Towards a microscopic theory for low-energy heavy-ion reactions

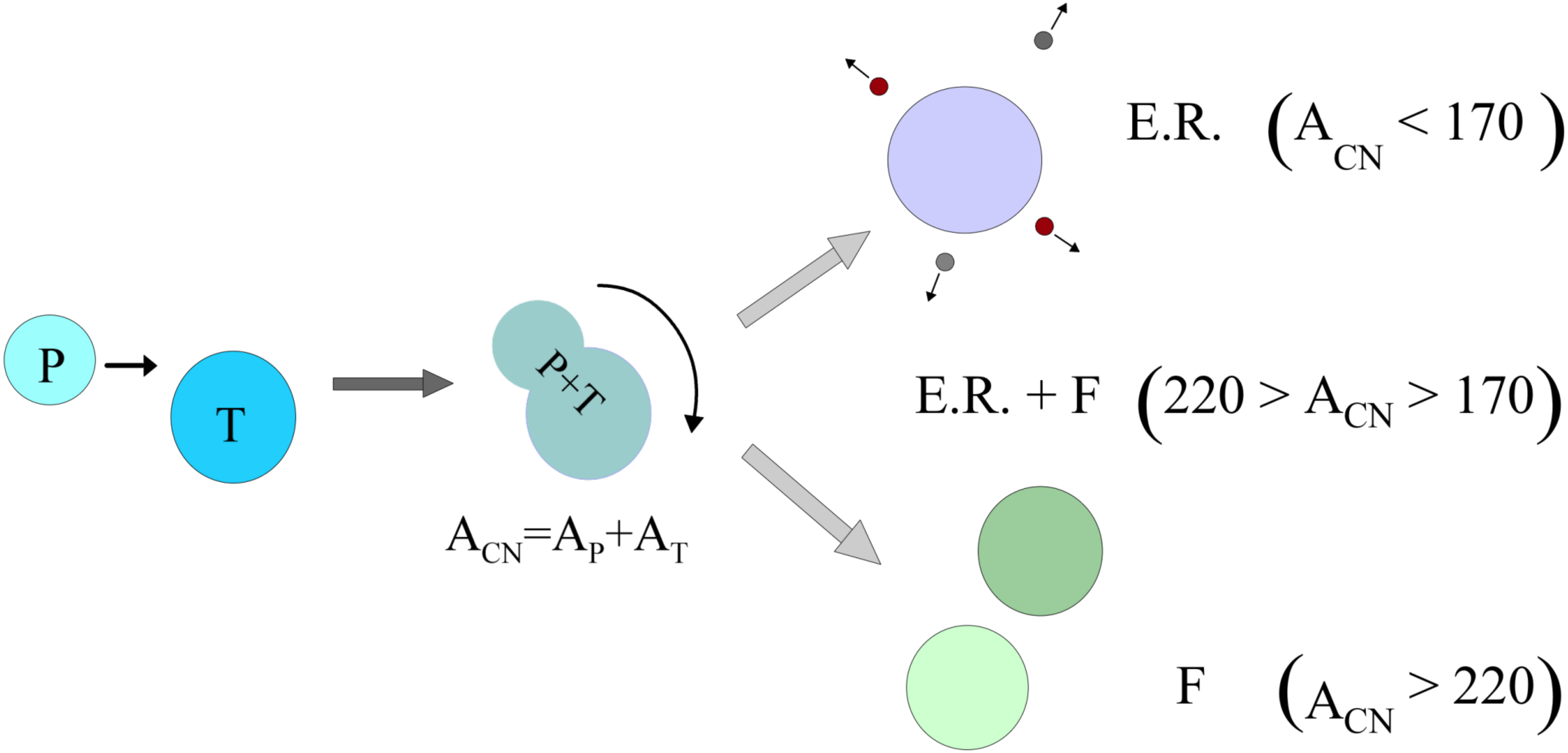
Role of internal degrees of freedom
in low-energy nuclear reactions

Kouichi Hagino (Tohoku University)

1. *Introduction: Environmental Degrees of Freedom*
2. *Application of RMT to subbarrier fusion*
3. *Discussions: Towards a microscopic theory for low-energy heavy-ion reactions*
4. *Summary*

