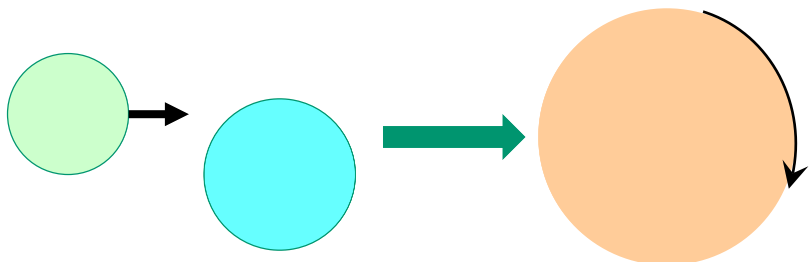
Evolving theoretical descriptions of heavy-ion fusion : from phenomenological to microscopic approaches

Kouichi Hagino
Tohoku University, Sendai, Japan



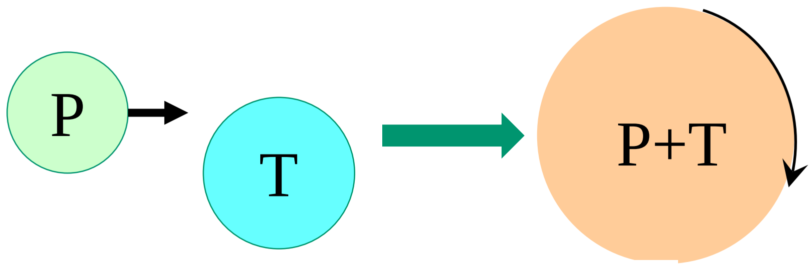
1. H.I. sub-barrier fusion reactions: theoretical overview
- *coupled-channels method*
- *barrier distributions*
- *theoretical challenges*

2. C.C. calculations with "beyond-mean-field" method
3. Summary

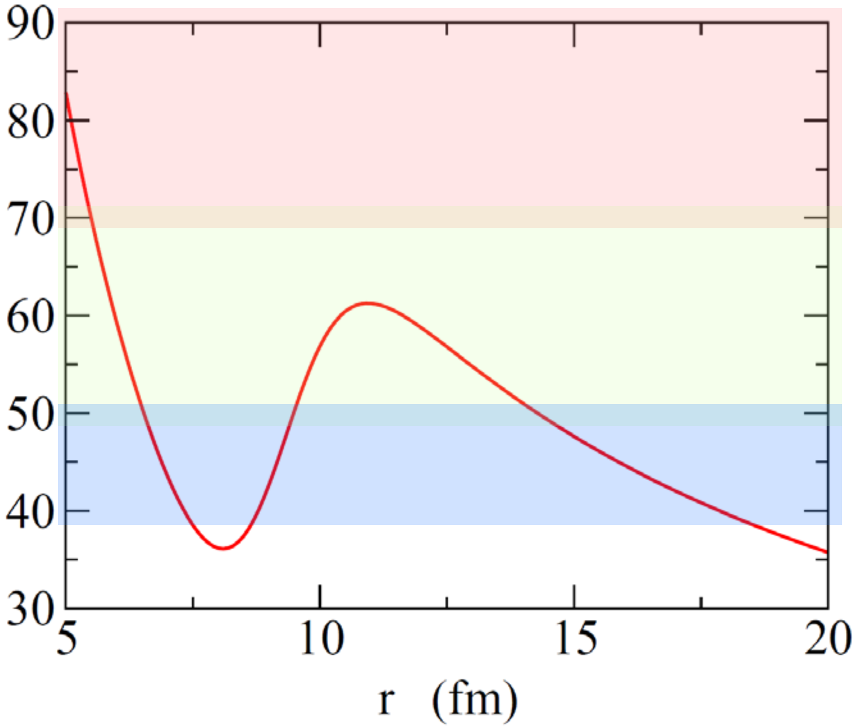
FUSION17, Tasmania, Australia, Feb. 20-24, 2017

Introduction: heavy-ion fusion reactions

Fusion: compound nucleus formation



compound nucleus



fusion reactions
in the sub-barrier energy region

$(|E - V_b| \lesssim 10\text{MeV})$

1. Coulomb force : long range, repulsive
2. Nuclear force : short range, attractive

⇒ Coulomb barrier

Why sub-barrier fusion?

Two obvious reasons:

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

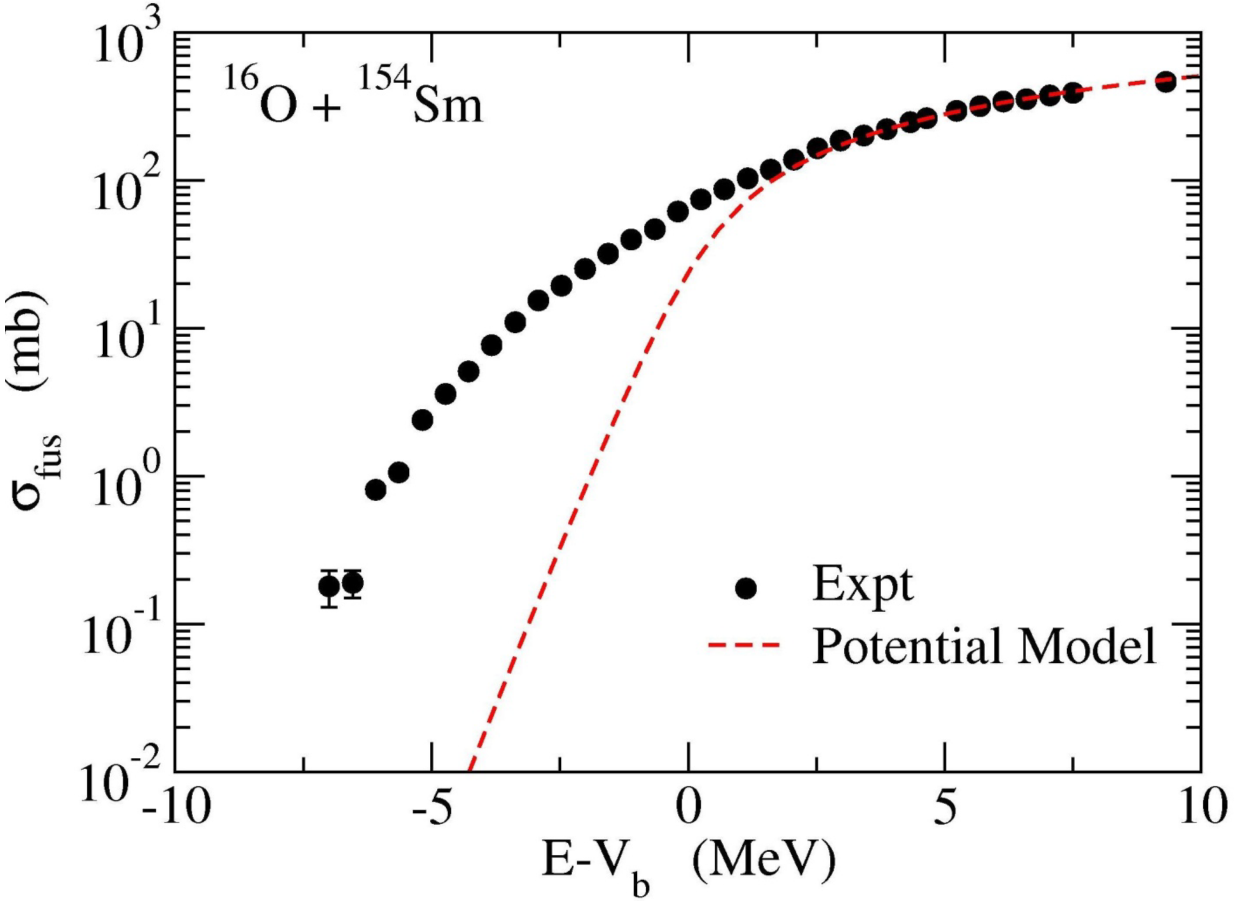
many talks also in this conf.

