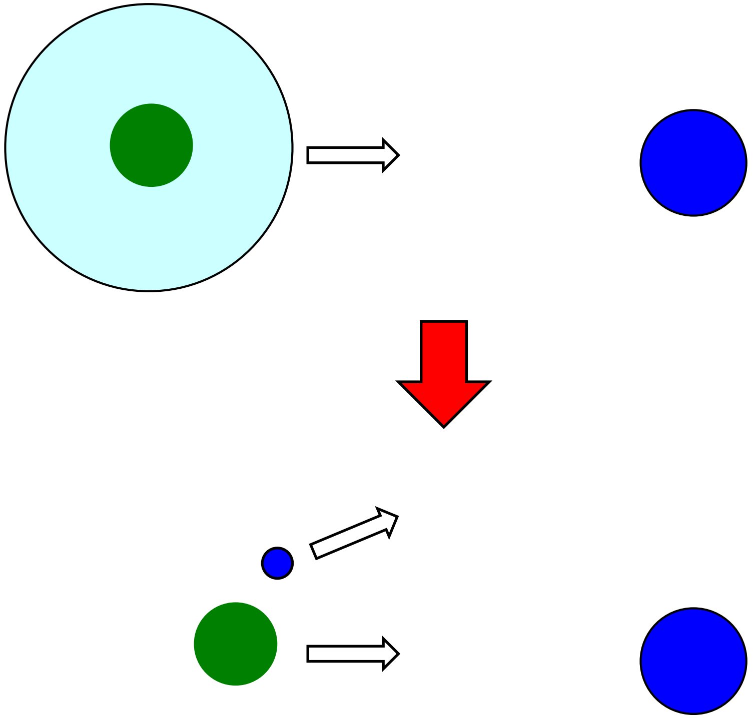
still not known completely

Two effets

1. Lowering of potential barrier due to a halo structure
   $\longrightarrow$ enhancement
2. effect of breakup



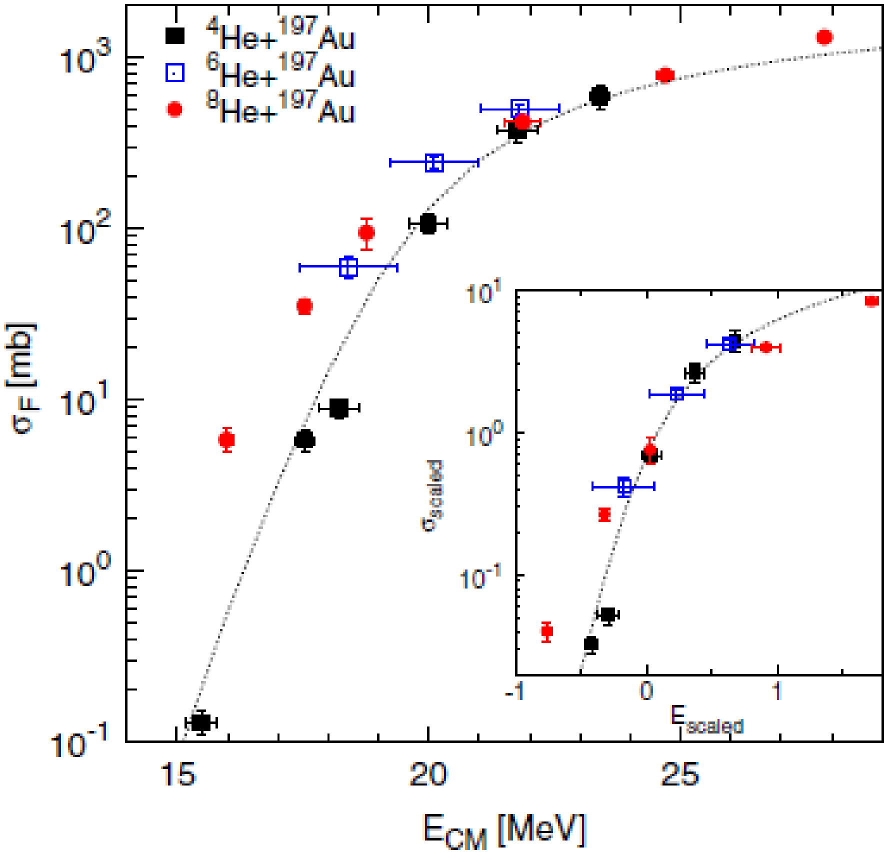
N. Takigawa and H. Sagawa, PLB265('91)23



- 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



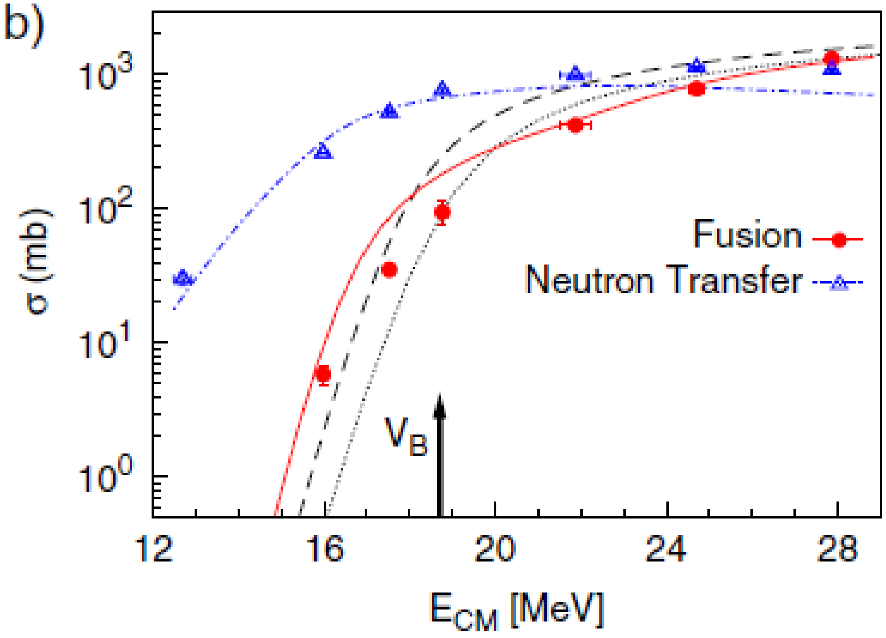
- some enhancement compared to ^{4}He
- similar behaviour between ^{6}He and ^{8}He
  (can we understand this?)

- no huge effects of breakup/transfer!?

