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

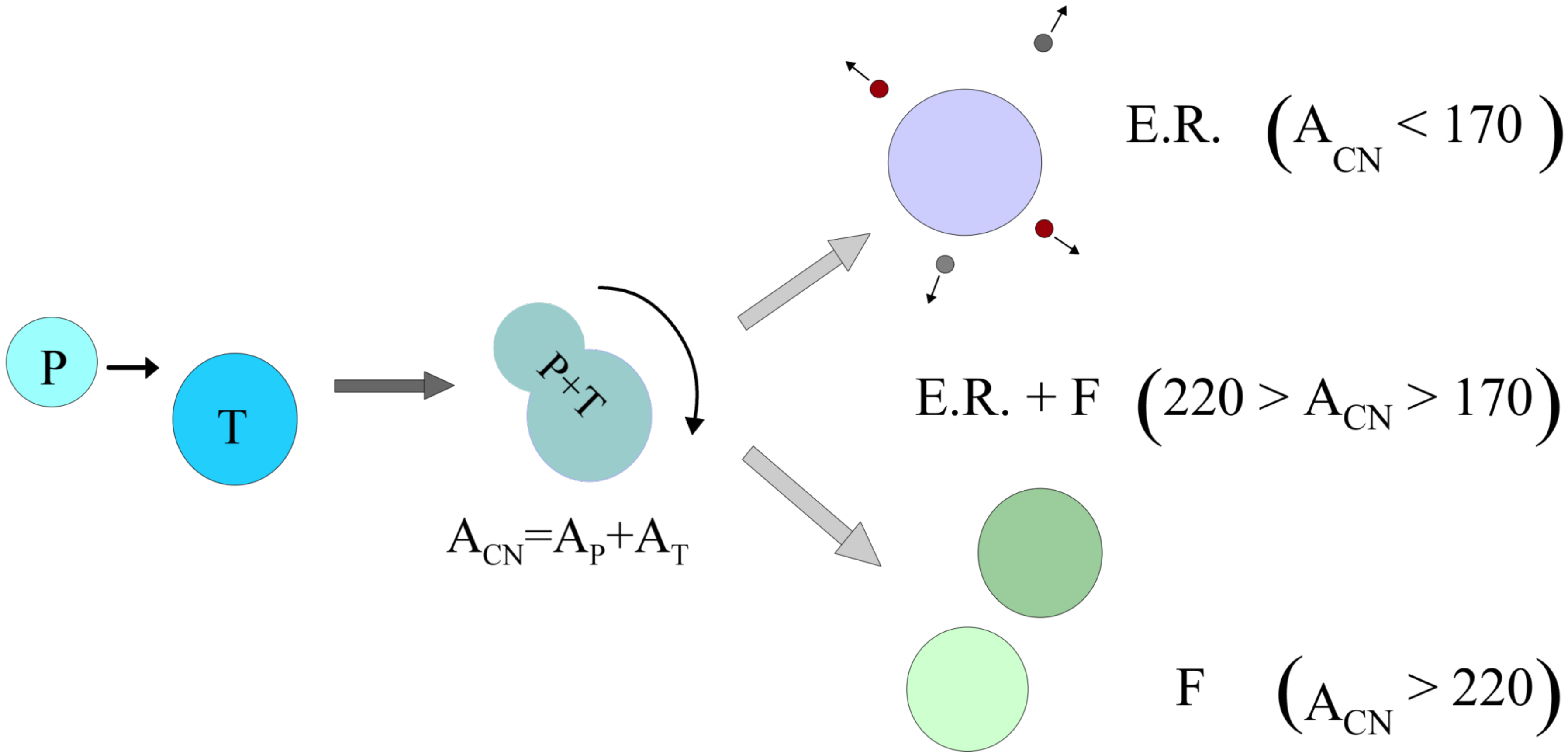
Role of internal degrees of freedom in low-energy nuclear reactions