Other reasons:

◆ reaction mechamism
strong interplay between reaction and nuclear structure
(channel coupling effects)
cf. high *E* reactions: much simpler reaction mechanism

◆ **many-particle tunneling**
✓ many types of intrinsic degrees of freedom
(several types of collective vibrations,
deformation with several multipolarities)
✓ energy dependence of tunneling probability
cf. alpha decay: fixed energy

Discovery of large sub-barrier enhancement of σ_{fus}



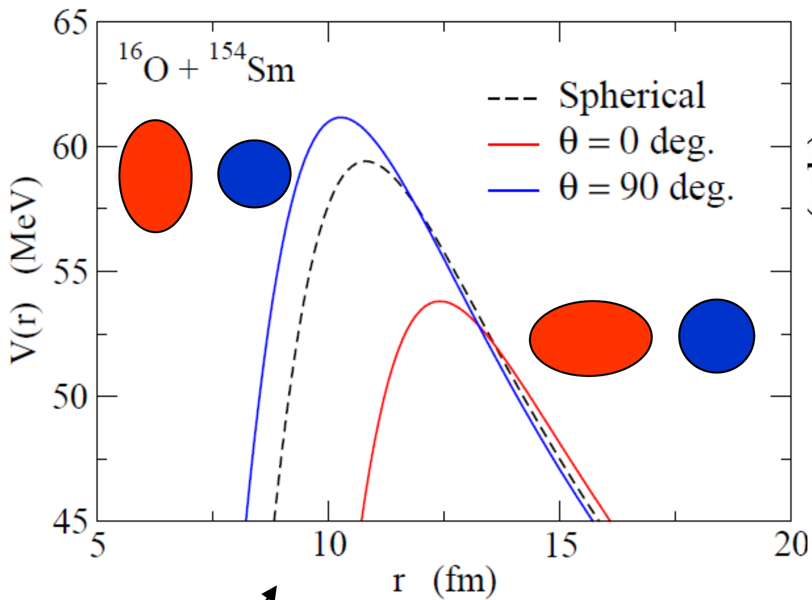
potential model: $V(r)$ + absorption

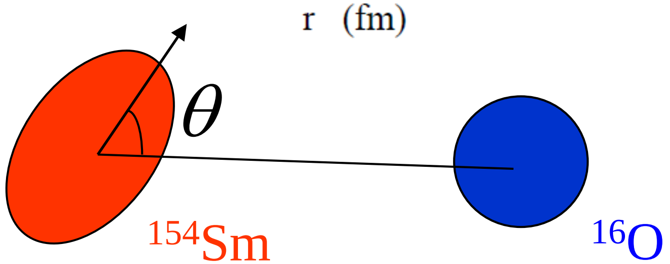
cf. seminal work:
R.G. Stokstad et al., PRL41('78) 465

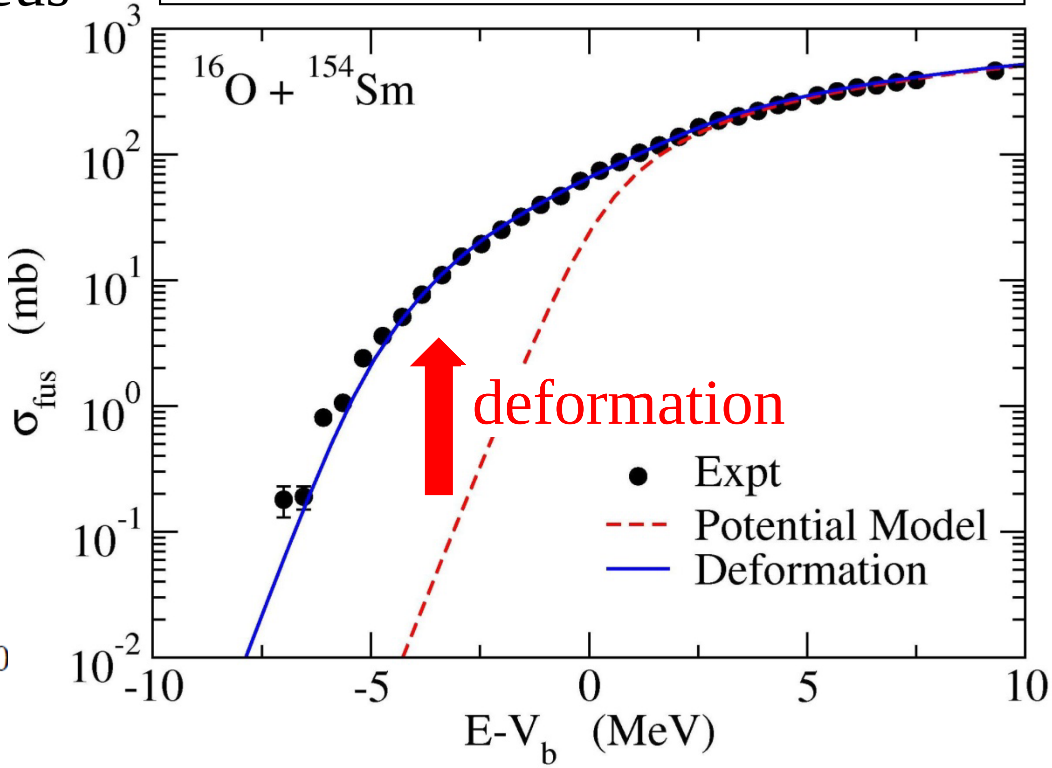
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus
with $\beta_2 \sim 0.3$