A. Lemasson et al., PRL103(‘09)232701

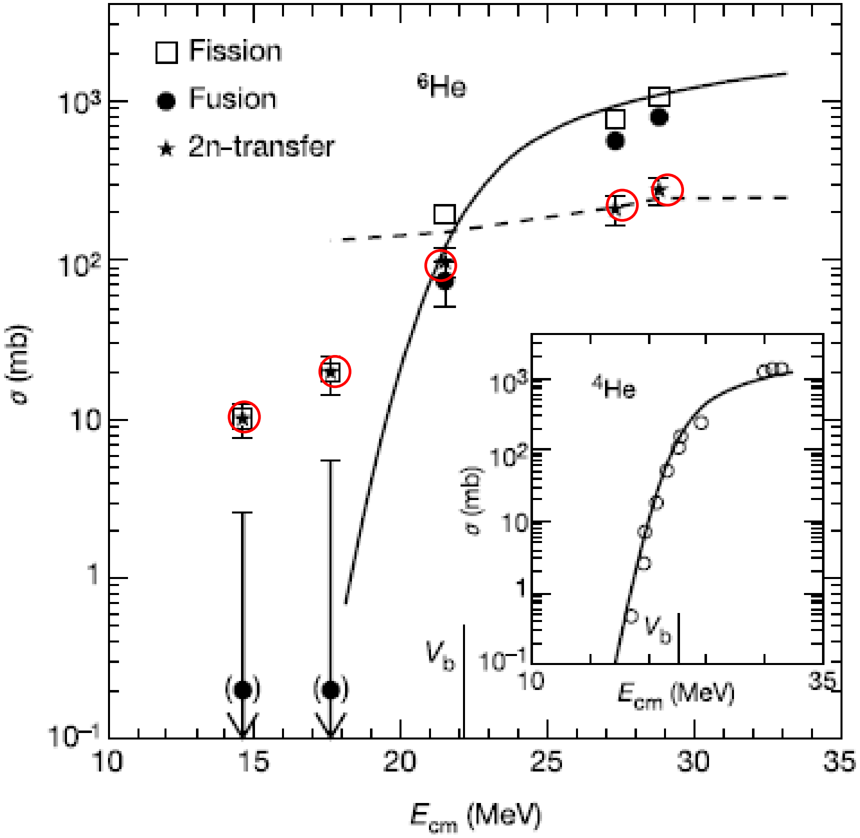
- large transfer cross sections

^{8}He + ^{197}Au

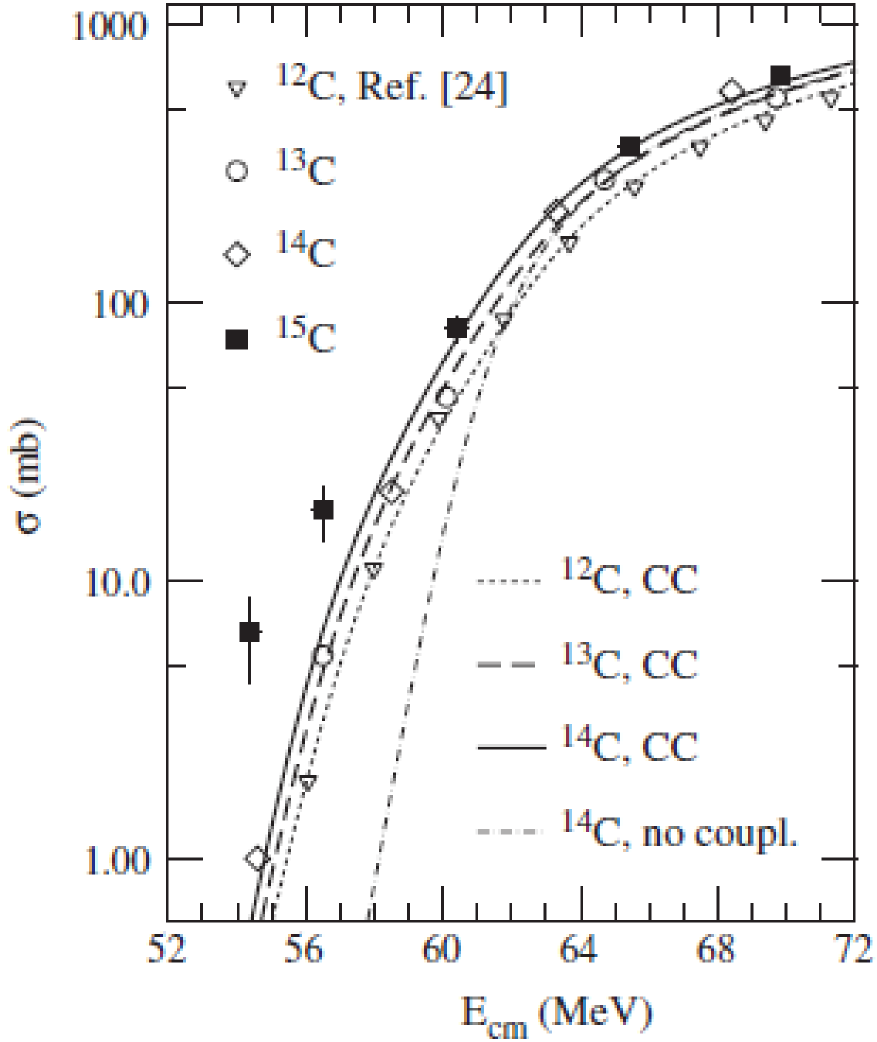


A. Lemasson et al.,
PRL103(‘09)232701

^{6}He + ^{238}U



R. Raabe et al.,
Nature 431 (‘04)823



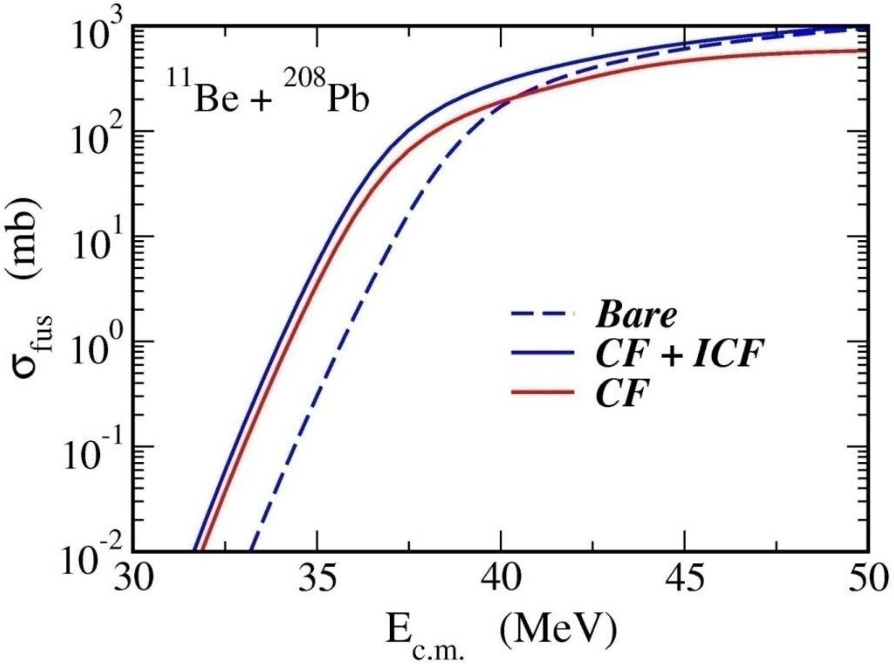
Very recent data for
^{12,13,14,15}C + ^{232}Th

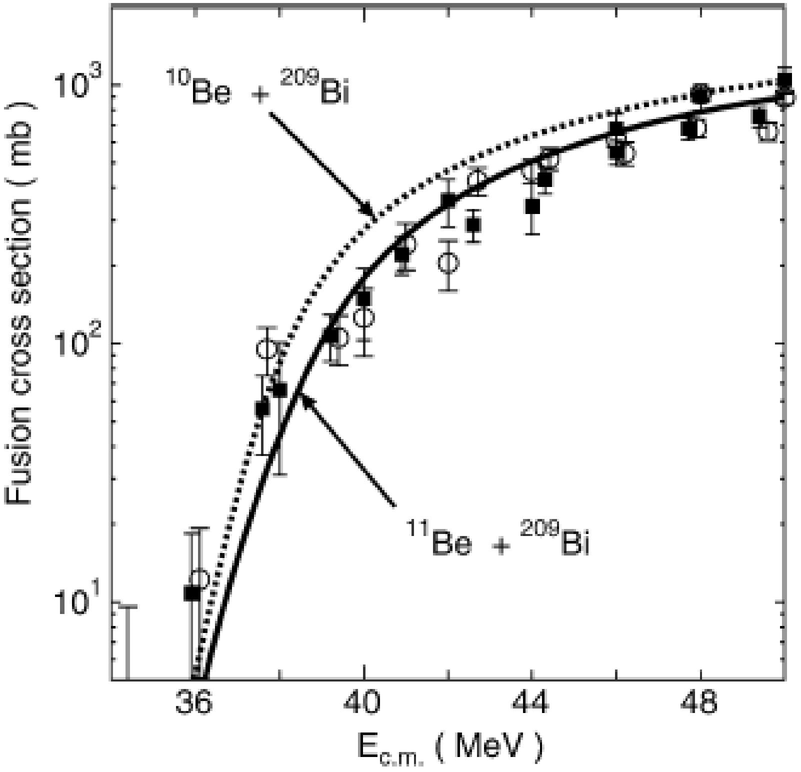
M. Alcorta et al.,
PRL106('11)172701

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

→ enhanced fusion cross sections

Calculations: need to include breakup and transfer in a consistent way (very hard)





CDCC-type calculation

- no transfer

K. Hagino, A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 (’00) 037602
A. Diaz-Torres and I.J. Thompson,
PRC65(’02)024606

Time-dependent approach

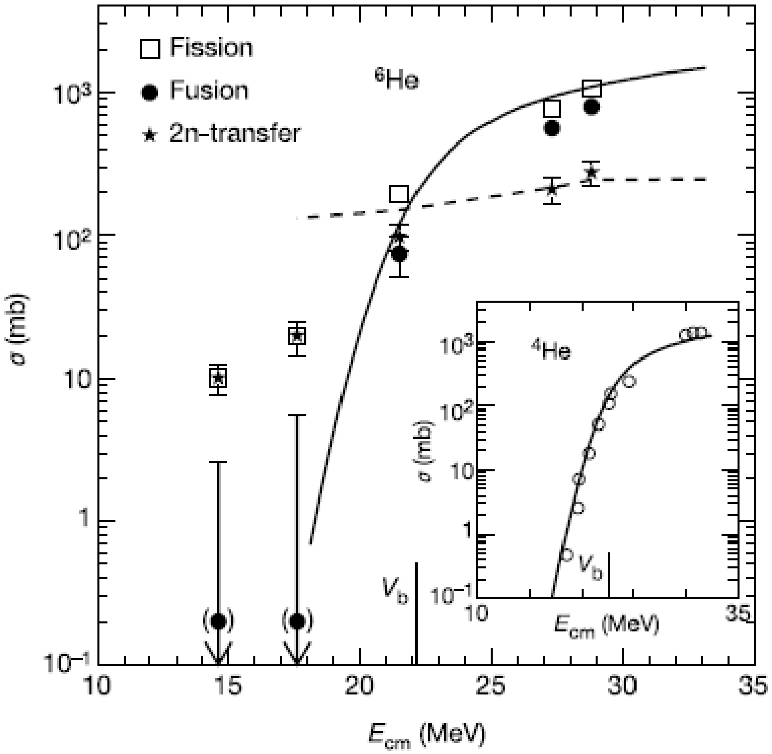
- breakup and transfer
- heavy computation