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*

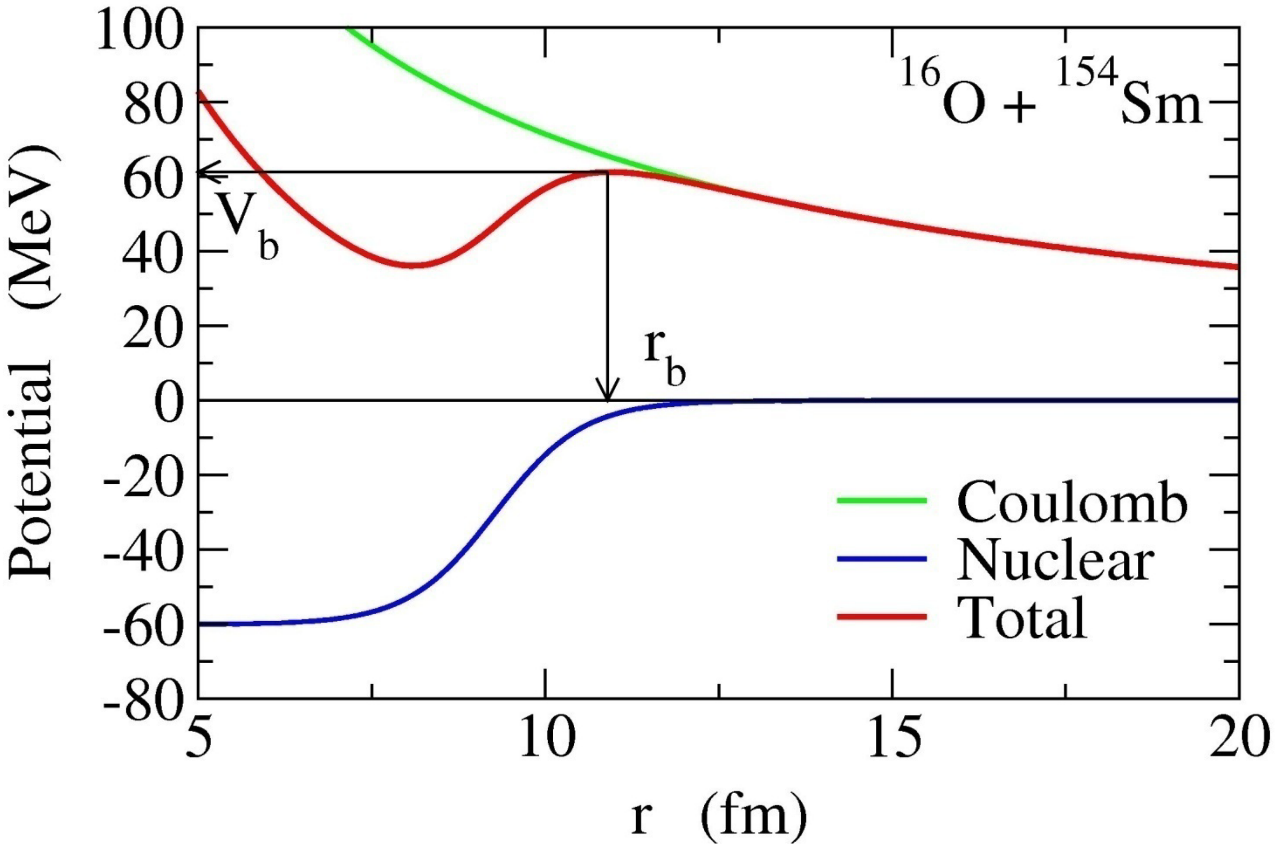
Introduction

Fusion: compound nucleus formation



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

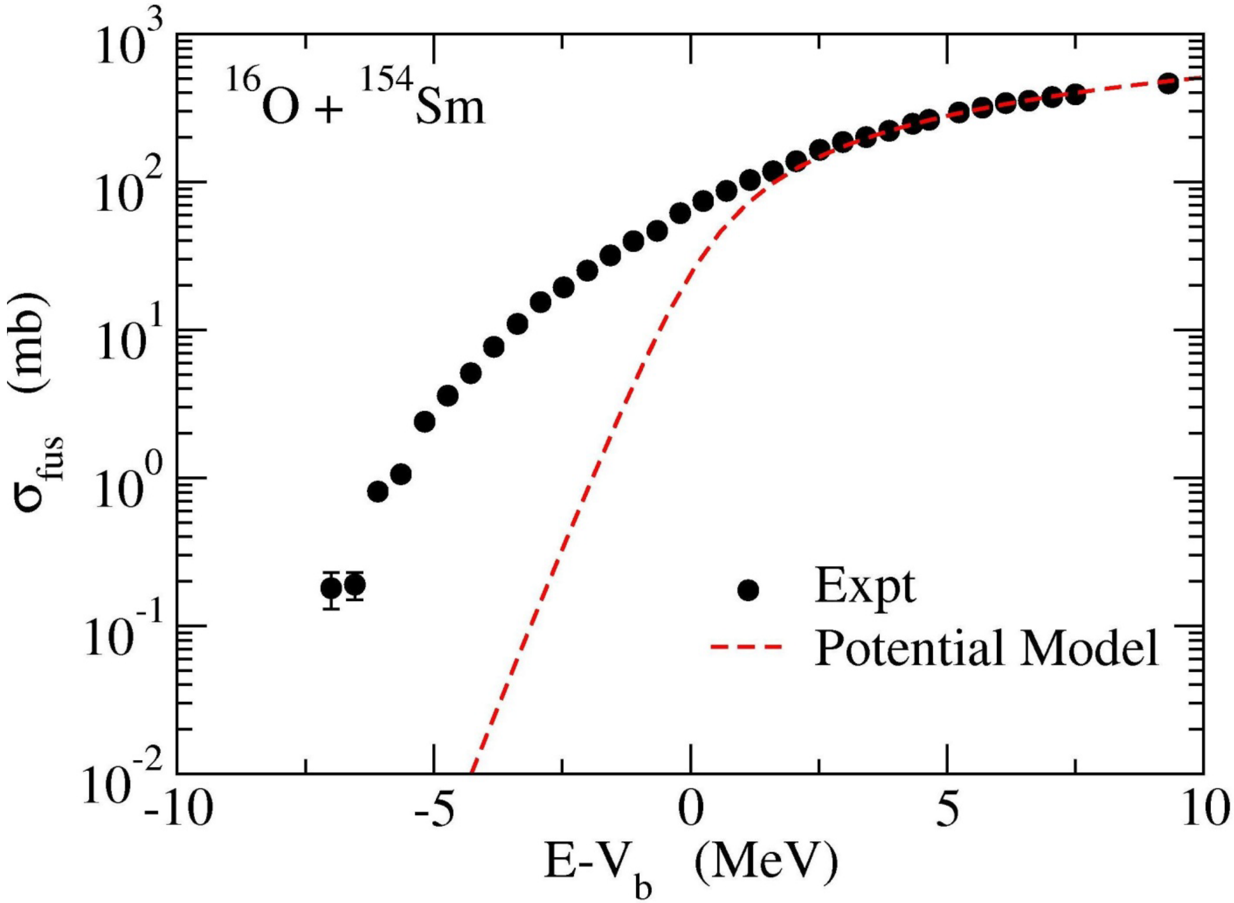
courtesy: Felipe Canto



the simplest approach to fusion cross sections: potential model