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





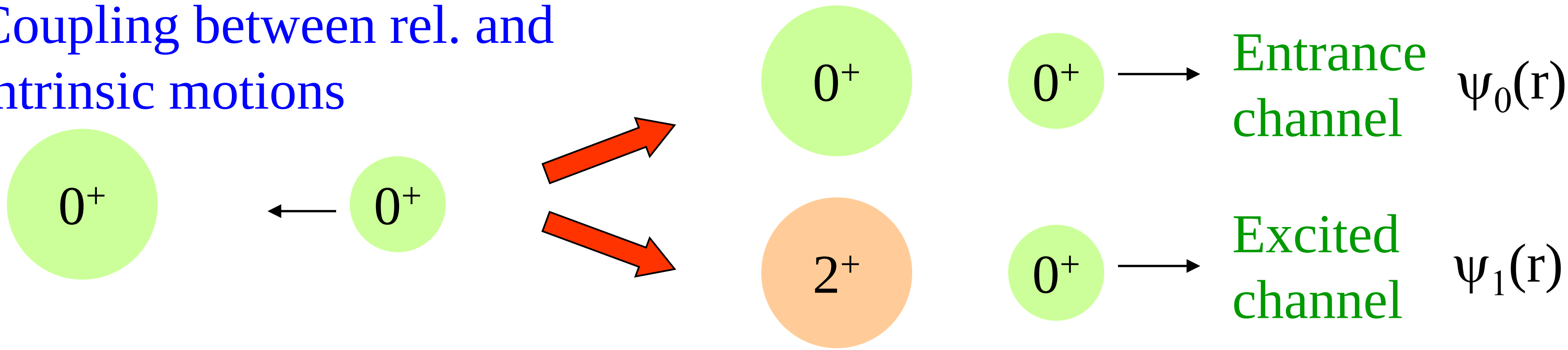


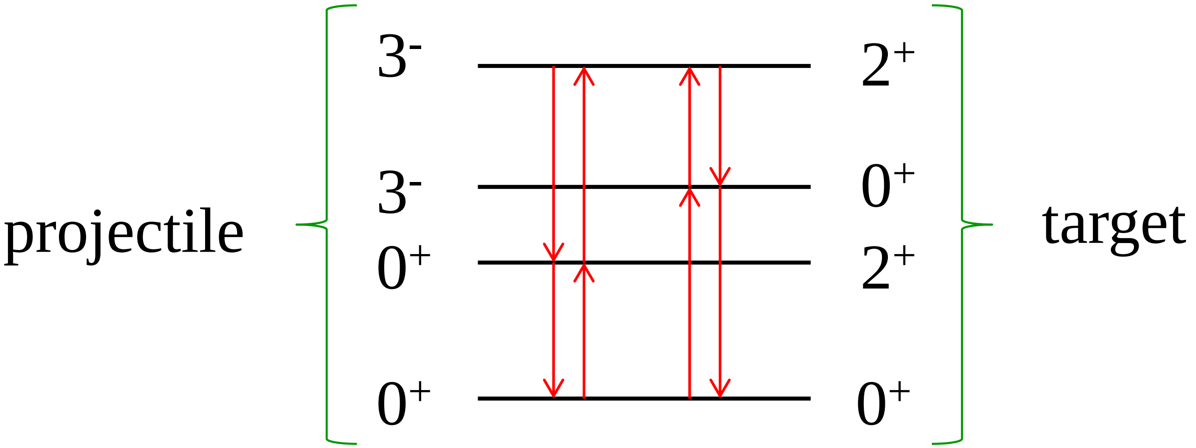
Fusion: strong interplay between nuclear structure and reaction

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

Coupled-Channels method

Coupling between rel. and intrinsic motions





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

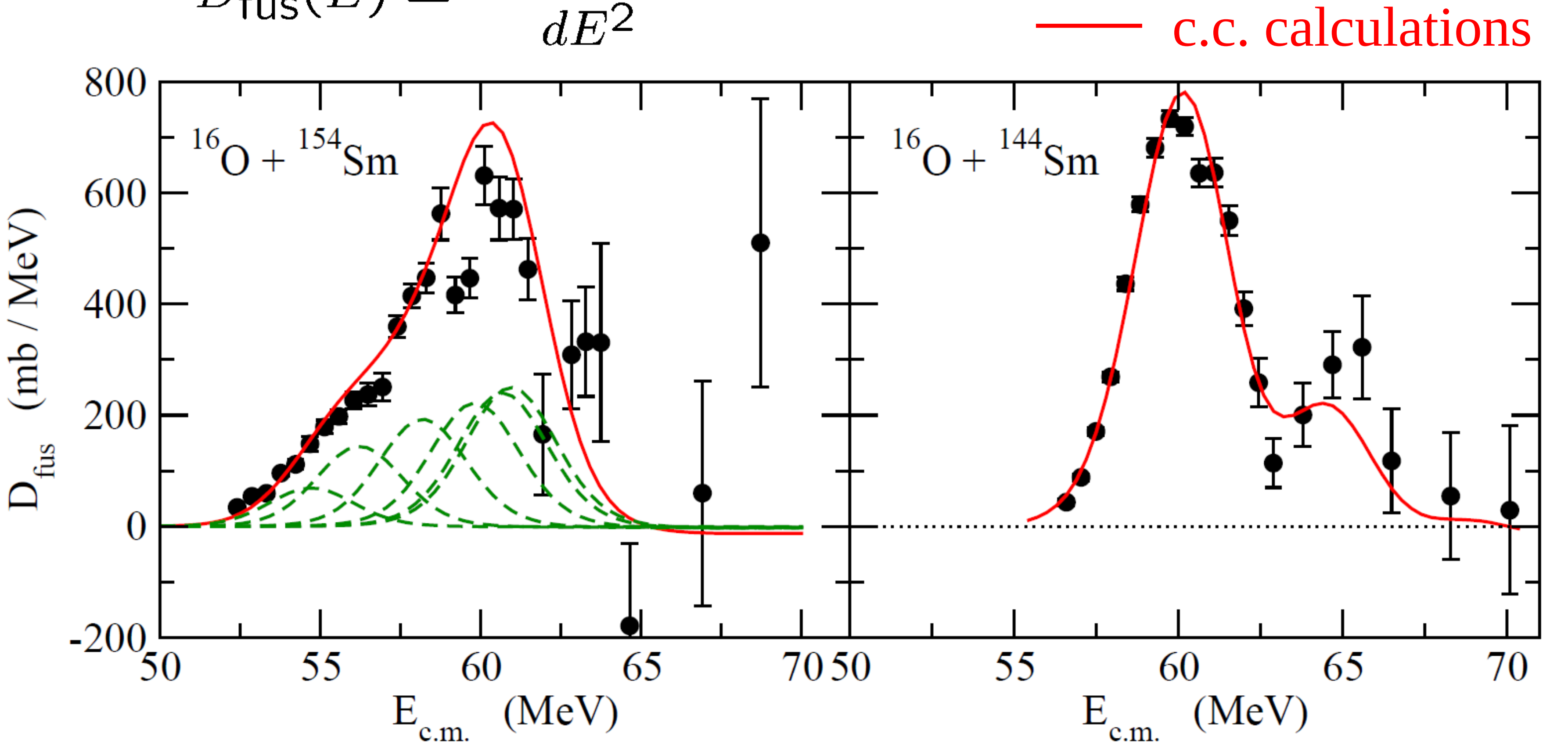
→ coupled Schroedinger equations for $\psi_k(r)$