Introduction

Fusion: compound nucleus formation


P

T

P+T

$A_{CN}=A_P+A_T$

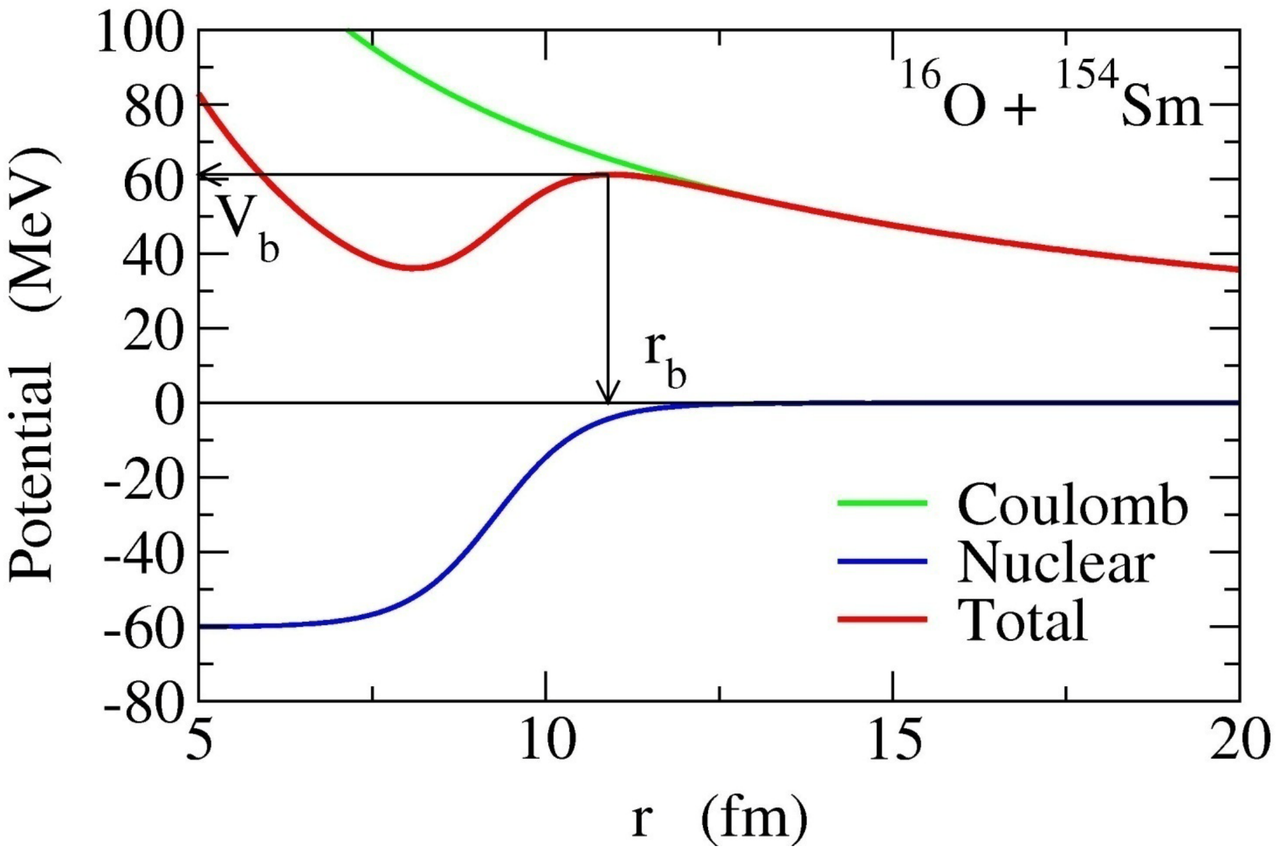
E.R. $\left(A_{CN} < 170\right)$

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

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

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

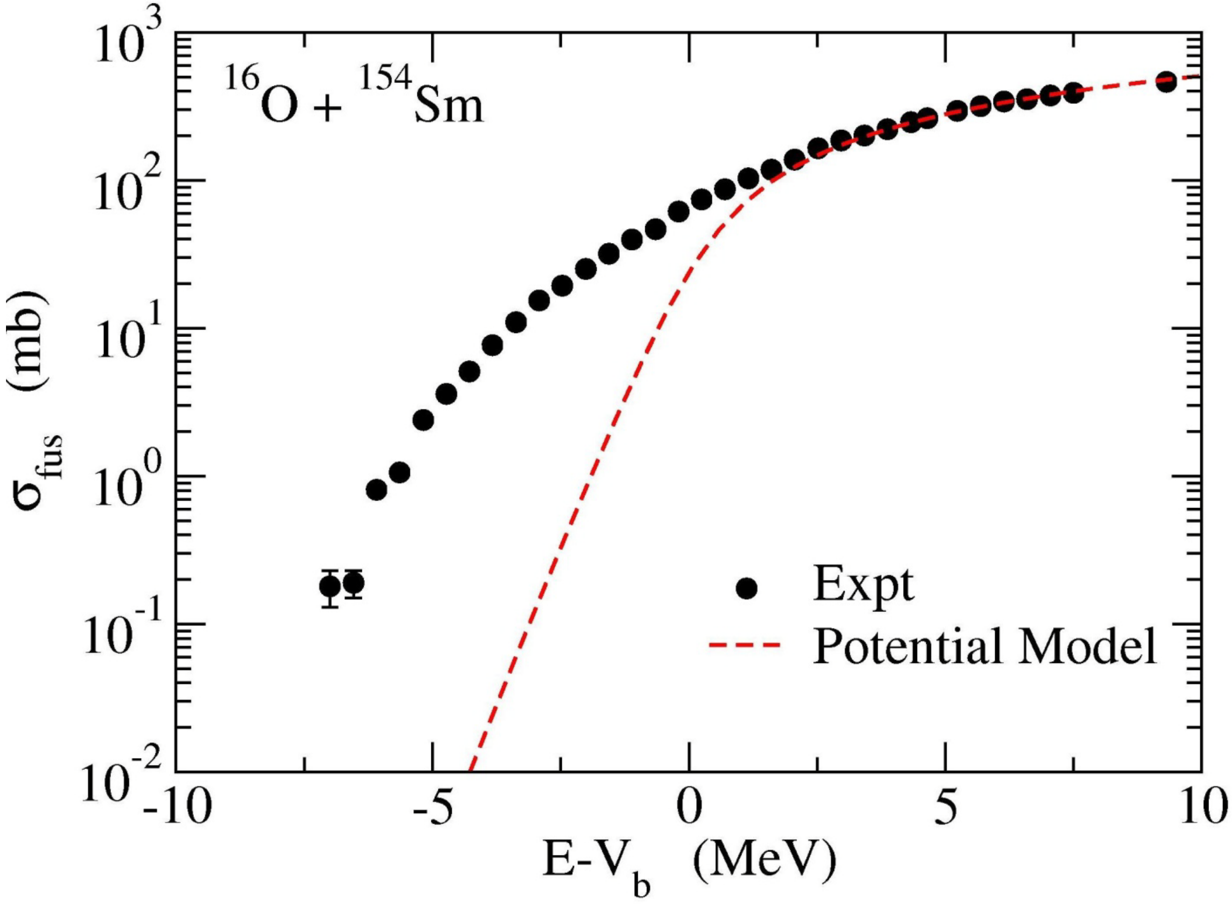
courtesy: Felipe Canto



the simplest approach to fusion cross sections: potential model

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

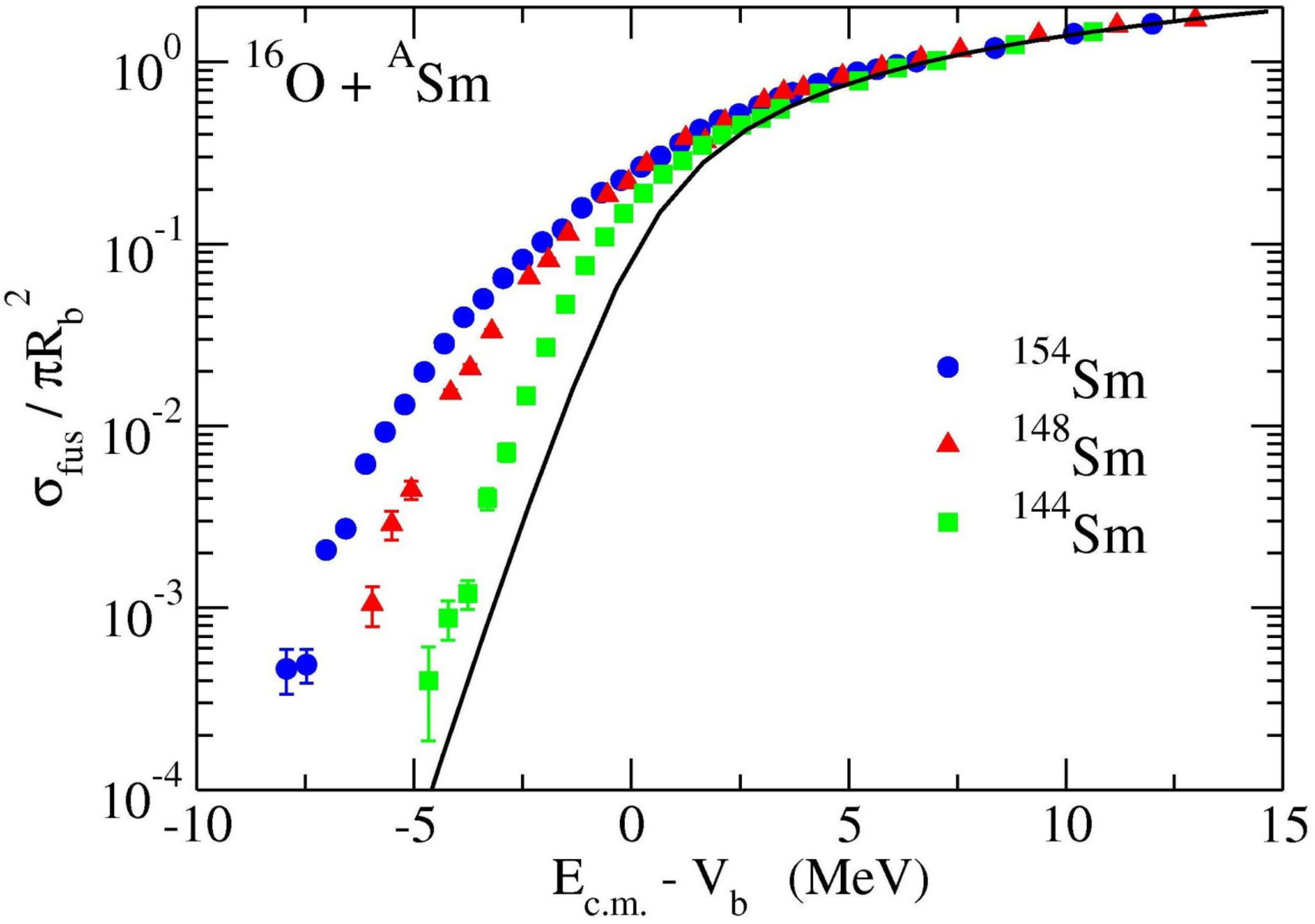
Subbarrier fusion reactions



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

Underpredicts σ_{fus} for
$E < V_b$

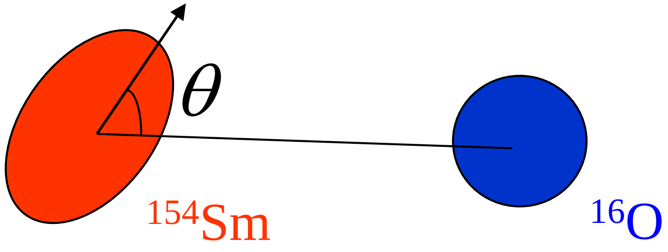
cf. seminal work:
R.G. Stokstad et al., PRL41(‘78)465
PRC21(‘80)2427

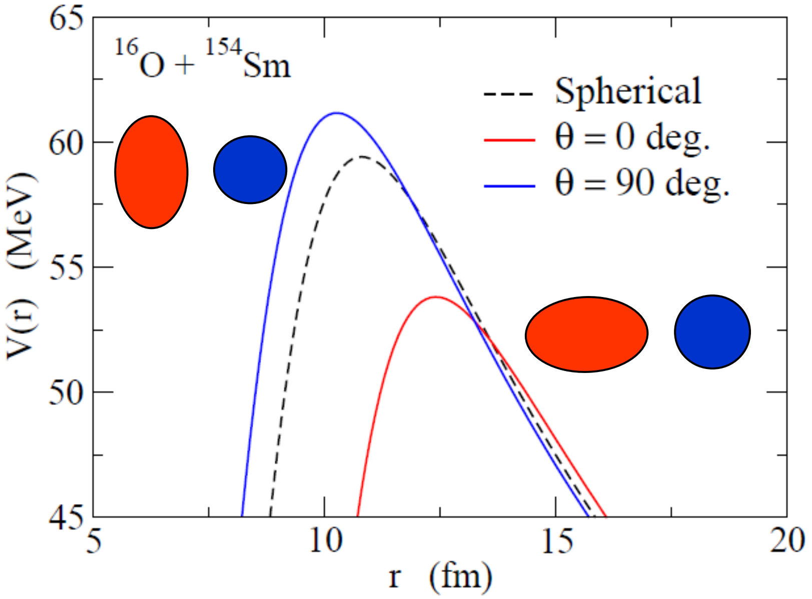


Strong target dependence at $E < V_b$

↔ low-lying collective excitations

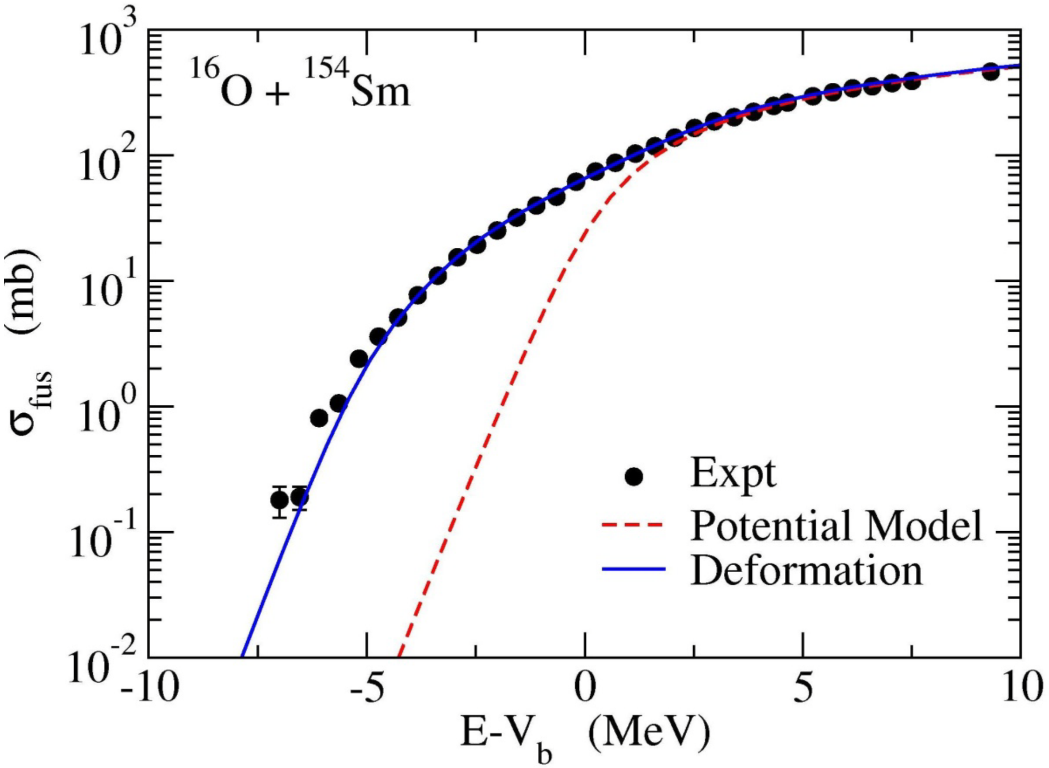
Subarrier fusion:
strong interplay between reaction and structure





coupled-channels equations

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

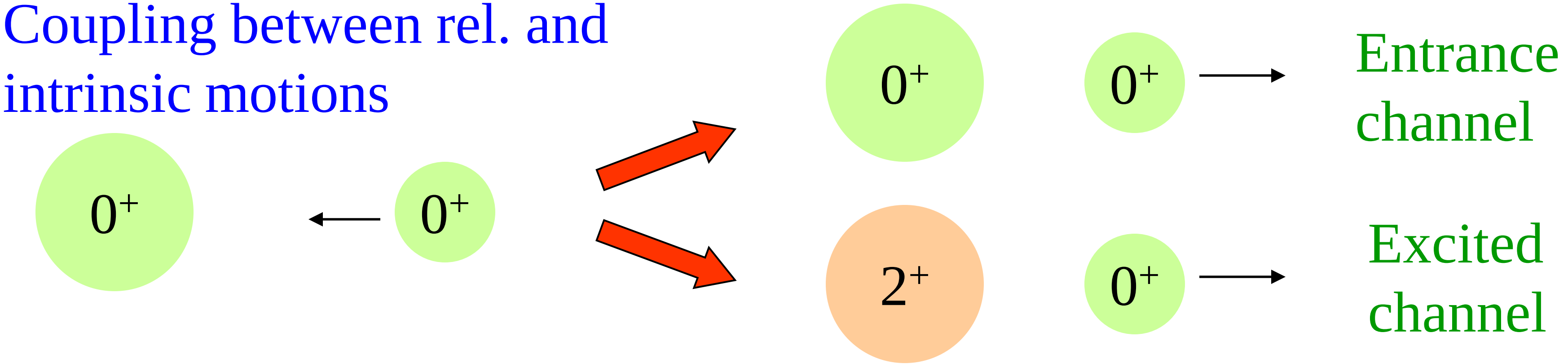


Def. Effect: enhances σ_{fus} by a factor of 10 ~ 100

Fusion: interesting probe for nuclear structure

Coupled-Channels method

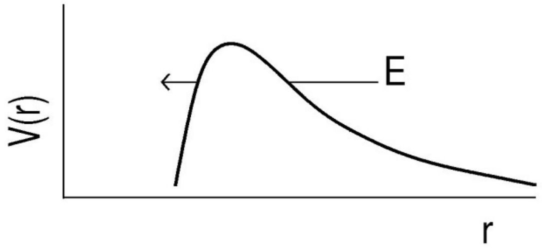
Coupling between rel. and intrinsic motions

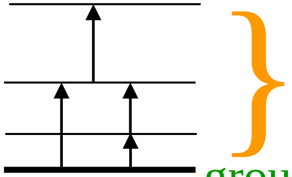


Entrance channel

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

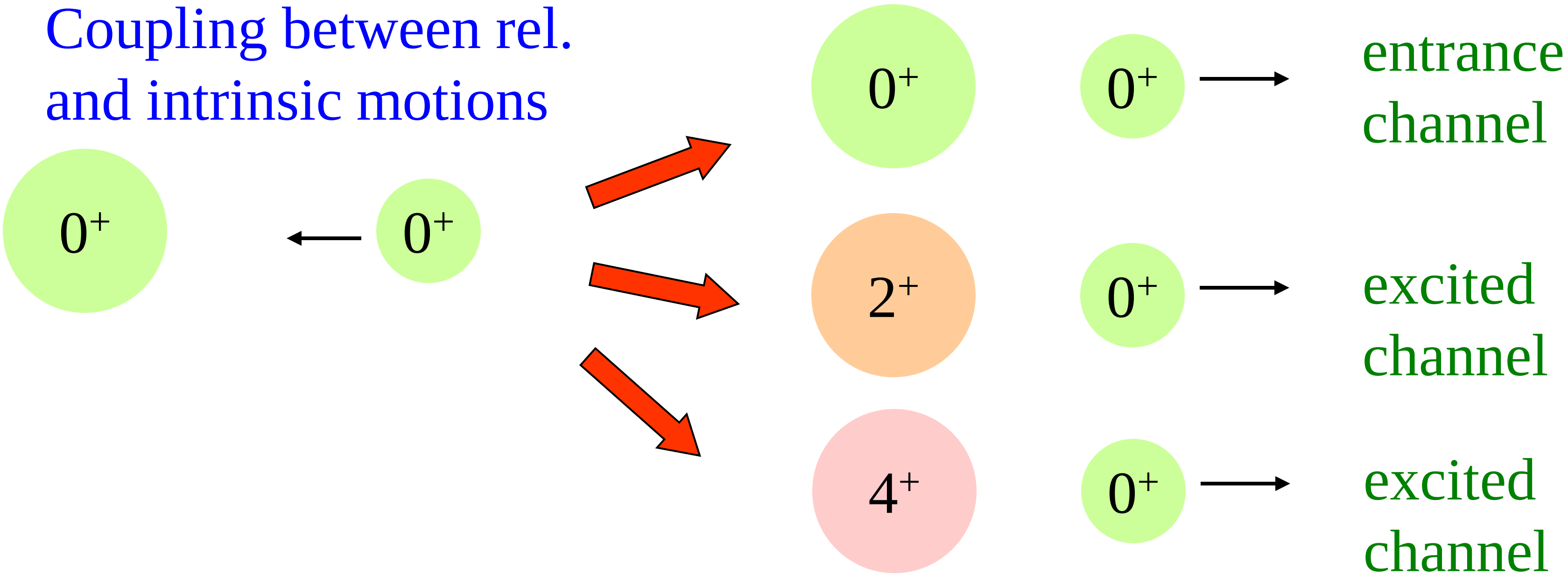
$$H_0(\xi)\phi_k(\xi) = \epsilon_k\,\phi_k(\xi)$$

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

coupled Schroedinger equations for $\psi_k(r)$

Coupled-channels framework

Coupling between rel. and intrinsic motions


0^+ ← 0^+

0^+ 0^+ → entrance channel

2^+ 0^+ → excited channel

4^+ 0^+ → excited channel

- Quantum theory which incorporates excitations in the colliding nuclei
- a few collective states (vibration and rotation) which couple strongly to the ground state + transfer channel
- several codes in the market: ECIS, FRESCO, CCFULL……

