Heavy-ion fusion reactions: quantum tunneling with many degrees of freedom and superheavy elements

Kouichi Hagino
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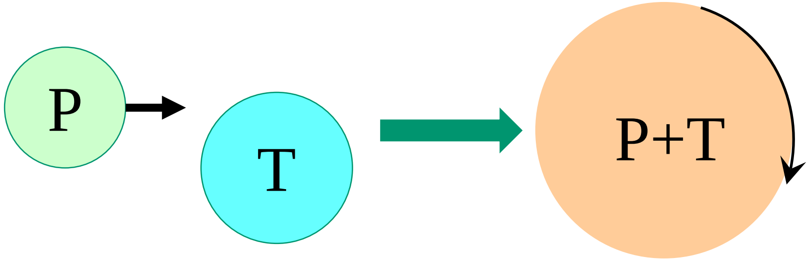
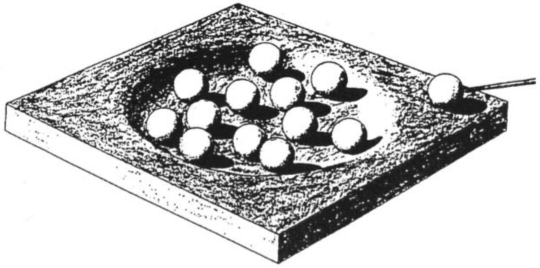
1. H.I. fusion reactions: why are they interesting?
2. Coupled-channels approach
3. Remaining challenges
4. Future perspectives: superheavy elements

Recent review article:
K. Hagino and N. Takigawa, Prog. Theo. Phys.128 (‘12)1061.

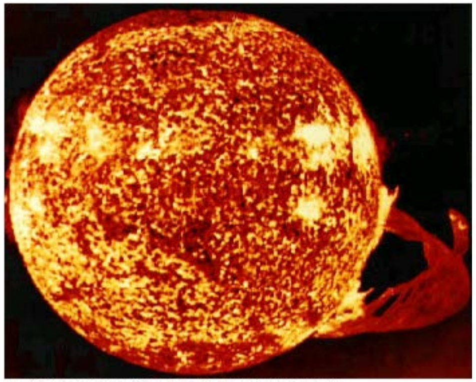
Fusion reactions: compound nucleus formation



compound
nucleus

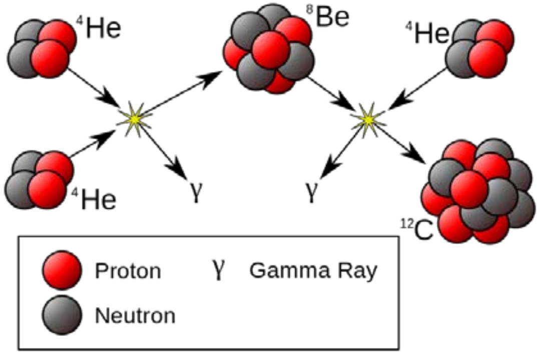


cf. Bohr ‘36

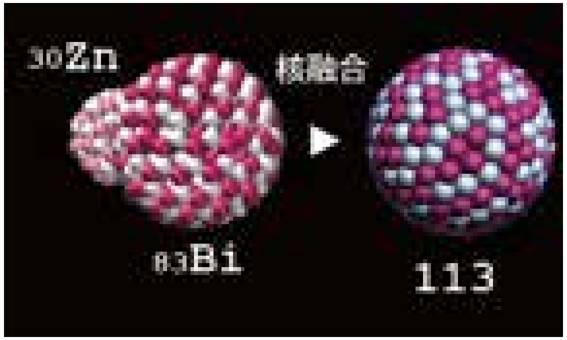


NASA, Skylab space station December 19, 1973, solar flare reaching 588 000 km off solar surface

energy production
in stars (Bethe ‘39)



nucleosynthesis

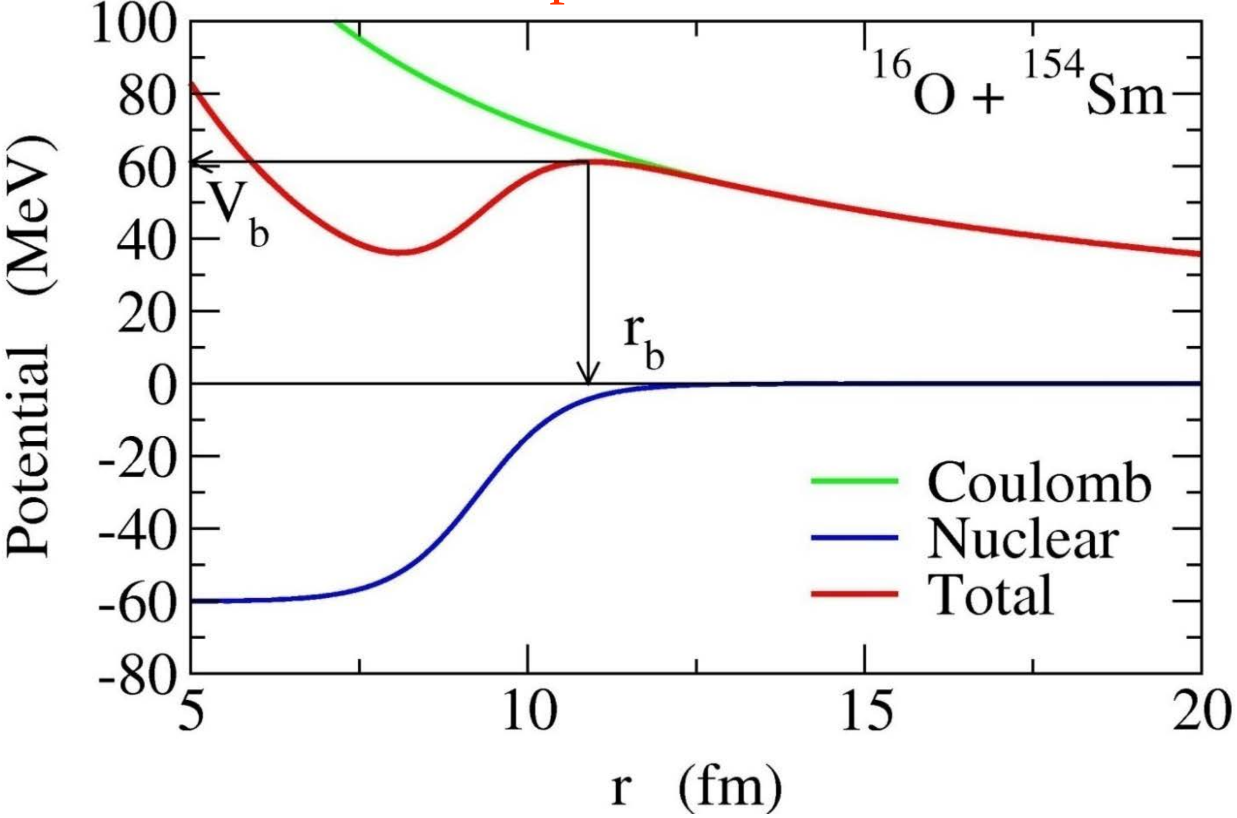


superheavy elements

Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

← microscopic understanding: an ultimate goal of nuclear physics

Inter-nucleus potential



Two interactions:

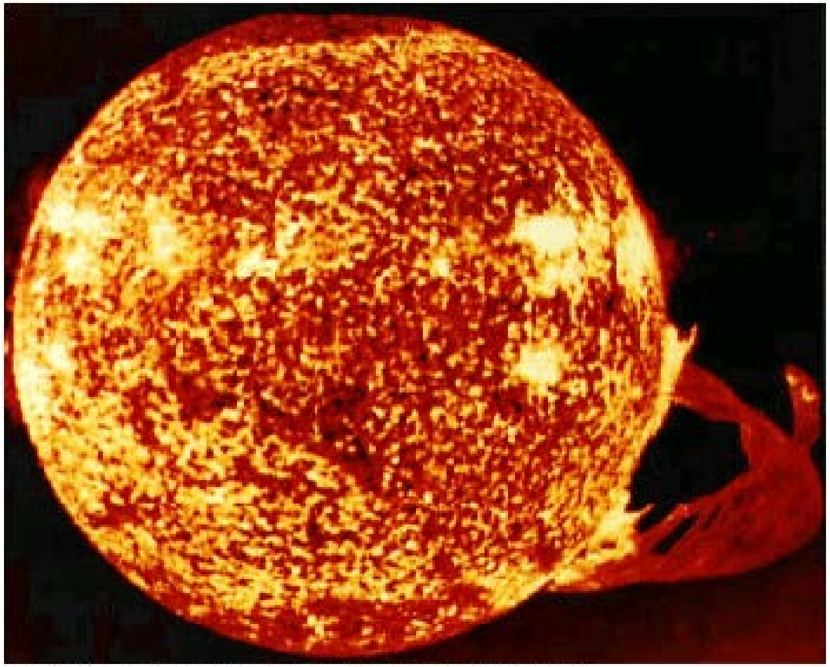
1. Coulomb force
   long range repulsion
2. Nuclear force
   short range attraction

<u>potential barrier</u>
due to a cancellation
between the two
(Coulomb barrier)

- •Above-barrier energies
- •Sub-barrier energies
- •Deep sub-barrier energies

Why sub-barrier fusion?

two obvious reasons:



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

superheavy elements

cf. $^{209}\mathrm{Bi}\,(^{70}\mathrm{Zn},n)\,^{278}\mathrm{Nh}$

$V_B \sim 260$ MeV

$E_{cm}^{(exp)} \sim 262$ MeV

nuclear astrophysics
(nuclear fusion in stars)

cf. extrapolation of data

Why sub-barrier fusion?

two obvious reasons:

✓superheavy elements ✓ nuclear astrophysics

other reasons:

✓reaction dynamics

strong interplay between reaction and structure

cf. high *E* reactions: much simpler reaction mechanisms

✓many-particle tunneling

cf. ▪tunneling in atomic collisions / chemical reactions

: less variety of intrinsic motions

（解離吸着）

cf. dissociative adsorption of H_2 on metal surface

K. Hagino and N. Takigawa, PTP128 (‘12) 1061

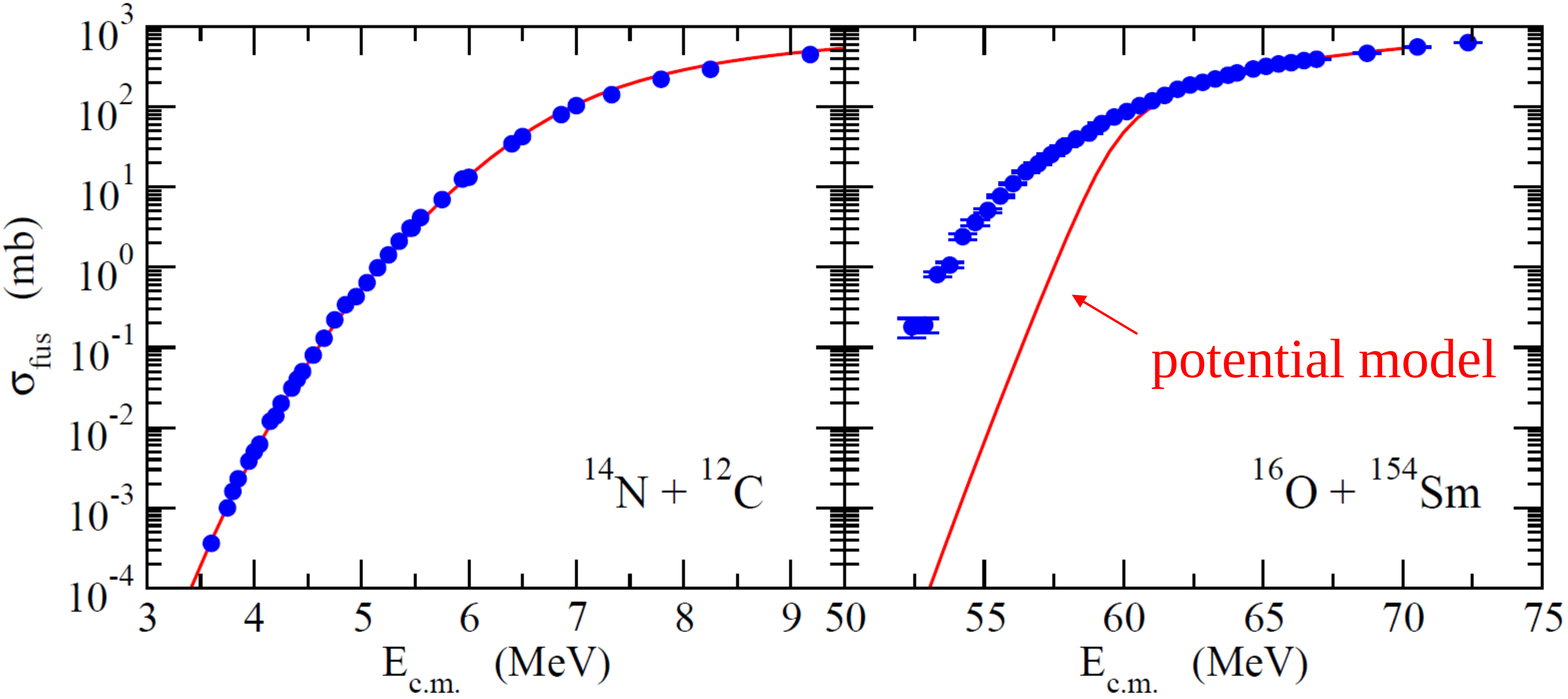
▪α decays: fixed energy

H.I. fusion reaction = an ideal playground to study quantum tunneling with many degrees of freedom

Large enhancement of fusion cross sections

Potential model: $V(r)$ + absorption

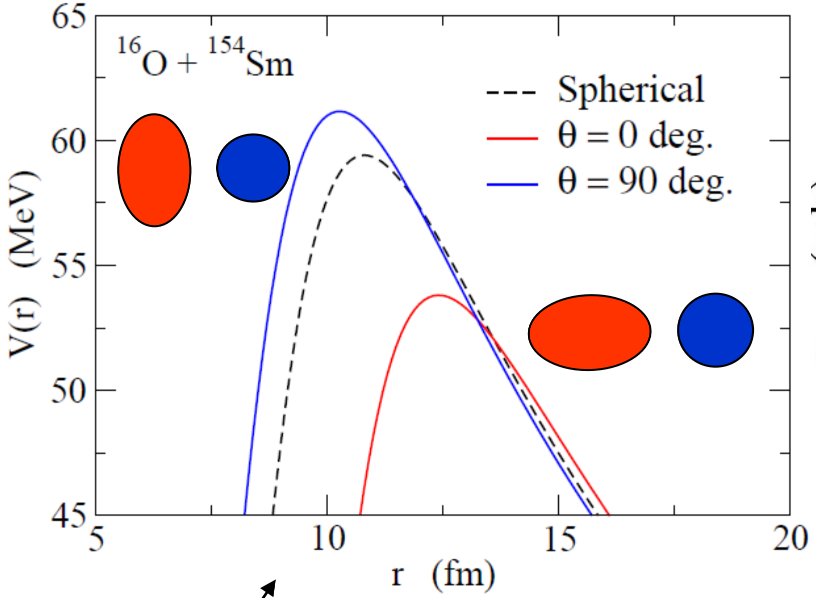
$$\boxed{\sigma_{\mathrm{fus}} = \frac{\pi}{k^2}\sum_l (2l+1)(1-|S_l|^2)}$$