C.C. approach: a standard tool for sub-barrier fusion reactions

cf. CCFULL (K.H., N. Rowley, A.T. Kruppa, CPC123 (‘99) 143)

✓ Fusion barrier distribution [Rowley, Satchler, Stelson, PLB254(‘91)]

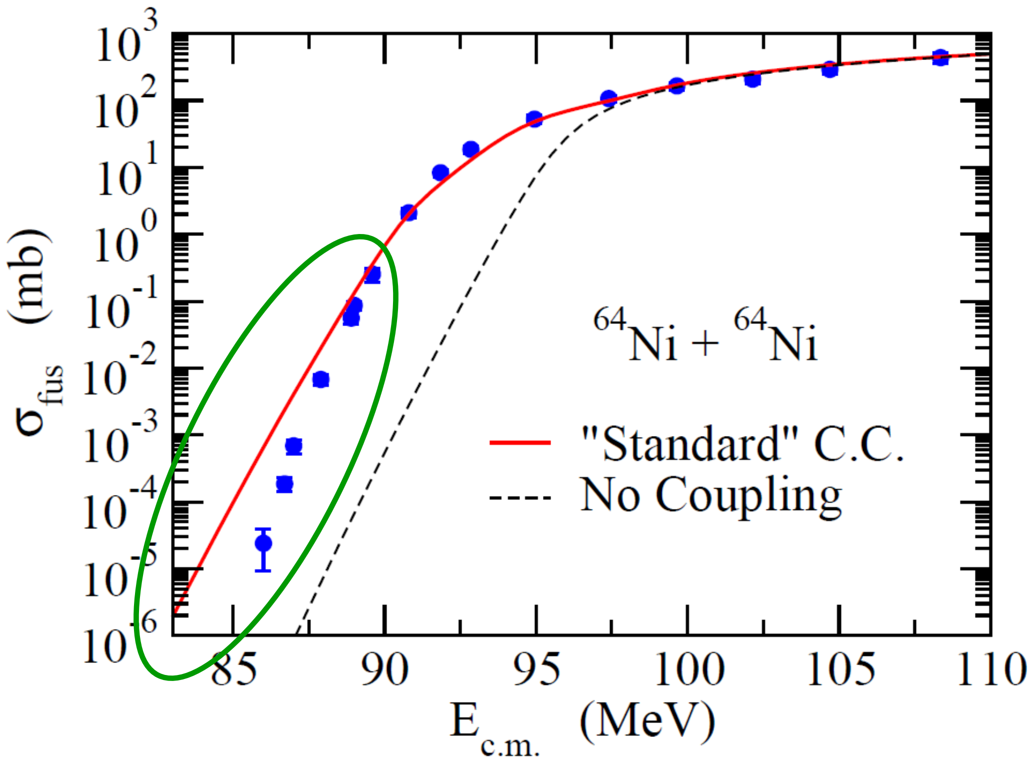
$$D_{\rm fus}(E) = \frac{d^2(E\sigma_{\rm fus})}{dE^2}$$



K.H., N. Takigawa, PTP128 (‘12) 1061

Remaining theoretical challenges

✓Deep sub-barrier hindrance of fusion cross sections



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

Theoretical models:

➢ Sudden model

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

✓ frozen density
✓ repulsive inner core

⟶ shallow potential

➢ Adiabatic model

T. Ichikawa, K.H., and
A. Iwamoto,
PRL103('09)202701

✓ density change after the touching
✓ neck formation

⟶ deep and thick potential

◆ how to model the dissipation around and after the touching?