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

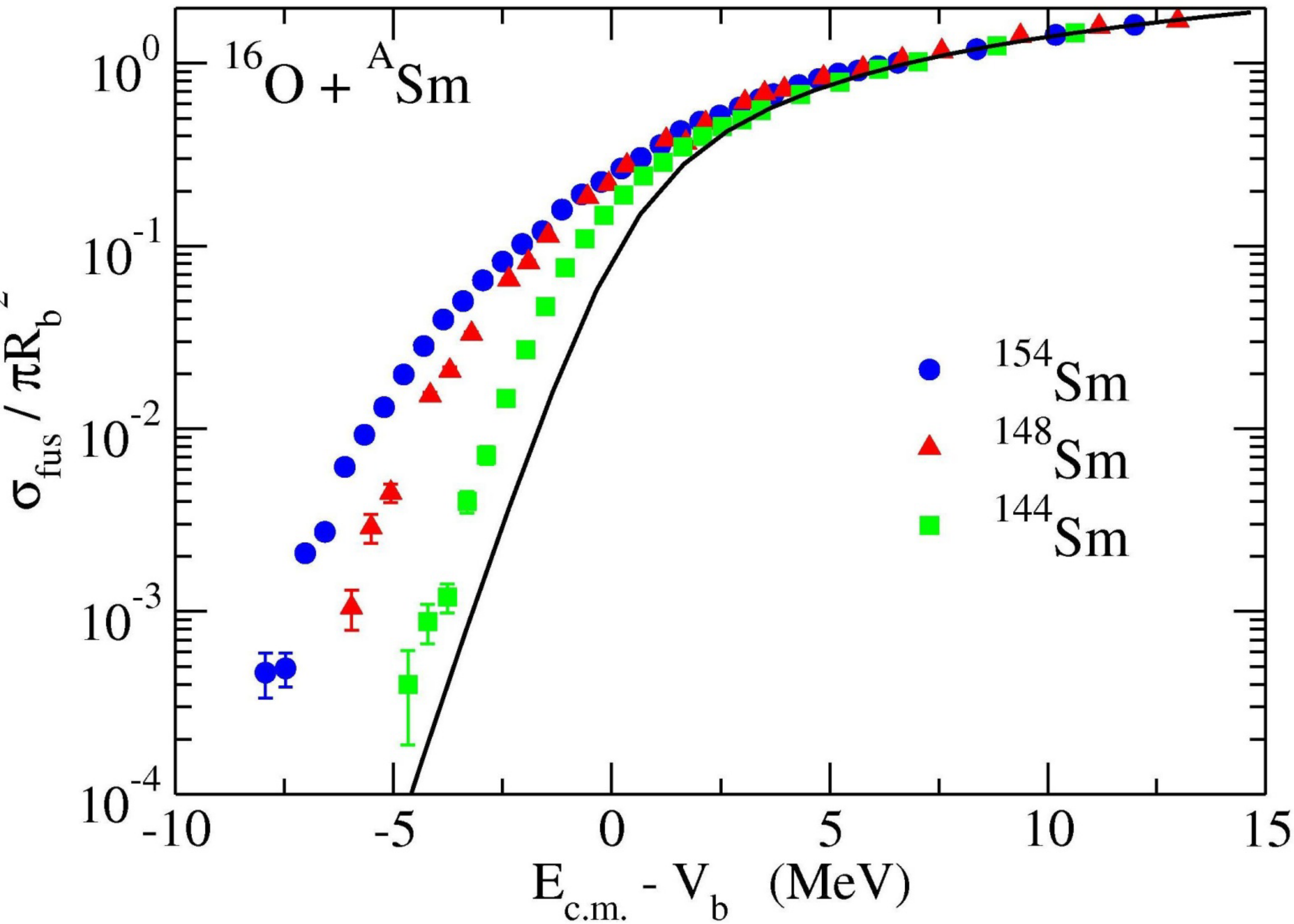
Subbarrier fusion reactions



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



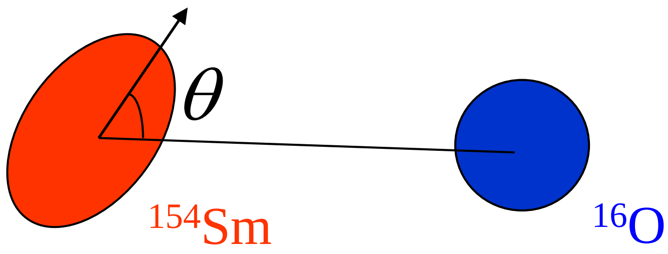
Strong target dependence at $E < V_b$

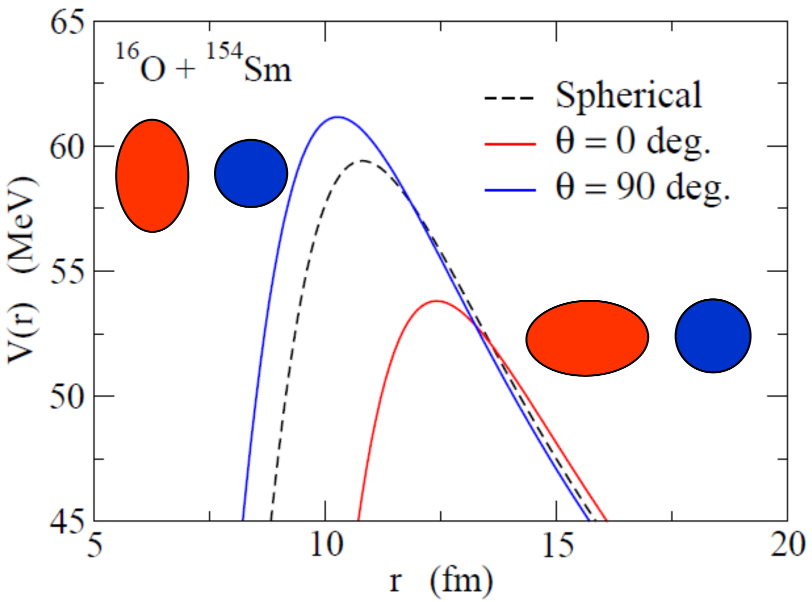
low-lying collective excitations

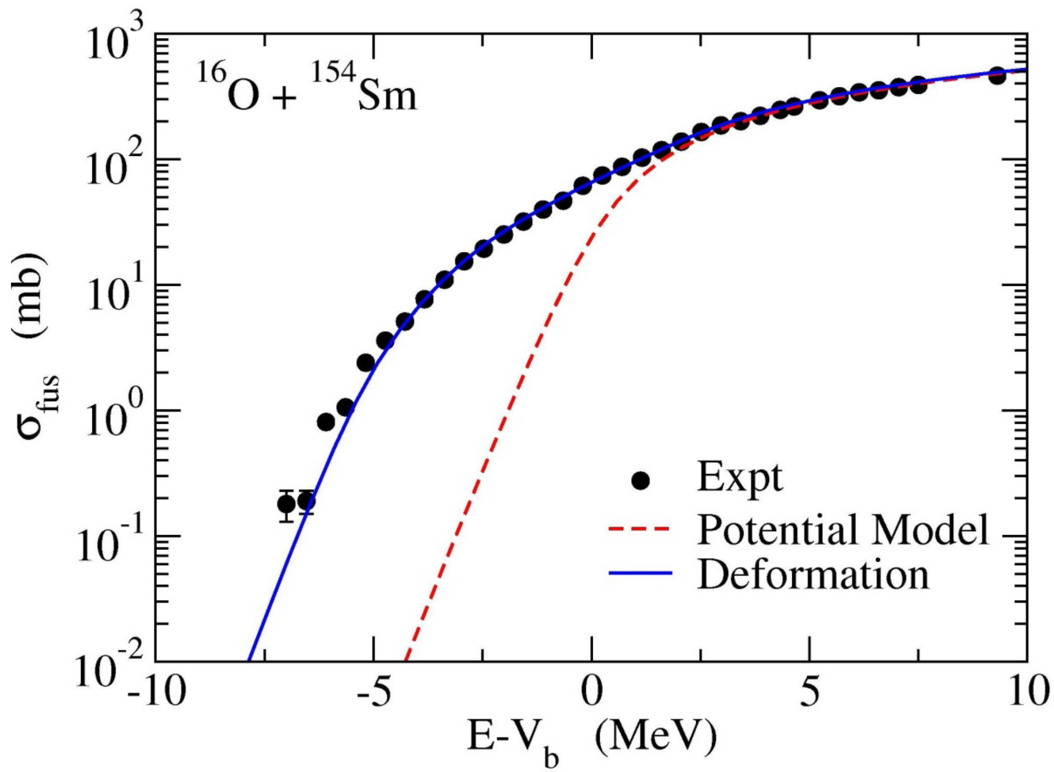