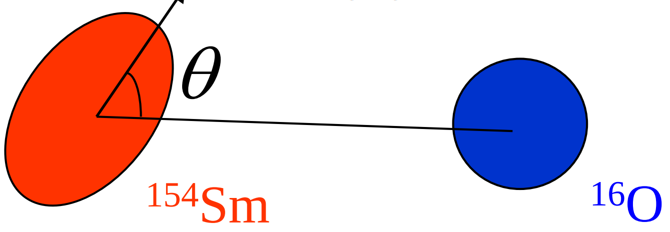


cf. seminal work:
R.G. Stokstad et al., PRL41('78) 465

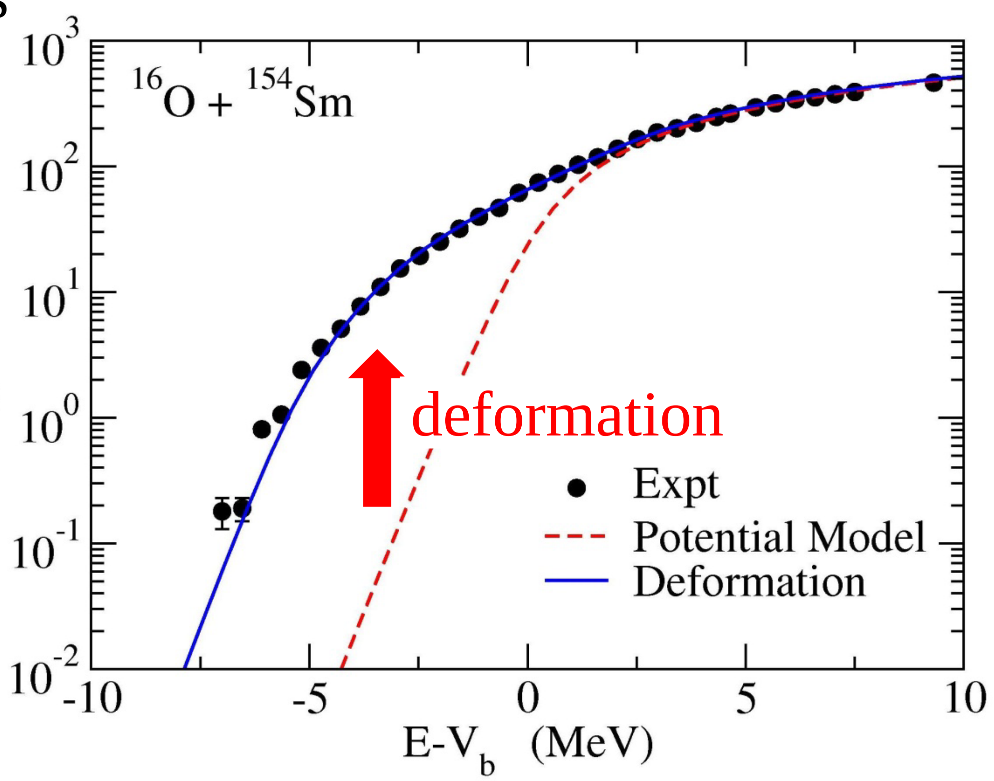
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus





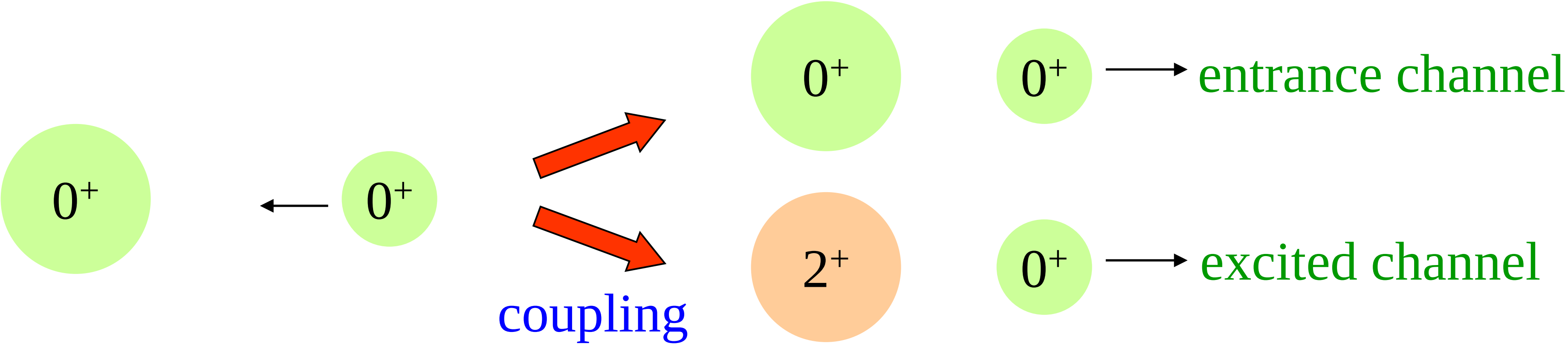
$$\boxed{\sigma_{\rm fus}(E) = \int_0^1 d(\cos\theta)\sigma_{\rm fus}(E;\theta)}$$



Fusion: strong interplay between nuclear structure and reaction

* Sub-barrier enhancement also for non-deformed targets:
couplings to low-lying collective excitations → coupling assisted tunneling

Coupled-channels method: a quantal scattering theory with excitations



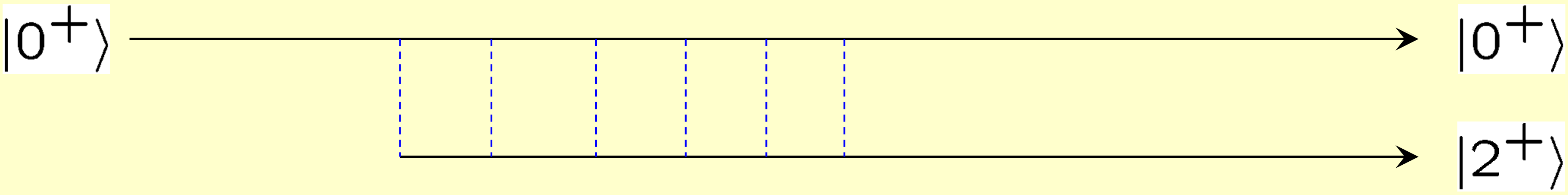
entrance channel

excited channel

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) + \epsilon_k - E\right]\psi_k(\boldsymbol{r}) + \sum_{k'}\langle\phi_k|V_{\mathrm{coup}}|\phi_{k'}\rangle\psi_{k'}(\boldsymbol{r}) = 0$$

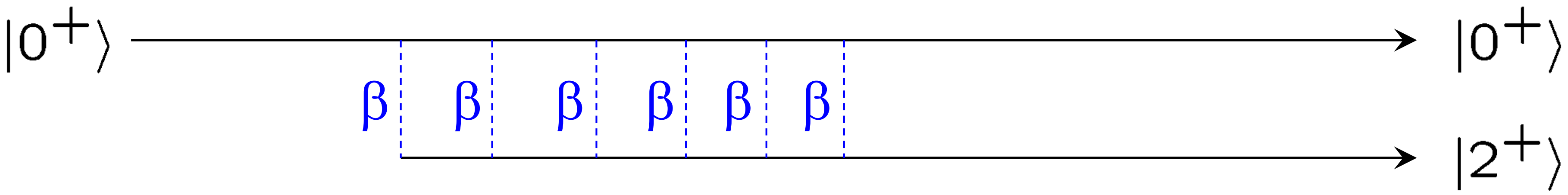
excitation energy

excitation operator



full order treatment of excitation/de-excitation dynamics during reaction

Inconsistency in linear coupling approximation



full order treatment of excitation/de-excitation dynamics during reaction

but only 1st order in Hamiltonian → inconsistency

$$V_{\mathrm{coup}}(r) \sim -R\beta\,\frac{dV_N(r)}{dr}$$

→ improve to include all orders also in Hamiltonian

$$\langle\phi_n|V(r-x)|\phi_m\rangle \sim V(r)\,\delta_{n,m} - \frac{dV(r)}{dr}\,\langle\phi_n|x|\phi_m\rangle$$

⇒ $$\boxed{\langle\phi_n|V(r-x)|\phi_m\rangle = \int dx\,\phi_n^*(x)\phi_m(x)\,V(r-x)}$$

K. Hagino, N. Takigawa, M. Dasgupta, D.J. Hinde,
and J.R. Leigh, PRC55 (‘97) 276

Inconsistency in linear coupling approximation

$$\boxed{\langle\phi_n|V(r-x)|\phi_m\rangle = \int dx\,\phi_n^*(x)\phi_m(x)\,V(r-x)}$$

improve to include all orders also in Hamiltonian

K. Hagino, N. Takigawa, M. Dasgupta, D.J. Hinde,
and J.R. Leigh, PRC55 (‘97) 276

later improvement: a more elegant method

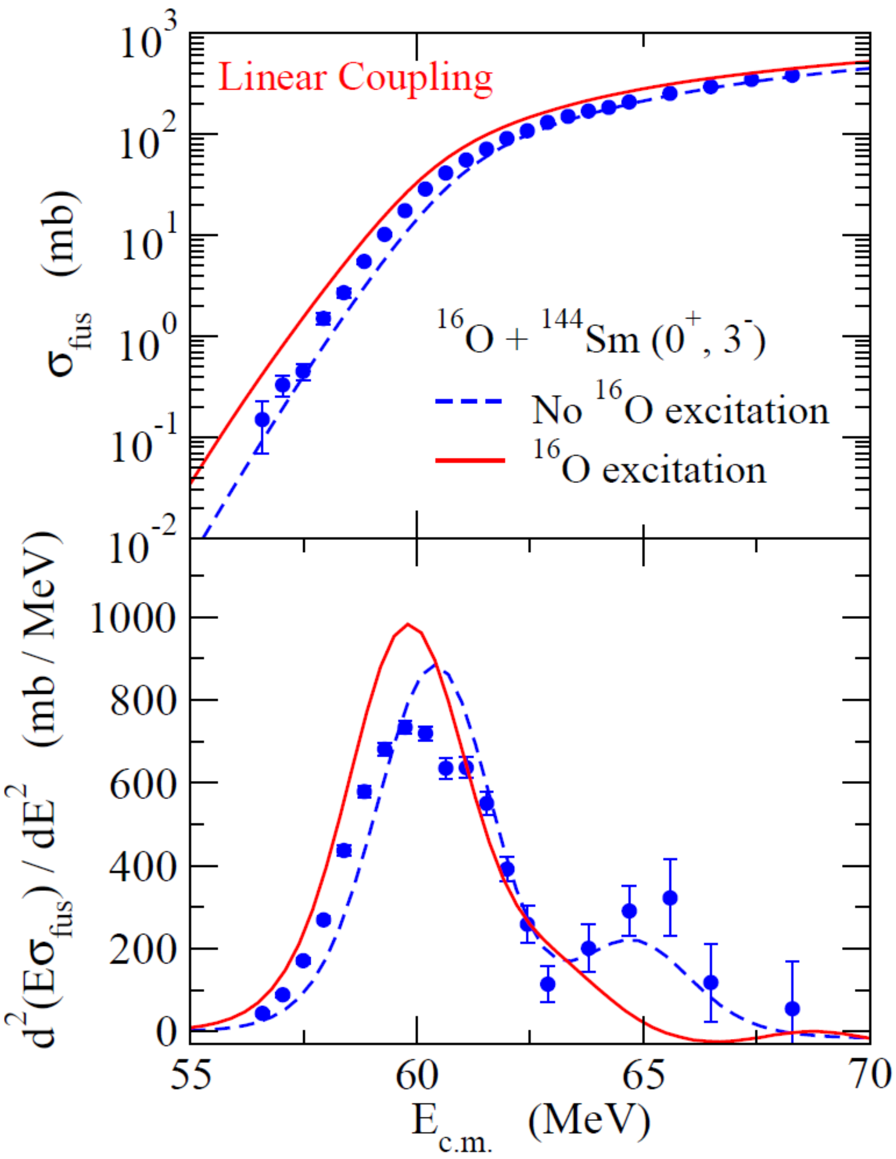
$$V(r-x) \to V(r-\{x_{nm}\}); \qquad x_{nm} = \langle\phi_n|x|\phi_m\rangle$$

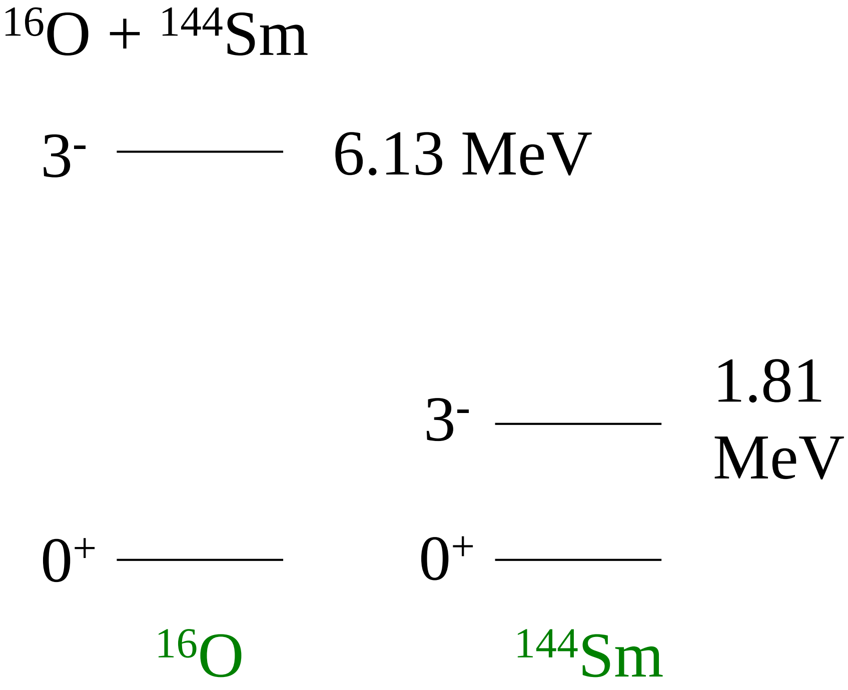
$$\Longrightarrow \quad \langle\phi_n|V(r-x)|\phi_m\rangle = \sum_k \langle\phi_n|u_k\rangle\,V(r-\lambda_k)\,\langle u_k|\phi_m\rangle$$