◆ microscopic justification of IWBC?
cf. SHE and quasi-fission

Remaining theoretical challenges

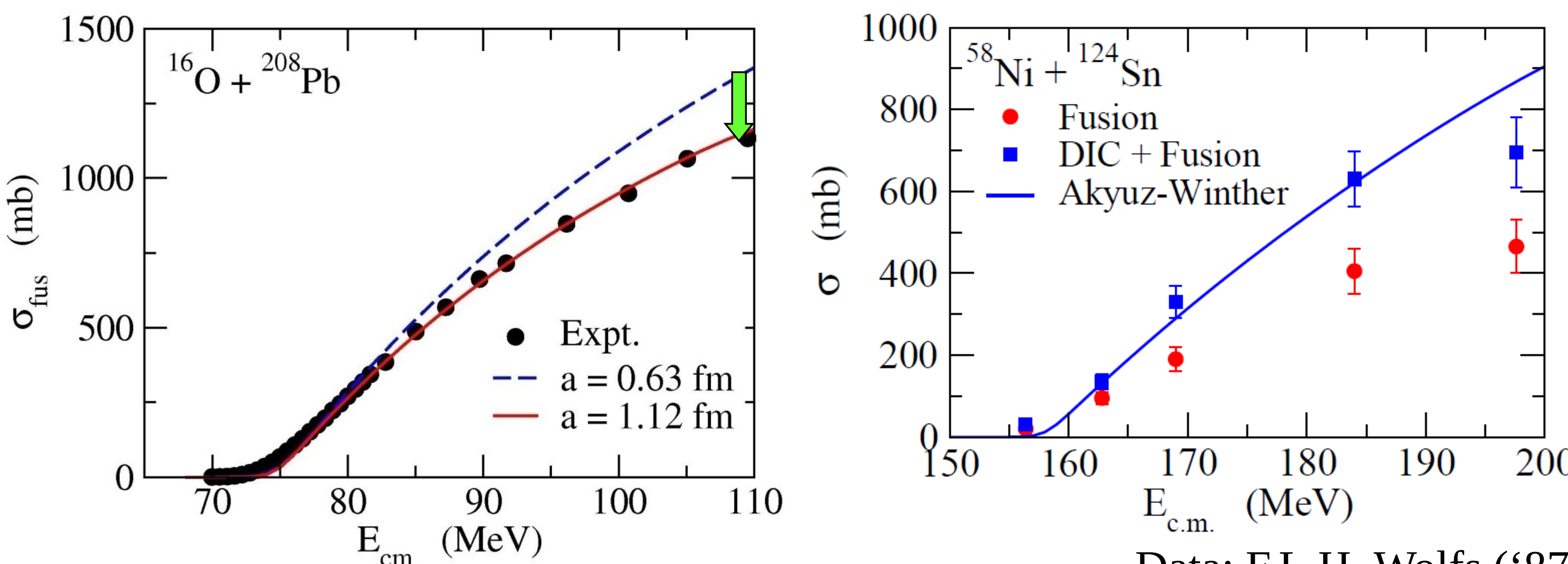
✓Deep sub-barrier hindrance of fusion cross sections

✓Fusion above the Coulomb barrier

- how well do we understand the dissipation?

Fusion model

⟶ "friction free": only strong absorption inside the barrier



Data: F.L.H. Wolfs ('87)

◆ A quantal theory for DIC?

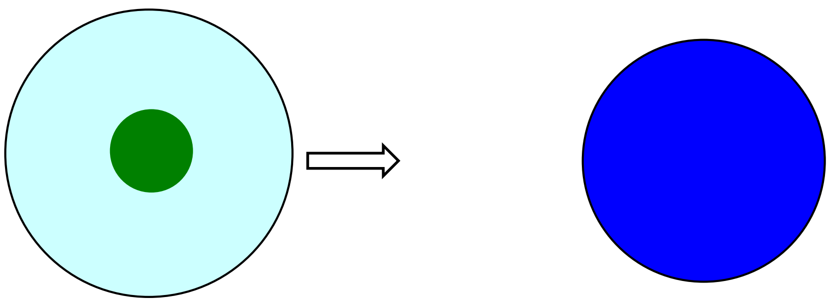
◆ Dissipative tunneling for fusion?