Subarrier fusion:
strong interplay between
reaction and structure

coupled-channels equations

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





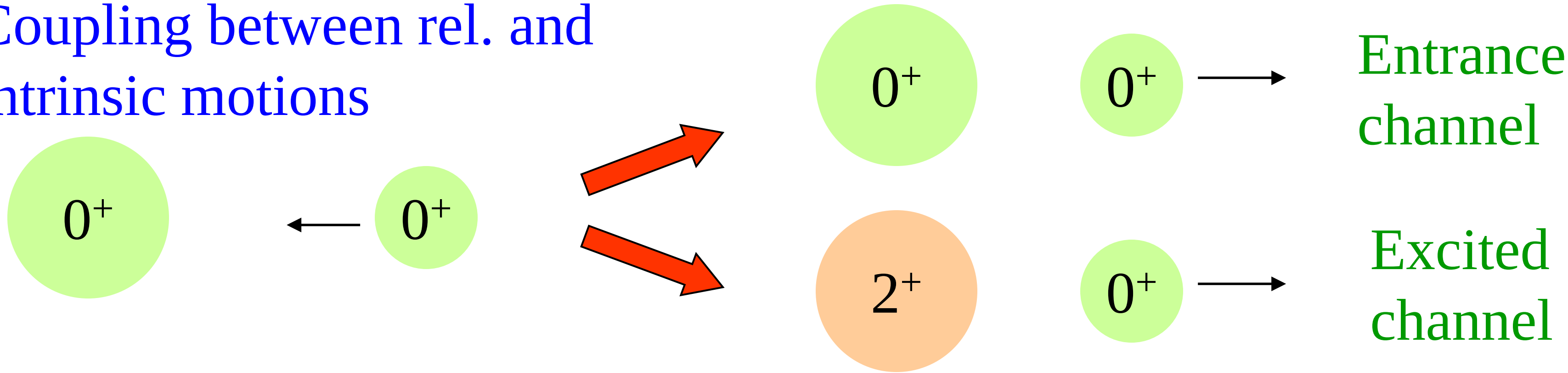


Def. Effect: enhances $\sigma_{\rm fus}$ by a factor of 10 ~ 100

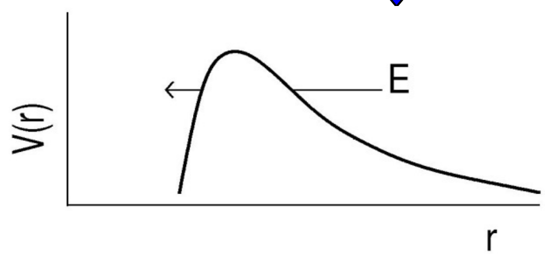
Fusion: interesting probe for nuclear structure