$$\hat{x}|u_k\rangle = \lambda_k|u_k\rangle$$

K. Hagino, N. Rowley, and A.T. Kruppa, CPC 123 (‘99) 143

the situation before 1997





^{16}O + ^{144}Sm

3^- 6.13 MeV

3^- 1.81 MeV

0^+ 0^+

^{16}O ^{144}Sm

✓ good reproduction if ^{16}O excitations are ignored

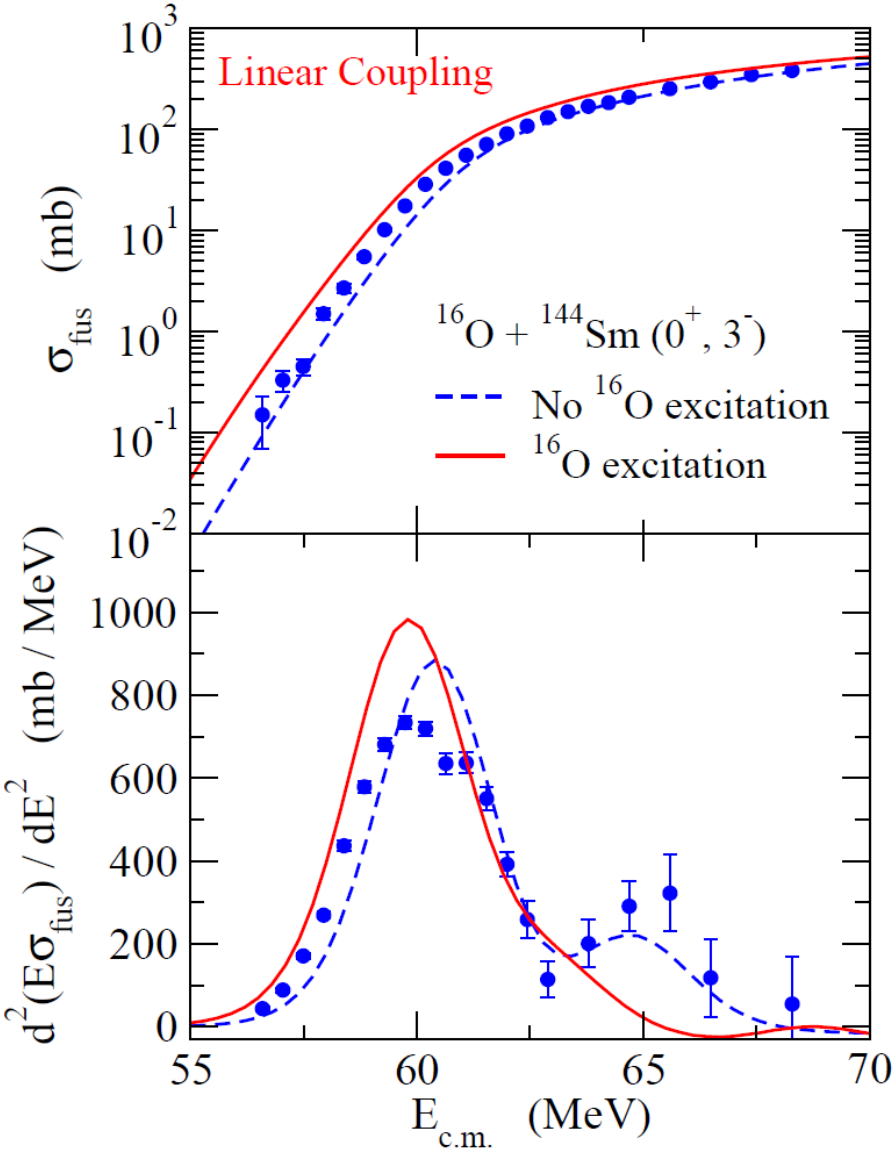
✓ worsen if ^{16}O excitations are taken into account

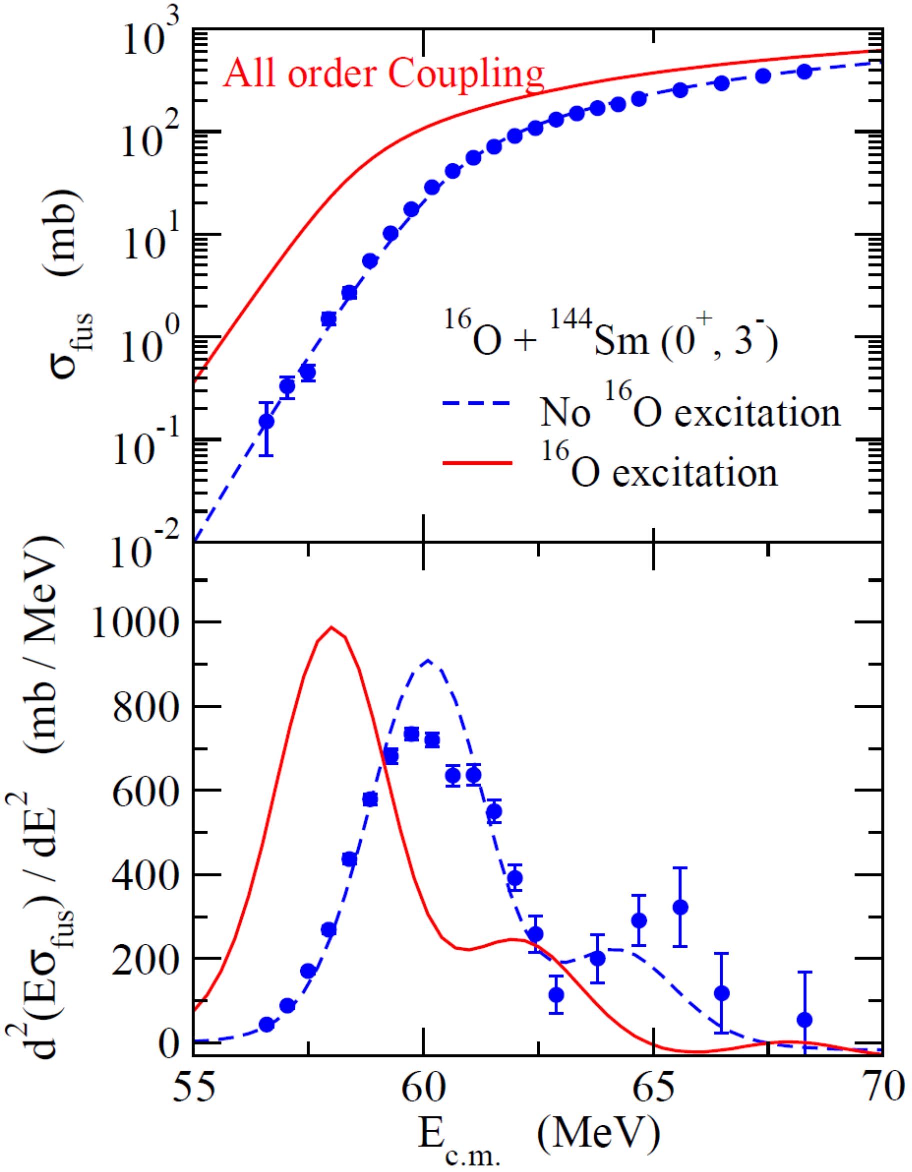
similar situation also in other reactions with ^{16}O

→ a big puzzle at that time

importance of consistent treatment

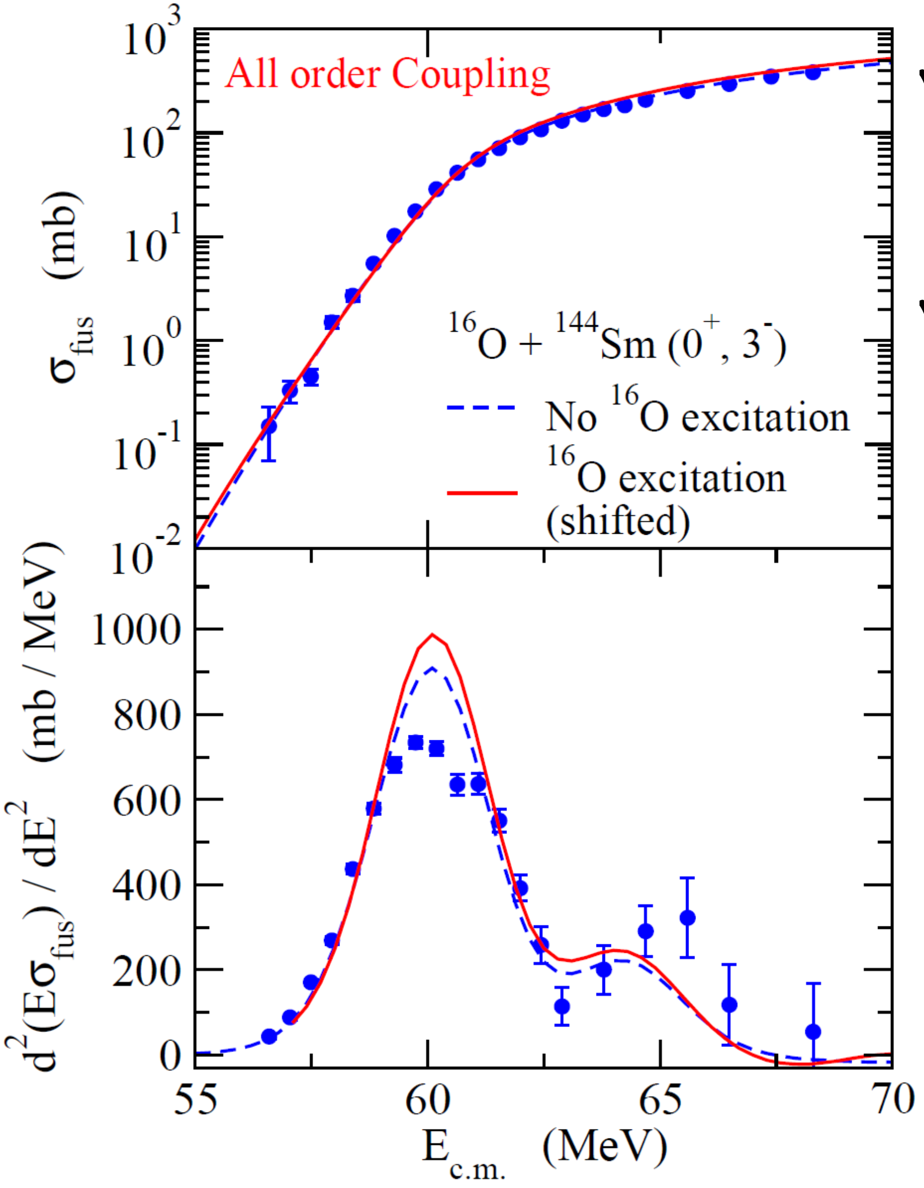
solution: all order couplings





K. Hagino, N. Takigawa, M. Dasgupta, D.J. Hinde, and J.R. Leigh, PRL79 (‘97) 2014

Adiabatic potential renormalization



- ✓ couplings to high-lying states
  : no change in *E*-dependence of fusion cross sections
- ✓ simply changes the static potential
  (adiabatic potential renormalization)

coupled-channels calculations: sufficient only with low-lying excitations

K. Hagino, N. Takigawa, M. Dasgupta, D.J. Hinde, and J.R. Leigh, PRL79 (‘97) 2014

CCFULL : a standard code in heavy-ion sub-barrier fusion reactions

K. Hagino, N. Rowley, A.T. Kruppa, CPC123 ('99) 143

CCFULL：a standard code in heavy-ion sub-barrier fusion reactions

K. Hagino, N. Rowley, A.T. Kruppa, CPC123 ('99) 143

my international collaborations with CCFULL (experimental groups)

My theory collaborations on heavy-ion fusion reactions

(black: collaborations on other topics)

Further developments : C.C. with several nuclear structure models

Inputs for C.C. calculations

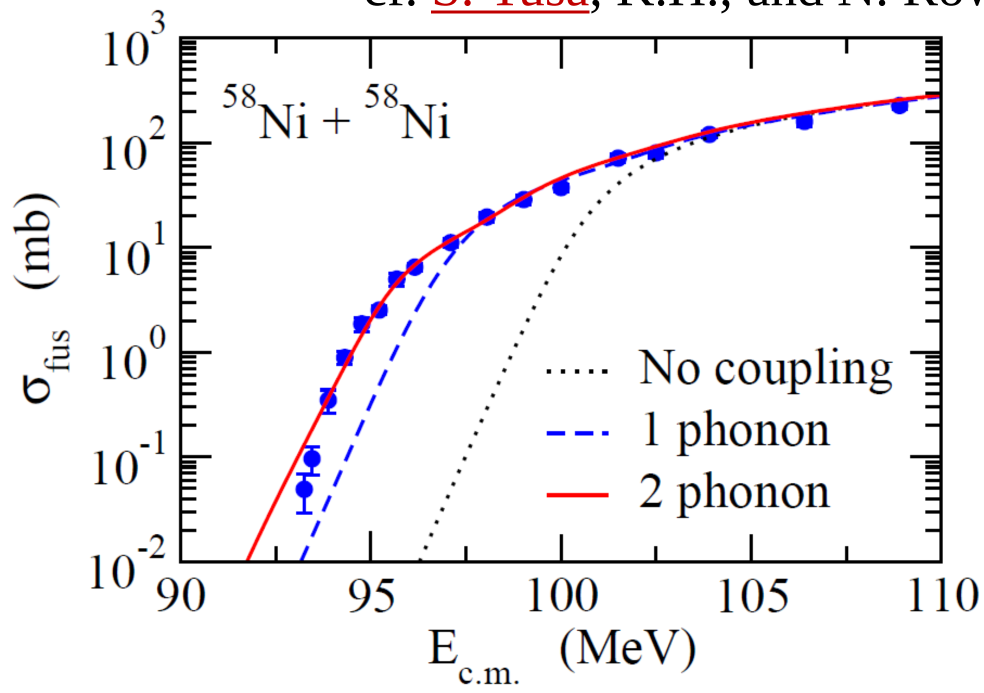
i) Inter-nuclear potential

a fit to experimental data at above barrier energies

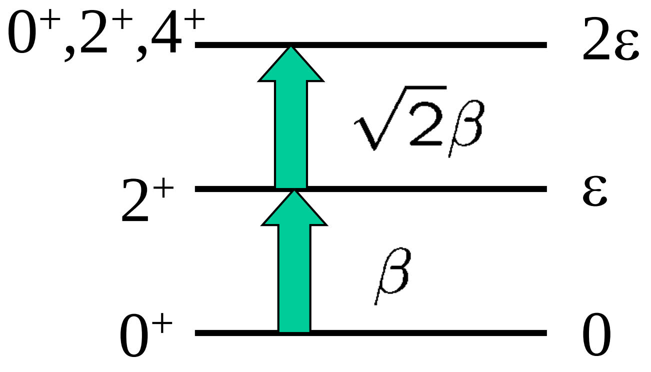
ii) Intrinsic degrees of freedom

in most of cases, (macroscopic) collective model
(rigid rotor / harmonic oscillator)