Remaining theoretical challenges

✓Deep sub-barrier hindrance of fusion cross sections

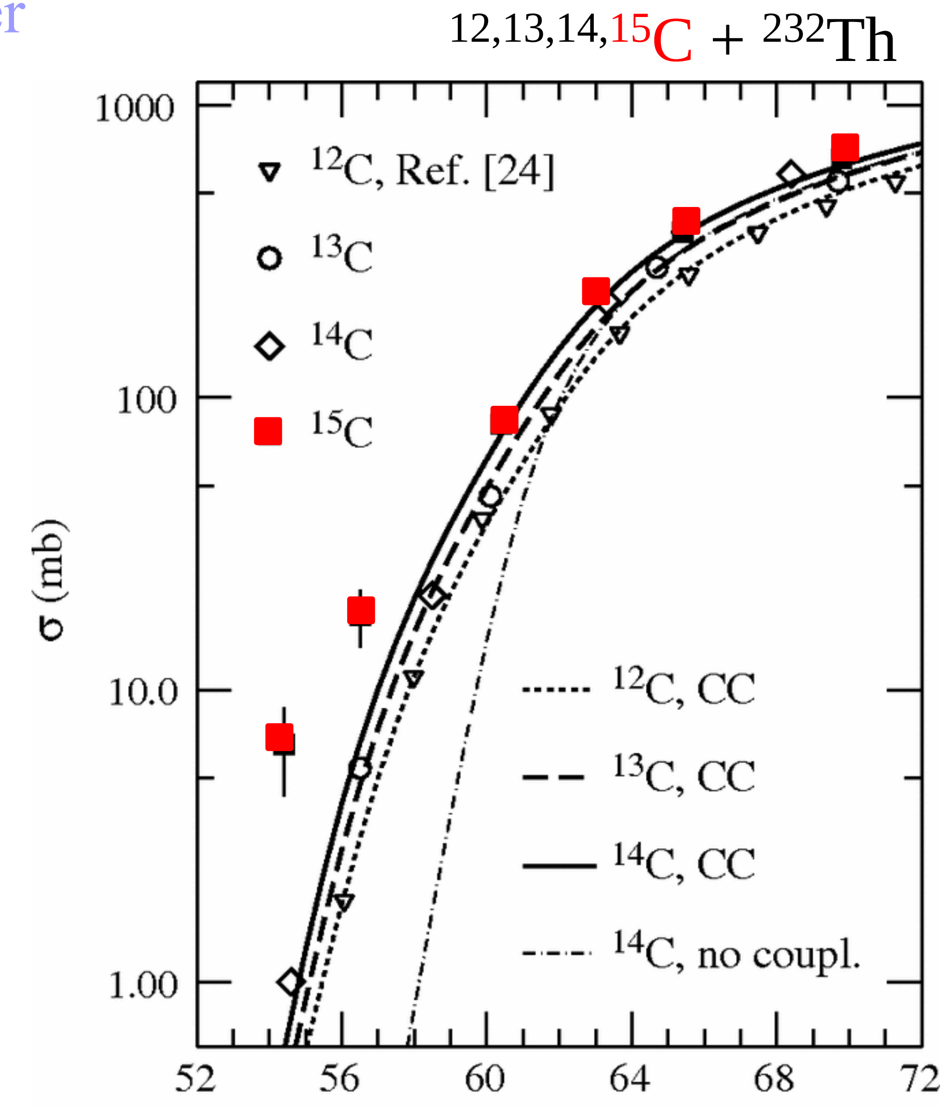
✓Fusion above the Coulomb barrier

✓Fusion of Unstable nuclei



simultaneous treatment
of breakup and transfer

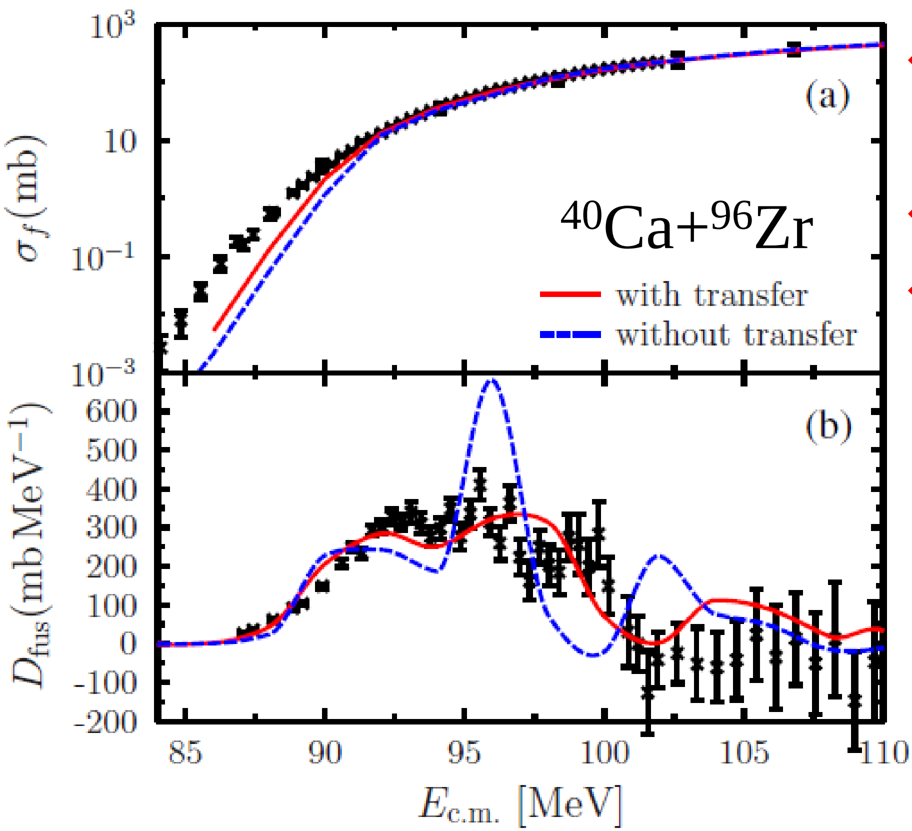
session 3



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

Remaining theoretical challenges

✓Deep sub-barrier hindrance of fusion cross sections
✓Fusion above the Coulomb barrier
✓Fusion of Unstable nuclei
✓Interplay between fusion and (multi-)nucleon transfer



- simultaneous reproduction of fusion and transfer?
- transfer to highly excited states?
- reaction dynamics of pair transfer?

- coupled-channels approach
- Time Dep. Hartree-Fock (TDHF)

session 7

G. Scamps and K.H., PRC92 (‘16) 054616

From macroscopic approach to more microscopic approaches

macroscopic
(phenomenological)

↕

microscopic

Coupled-channels (C. C.) approach with the collective model

C. C. approaches with microscopic nuclear structure calculations

* Hagino-Yao
* Ichikawa-Matsuyanagi

C. C. approaches with inputs based on TDHF

* Umar (DC-TDHF)
* Washiyama-Lacroix
* Simenel et al.

TDHF simulations

* Simenel
* Sekizawa
* Scamps
* Washiyama

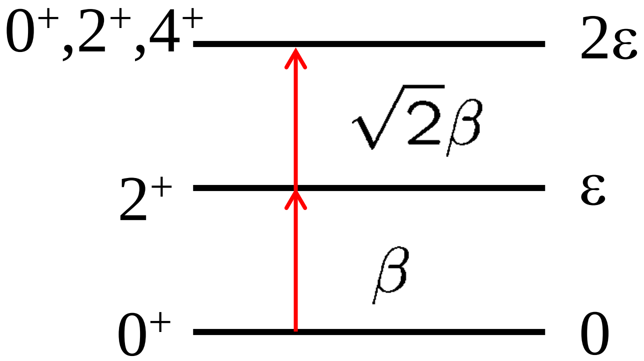
…but, no tunneling

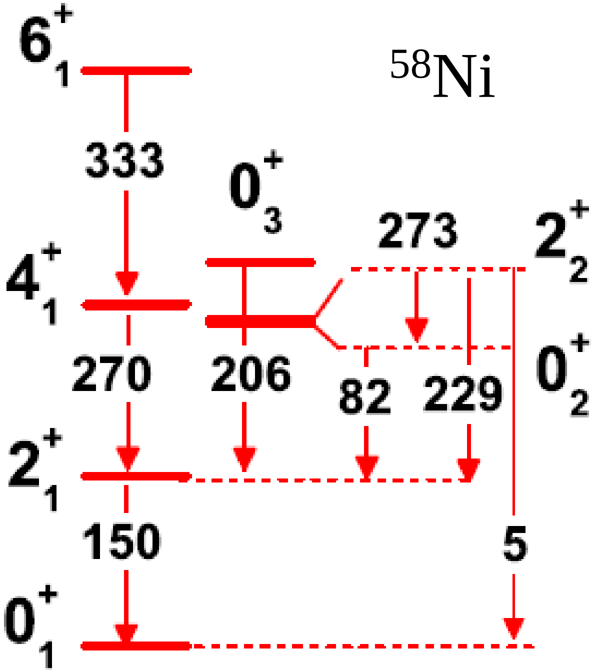
Semi-microscopic modeling of sub-barrier fusion

K.H. and J.M. Yao, PRC91('15) 064606

CCFULL
+ microscopic nuclear structure
calculations
(GCM, Shell Model, IBM…..)