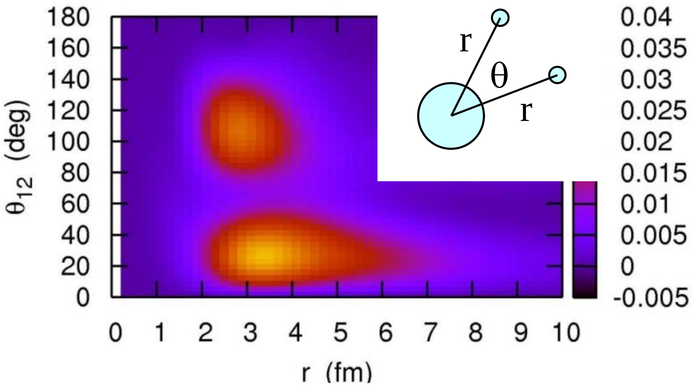
M. Ito, K. Yabana, T. Nakatsukasa,
and M. Ueda, PLB637(‘06)53

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

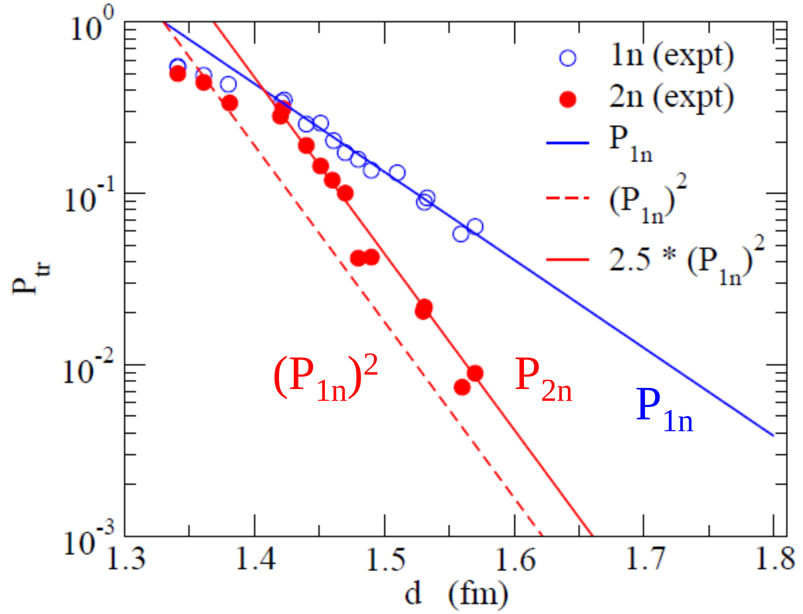
role of dineutron correlation?

Pair correlation and pair transfer

pair transfer probability strongly reflects the pairing correlation

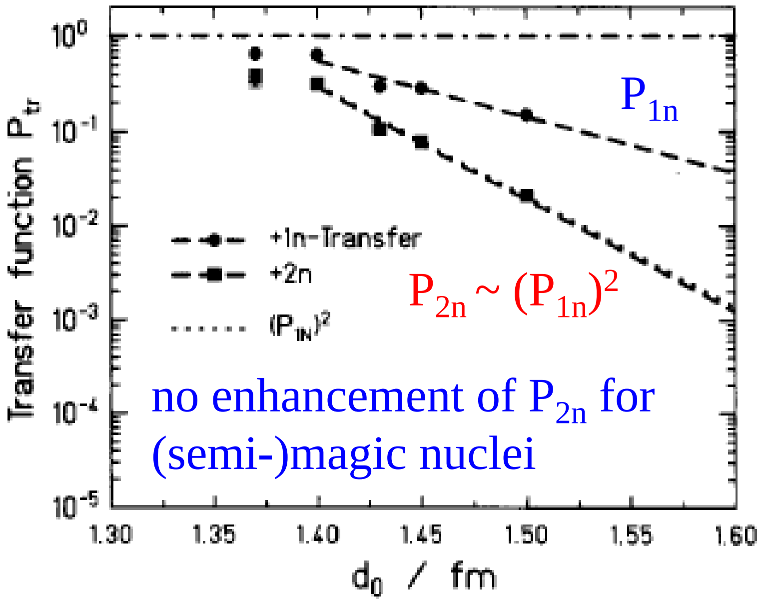
pair transfer probability: $P_{\mathrm{tr}} \sim \dfrac{d\sigma_{\mathrm{tr}}}{d\sigma_R}$

$^{112}\mathrm{Sn} + {}^{120}\mathrm{Sn}$



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

$^{144}\mathrm{Sm} + {}^{208}\mathrm{Pb}$



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:

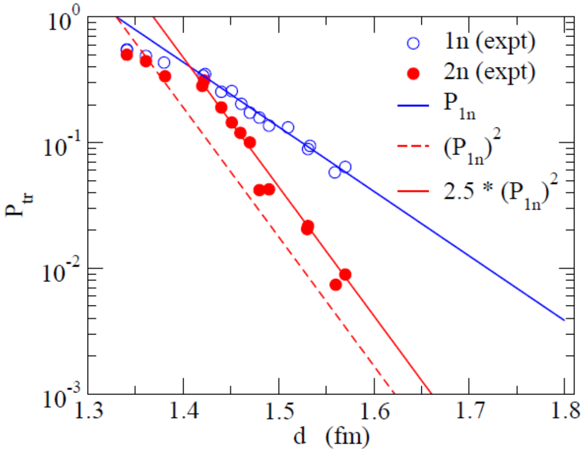
✓**Reaction mechanism?**

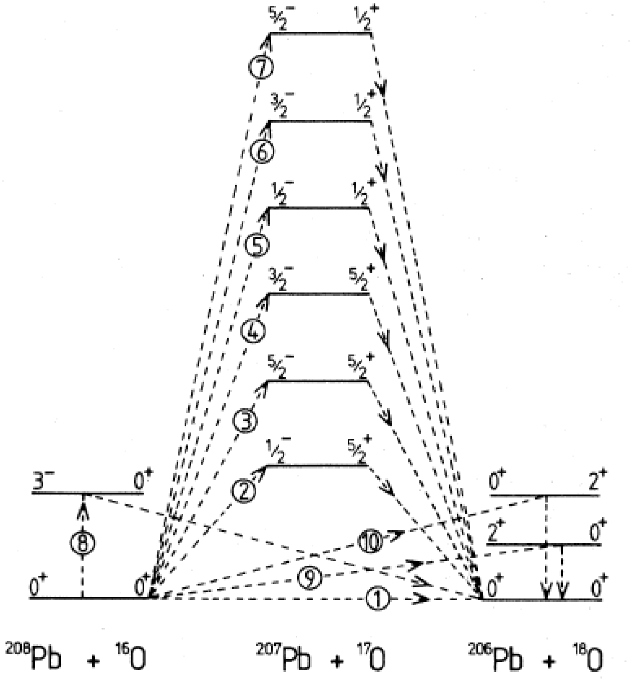
- sequential vs simultaneous
- Q-value, angular momentum matchings

✓Role of dineutron correlation (on the surface)?