cf. S. Yusa, K.H., and N. Rowley, Phys. Rev. C88 ('13) 054621

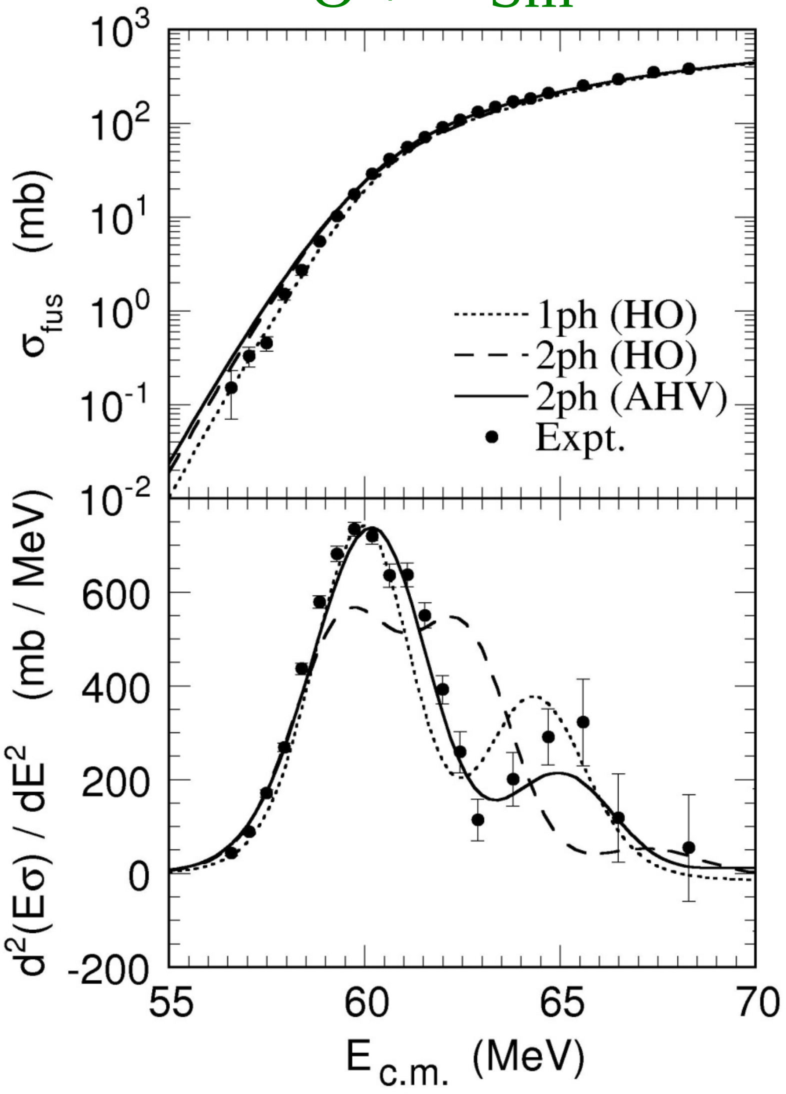


simple harmonic oscillator



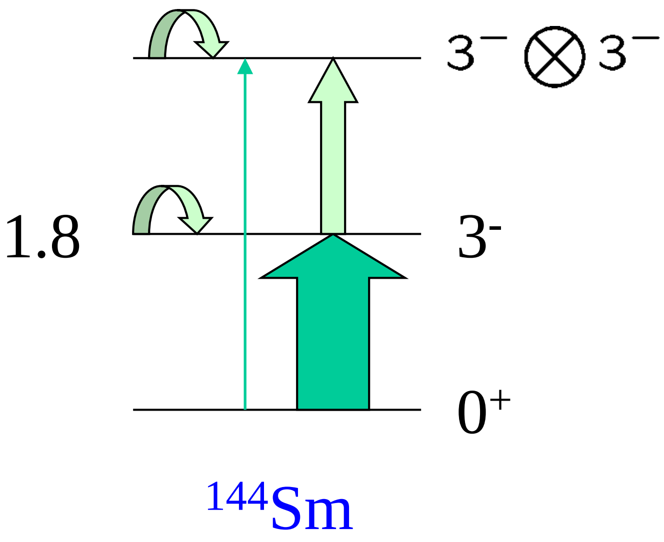
analysis with Interacting Boson Model (IBM)

^{16}O + ^{144}Sm



K.Hagino, N. Takigawa, and S. Kuyucak,
PRL79('97)2943

anharmonic vibrations

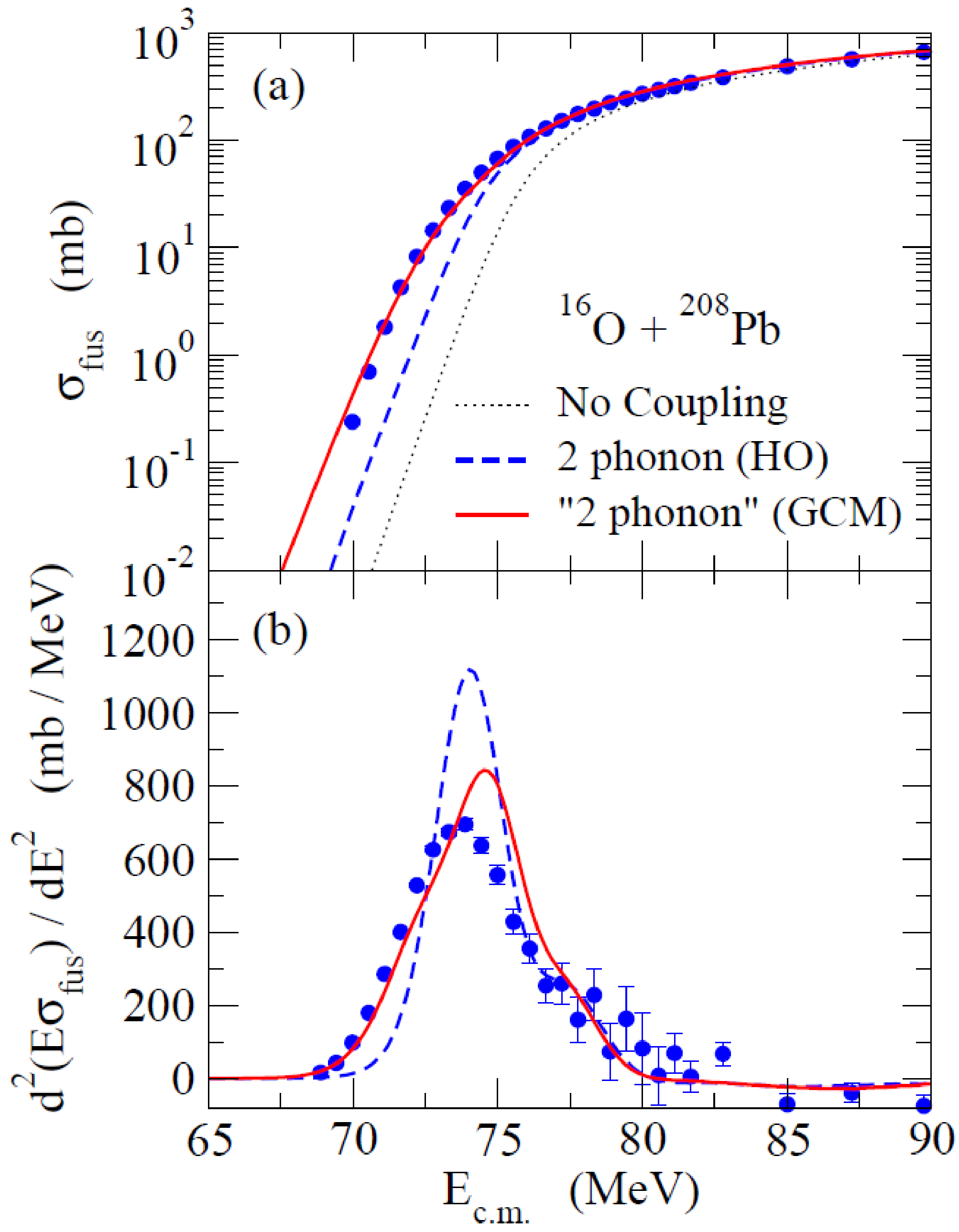


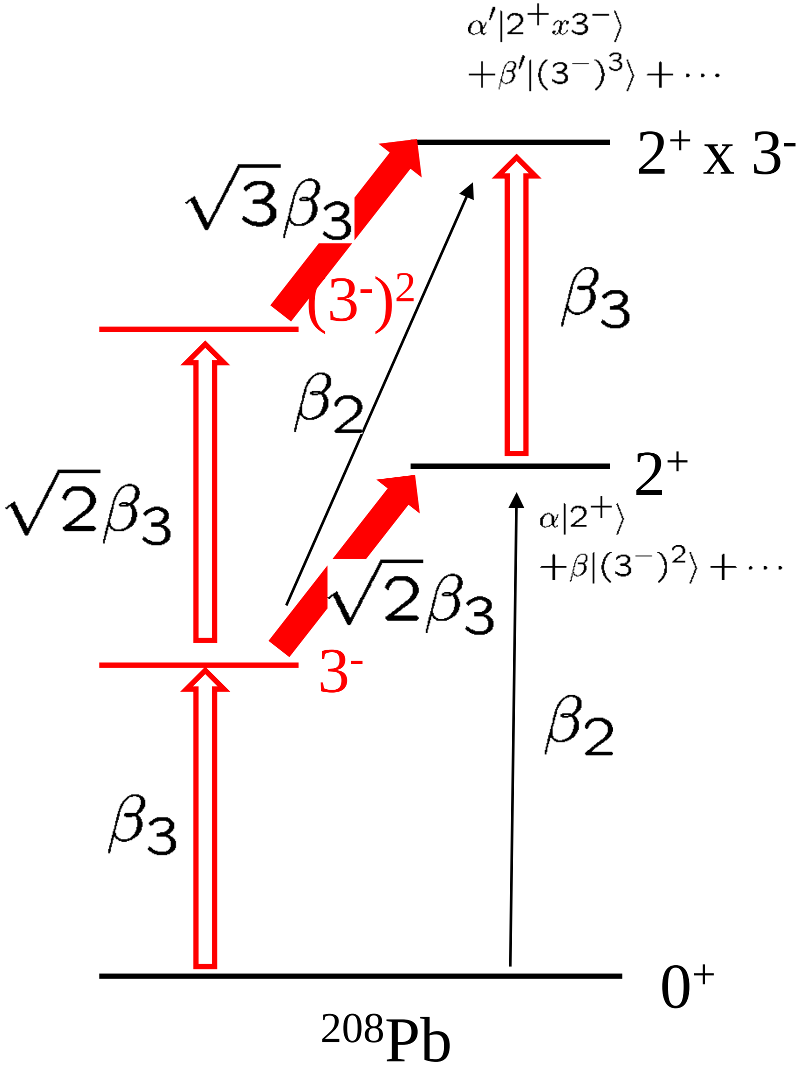
quadrupole moment:

$$Q(3^-) = -0.70 \pm 0.02\text{b}$$

* on-going:
a model development
with E. Williams at ANU
(CCFULL + IBM)

Relativistic Mean-Field + fluctuation of MF (GCM) + C.C.

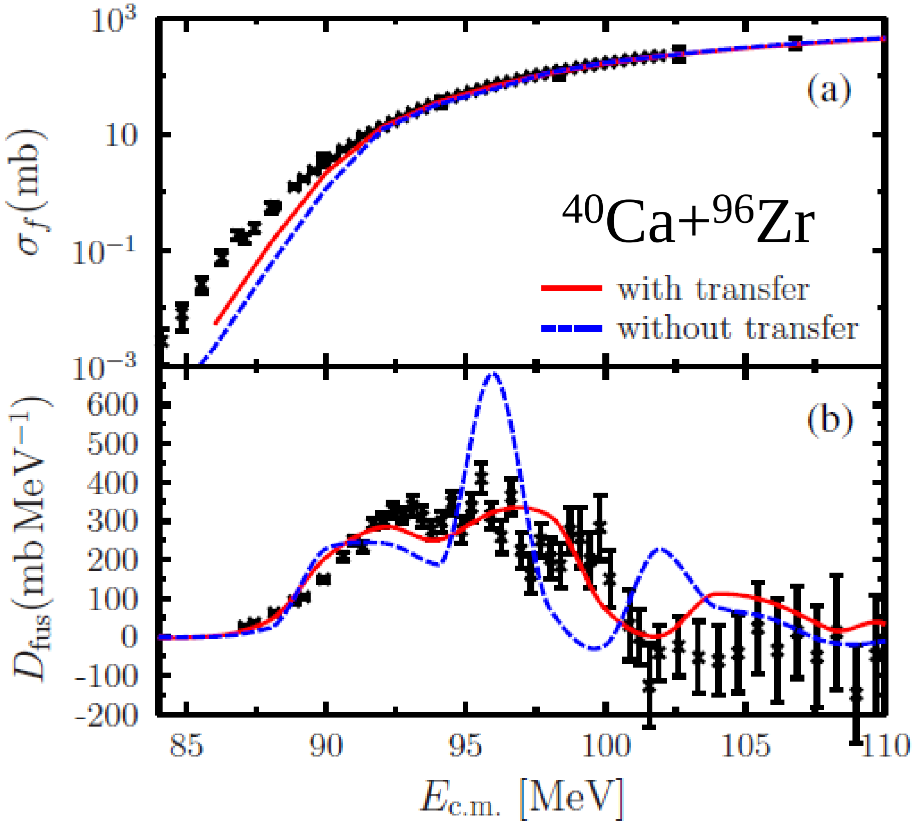




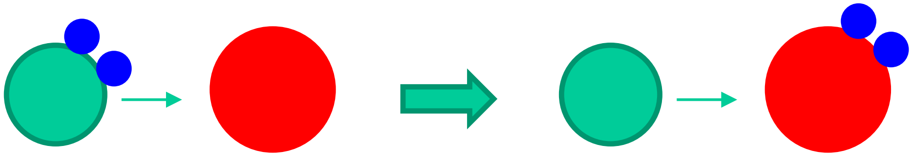
J.M. Yao and K. Hagino,
PRC94 (‘16) 11303(R)

Remaining challenges

1. Interplay between fusion and (multi-) nucleon transfer processes



G. Scamps and K. Hagino,
PRC92 ('16) 054616



fusion with multi-nucleon transfer
: needs a further development

◆ explain simultaneously
fusion and transfer cross sections?

◆ reaction dynamics of pair transfer?