➡ has been successful in describing heavy-ion reactions

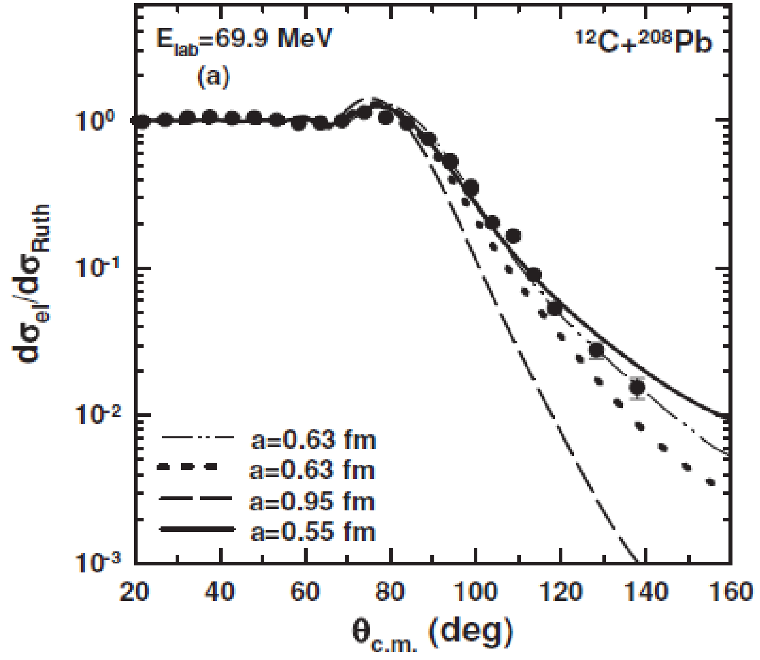
However, many recent challenges in C.C. calculations

surface diffuseness anomaly

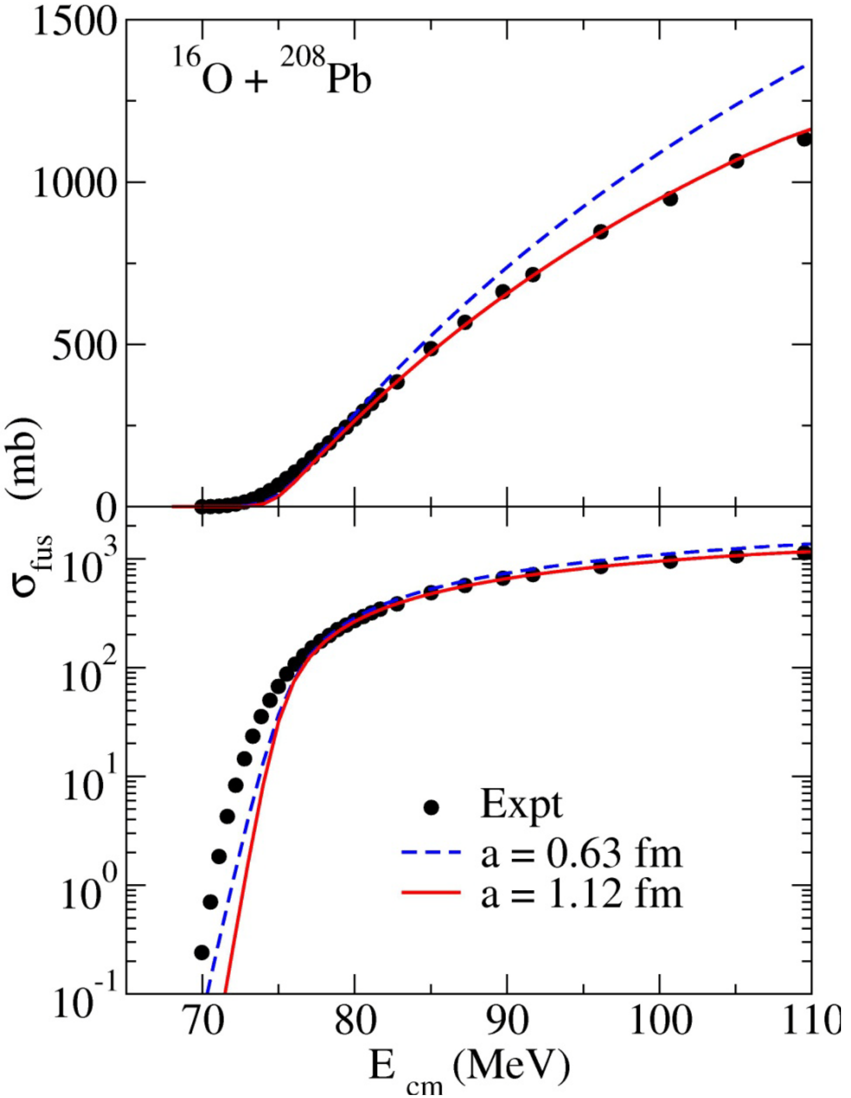
Scattering processes:

Double folding potential
Woods-Saxon (a ~ 0.63 fm)

→ successful



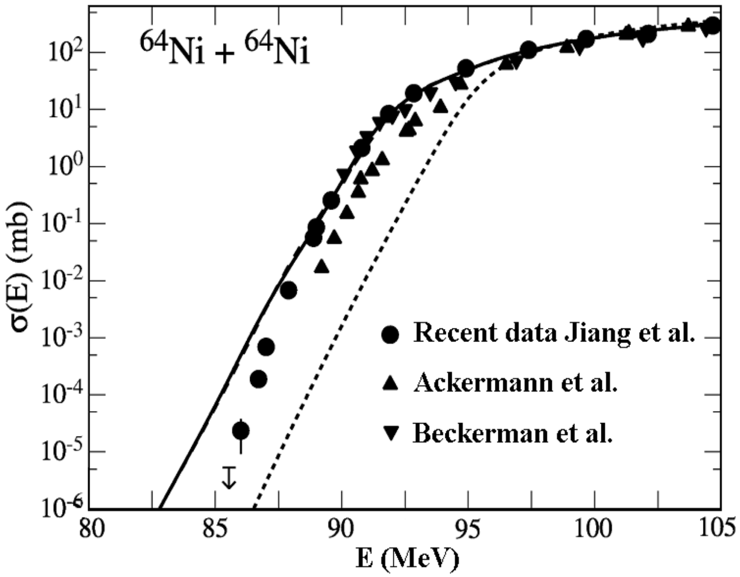
A. Mukherjee, D.J. Hinde, M. Dasgupta, K.H., et al.,
PRC75('07)044608



Fusion process: not successful

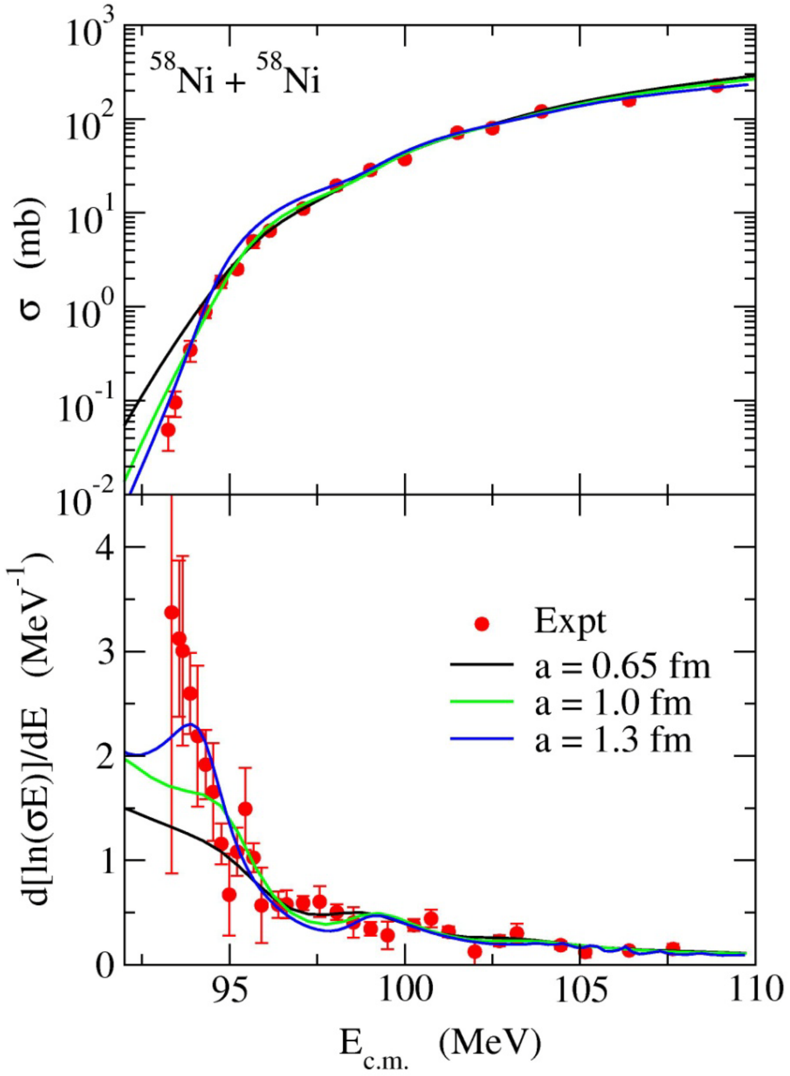
→ *a* ~ 1.0 fm required (if WS)

Deep subbarrier fusion data



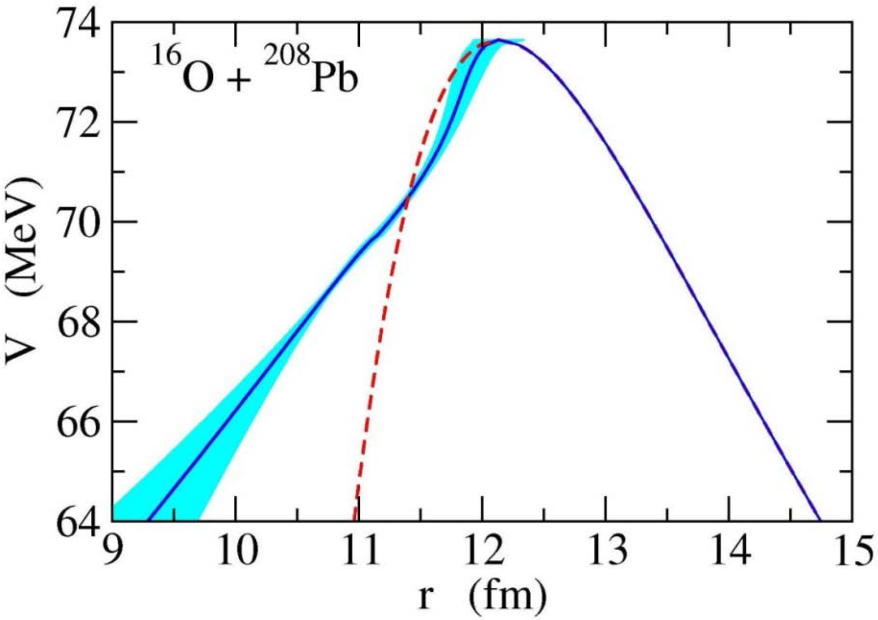
C.L. Jiang et al., PRL93('04)012701

"steep fall-off of fusion cross section"

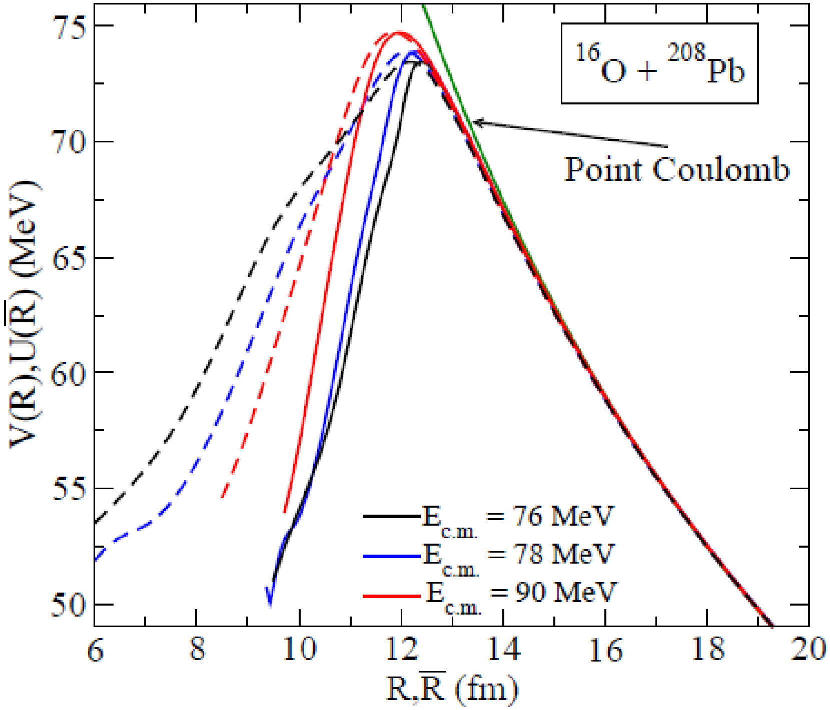


K. H., N. Rowley, and M. Dasgupta,
PRC67('03)054603

potential inversion with deep subbarrier data



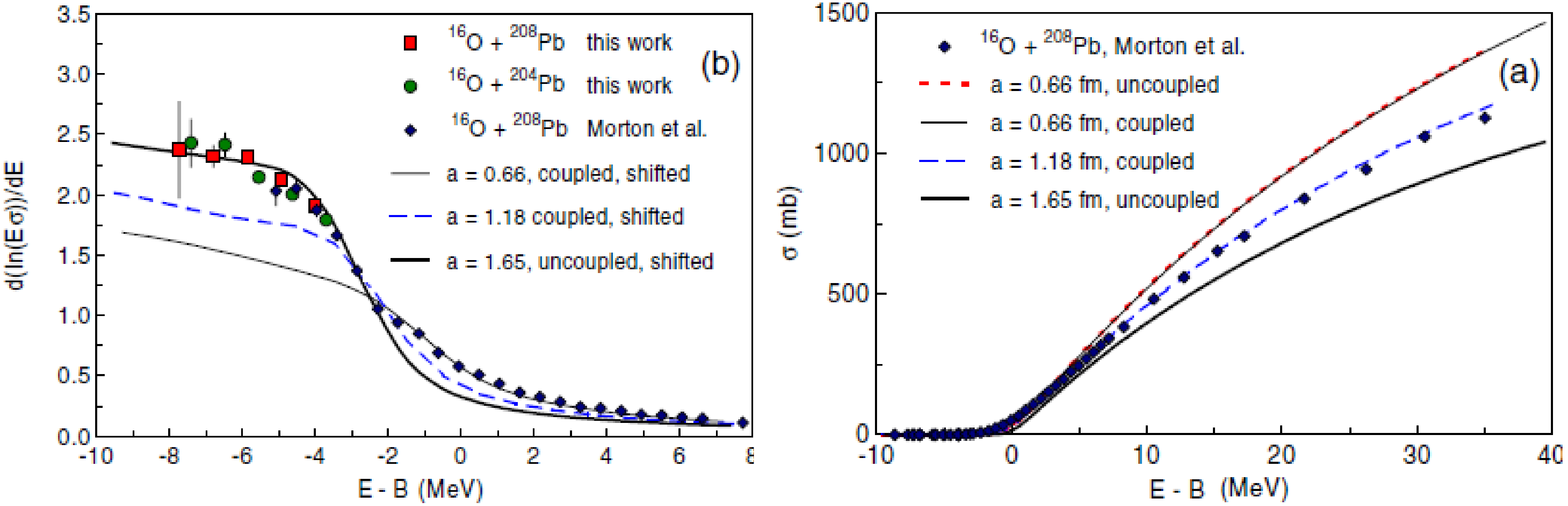
K.H. and Y. Watanabe,
PRC76 (’07) 021601(R)