✓Influence to other reaction processes (e.g., subbarrier fusion)?

have not yet been fully clarified

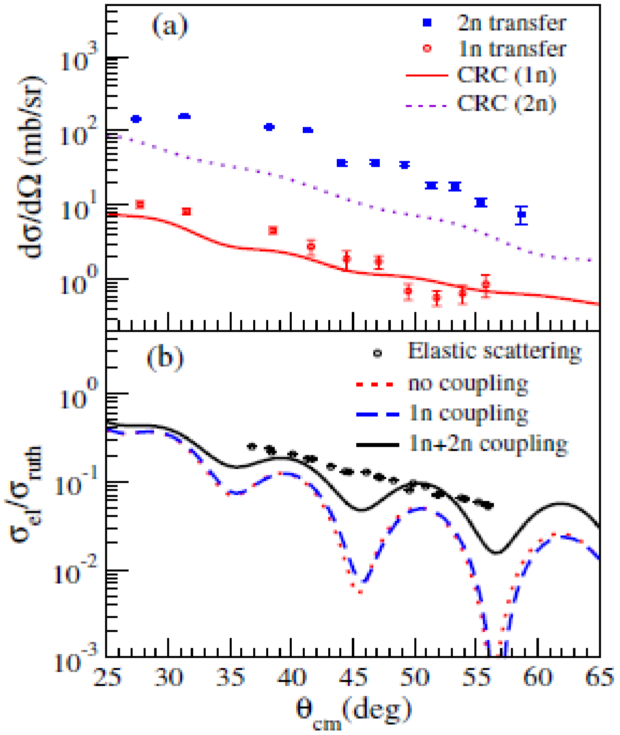




how is the reaction mechanism modified
if most of intermediate states are unbound?

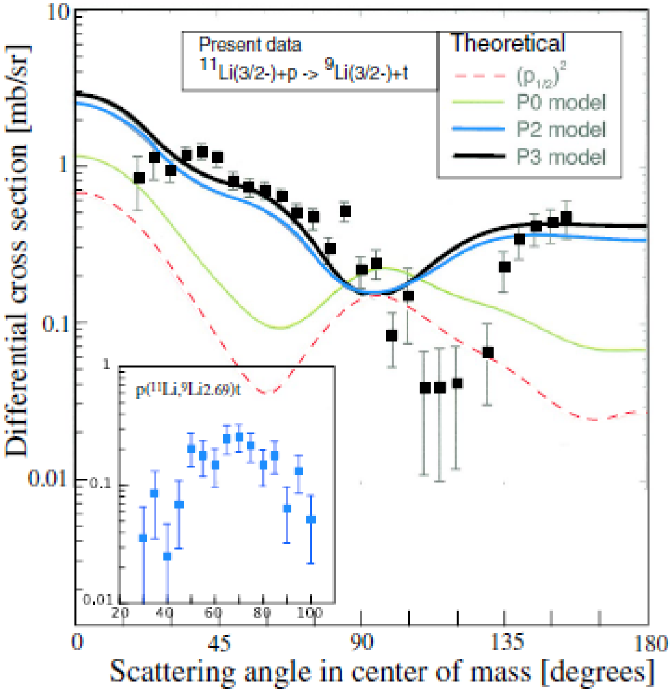
Recent experiments for transfer reaction of neutron-rich nuclei

^{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:

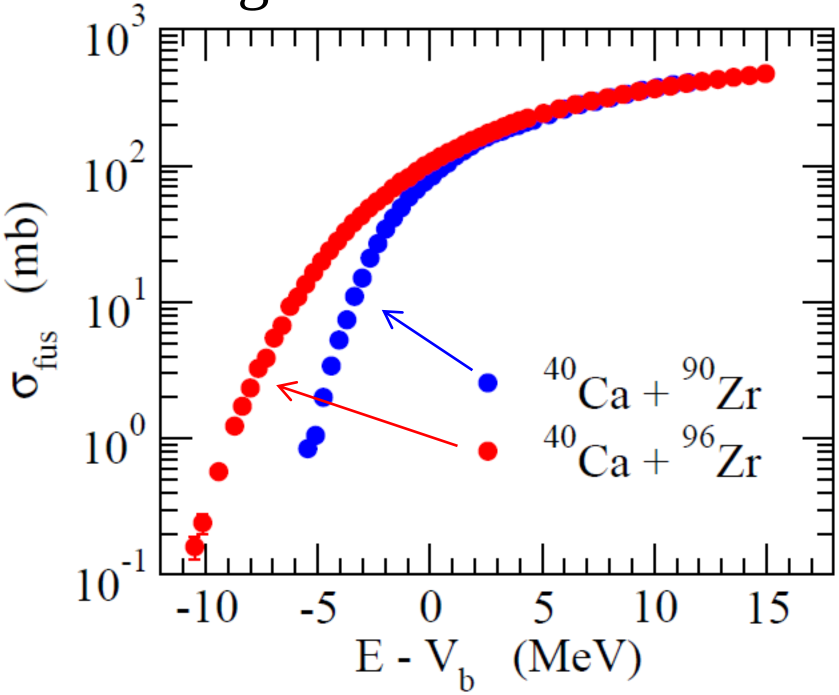
a new theory of pair transfer with dineutron correlation.

⟶ need a deep understanding of reaction dynamics

influence on subbarrier fusion? (open question)

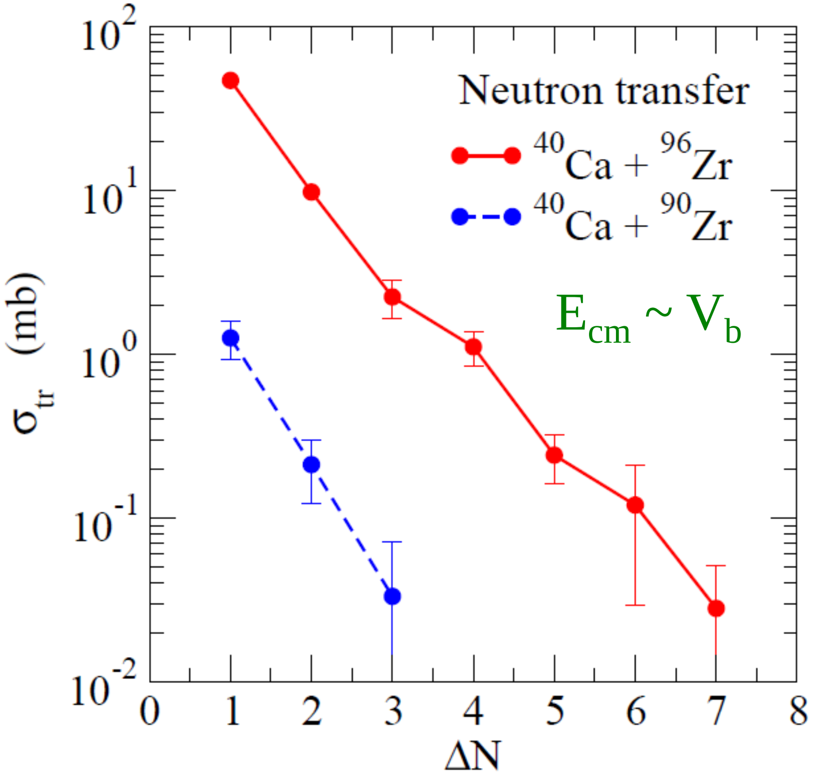
Role of multi-neutron transfer process in subbarrier fusion