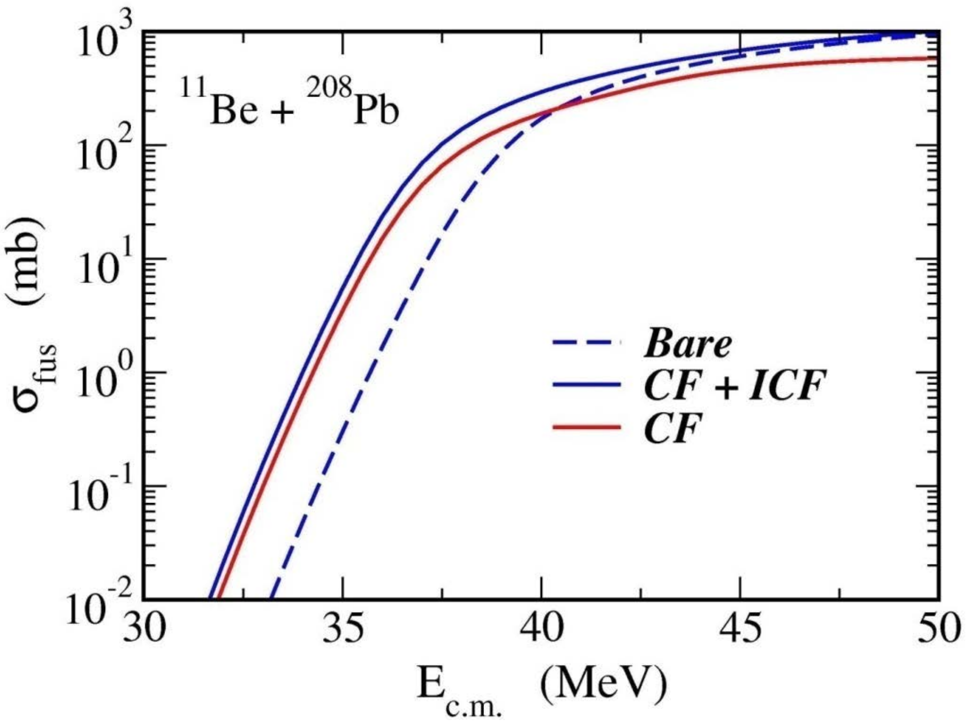
cf. pairing in neutron-rich nuclei

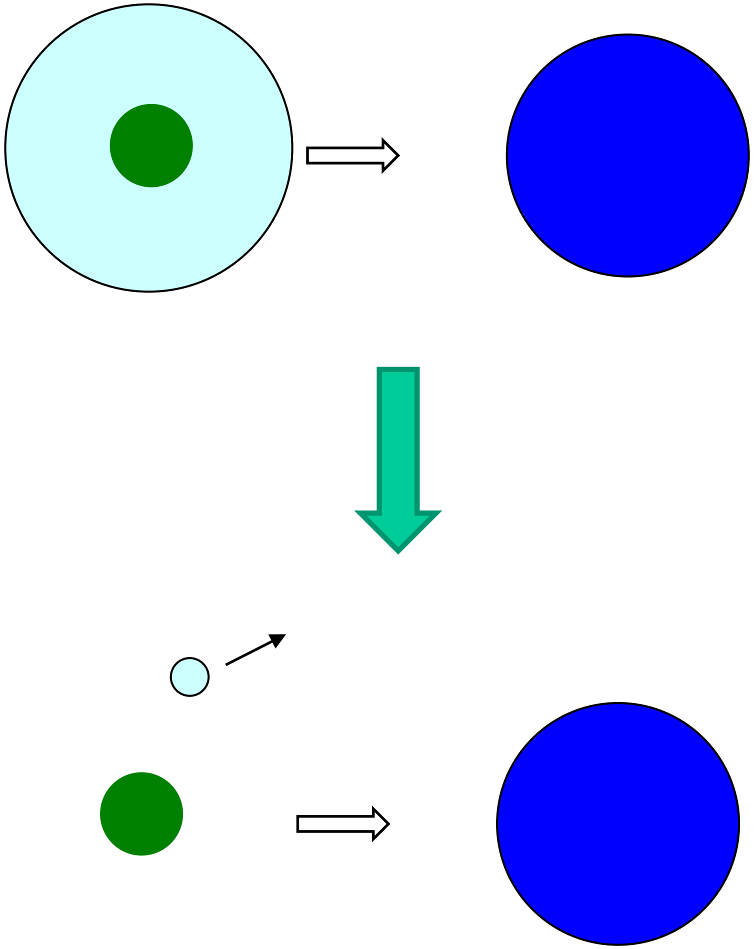
K. Hagino and H. Sagawa,
PRC72 ('05) 044321

Remaining challenges

2. Fusion of halo nuclei

calculations with breakup channels



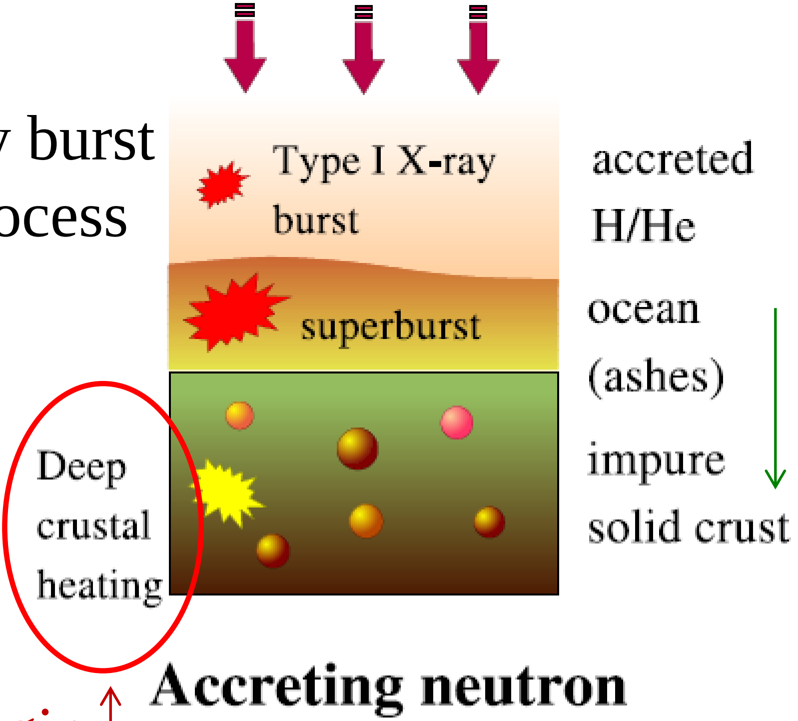


K. Hagino, A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 ('00) 037602

→ needs an extension with breakup and particle transfer at the same time

fusion of neutron-rich nuclei in accreting（質量降着）neutron stars

X-ray burst
rp-process



origin ↑

fusion of neutron-rich nuclei
when Z becomes small enough

^{24}O + ^{24}O, ^{28}Ne + ^{28}Ne etc.

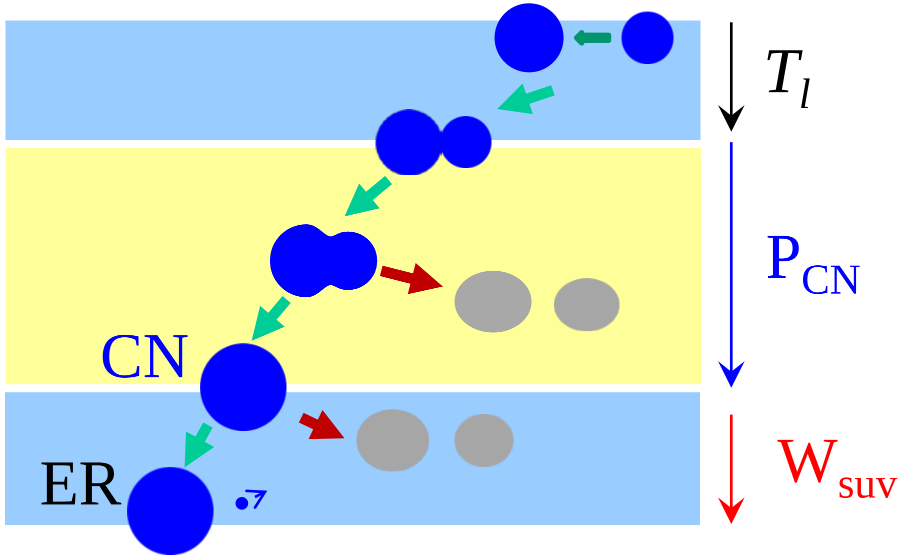
electron capture

$(A,Z) + e^- \rightarrow (A,Z-1) + \nu_e$

towards neutron-rich nuclei

N. Chamel and P. Haensel,
Living Rev. Relativity, 11 (‘08) 10.

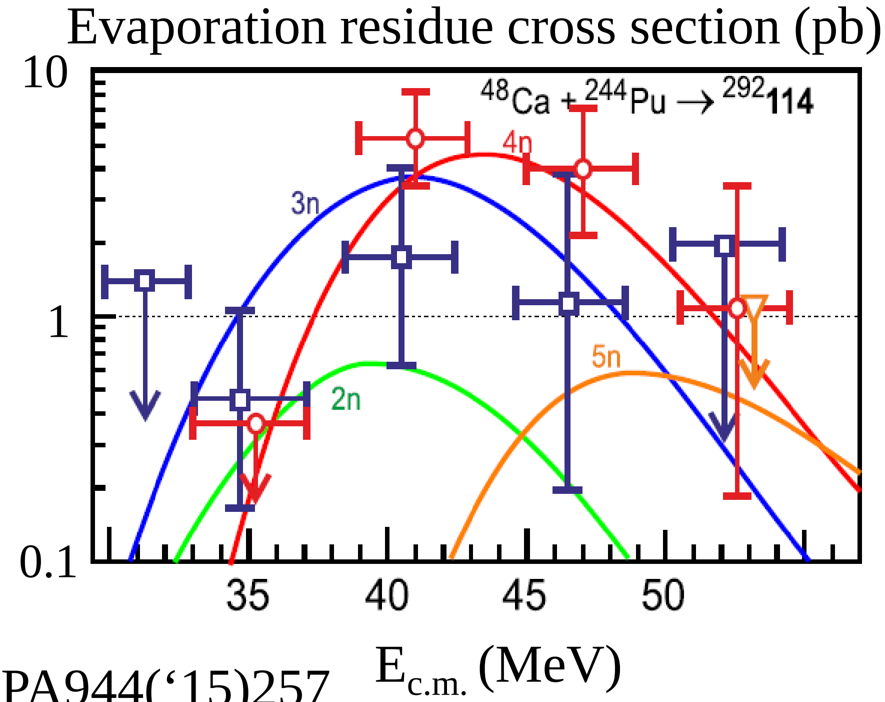
Future perspectives: Superheavy elements



CN = compound nucleus
ER = evaporation residue

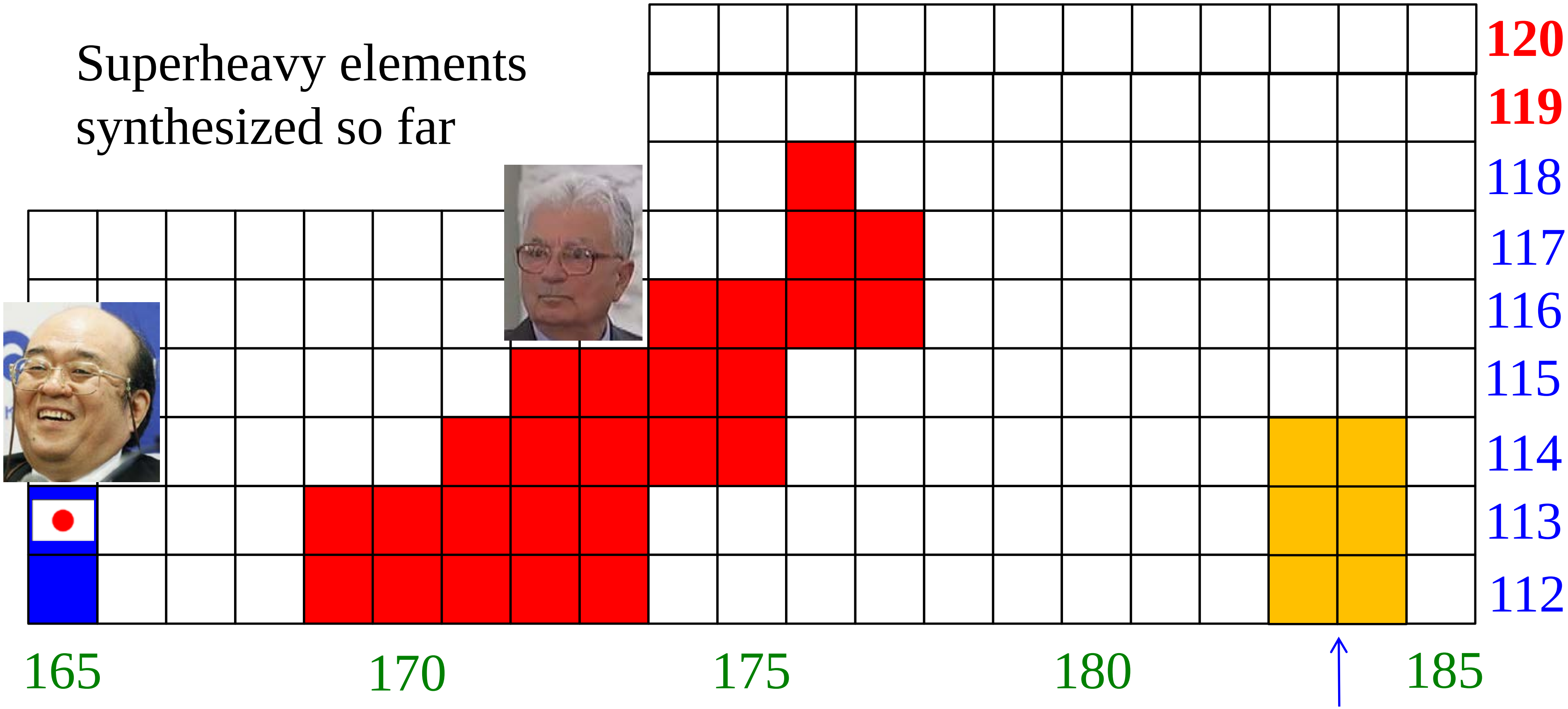
$$\sigma_{\rm ER}(E) = \frac{\pi}{k^2}\sum_l (2l+1)T_l(E) \times P_{\rm CN}(E,l)\, W_{\rm suv}(E^*,l)$$

cf. no experimental data for P_{CN}
→ large uncertainty



V.I. Zagrebaev and W. Greiner, NPA944('15)257

Future directions



Superheavy elements synthesized so far

the island of stability?

- Towards Z=119 and 120 nuclei

  reaction dynamics? reliable prediction of fusion cross sections?

- Towards the island of stability

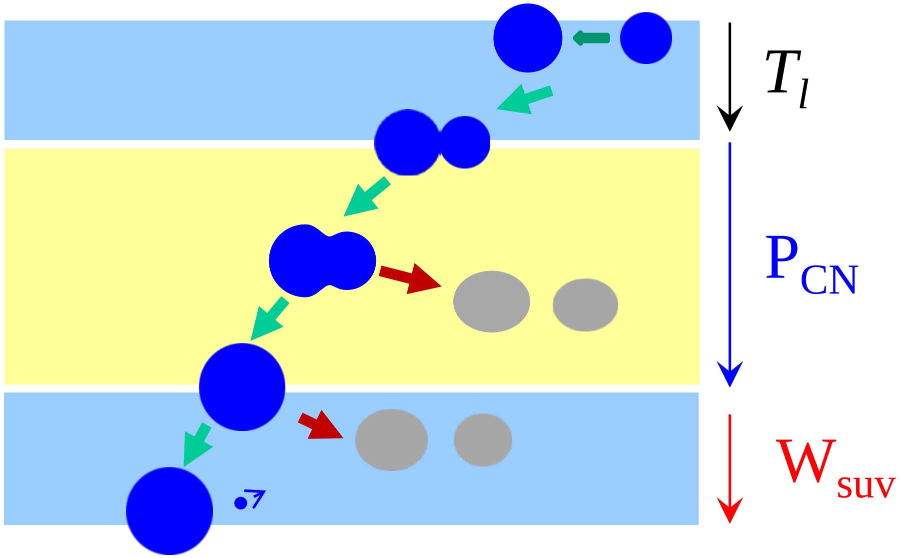
  neutron-rich beams: indispensable

Future directions -1

- Towards Z=119 and 120 nuclei

^{48}Ca projectile (hot fusion) → $^{50}_{22}$Ti, $^{51}_{23}$V, $^{54}_{24}$Cr projectile
+ deformed target nucleus

needs a proper understanding of deformation effects
on SHE synthesis reactions

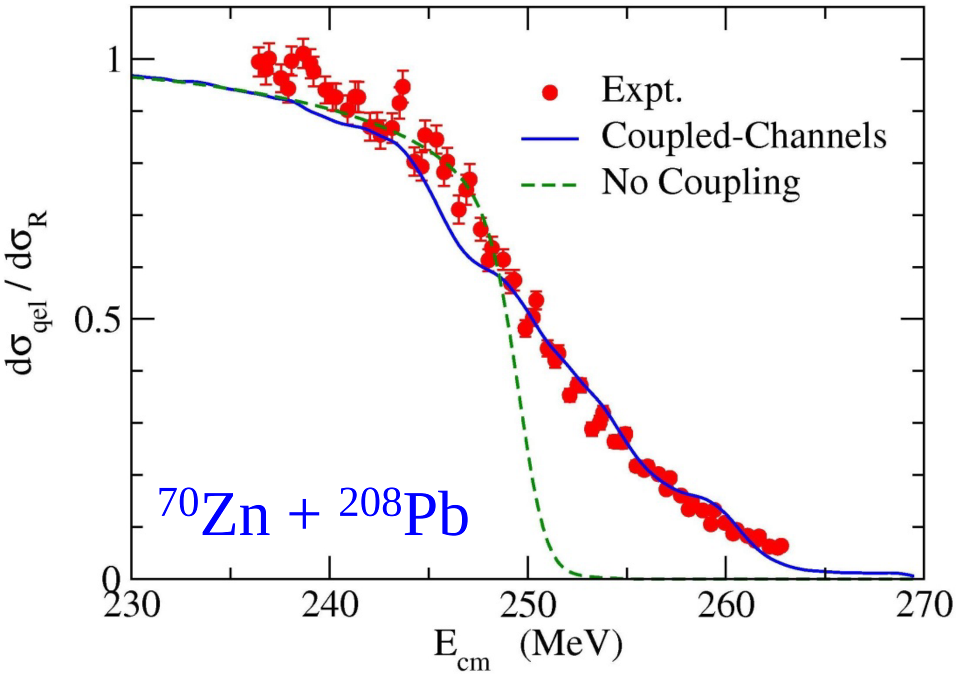


✓ First step:
how to extract T_l from σ_{cap}

$$\sigma_{\rm cap} = \frac{\pi}{k^2}\sum_l (2l+1)T_l$$

✓ Second step:
deformation effects on P_{CN}

Extraction of T_l from H.I. quasi-elastic (QEL) scattering (easier measurement than σ_{cap})