cf. Earlier work on potential inversion:
A.B. Balantekin, S.E. Koonin, and
J.W. Negele, PRC28(’83)1565

cf. Density-Constrained TDHF:
A.S. Umar and V.E. Oberacker,
Euro. Phys. J. A39 (‘09)243

energy dependence of surface diffuseness parameter

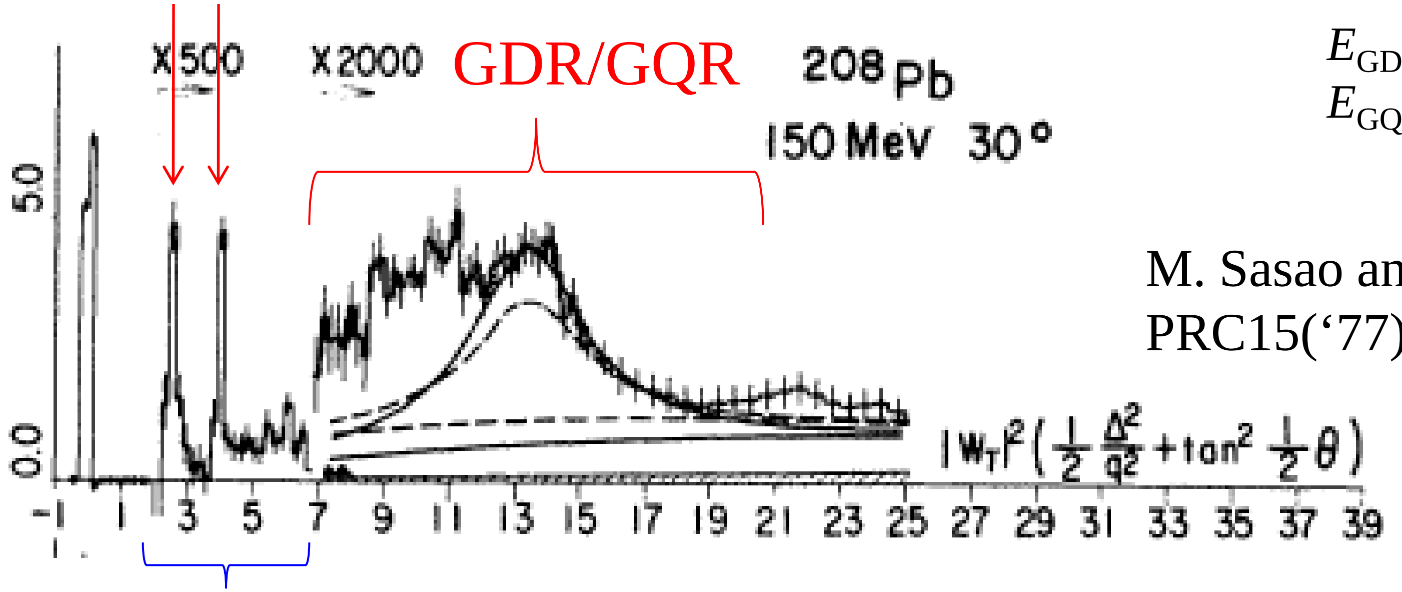


M. Dasgupta et al., PRL99('07)192701

- ➢dynamical effects not included in C.C. calculation?
- ➢energy and angular momentum dissipation?
- ➢weak channels? ← this talk

typical excitation spectrum: electron scattering data

low-lying collective excitations



GDR/GQR

$E_{\mathrm{GDR}} \sim 79A^{-1/3}$ MeV
$E_{\mathrm{GQR}} \sim 65A^{-1/3}$ MeV

M. Sasao and Y. Torizuka,
PRC15(‘77)217

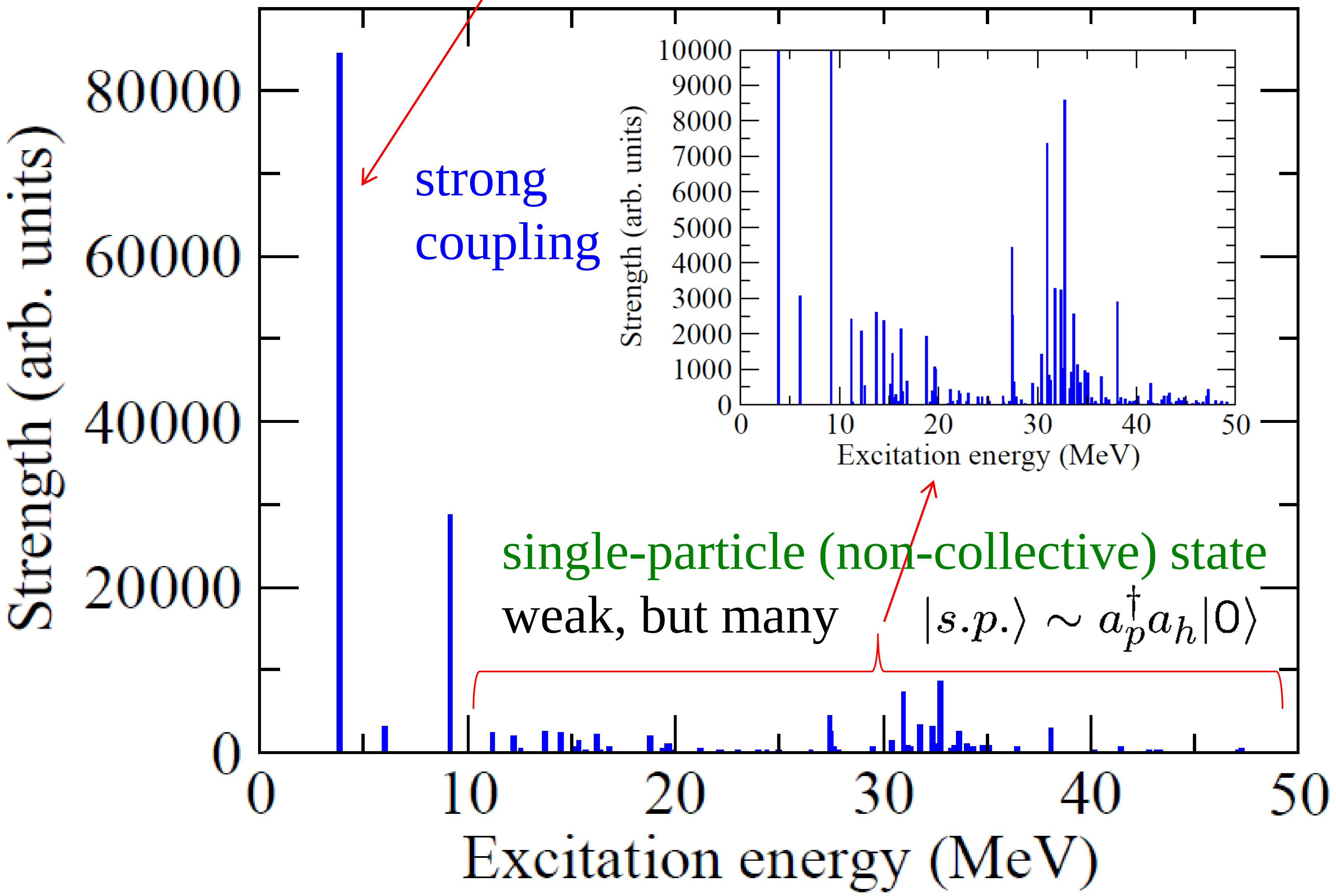
E_x (MeV)

low-lying non-collective excitations

- Giant Resonances: high E_x, smooth mass number dependence $\longrightarrow$ adiabatic potential renormalization
- Low-lying collective excitations: barrier distributions, strong isotope dependence
- Non-collective excitations: either neglected completely or implicitly treated through an absorptive potential

IS Octupole response of ^{48}Ca (Skyrme HF + RPA calculation: SLy4)

collective state: $|coll\rangle \sim \sum_{ph} X_{ph} a_p^\dagger a_h |0\rangle$



strong coupling

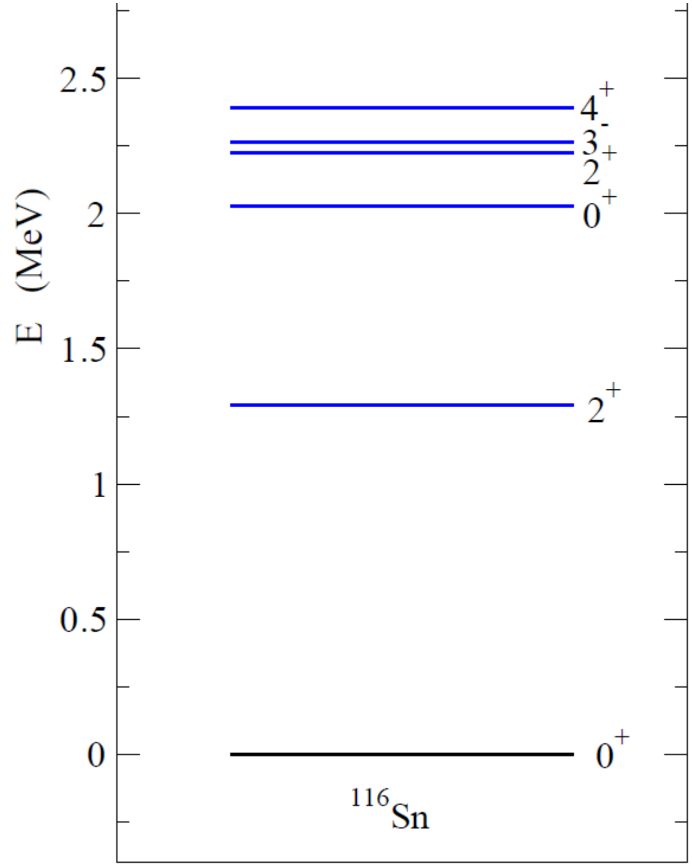
single-particle (non-collective) state

weak, but many

$|s.p.\rangle \sim a_p^\dagger a_h |0\rangle$

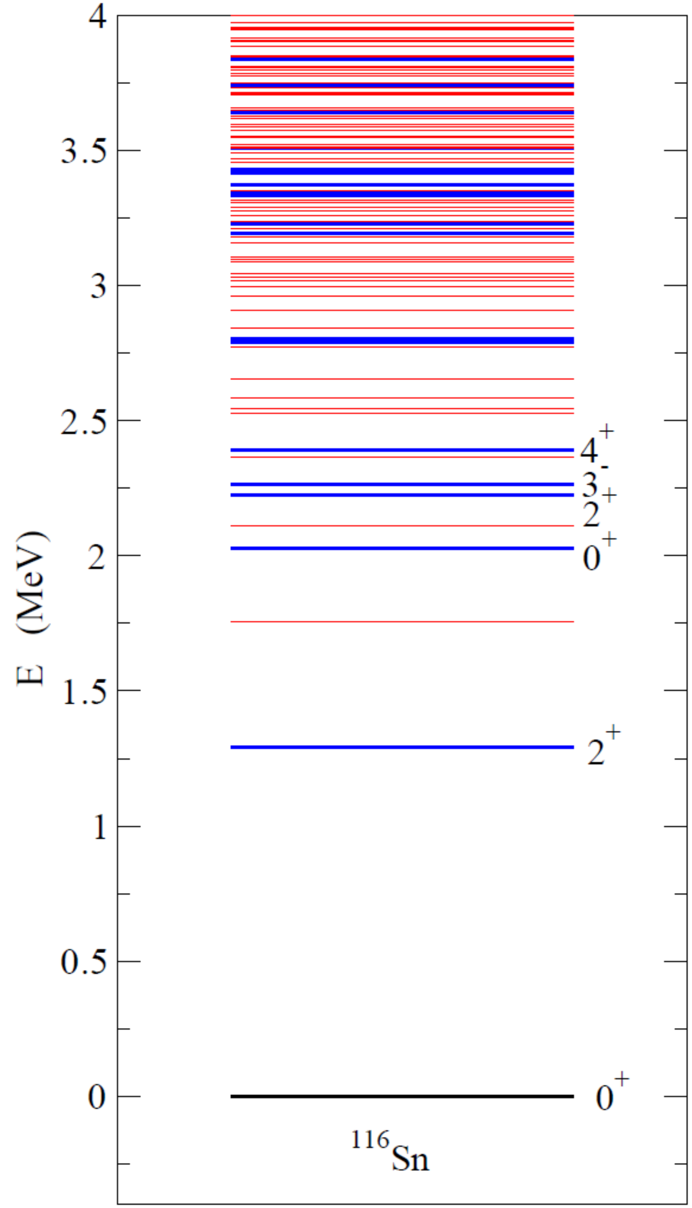
Our interest: couplings to (relatively) low-lying single-particle levels