simple harmonic
oscillator

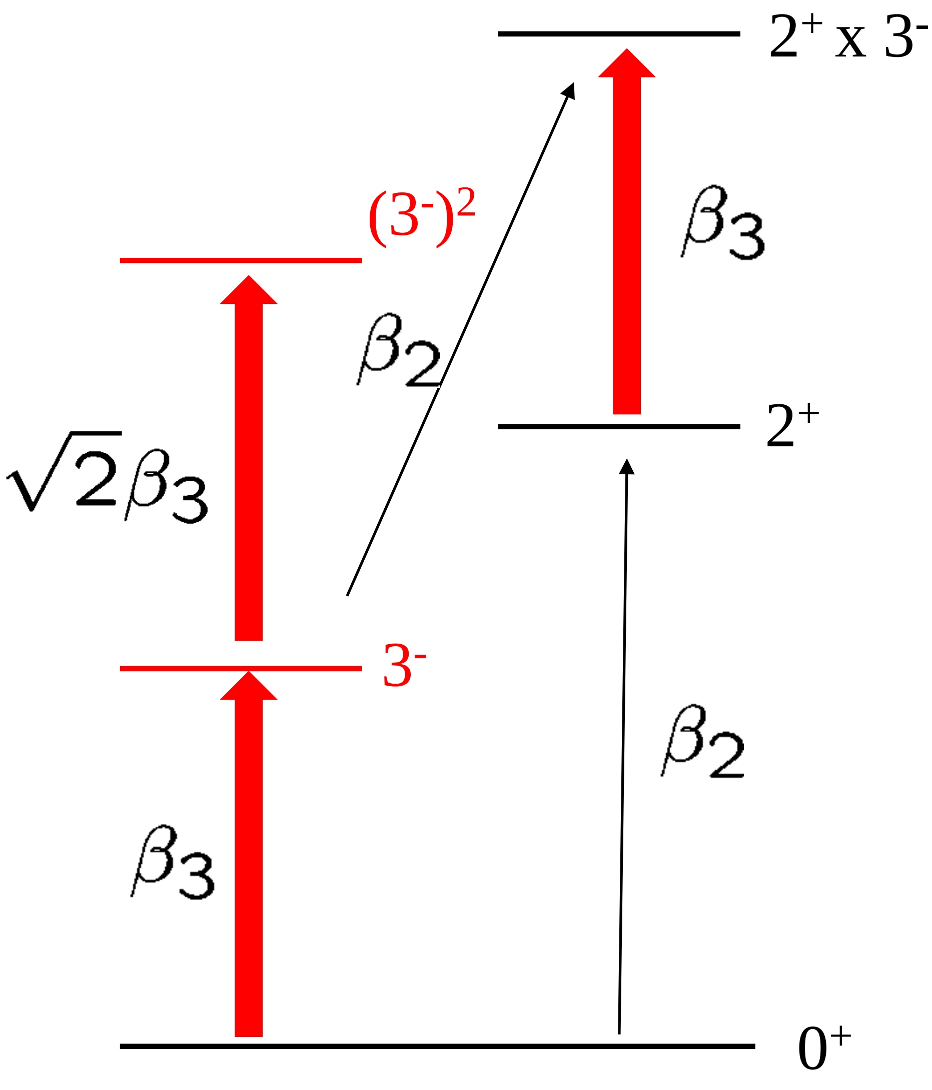


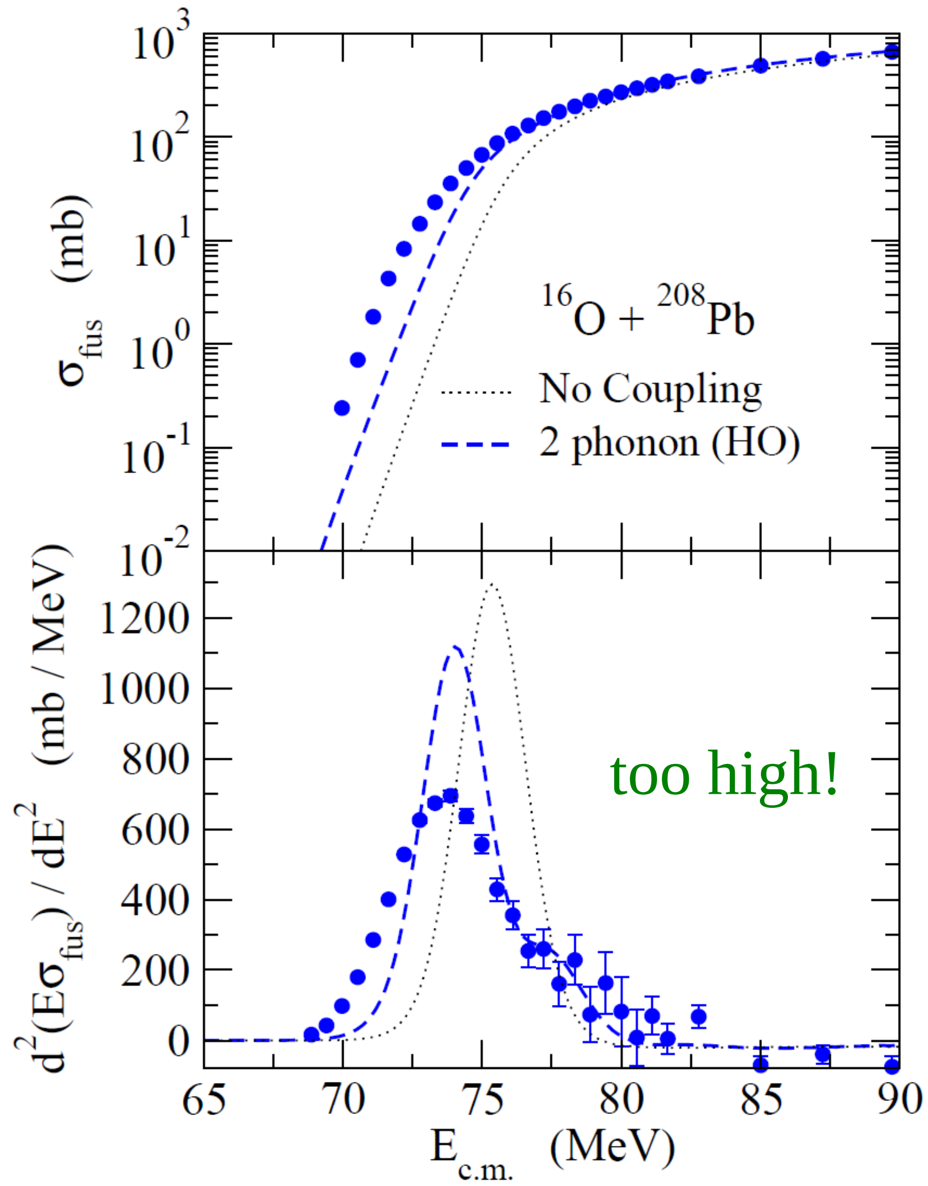


relativistic MF + GCM

anharmonicity of phonon spectra

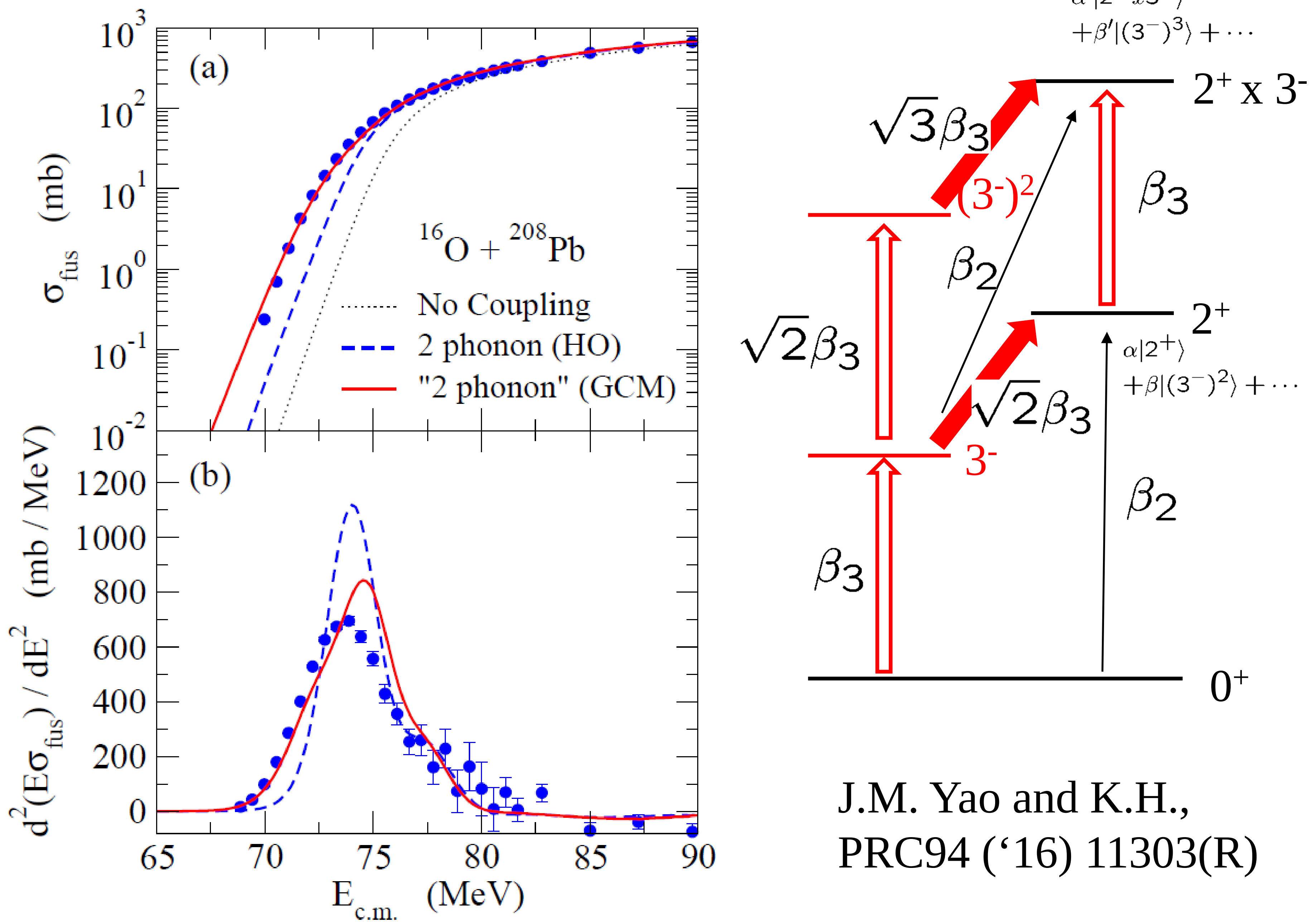
Application to $^{16}O + ^{208}Pb$ fusion reaction





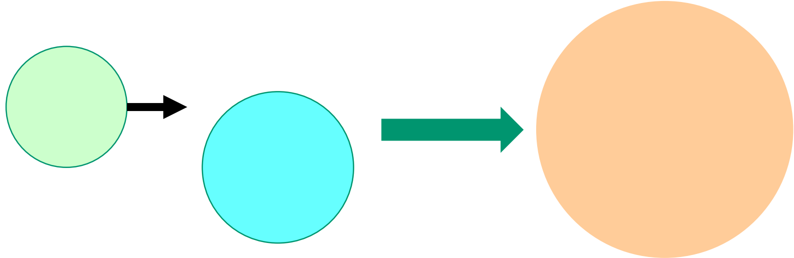
cf. C.R. Morton et al., PRC60('99) 044608

CCFULL with RMF+GCM



J.M. Yao and K.H., PRC94 ('16) 11303(R)

Summary



Heavy-ion subbarrier fusion reactions

✓strong interplay between reaction and structure