Exp. : Mitsuoka et al. (JAEA, 2007)

Calc.: M. Zamrun F. (Tohoku → Dean of Facul. Sci. at Haluoreo U.) , K. Hagino, S. Mitsuoka, and H. Ikezoe, PRC77('08)034604.

fitting of QEL data with a few barriers

✓ Bayesian statistics for the number of barriers
K. Hagino, PRC93 ('16) 061601(R)

⇩

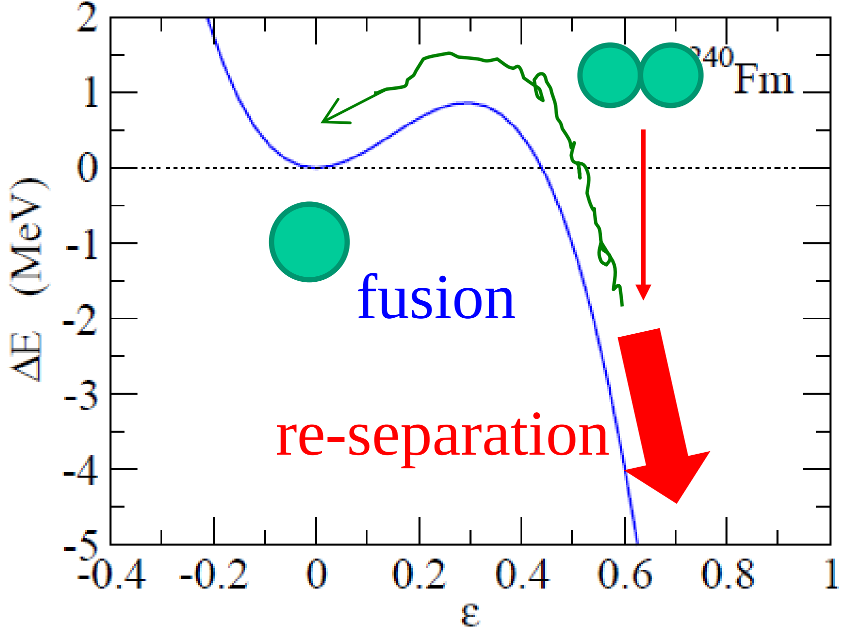
mapping from σ_{qel} to transmission probability T_l for the *l*-th partial wave

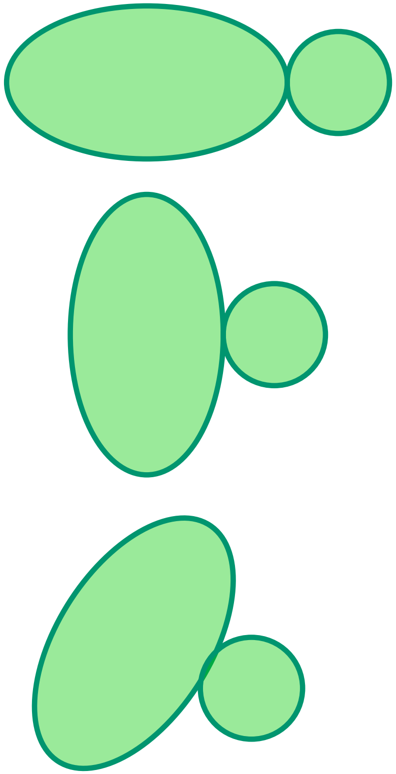
cf. Expt. of σ_{qel} with GARIS (Morita et al. ,2015)

Fusion reactions of deformed nuclei

Thermal activation

→ Langevin equation
(Brownian motion)





distant contact point
→ re-separation

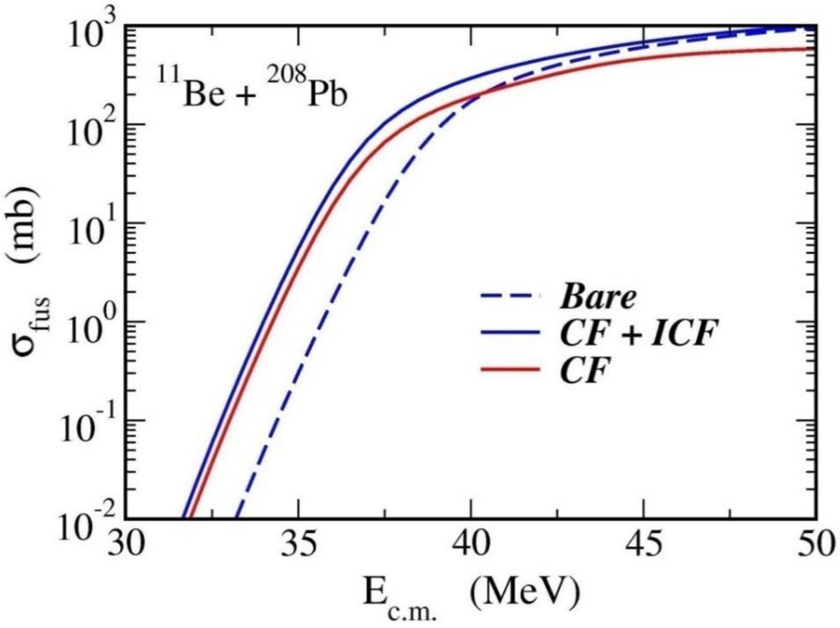
close contact point
→ advantage for
fusion

?

- ➢ how to evolve towards a compound nucleus?
  (what are intermediate shapes?)
- ➢ deformation: quantum effects
  how deformation reduces during the heat-up process?

Future directions - 2

- Towards the island of stability
  neutron-rich beams
  : indispensable

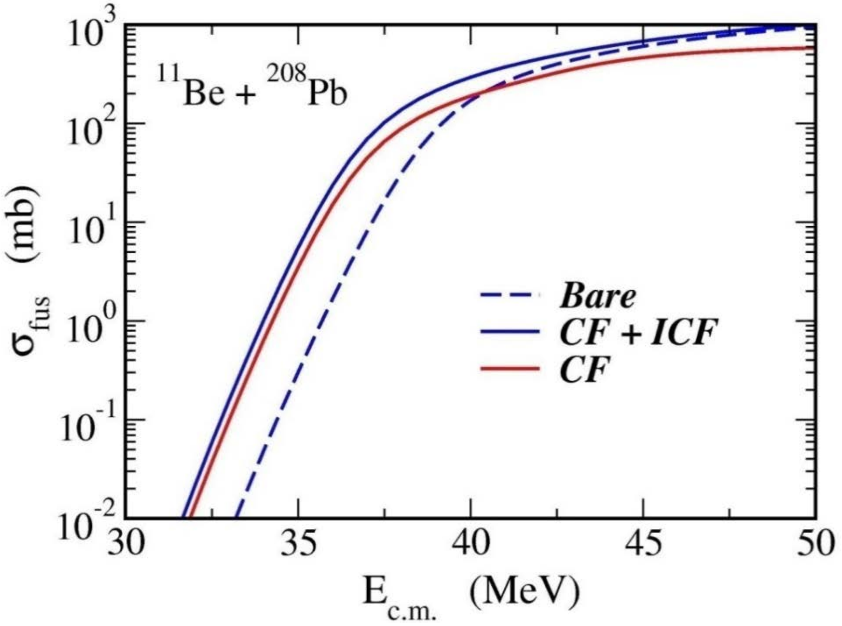


K. Hagino, A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 ('00) 037602

Understanding of reaction dynamics
(breakup, particle transfer, fusion)

Future directions - 2

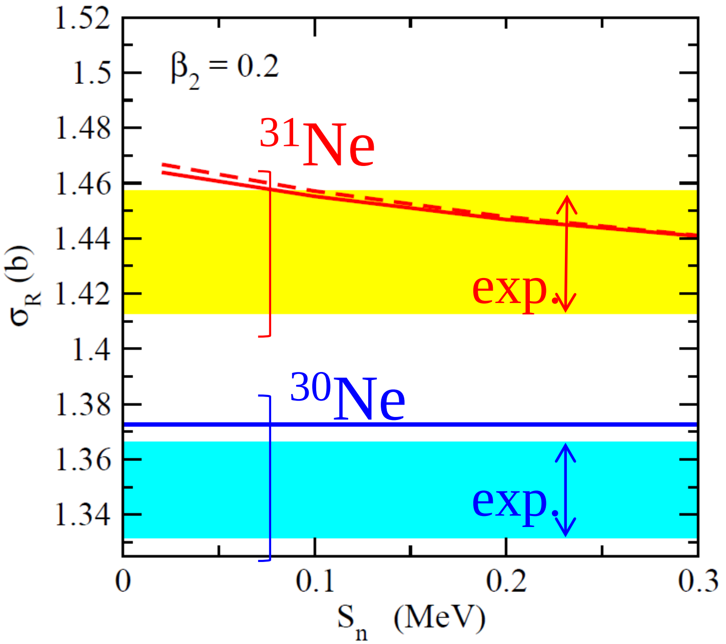
- Towards the island of stability
  neutron-rich beams
  : indispensable



K. Hagino, A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 ('00) 037602

+

structure of neutron-rich nuclei
: equally important



Y. Urata, K. Hagino, and H. Sagawa,
PRC86('12) 044613

F. Minato (JAEA)
T. Oishi (Padova U. PD)
Y. Tanimura (GSI PD)
Y. Urata

Understanding of reaction dynamics

possibilities of physics of SHE — with neutron-rich nuclei as a keyword

Summary

Heavy-ion fusion reactions around the Coulomb barrier

- ✓Strong interplay between nuclear structure and reaction
- ✓Quantum tunneling with various intrinsic degrees of freedom
- ✓theory of coupled-channels method and a world standard code
- ✓2 Ph.D. and 4 master students (out of 8 Ph.D. and 10 masters)

Remaining challenges

- ✓fusion of halo nuclei (influence of breakup and particle transfer)
- ✓Microscopic understanding of low-E fusion reactions?
- ✓ how to understand many-particle tunneling phenomena?
- ✓ microscopic understanding of large amplitude motions

Future perspectives: superheavy elements

- ✓ Towards heavier SHE (Z = 119, 120)
- ✓ Towards the island of stability

investigations of physics of SHE with neutron-rich nuclei as a keyword

From phenomenological approach to microscopic approach

Macroscopic (phenomenological)

C.C. with collective model

C.C. with inputs from microscopic nuclear structure calculations

- * Hagino-Yao
- * Ichikawa-Matsuyanagi

C.C. with inputs based on TDHF

- * Umar (DC-TDHF)
- * Washiyama-Lacroix

TDHF simulations

- * Simenel
- * Sekizawa
- * Washiyama
- * Iwata-Otsuka etc.

ab initio, but no tunneling

Microscopic

From phenomenological approach to microscopic approach

TDHF simulations
- Simenel
- Sekizawa
- Washiyama
- Iwata-Otsuka etc.

ab initio, but no tunneling

➢ "Beyond mean-field" approximations

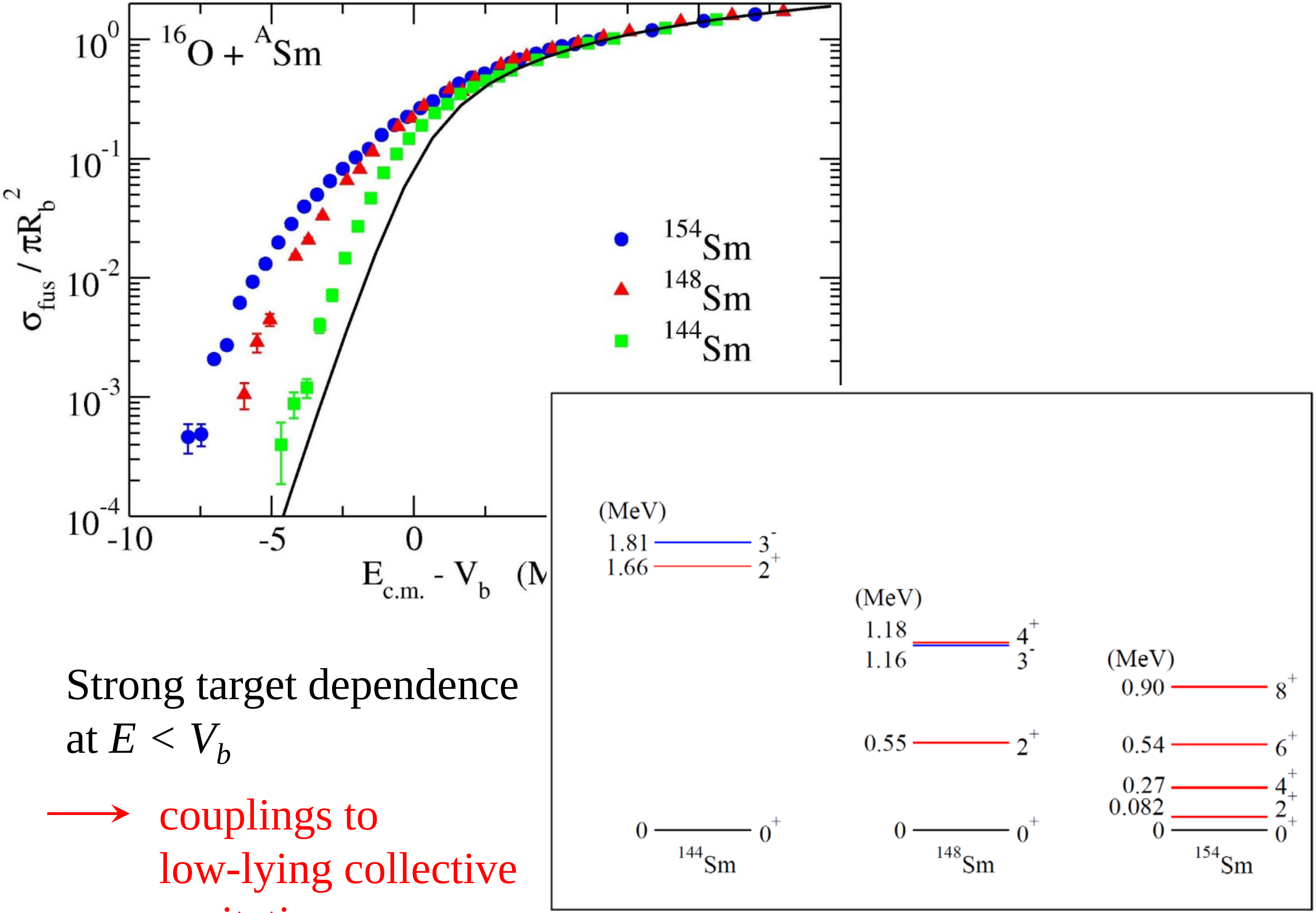
Nuclear structure: GCM $|\Psi\rangle = \int dq\, f(q)|\Phi_q\rangle$