e.g., collective levels in ^{116}Sn



model space in a typical C.C. calculation

Our interest: couplings to (relatively) low-lying single-particle levels



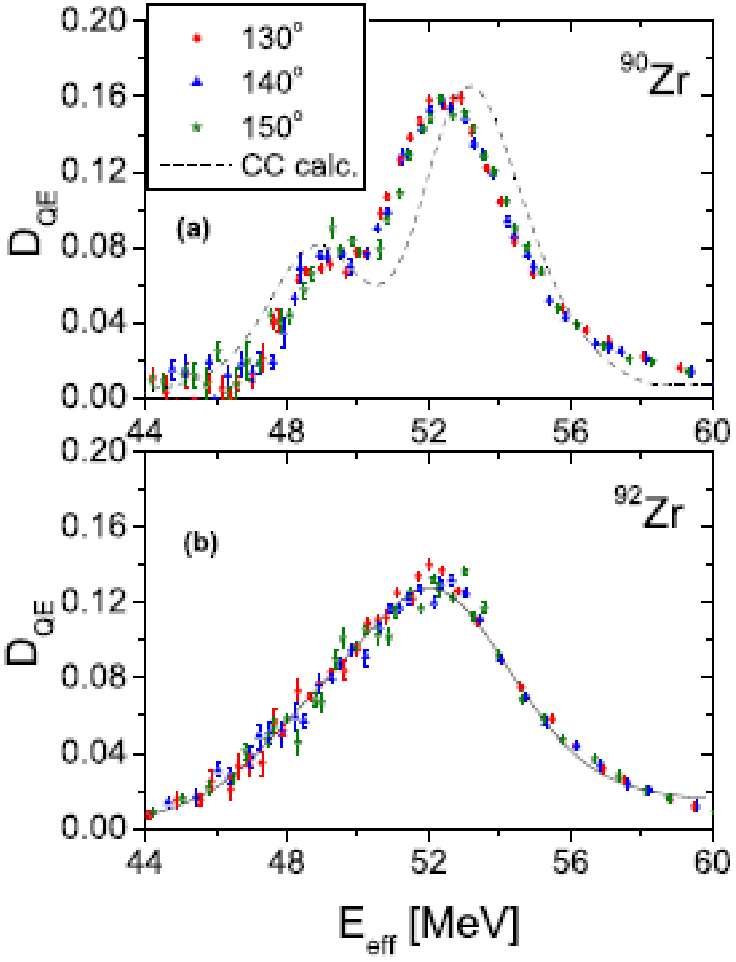
112 levels up to 4.1 MeV
(93 single-particle levels)
nearly “complete” level scheme

S. Raman et al.,
PRC43(‘91)521

role of these s.p. levels in reaction dynamics?

Indications of non-collective excitations : a comparison between ^{20}Ne+^{90}Zr and ^{20}Ne+^{92}Zr

^{20}Ne+^{90,92}Zr



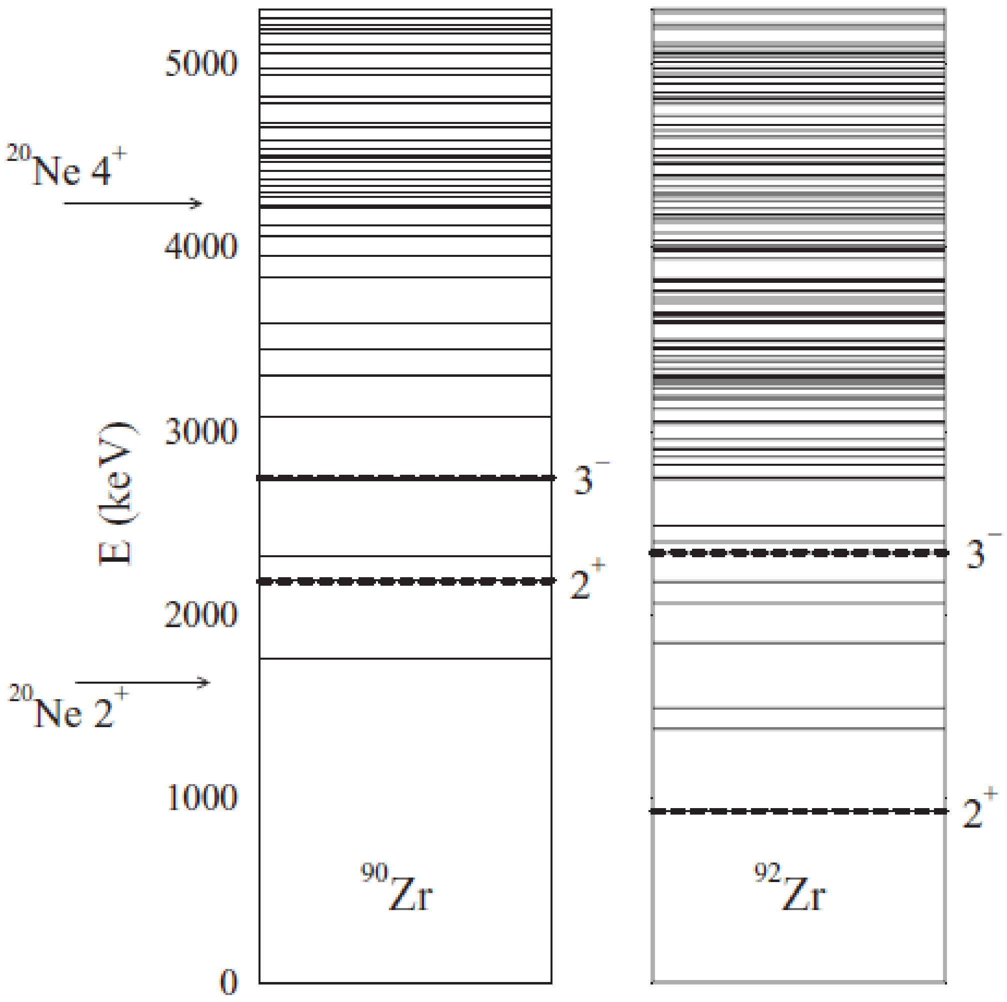
E. Piasecki et al.,
PRC80(‘09)054613

$$D_{\rm qel}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_R(E,\pi)}\right)$$

QEL = elastic + inelastic + transfer

- C.C. results are almost the same between the two systems
- Yet, quite different barrier distribution and Q-value distribution

non-collective excitations?



^{90}Zr (Z=40 sub-shell closure,
N=50 shell closure)
^{92}Zr = ^{90}Zr + 2n

a problem: the nature of non-collective states is
poorly known (the energy, spin, parity only)
i.e., no information on the coupling strengths

Random Matrix Model

Coupled-channels equations:

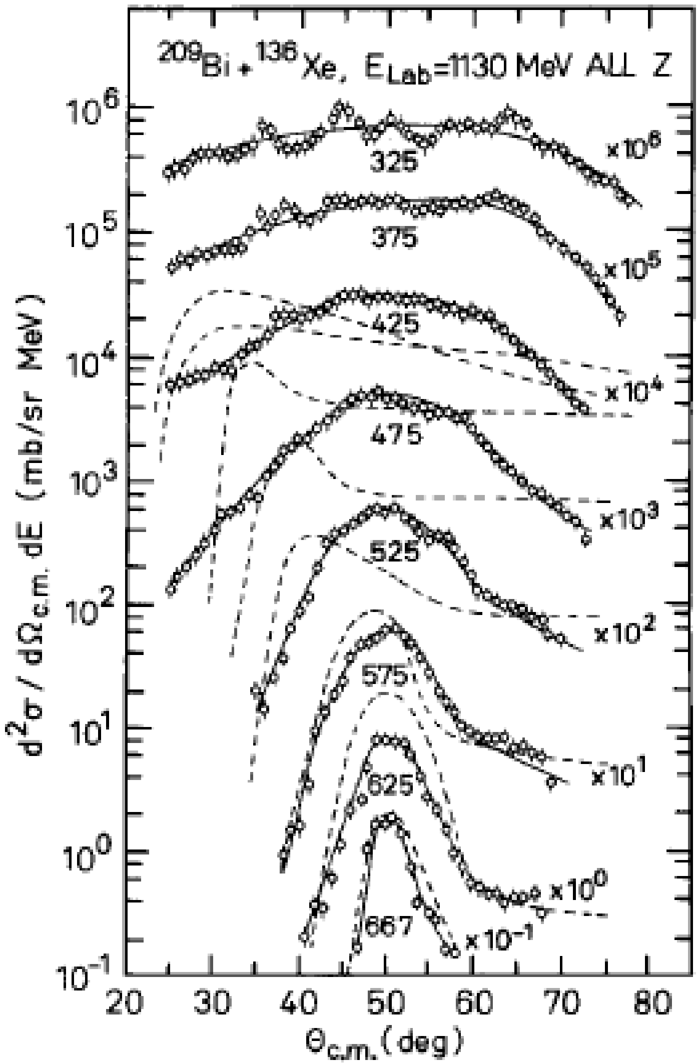
$$\left[-\frac{\hbar^2}{2\mu}\nabla^2+V_0(r)+\epsilon_k-E\right]\psi_k(\boldsymbol{r})+\sum_{k'}\langle\phi_k|V_{\rm coup}|\phi_{k'}\rangle\psi_{k'}(\boldsymbol{r})=0$$

$|\phi_k\rangle$: complicated single-particle states

coupling matrix elements $V_{kk'}=\langle\phi_k|V_{\rm coup}|\phi_{k'}\rangle$ are random numbers generated from a Gaussian distribution:

$$\begin{aligned}\overline{V_{ij}(r)} &= 0,\\ \overline{V_{ij}(r)V_{kl}(r')} &= (\delta_{ik}\delta_{jl}+\delta_{il}\delta_{jk})\,\frac{w_0}{\sqrt{\rho(\epsilon_i)\rho(\epsilon_j)}}\\ &\quad\times e^{-\frac{(\epsilon_i-\epsilon_j)^2}{2\Delta^2}}\cdot e^{-\frac{(r-r')^2}{2\sigma^2}}\cdot h(r)h(r')\end{aligned}$$

D. Agassi, C.M. Ko, and H.A. Weidenmuller, Ann. of Phys. 107('77)140



D. Agassi, H.A. Weidenmuller, and
C.M. Ko, PL 73B('78)284

RMT model for H.I. reactions:

✓originally developed by Weidenmuller et al. to analyze DIC

✓similar models have been applied to discuss *quantum dissipation*

- M. Wilkinson, PRA41('90)4645
- A. Bulgac, G.D. Dang, and D. Kusnezov, PRE54('96)3468
- S. Mizutori and S. Aberg, PRE56('97)6311

Application to ^{20}Ne + ^{90,92}Zr reactions

- Internuclear potential

Woods-Saxon potential V_0 = 55 MeV (^{90}Zr), 62.3 MeV (^{92}Zr),
r_0 = 1.2 fm, a=0.65 fm

- Coupling form factor $h(r)$

derivative of Woods-Saxon

- Non-collective couplings

up to 5.7 MeV, only from the ground state

$\longrightarrow$ 38 channels for ^{90}Zr, 75 channels for ^{92}Zr

energy and radial coherence lengths: Weidenmuller et al.

Δ = 7 MeV, σ = 4 fm

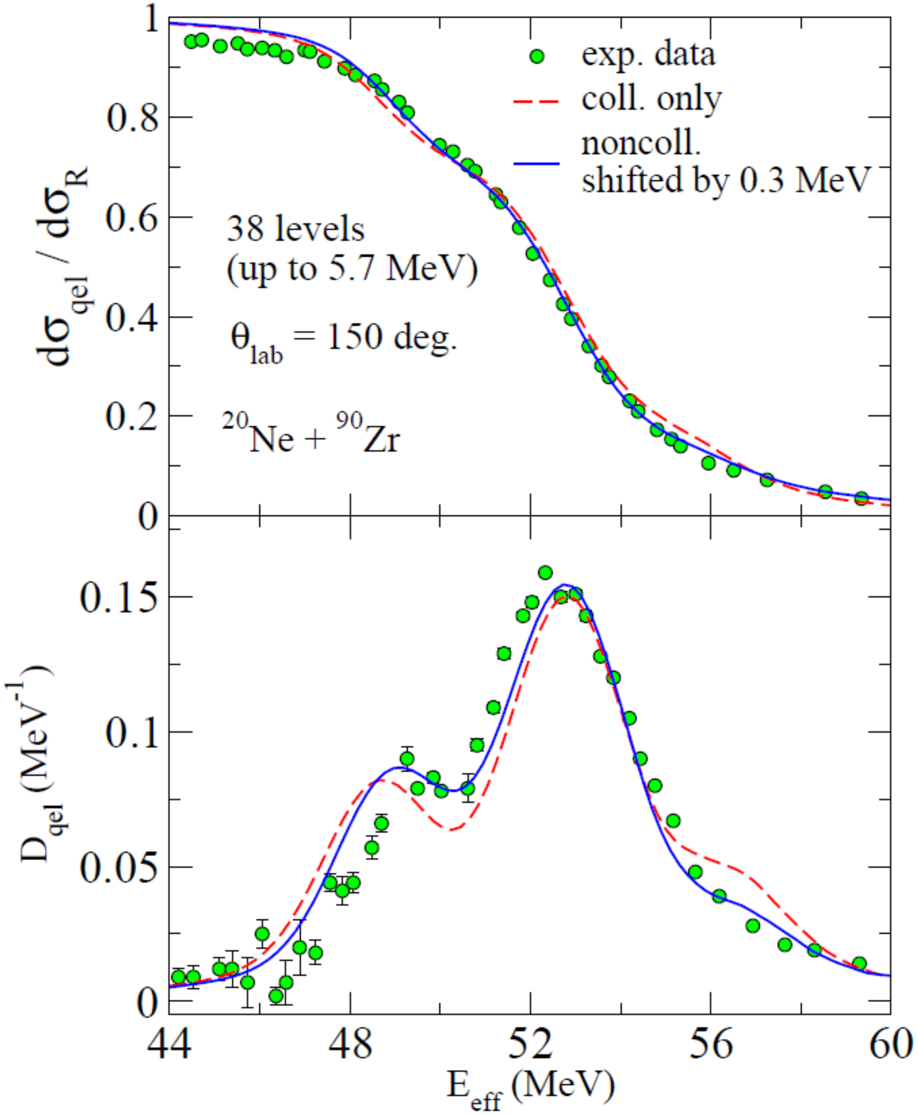
the overall coupling strength: adjustable parameter