Legnaro data for ^{40}Ca + ^{90,96}Zr



H. Timmers et al., NPA633('98)421

Experimental data for
total transfer cross sections



G. Montagnoli et al.,
J. of Phys. G23('97)1431

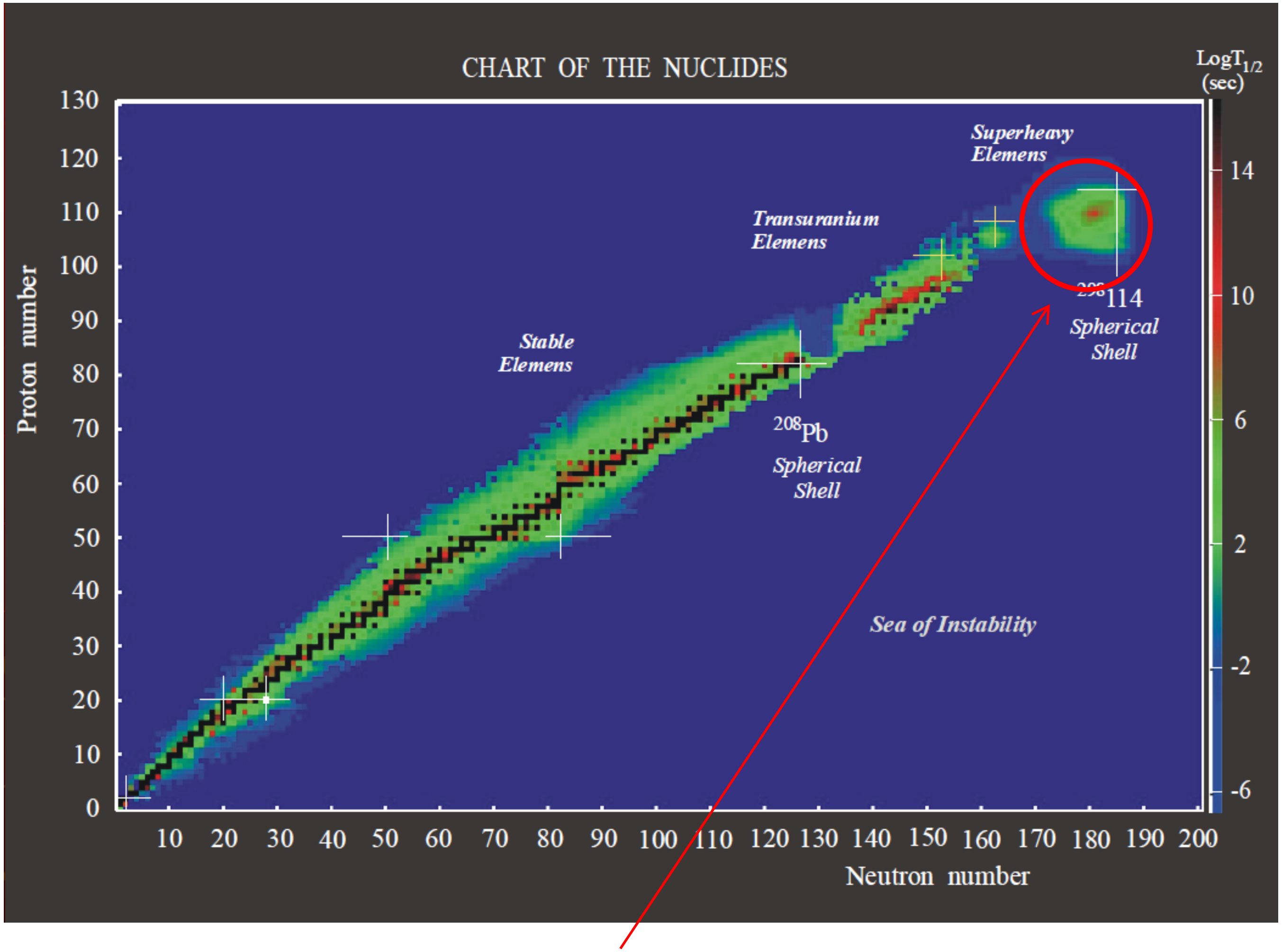
^{40}Ca + ^{96}Zr

- more enhancement of fusion cross sections

✓multi-neutron transfer process

cf. fusion of skin nuclei

Heavy-ion fusion for SHE



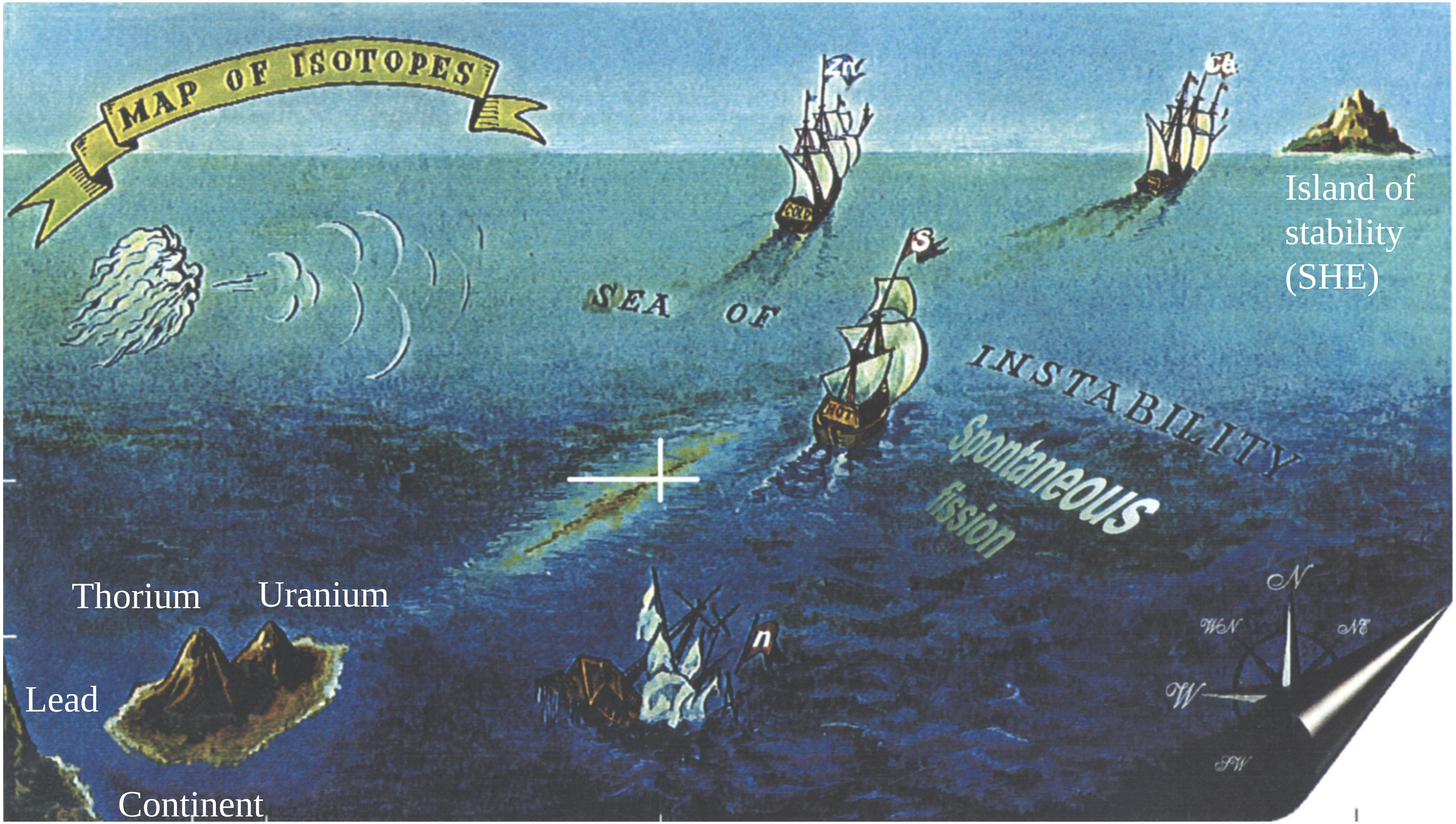
Yuri Oganessian

island of stability around Z=114, N=184

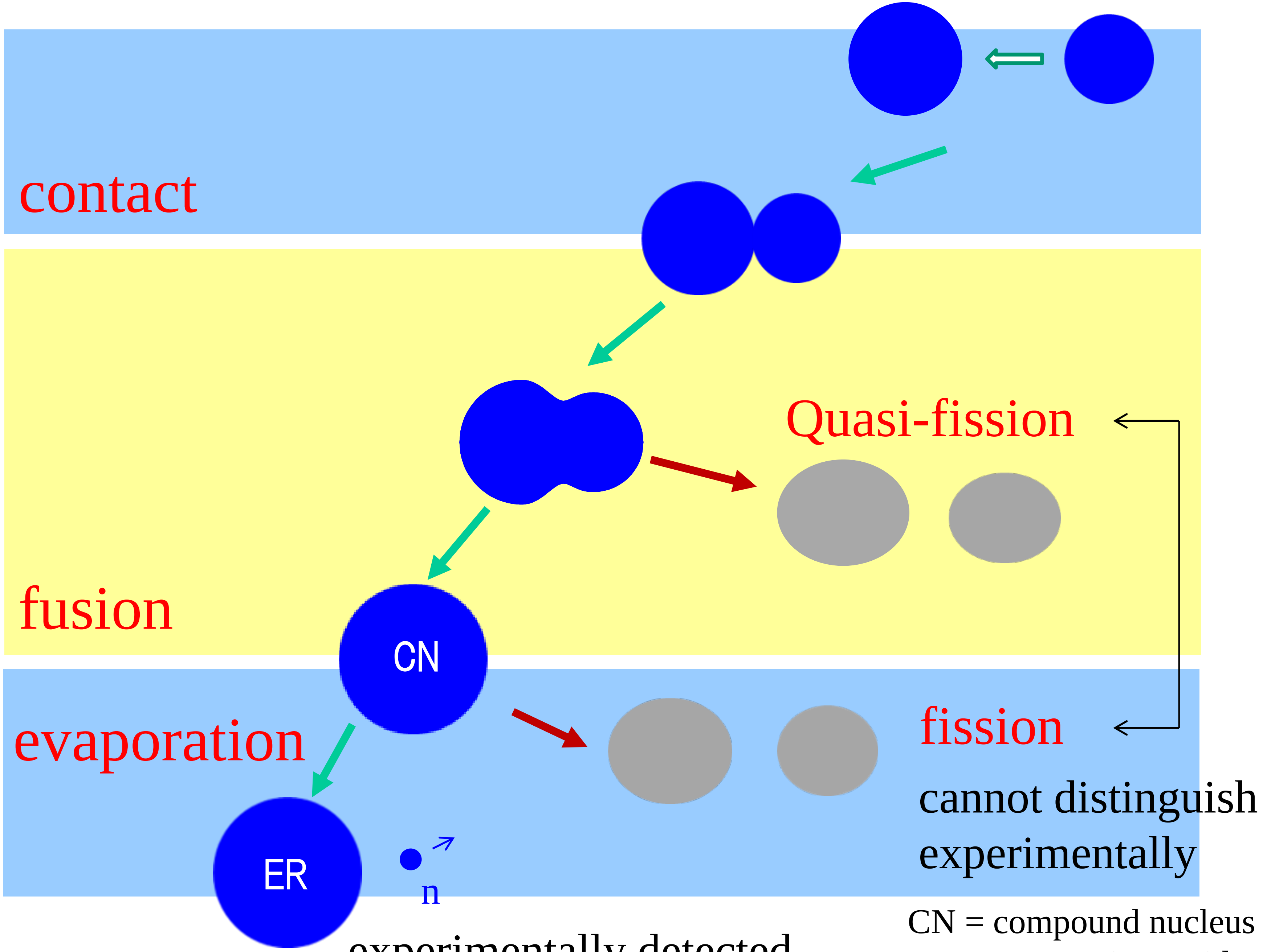
W.D. Myers and W.J. Swiatecki (1966), A. Sobiczewski et al. (1966)