Full time-dependent GCM? $|\Psi(t)\rangle = \int dq\, f(q,t)|\Phi_q(t)\rangle$

$\longrightarrow$ many-particle tunneling and large amplitude collective motions

* discussions with prof. Tsuyoshi Kato
(AP at U. of Tokyo, theoretical chemistry)

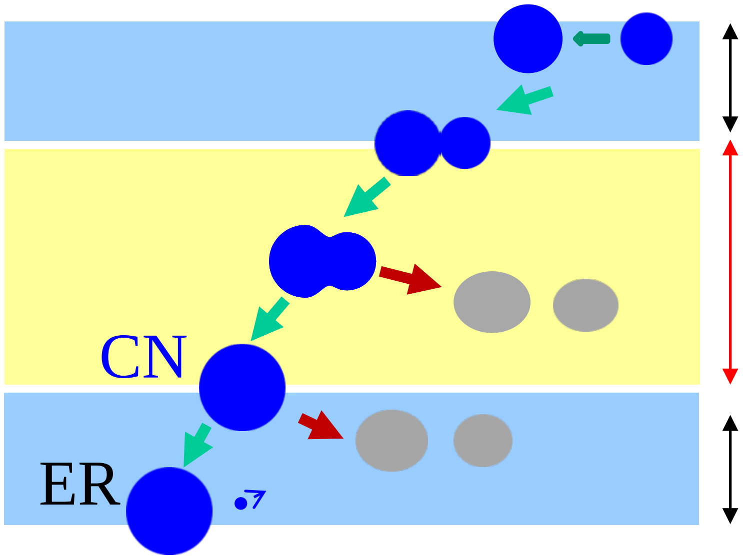
Back-up slides



Strong target dependence at $E < V_b$

→ couplings to low-lying collective excitations

Future perspectives: Superheavy elements



Coupled-channels method

Langevin equation

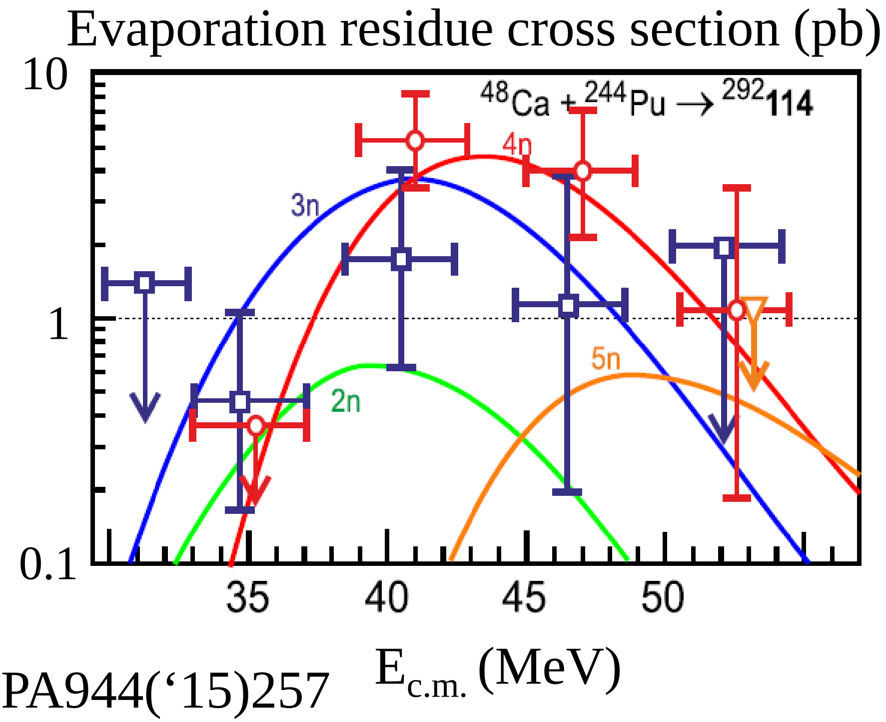
$$m\frac{d^2q}{dt^2} = -\frac{dV(q)}{dq} - \gamma\frac{dq}{dt} + R(t)$$

Statistical model (CN decay)

CN = compound nucleus
ER = evaporation residue

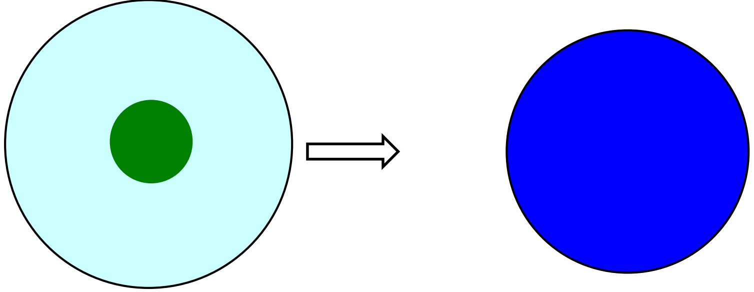
$$\sigma_{\rm ER}(E) = \frac{\pi}{k^2}\sum_l (2l+1)T_l(E) \times P_{\rm CN}(E,l)\, W_{\rm suv}(E^*,l)$$

cf. no experimental data for P_{CN}
→ large uncertainty



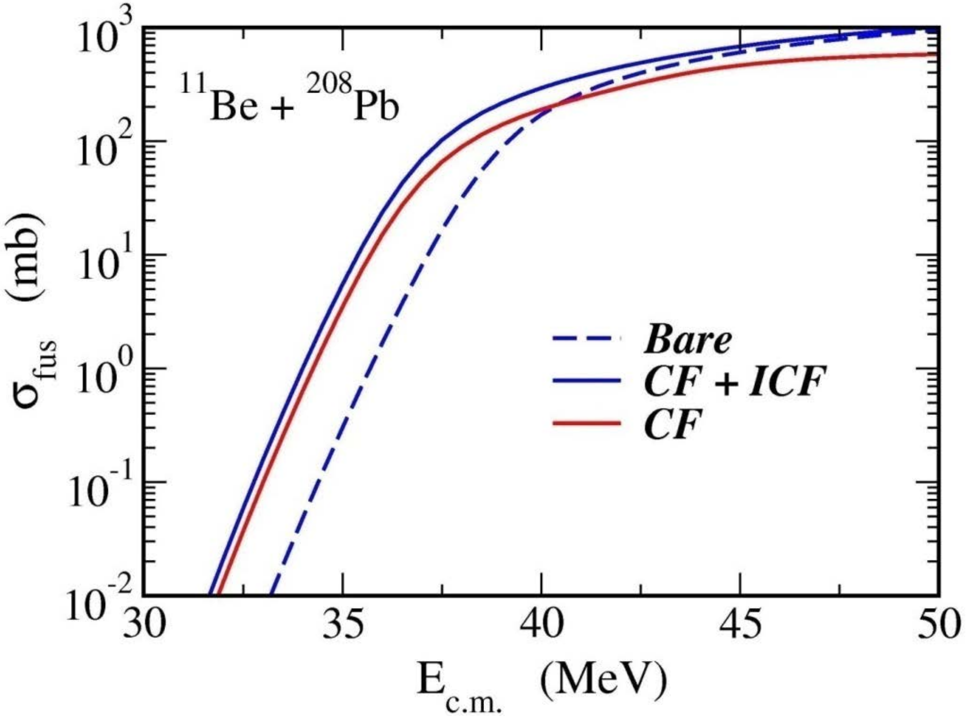
V.I. Zagrebaev and W. Greiner, NPA944('15)257

Remaining challenges

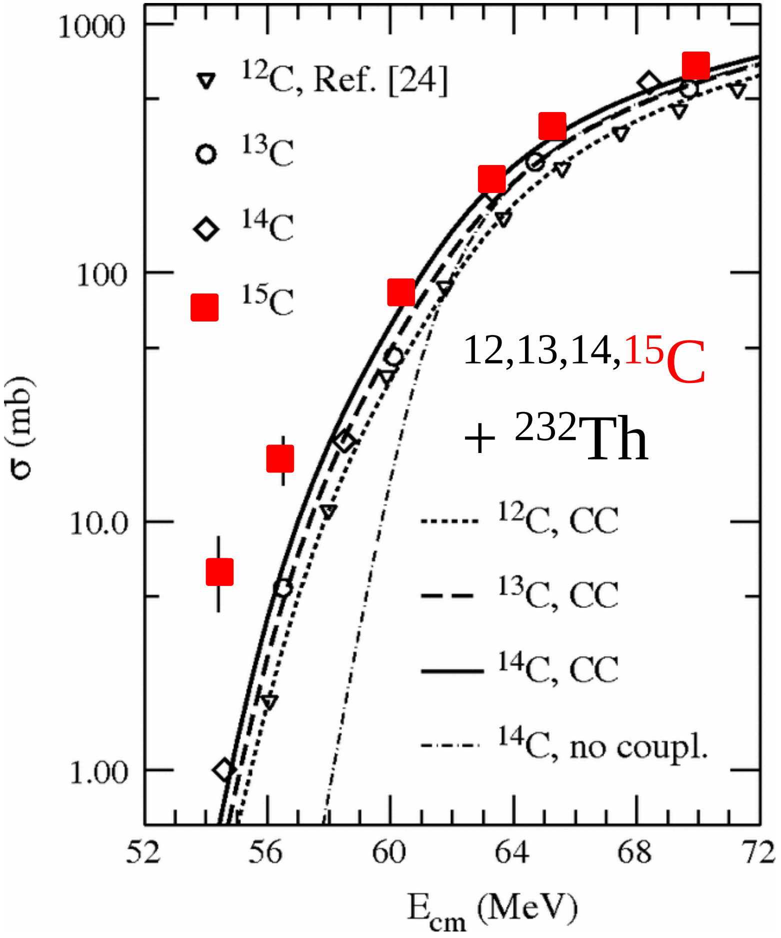


2. Fusion of halo nuclei

calculations with breakup channels



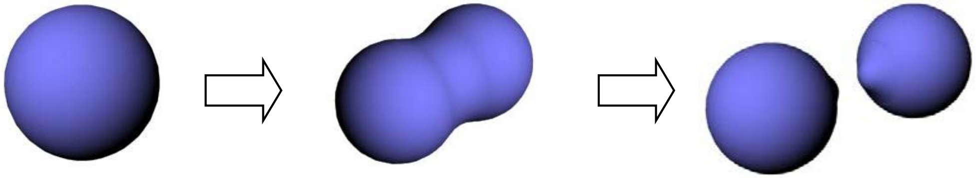
K. Hagino, A. Vitturi, C.H. Dasso,
and S.M. Lenzi, Phys. Rev. C61 ('00) 037602



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

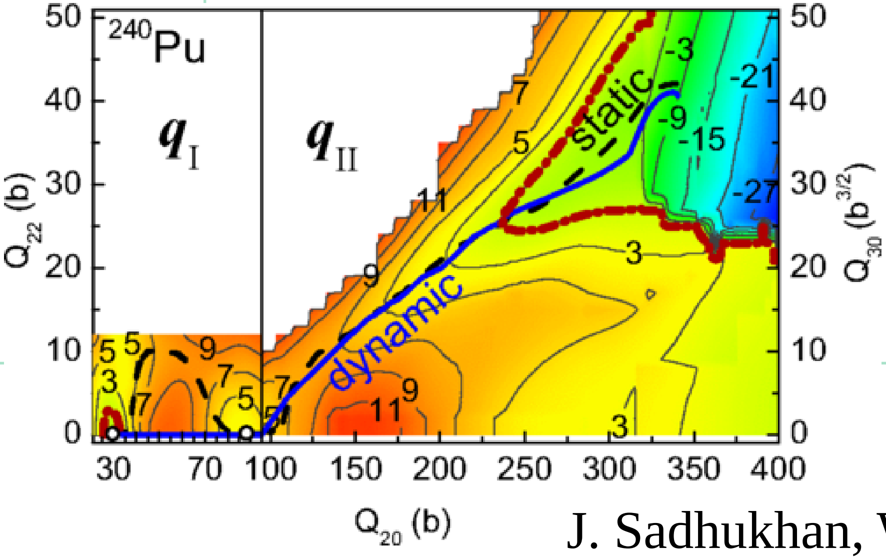
→ needs an extension with breakup and particle transfer at the same time

Fission



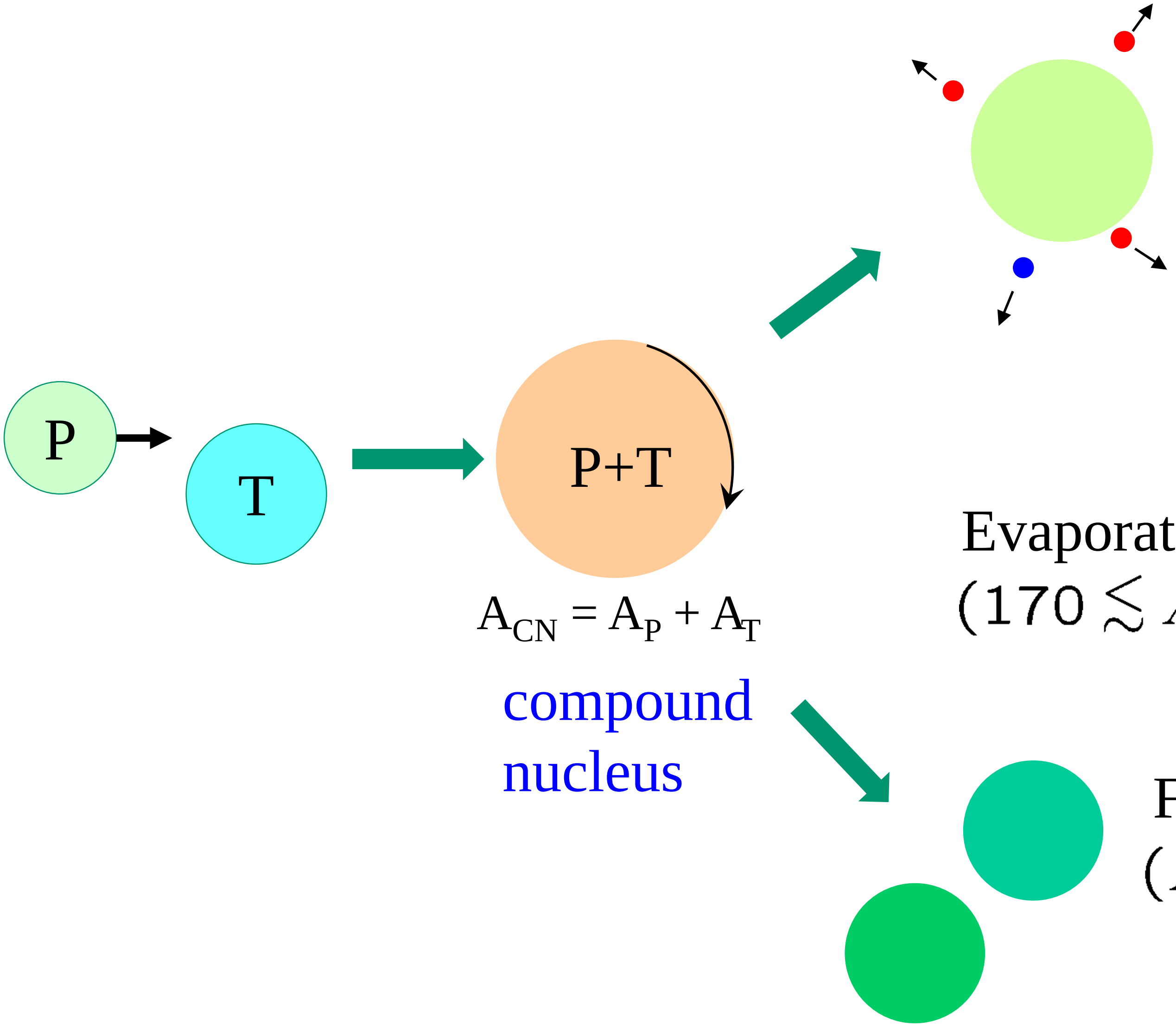
still a very challenging problem for nuclear theory