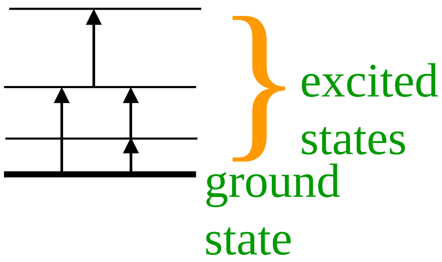
Coupled-Channels method

Coupling between rel. and intrinsic motions



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



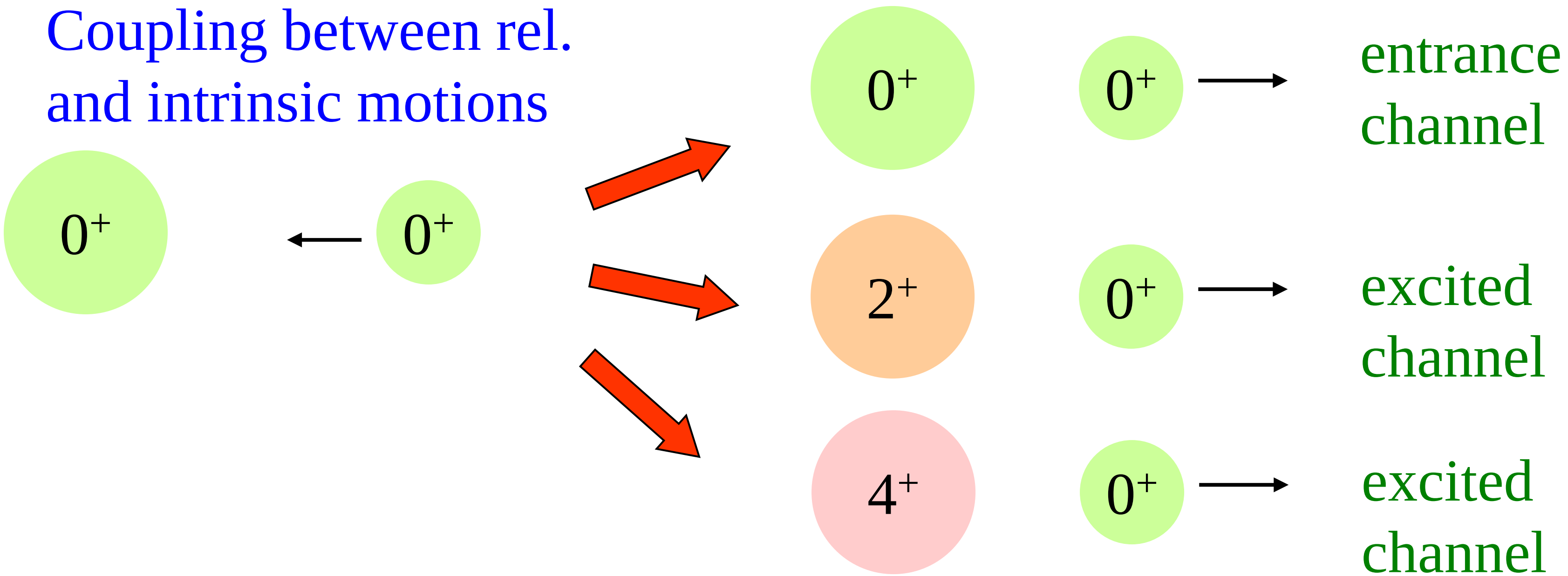


$$H_0(\xi)\phi_k(\xi) = \epsilon_k\,\phi_k(\xi)$$

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

coupled Schroedinger equations for $\psi_k(r)$

Coupled-channels framework



- 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……

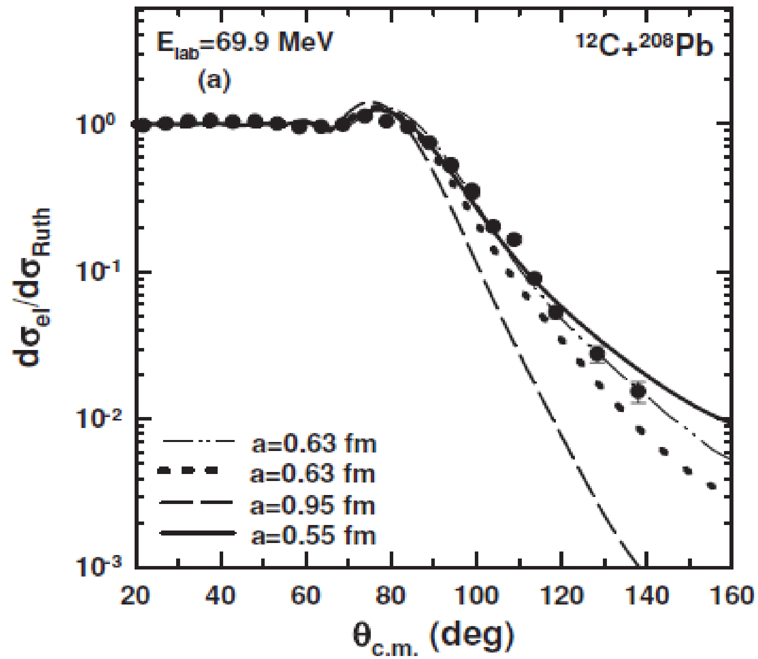
→ has been successful in describing heavy-ion reactions