⟶ modern calculations: Z=114,120, or 126, N=184

e.g., H. Koura et al. (2005)



Yuri Oganessian



contact

fusion

Quasi-fission

CN

evaporation

fission

cannot distinguish experimentally

ER

n

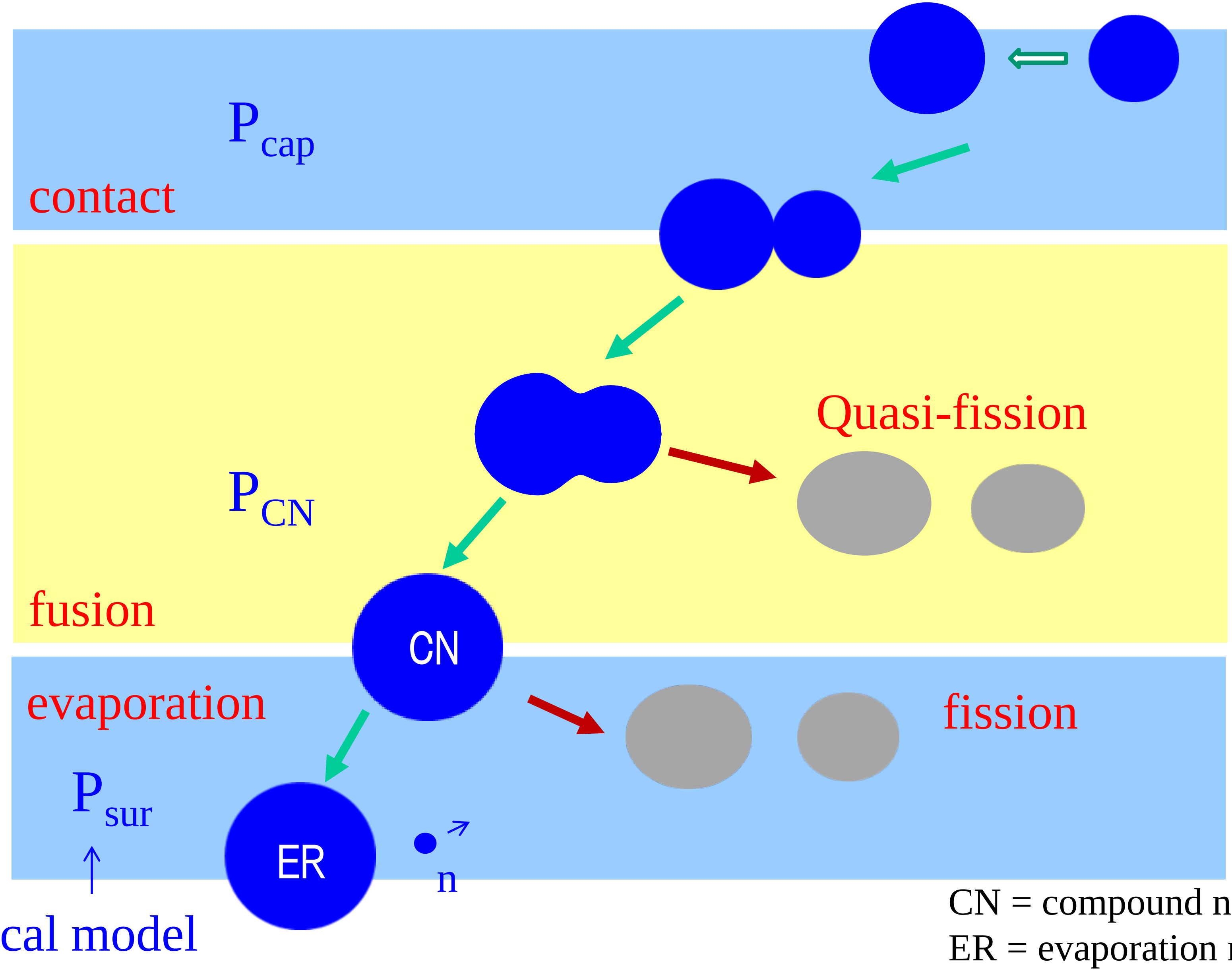
experimentally detected

CN = compound nucleus

ER = evaporation residue

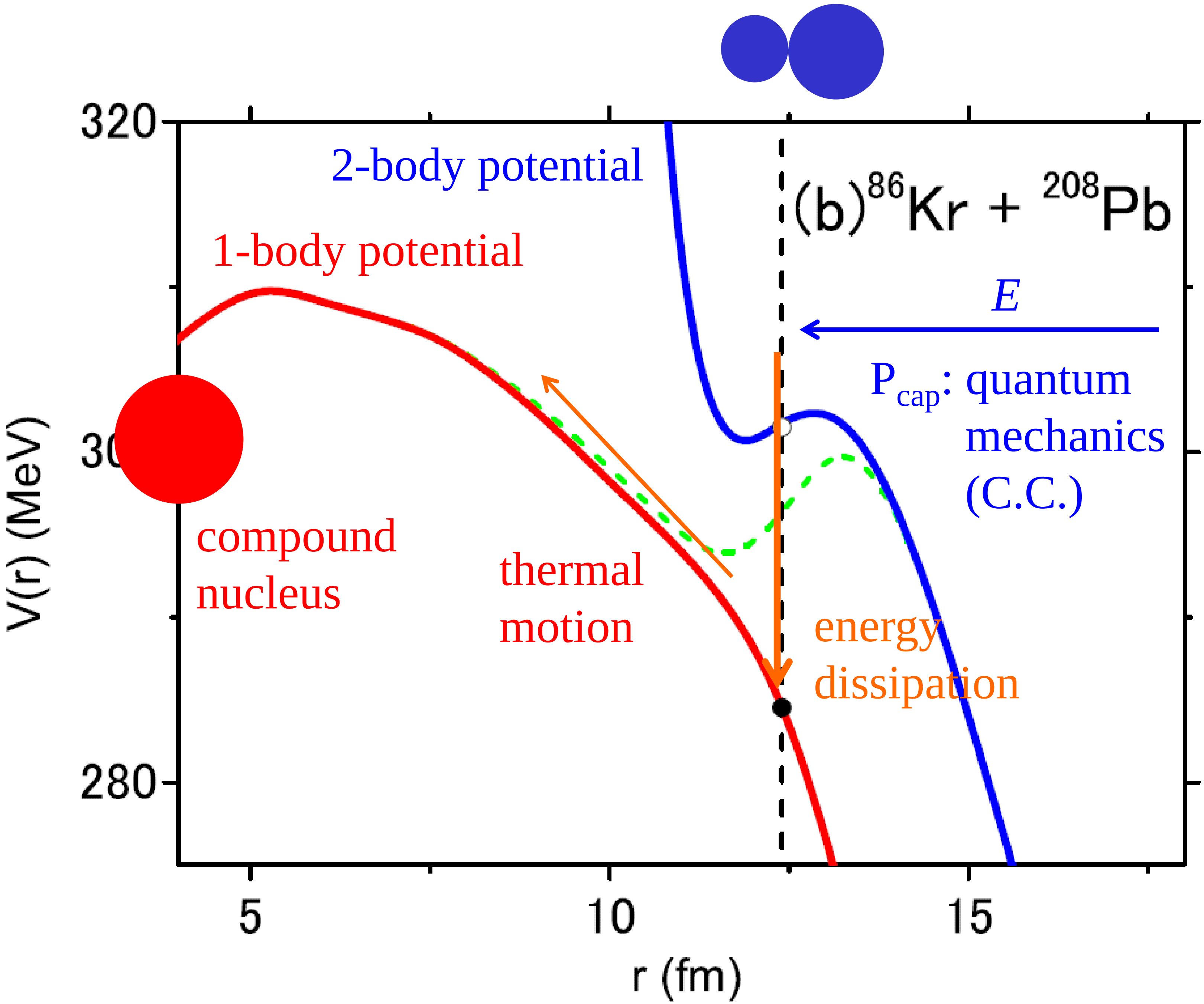
Theoretical treatment

$$\boxed{P_{\mathrm{ER}} = P_{\mathrm{cap}} \cdot P_{\mathrm{CN}} \cdot P_{\mathrm{sur}}}$$