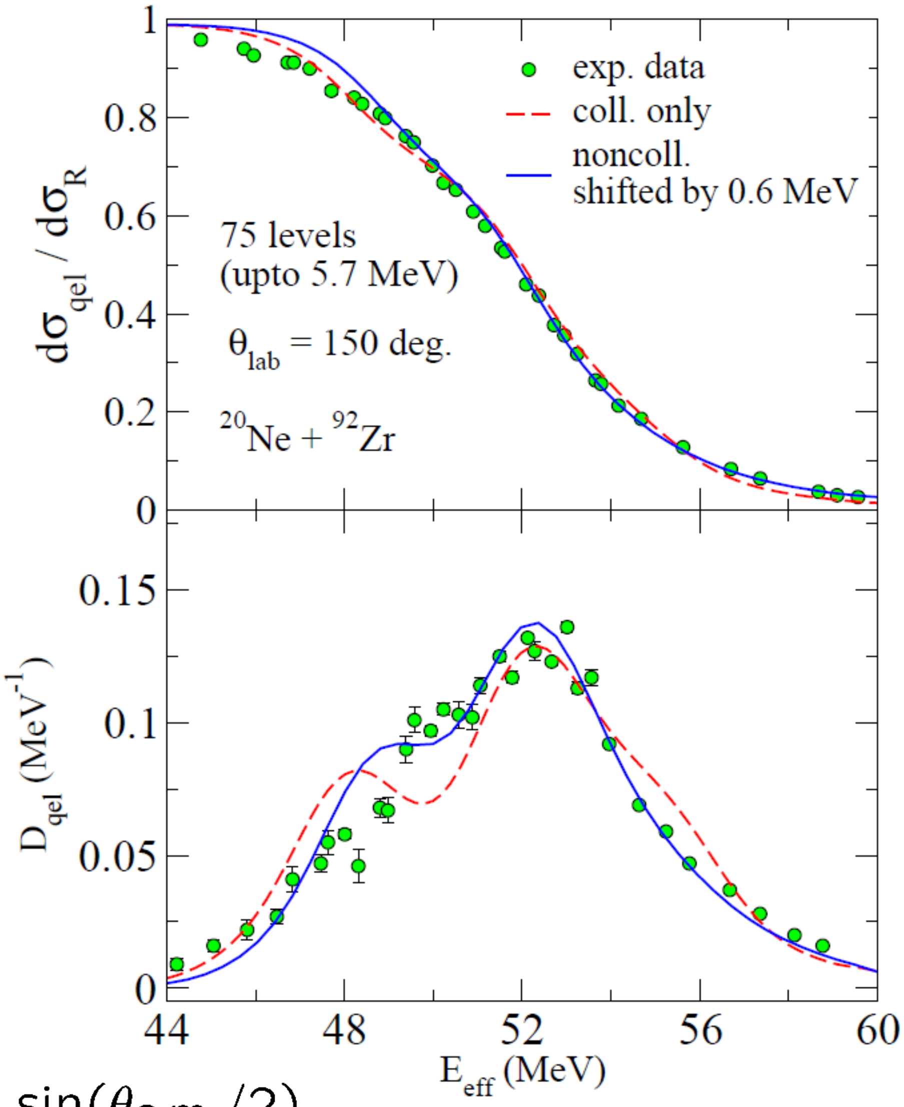
(the same value between ^{90}Zr and ^{92}Zr)

- Collective couplings

rot. states of ^{20}Ne up to 6^+ + 2^+ and 3^- two-phonons in Zr

Quasi-elastic cross sections

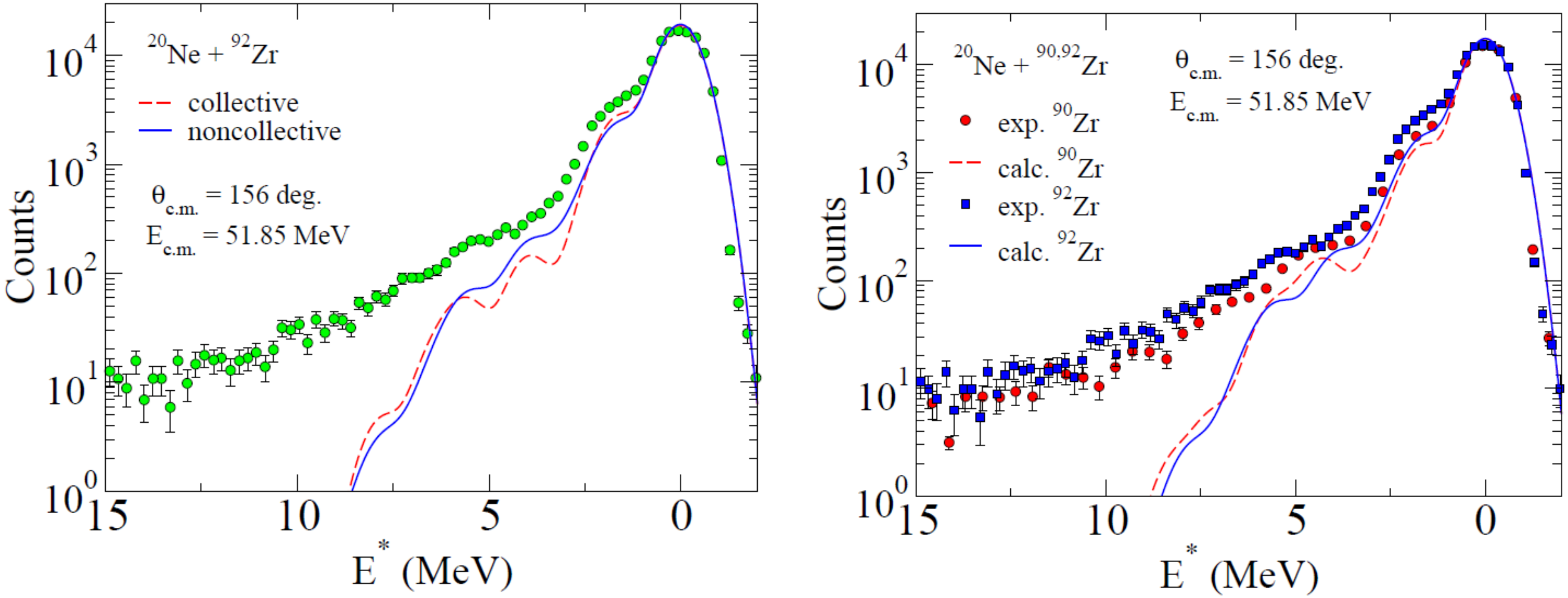




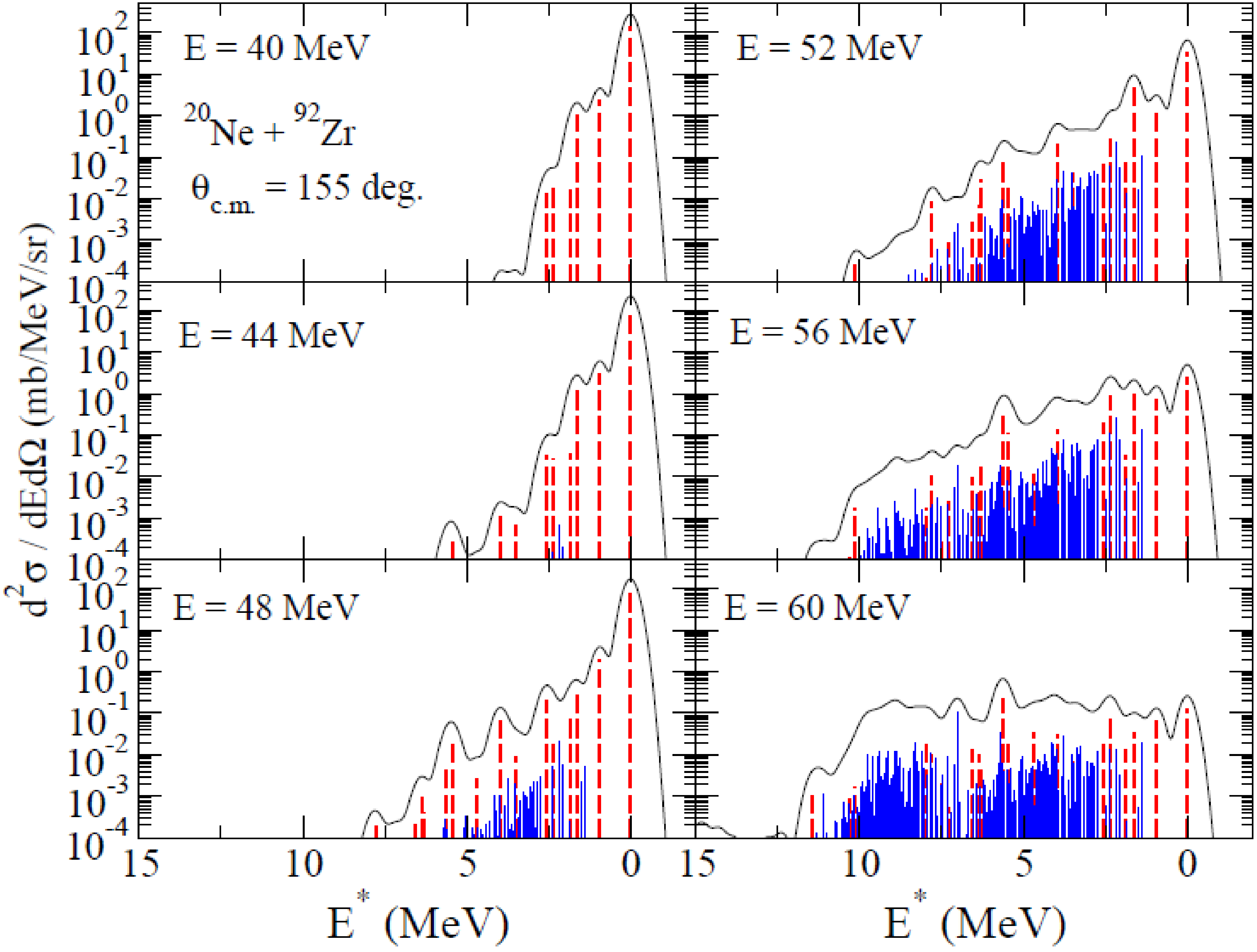
$$E_{\text{eff}} = 2E\frac{\sin(\theta_{\text{c.m.}}/2)}{1+\sin(\theta_{\text{c.m.}}/2)}$$

S. Yusa, K.H., and N. Rowley, arXiv:1309.4674

Q-value distributions

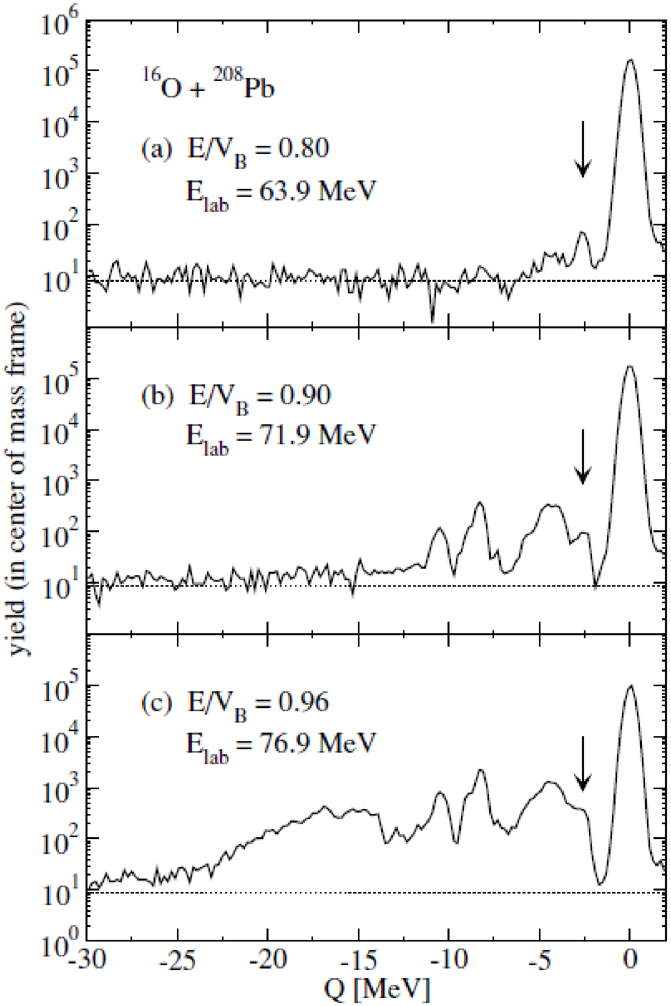


S. Yusa, K.H., and N. Rowley, arXiv:1309.4674

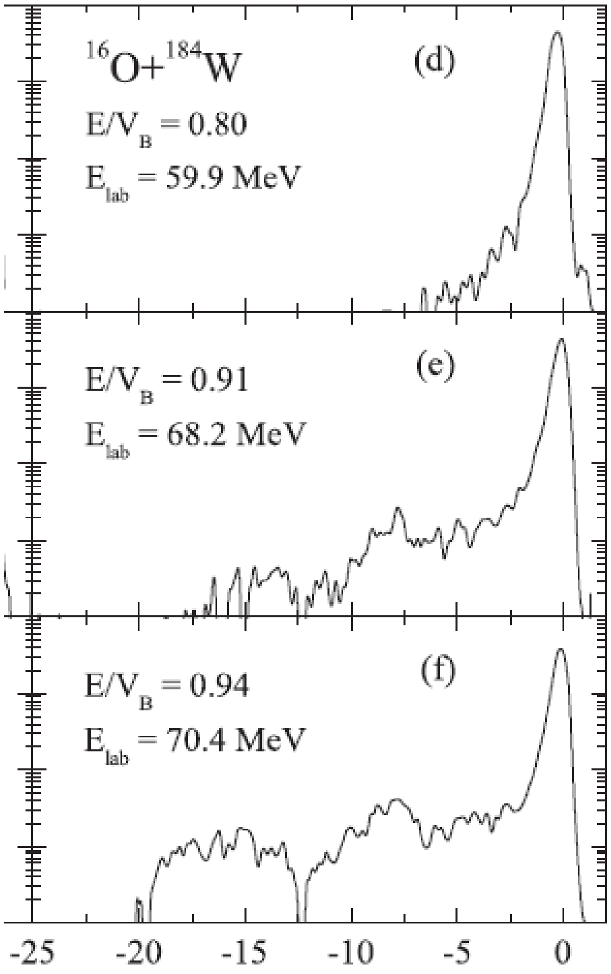


S. Yusa, K.H., and N. Rowley, arXiv:1309.4674

cf. Q-value distribution from backward scattering:



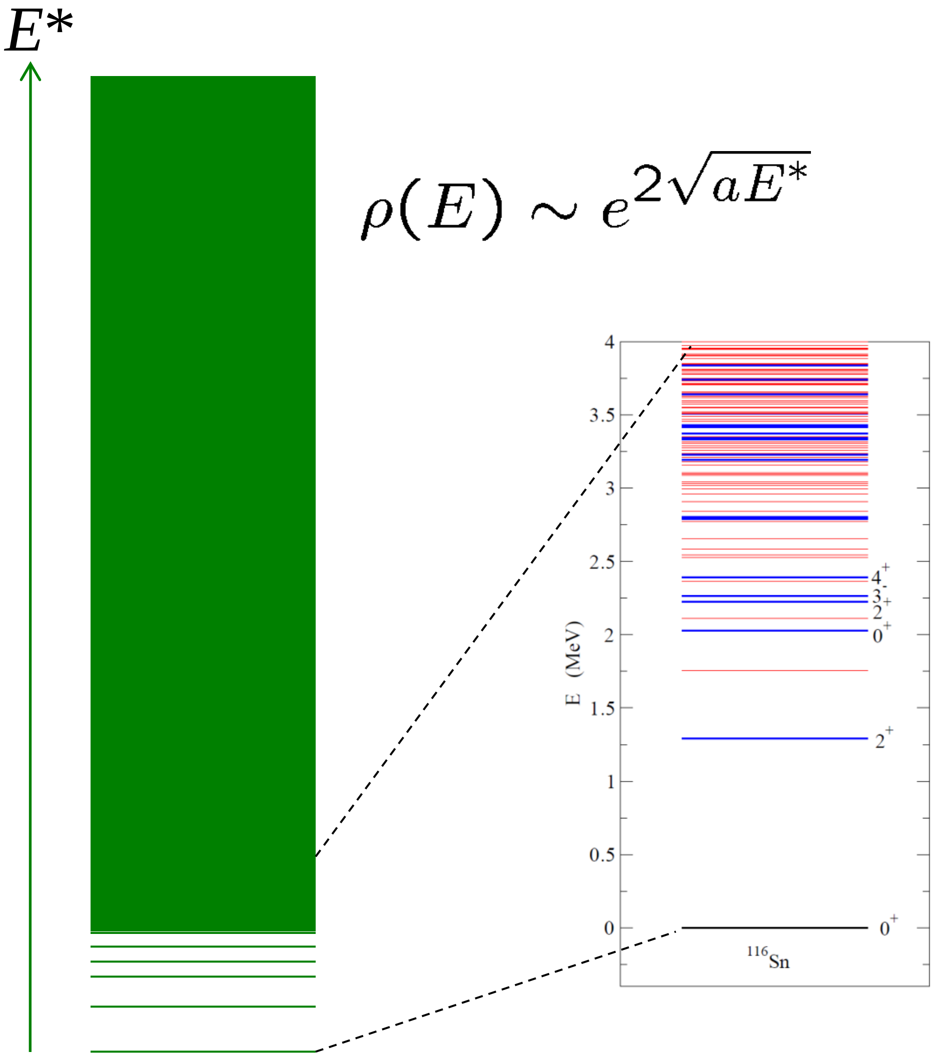
M. Evers et al.,
PRC78(‘08)034614



C.J. Lin et al.,
PRC79(‘09)064603

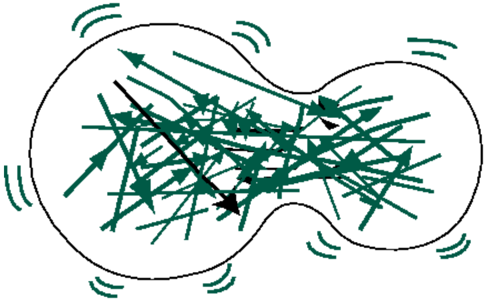
(elastic + collective) peaks + non-collective bumps

Discussions: towards a microscopic reaction theory



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

nuclear spectrum



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

⇩

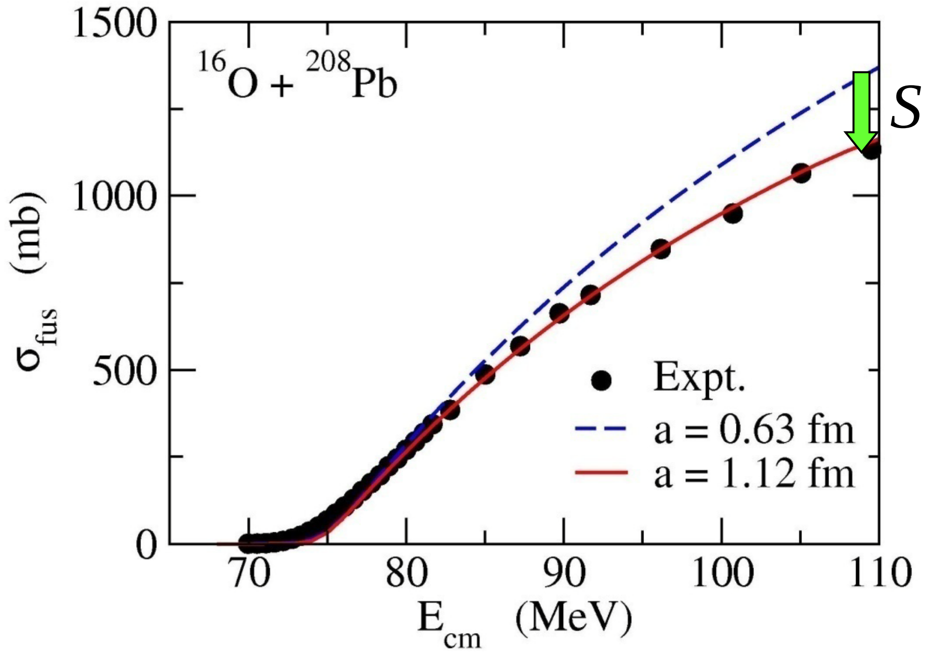
nuclear intrinsic d.o.f.
act as environment for
nuclear reaction processes

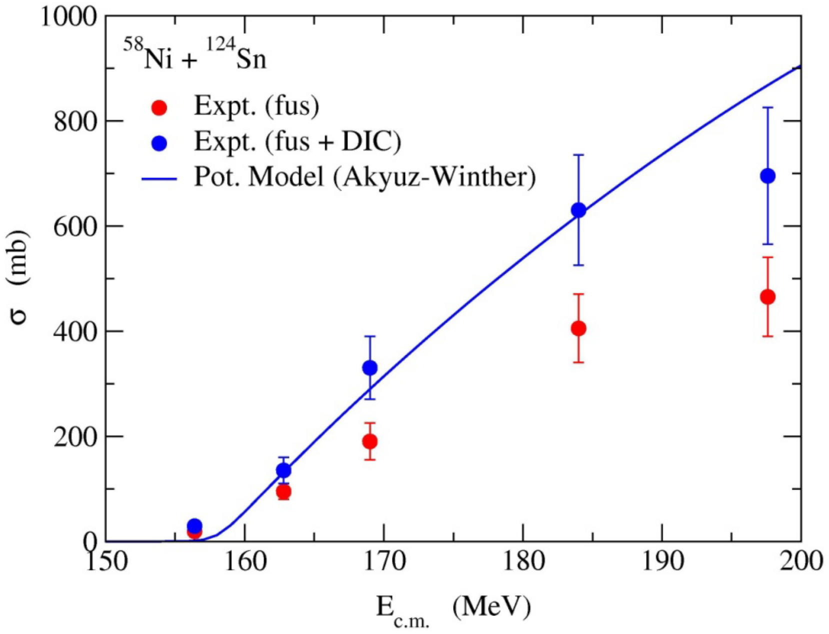
"*intrinsic* environment"

coupling to environment ⟷ dissipation & friction

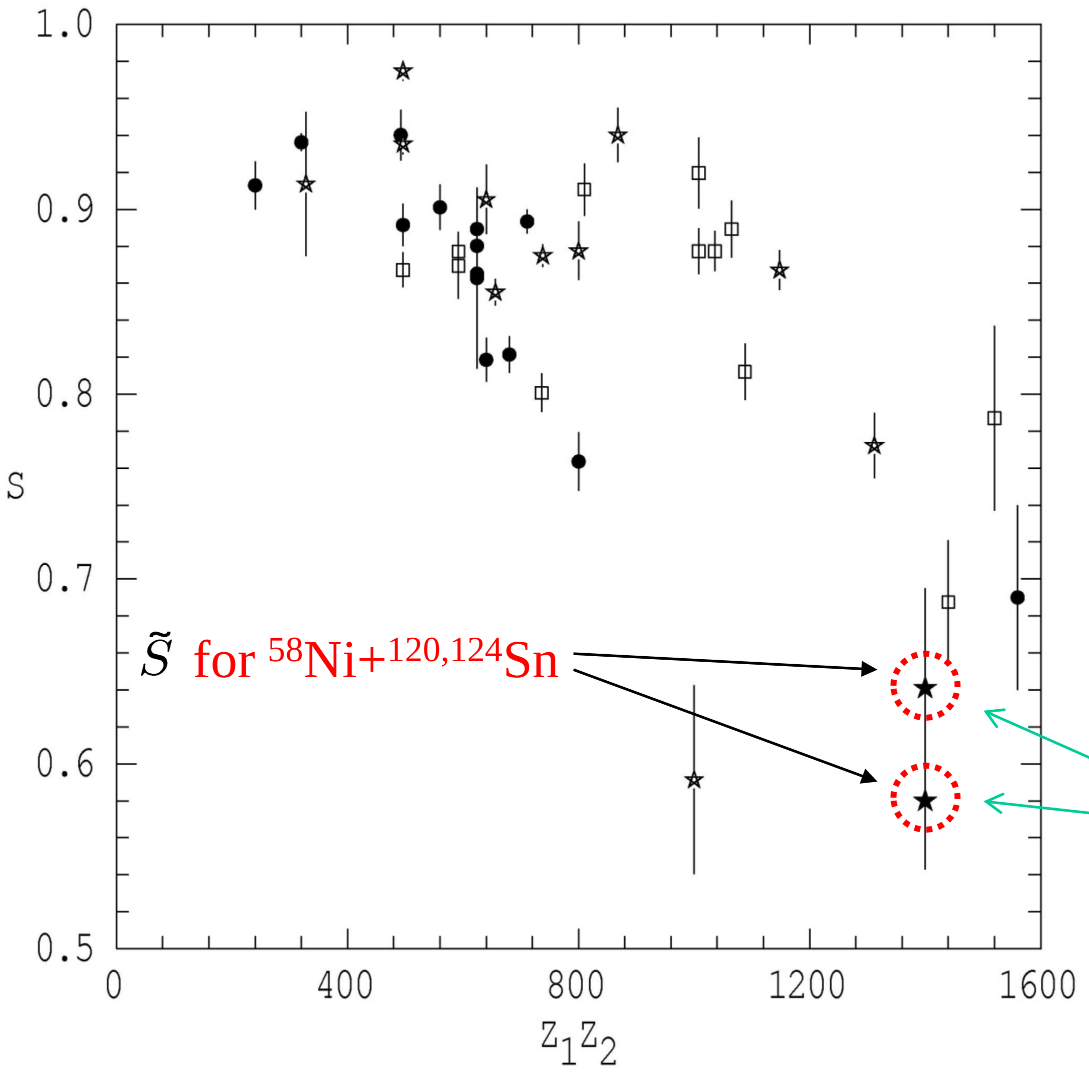
How much do we know about "friction"?

Fusion model ⟶ friction free: strong absorption inside the barrier





$$\sigma_{\text{fus}}^{(\text{exp})}(E) = S \cdot \sigma_{\text{capt}}^{(\text{th})}(E; a = 0.63)$$



$\tilde{S}$ for ^{58}Ni+^{120,124}Sn

DIC also in light systems?