However, many recent challenges in C.C. calculations surface diffuseness anomaly

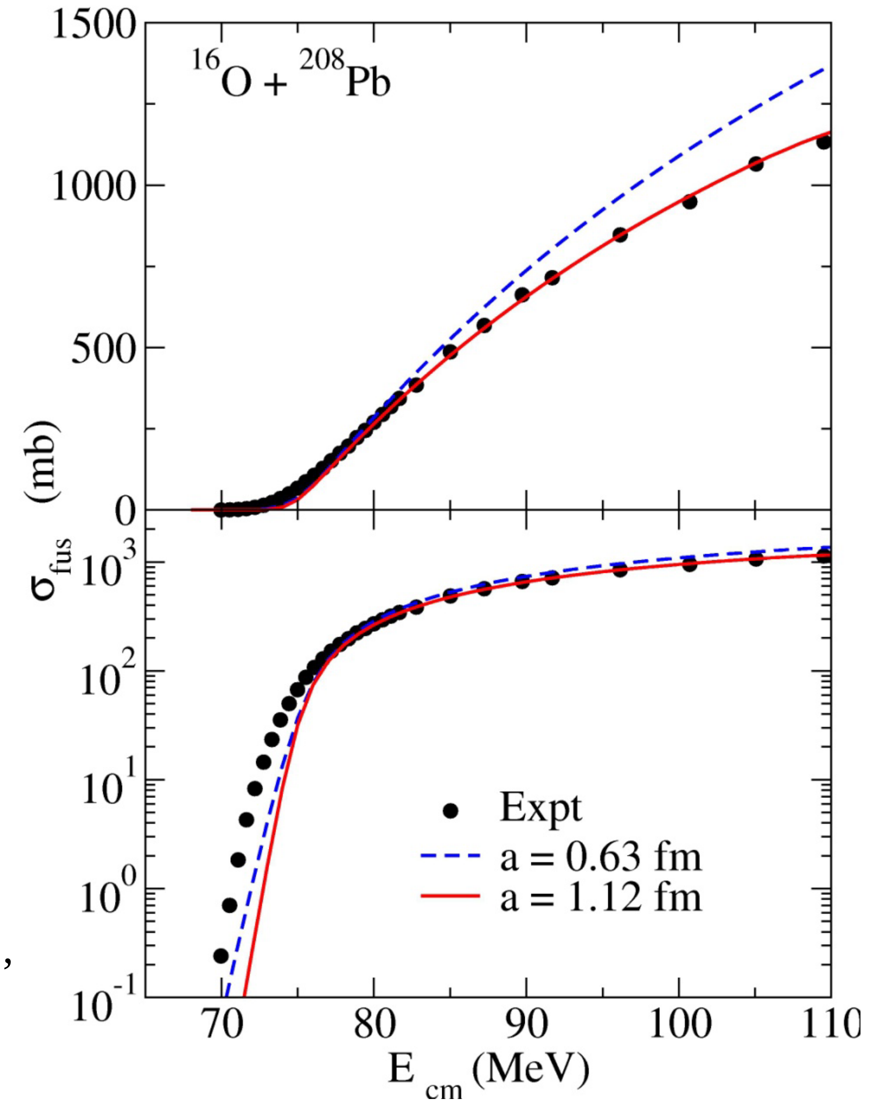
Scattering processes:

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

→ successful



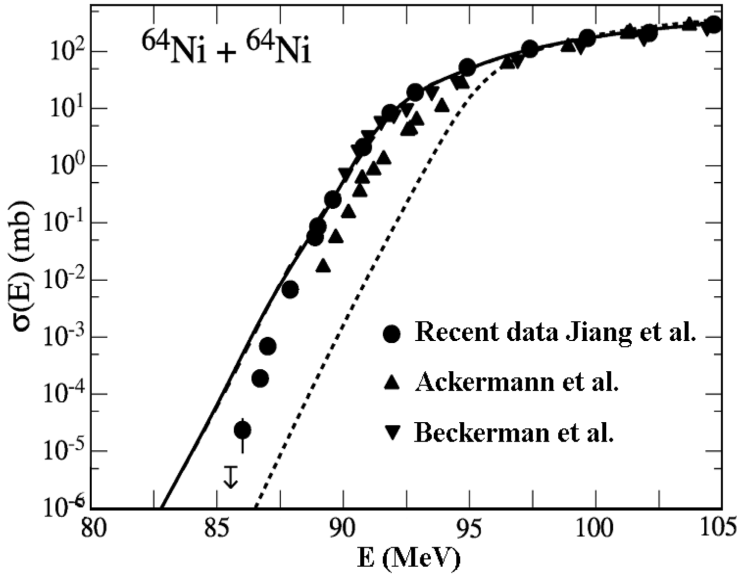
A. Mukherjee, D.J. Hinde, M. Dasgupta, K.H., et al., PRC75('07)044608



Fusion process: not successful

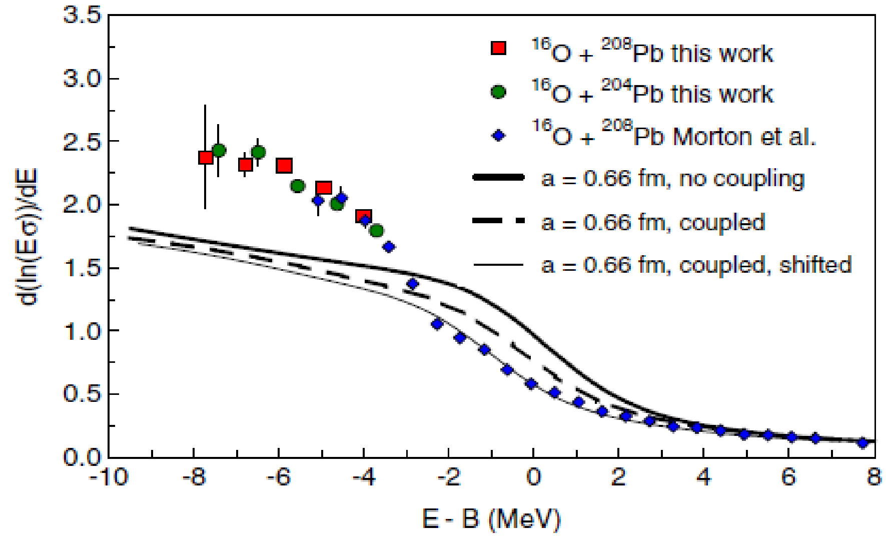
→ *a* ~ 1.0 fm required (if WS)

Deep subbarrier fusion data



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

"steep fall-off of fusion cross section"