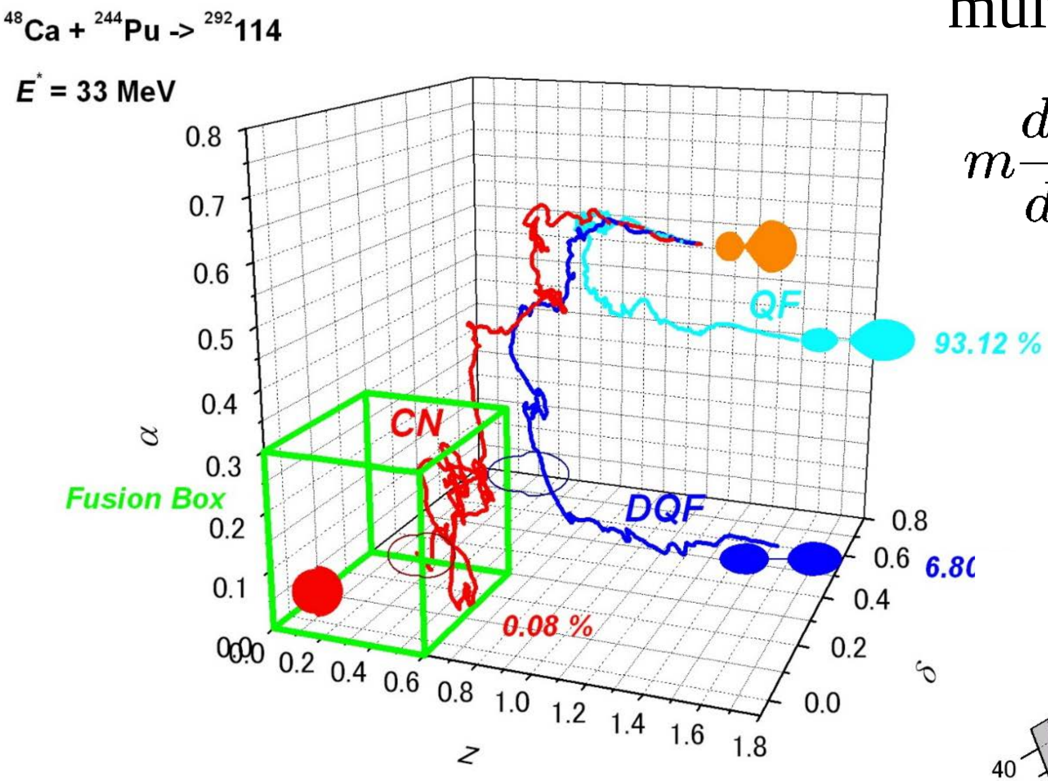


↑
statistical model

CN = compound nucleus
ER = evaporation residue


2-body potential
(b) ^{86}Kr + ^{208}Pb
1-body potential
E
P_{cap}: quantum mechanics (C.C.)
compound nucleus
thermal motion
energy dissipation
320
300
280
5
10
15
V(r) (MeV)
r (fm)

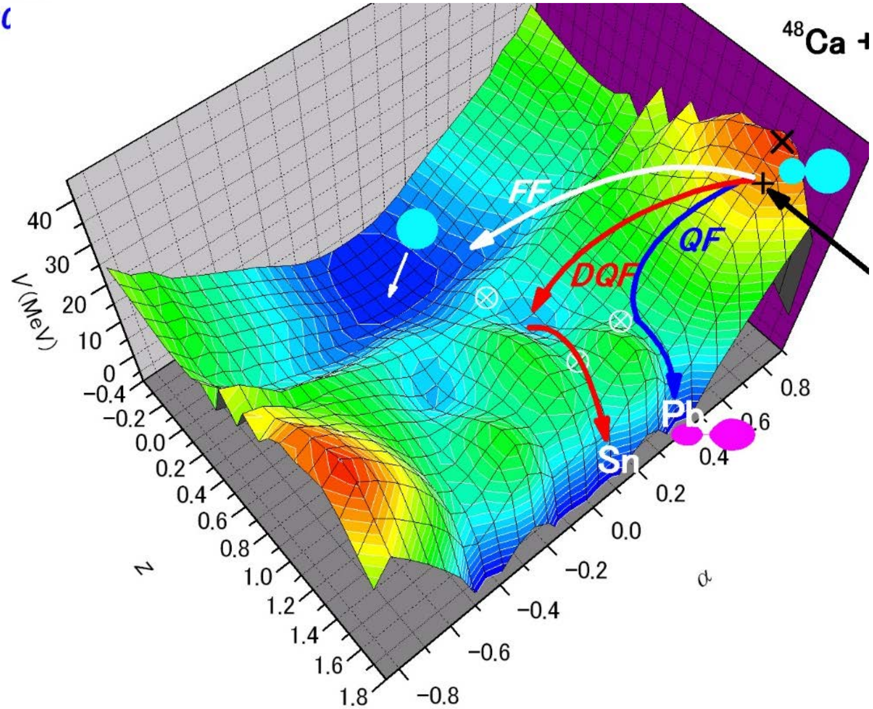
Theory: Lagenvin approach



multi-dimensional extension of:

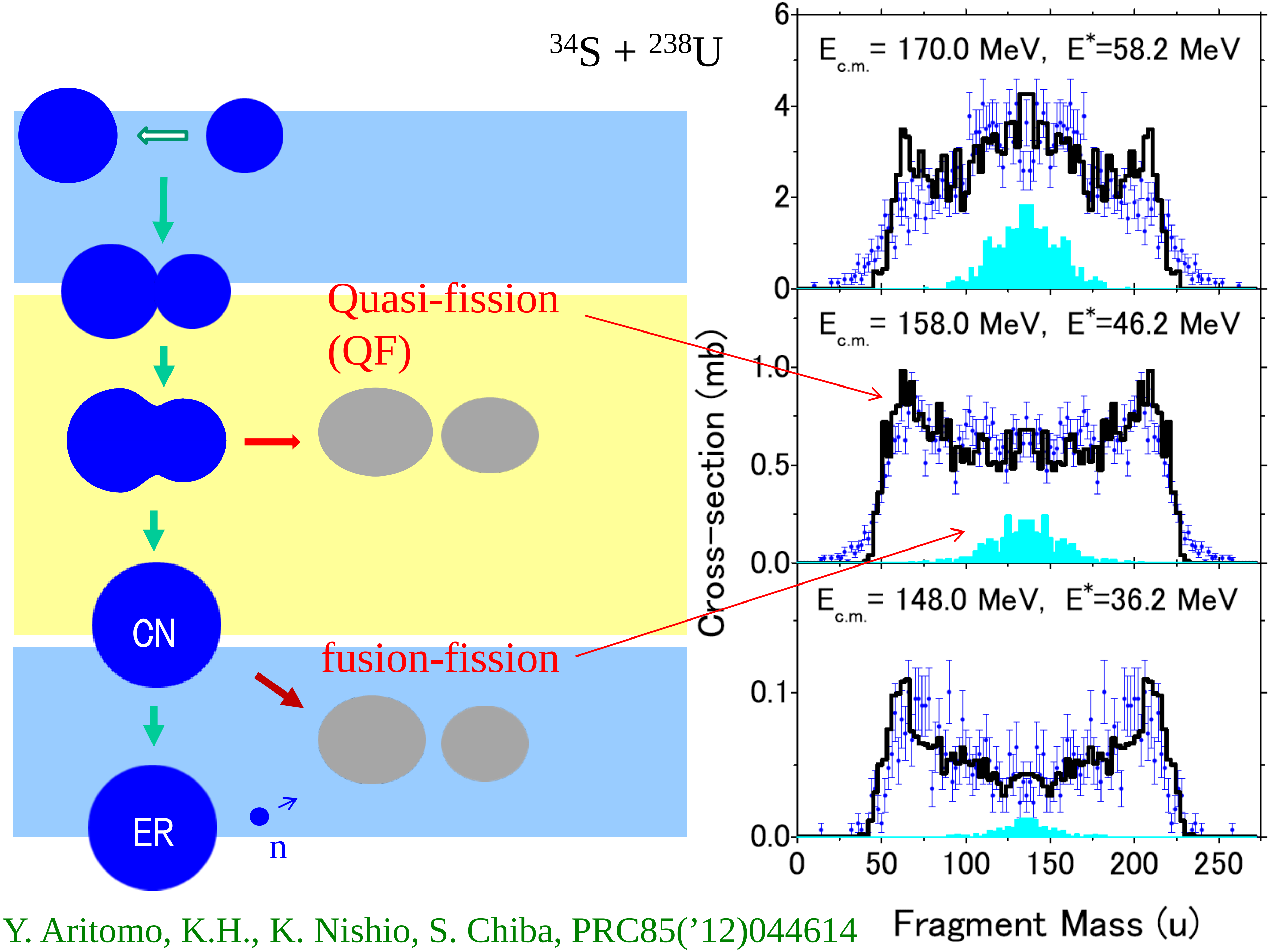
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