✓SHE, nuclear astrophysics, many-particle tunneling

From phenomenology to more microscopic modelling

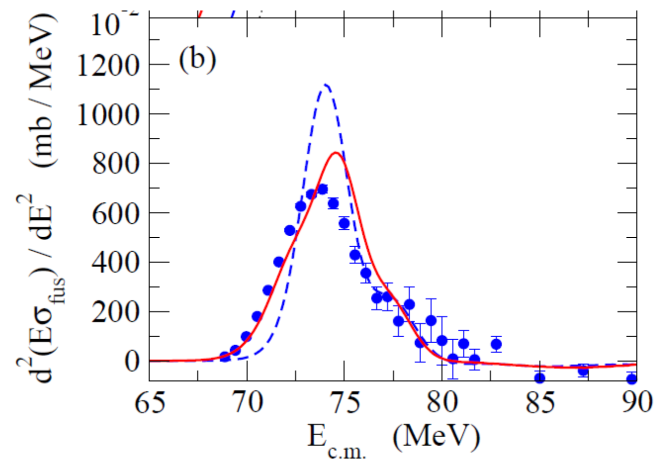
✓full TDHF simulations

✓C.C. with microscopic inputs

CCFULL + Relativistic GCM

✓ anharmonicity

✓ octupole vibrations: $^{16}O + ^{208}Pb$



Theoretical challenges

✓deep subbarrier hindrance

✓fusion above the barrier and dissipation

✓fusion of unstable nuclei

✓interplay between fusion and transfer

….. many of these will be discussed during this meeting