	Time-indep. approach	**Time-dep. approach**
Induced fission	✓Bohr-Wheeler	✓Langevin-type ✓Discrete basis (Bertsch)
Spontaneous fission	✓PES+Mass+WKB	✓Im.-time TDHF (Negele) ✓Time-dep. Hill-Wheeler (Goutte et al.) ✓TDHF (after the barrier)



J. Sadhukhan, W. Nazarewicz, N. Schunck, PRC93(‘16)011304(R)

Fusion reactions: compound nucleus formation



$A_{CN} = A_P + A_T$

compound nucleus

Evaporation

$(A_{\mathrm{CN}} \lesssim 170)$

n,p,α emissions

γ decay

Evaporation + Fission

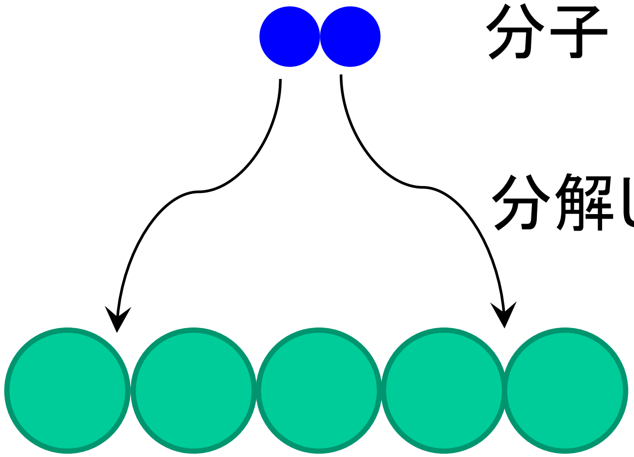
$(170 \lesssim A_{\mathrm{CN}} \lesssim 220)$

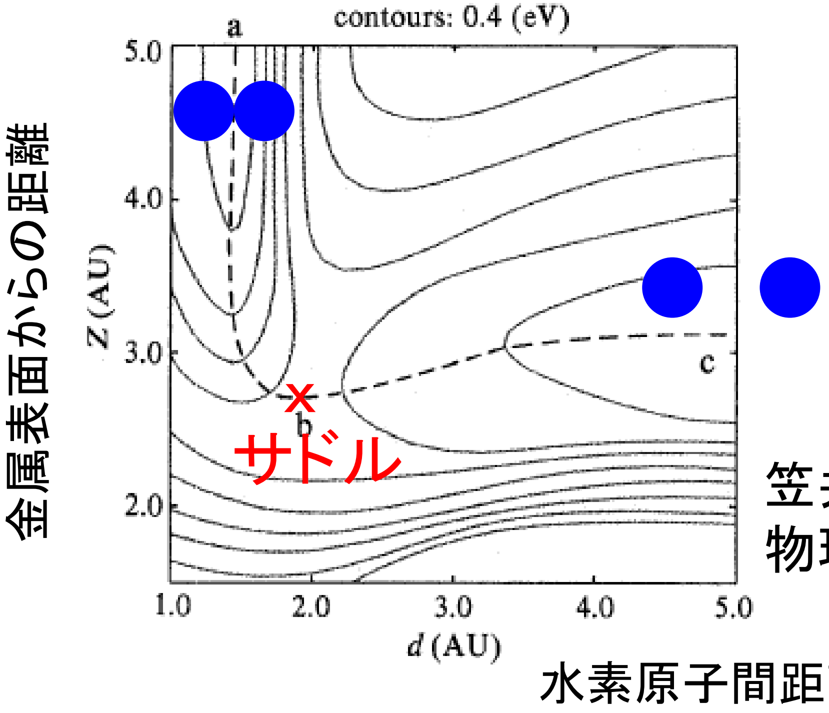
Fission

$(A_{\mathrm{CN}} \gtrsim 220)$

cf. superheavy elements

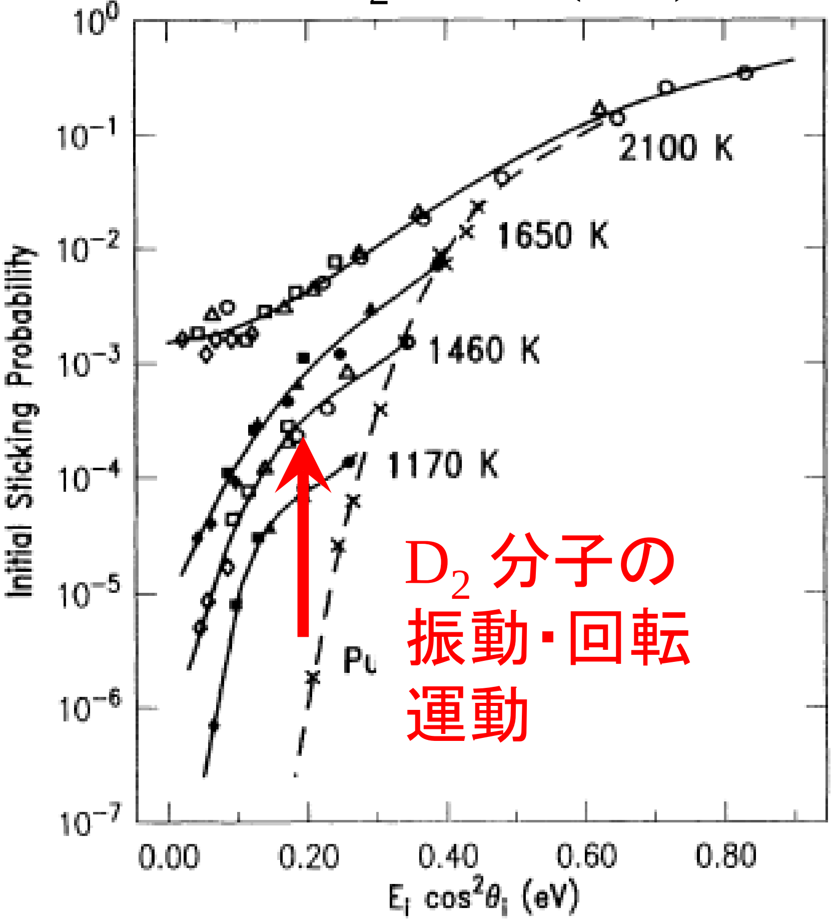
H_2/D_2 分子の金属表面への解離吸着





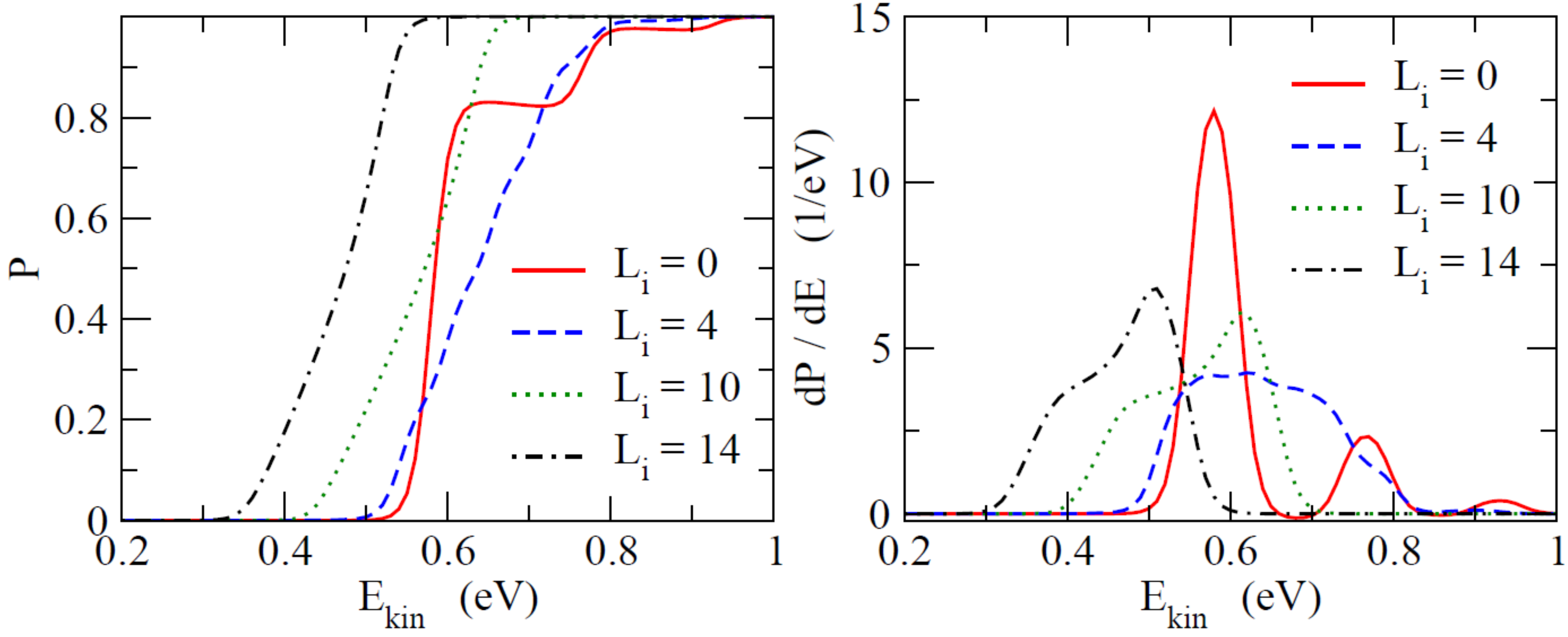
笠井、Dino、興地
物理学会誌 52 (‘97) 824

D_2 on Cu(111)



C.T. Rettner et al.,
PRL68(‘92)1164

H_2 分子の解離吸着に対する H_2 分子の回転運動の効果

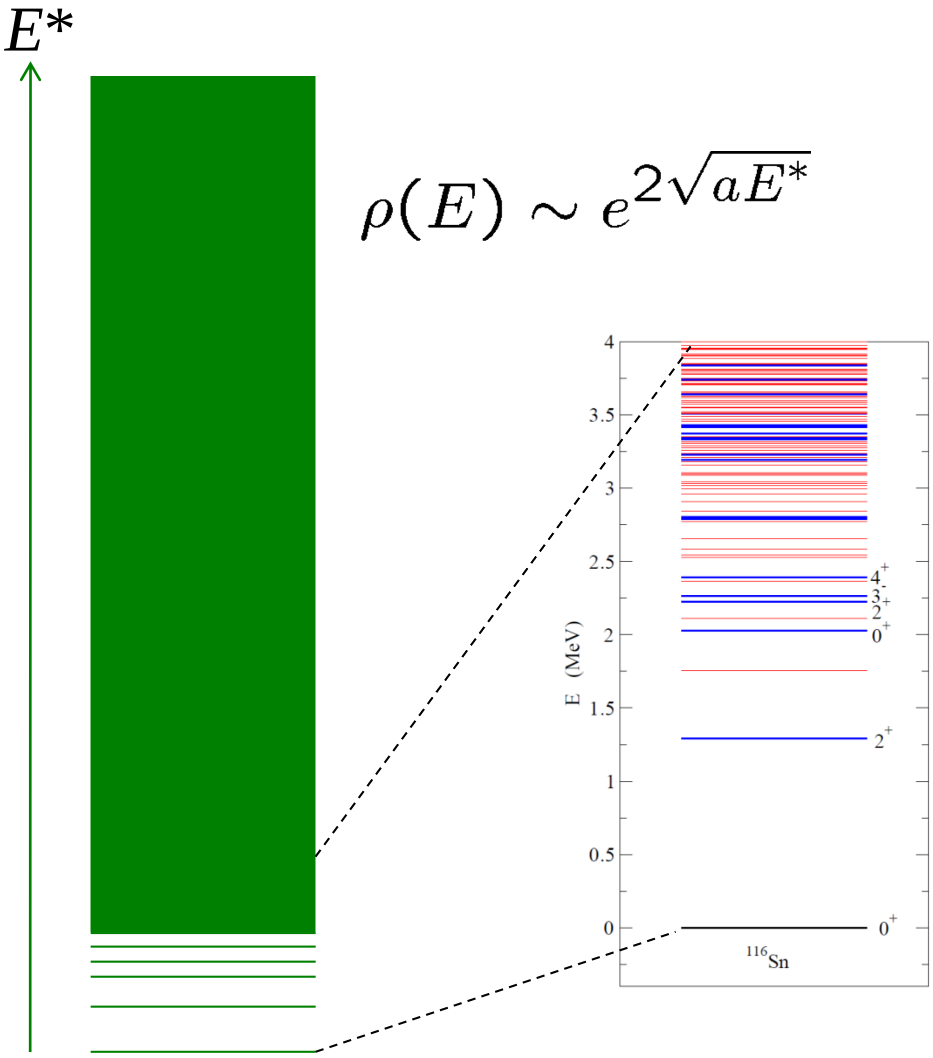


L_i : 反応が始まる前の回転状態の角運動量

$$\frac{6\hbar^2}{2\mu r_0^2} = 0.046 \text{ eV}$$

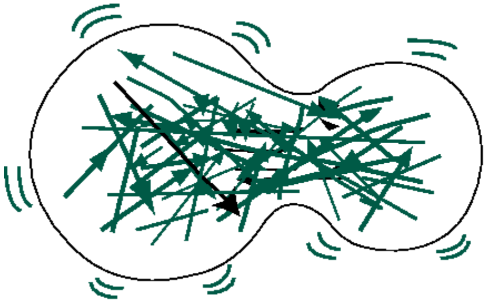
K. Hagino and N. Takigawa, PTP128 (‘12) 1061

原子核の摩擦と重イオン核融合反応



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

原子核のスペクトル



これらの無数の状態は核反応の途中で複雑に励起

⇩

原子核の内部自由度は核反応に対して「環境」のように振舞う

「内的環境自由度」