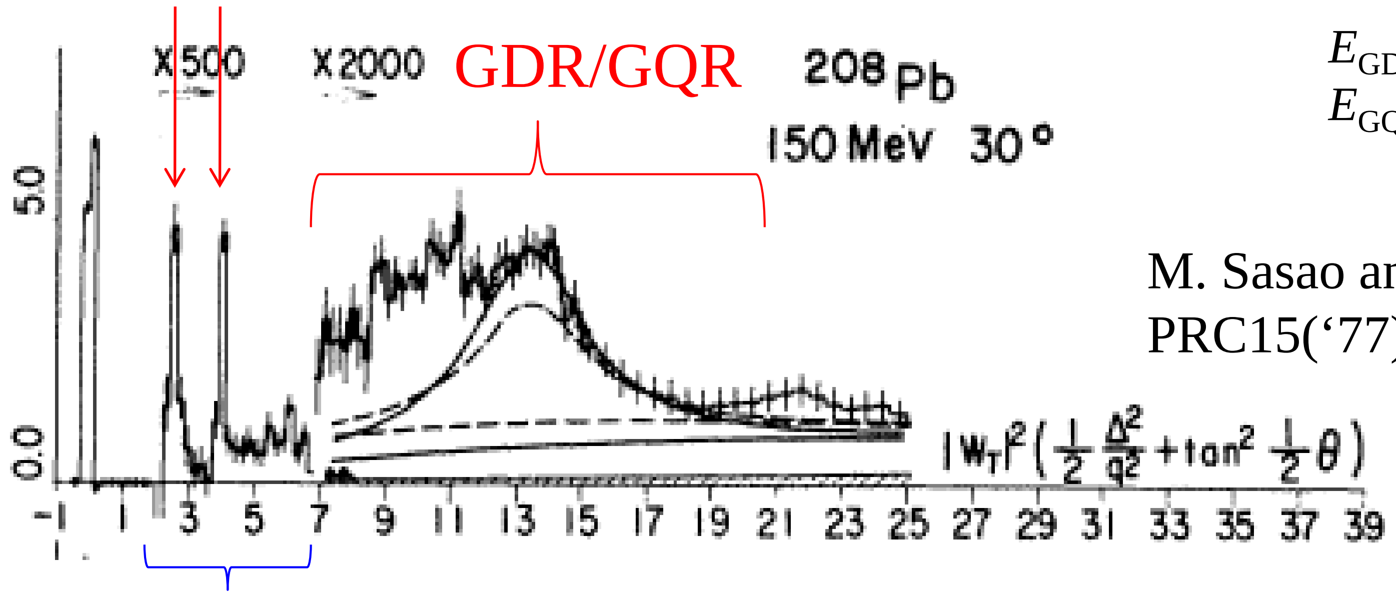


M.Dasgupta et al., PRL99('07)192701

- 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



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

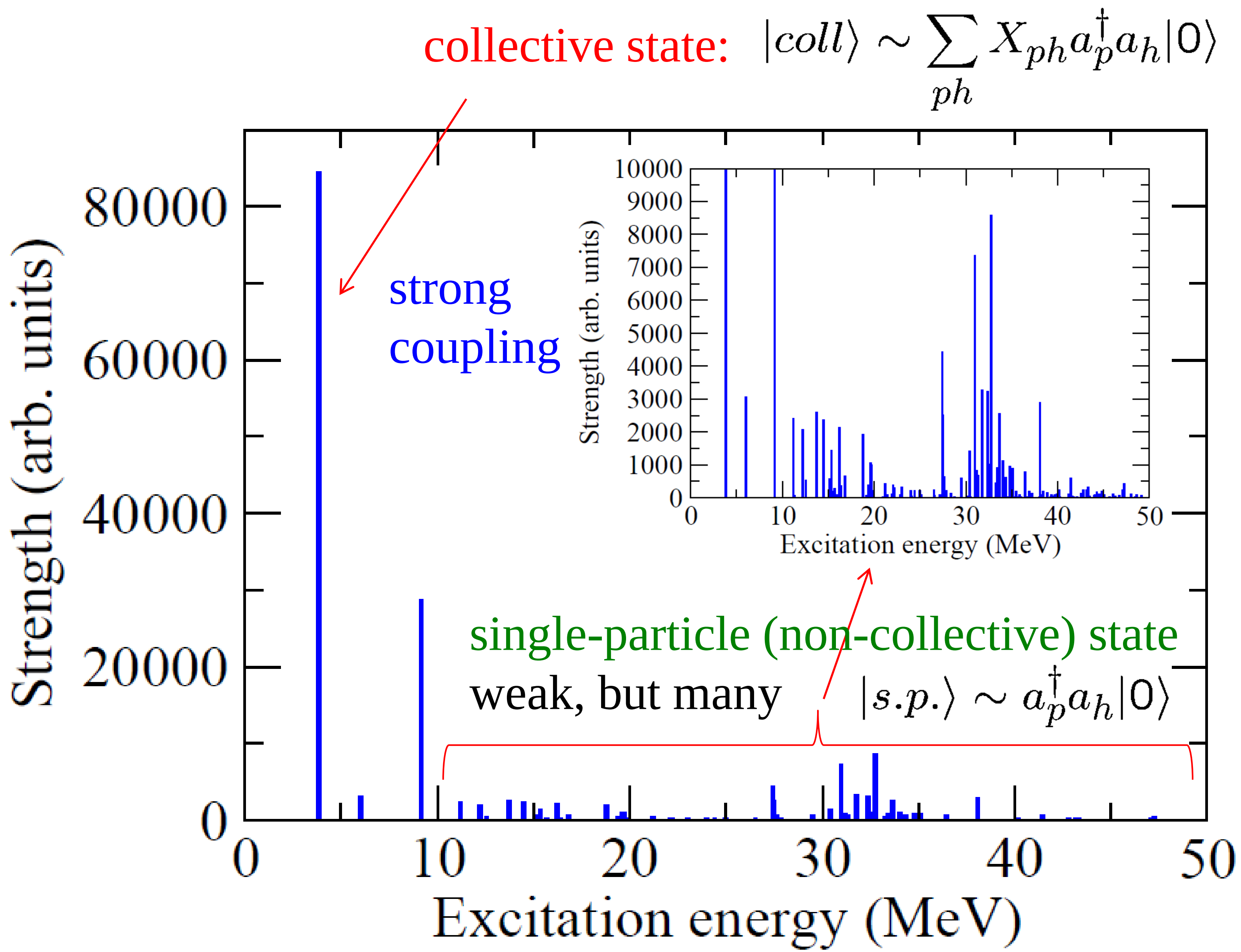
M. Sasao and Y. Torizuka, PRC15('77)217

E_x (MeV)