γ: friction coefficient
R(*t*): random force

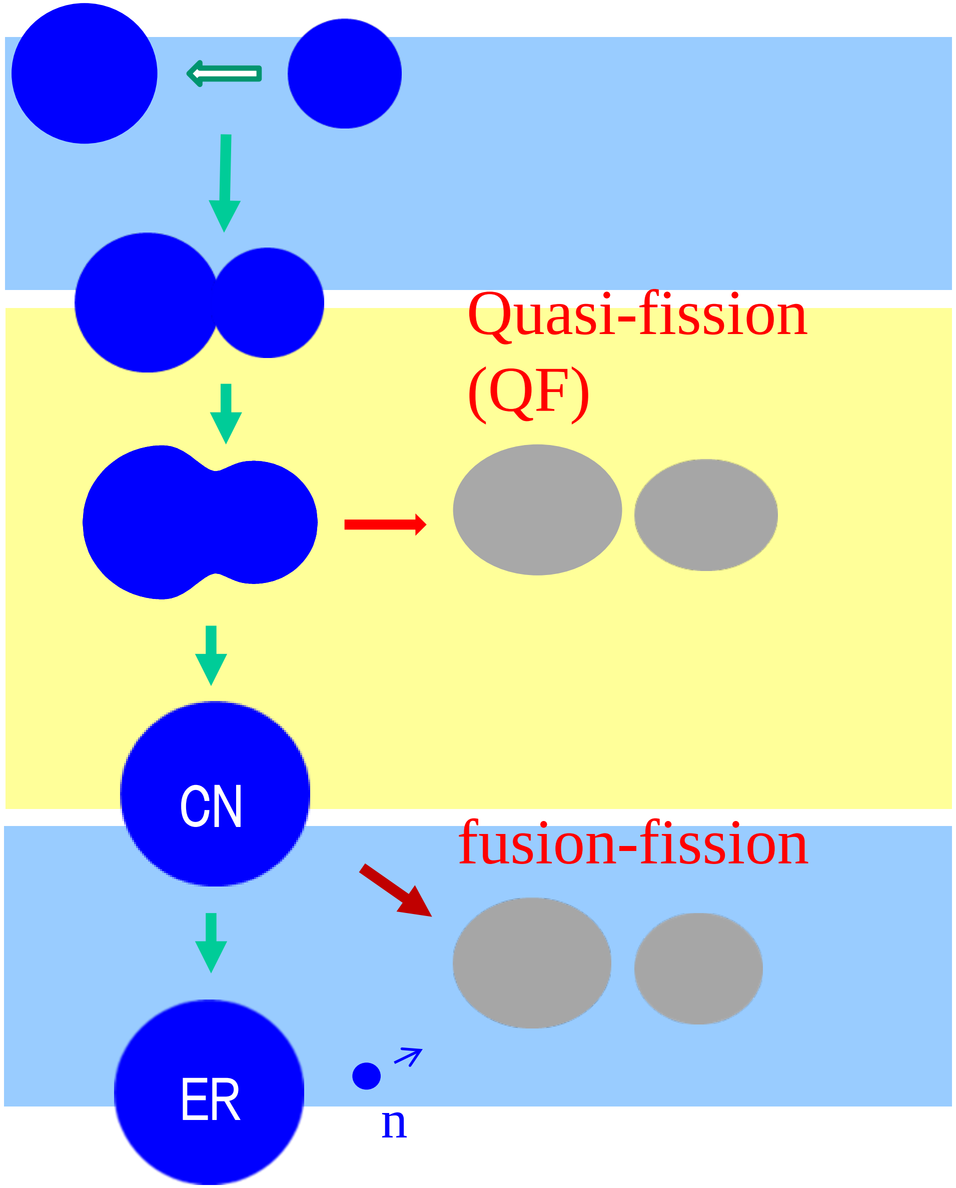


q: ▪internuclear separation (*z*),
▪deformation (δ),
▪asymmetry of the two fragments (α)

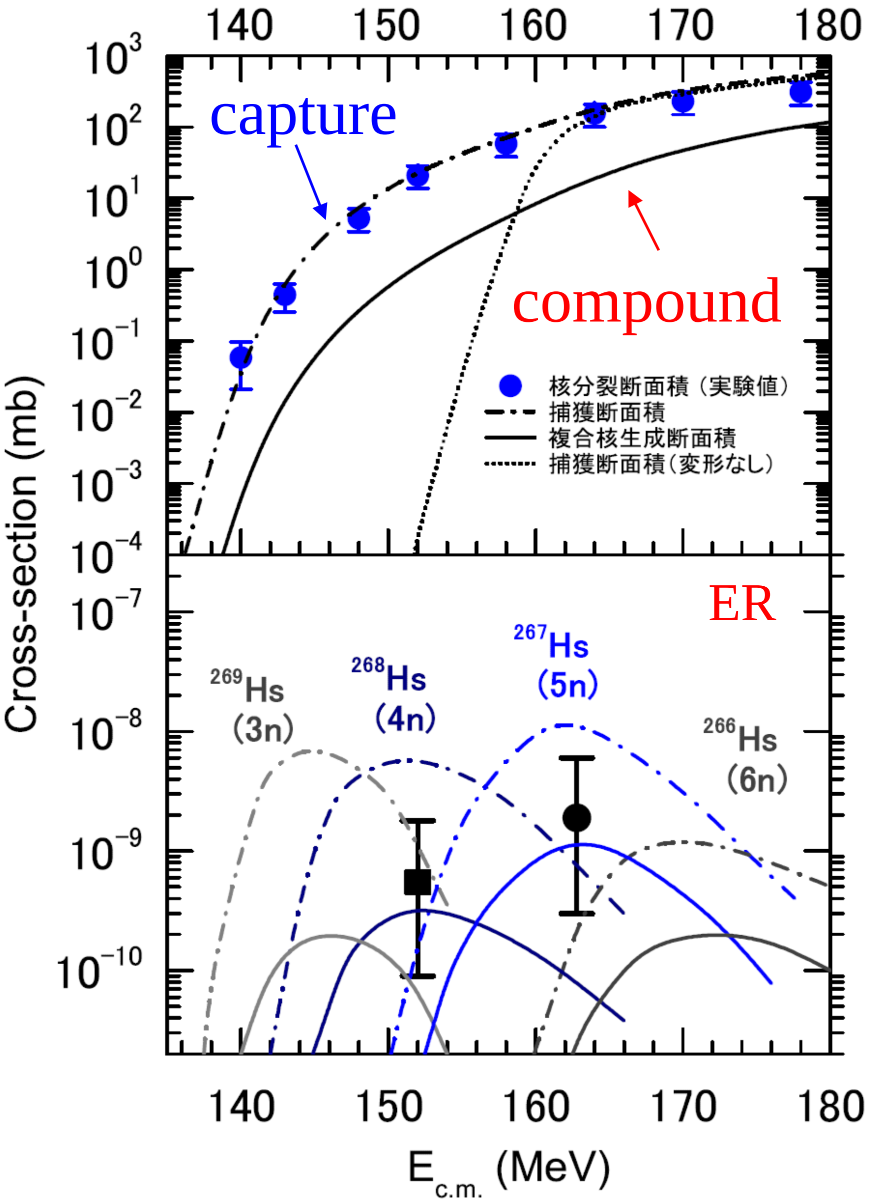
$^{34}S + ^{238}U$



Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85('12)044614



^{34}S + ^{238}U



Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85('12)044614

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
✓ fusion for superheavy elements - quantum effects?