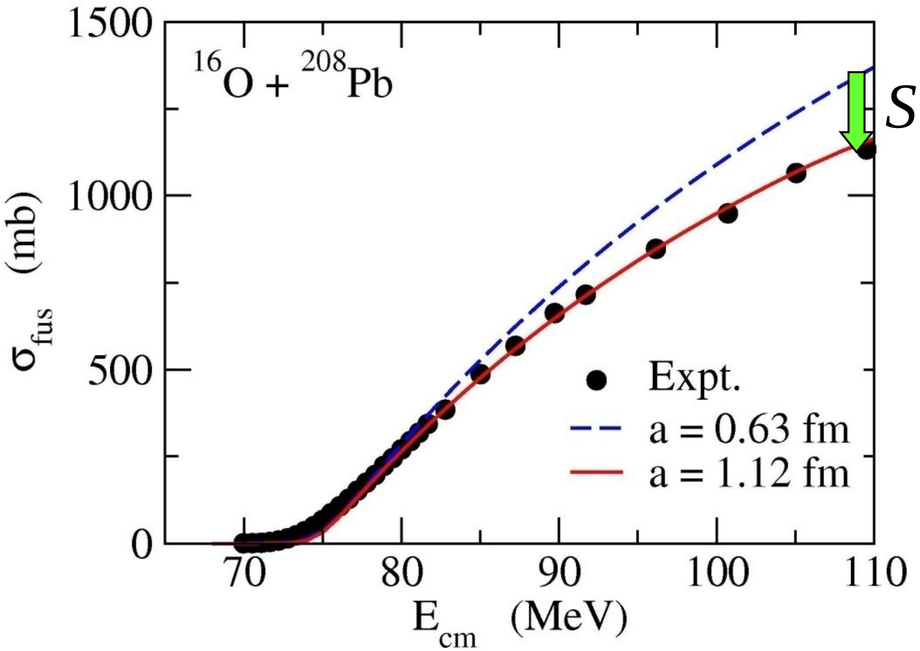
Transfer processes with large negative Q-value?

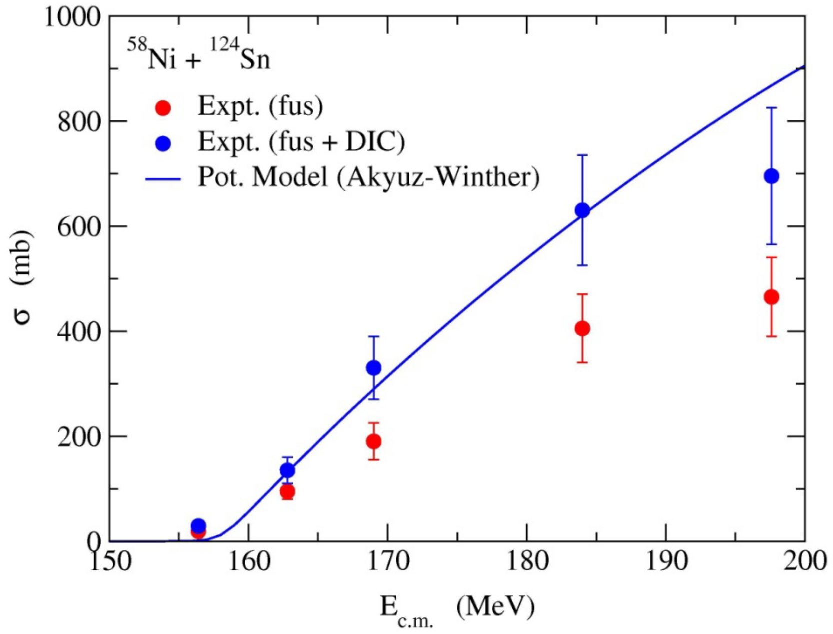
$$\tilde{S} \equiv \frac{\sigma_{\text{fus}}^{(\text{exp})}(E)}{\sigma_{\text{fus}}^{(\text{exp})}(E) + \sigma_{\text{DIC}}^{(\text{exp})}(E)}$$

J.O. Newton, K.H. et al., PRC70('04)024605 coupling to environment ⟷ dissipation & friction

How much do we know about “friction”?

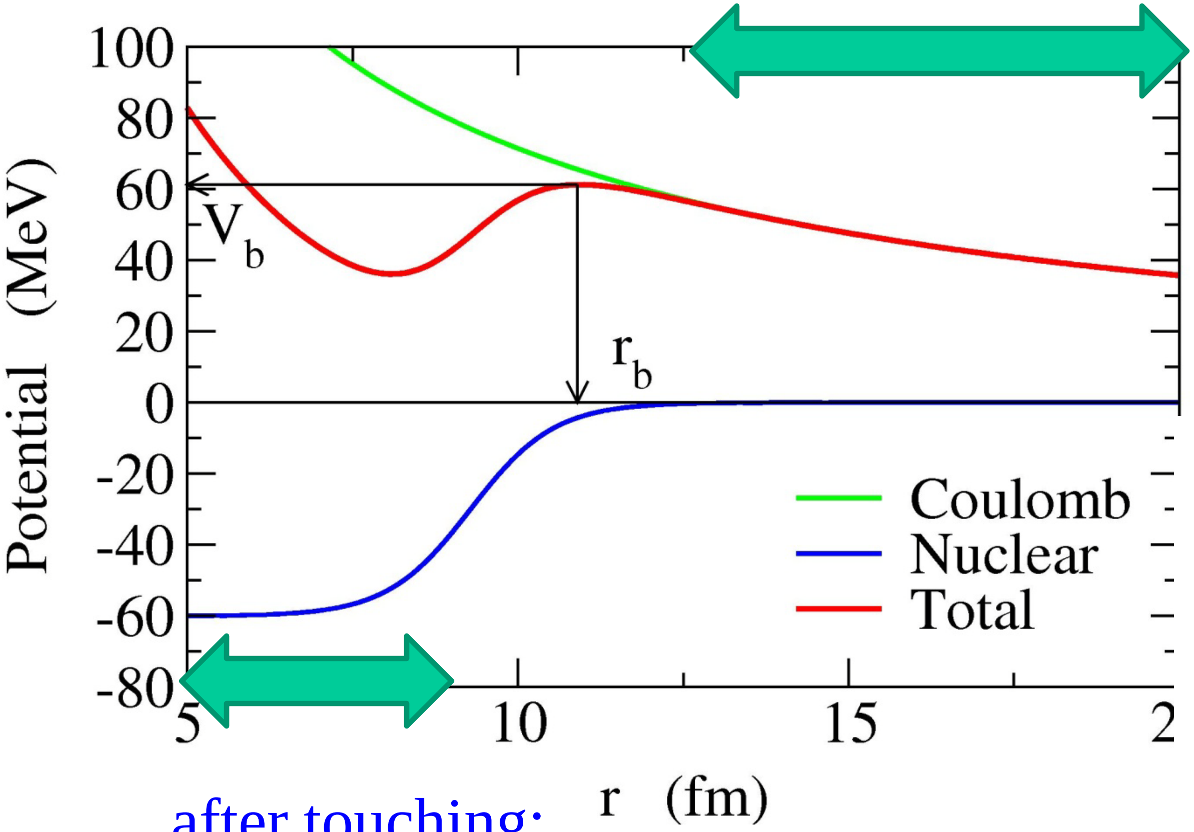
Fusion model ⟶ friction free: strong absorption inside the barrier



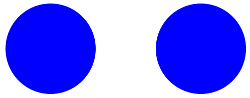


➡ The topic of energy dissipation in fusion should be re-visited

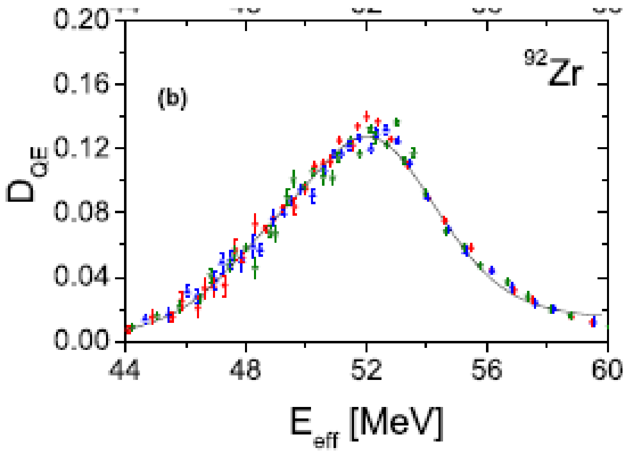
- re-analyses of DIC data: maybe helpful
- Consistent theoretical model (dissipative quantum tunneling)



Non-collective excitations in isolated nuclei

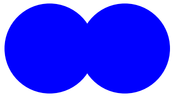


^{20}Ne + ^{92}Zr



after touching:

molecular excitations



- Deep subbarrier fusion

- Random matrix model?

Unified qnatum theory for fusion (subbarrier, deep subbarrier) & DIC?

⟷ Single-particle (non-collective) excitations in H.I. reactions

quantum mechanical model for Wall-Window friction?

(Big) open question:

- Construction of a 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

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

many reaction theories correspond to this type

⬇

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

Microscopic nuclear reaction theories

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

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, TD-GCM, ASCC ?
imaginary-time TDHF?

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

Another issue

Is reaction fast or slow?

Many-body (N-particle system) Hamiltonian $$H = \sum_i t_i + \sum_{i<j} v_{ij}$$

→ Large Amplitude Collective Motion

$$H = H_{rel} + H_{s.p.} + H_{coup}$$

✧Sudden approach (fast collision)

Double Folding Model
Optical Model
Coupled-channels model
} const. reduced mass μ

Resonating Group Method (RGM)

✧Adiabatic approach (slow collision)

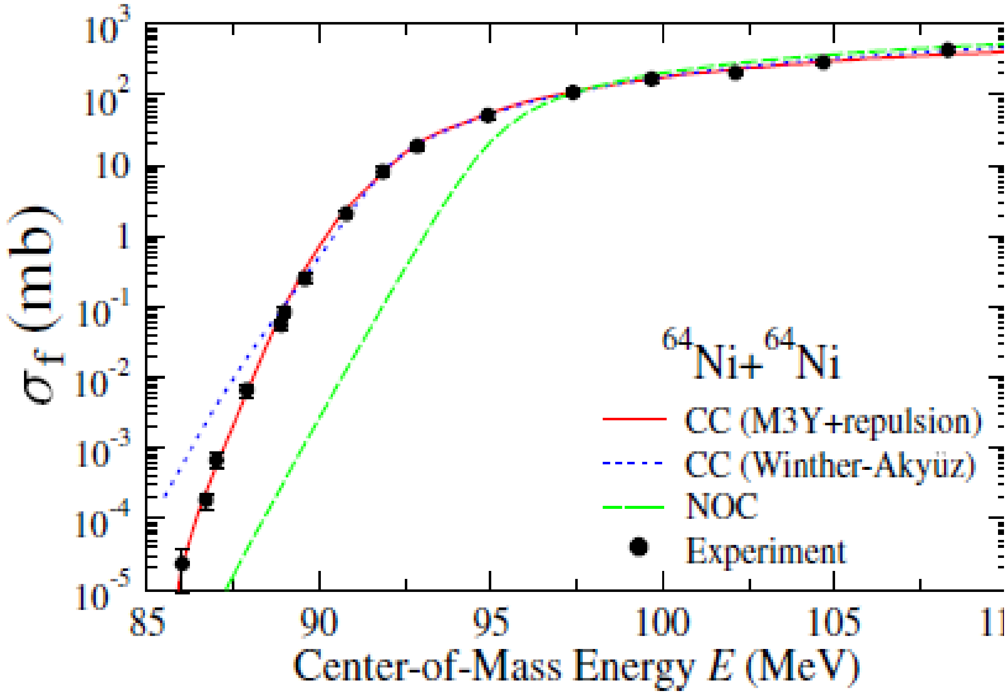
Liquid-drop model (+ shell correction)
Adiabatic TDHF

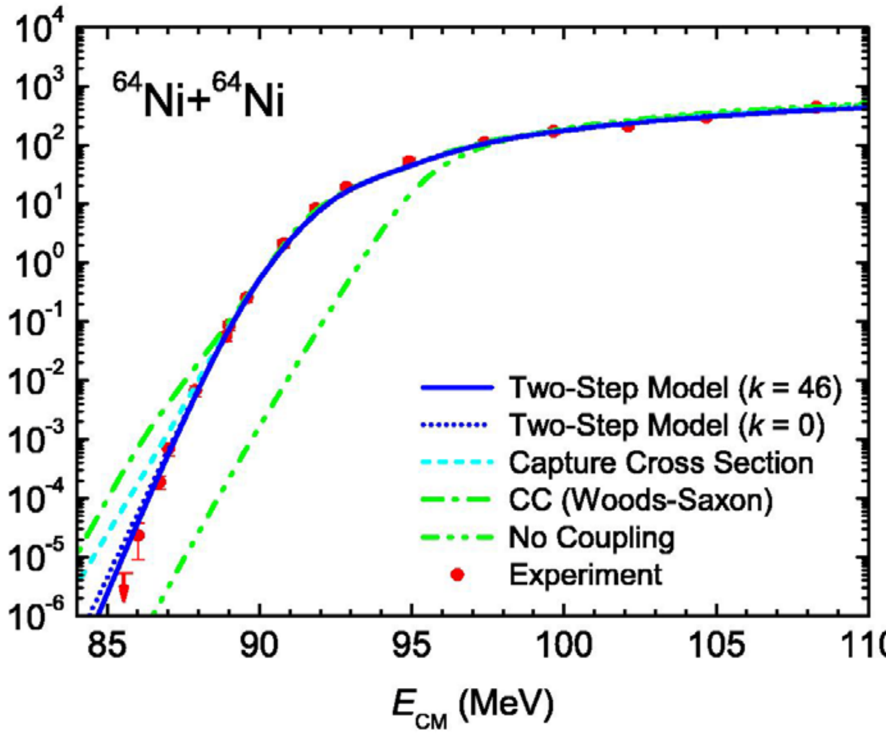
← Coordinate dependent mass μ(r)

cannot discriminate one of them at present

sudden approach (frozen density)

adiabatic approach





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

T. Ichikawa, K.H., A. Iwamoto,
PRC75(’07)057603

- ✓need further studies from several perspectives
- ✓construction of dynamical model without any assumption on adiabaticity

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 noncollective excitations?
  - dissipation, friction
✓microscopic understanding of subbarrier fusion?
✓unified theory of fusion and DIC?