low-lying non-collective excitations

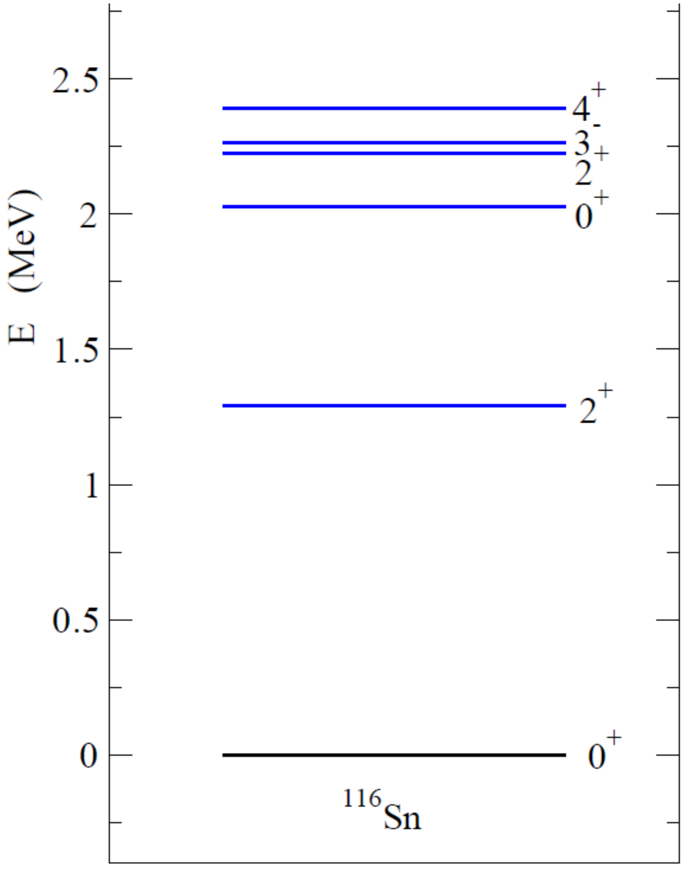
- Giant Resonances: high E_x, smooth mass number dependence
  $\longrightarrow$ adiabatic potential renormalization
- Low-lying collective excitations: barrier distributions,
  strong isotope dependence
- Non-collective excitations: either neglected completely or
  implicitly treated through an absorptive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

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



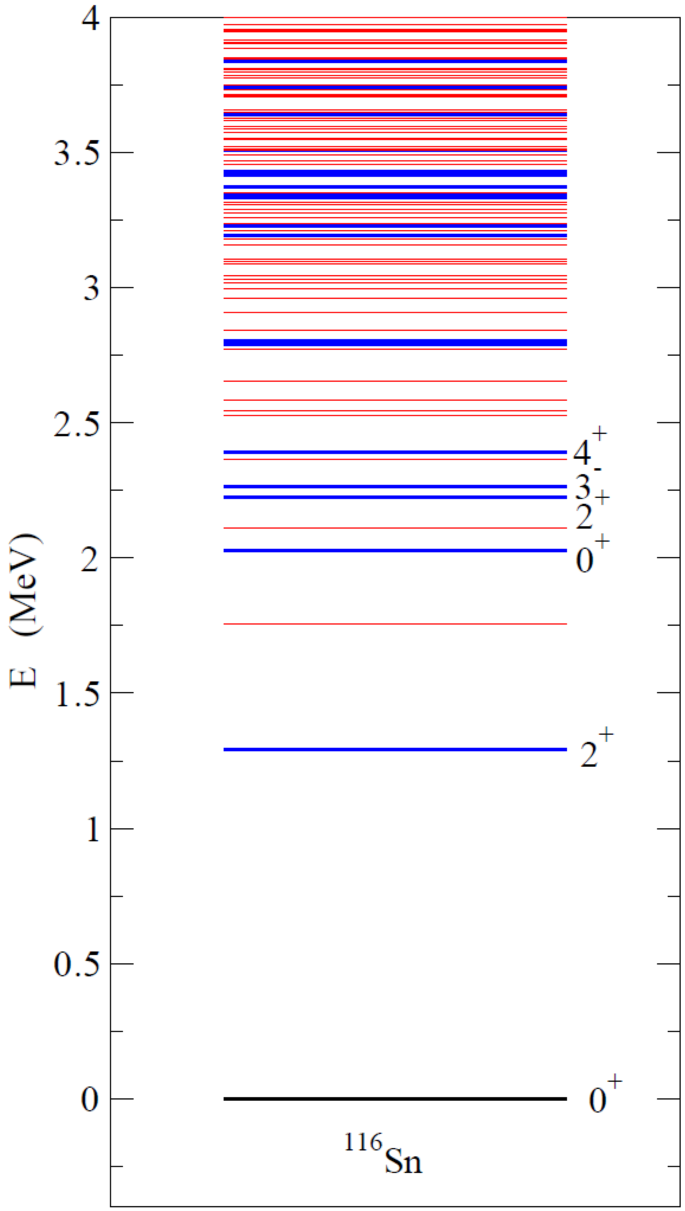
Our interest: couplings to (relatively) low-lying single-particle levels

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

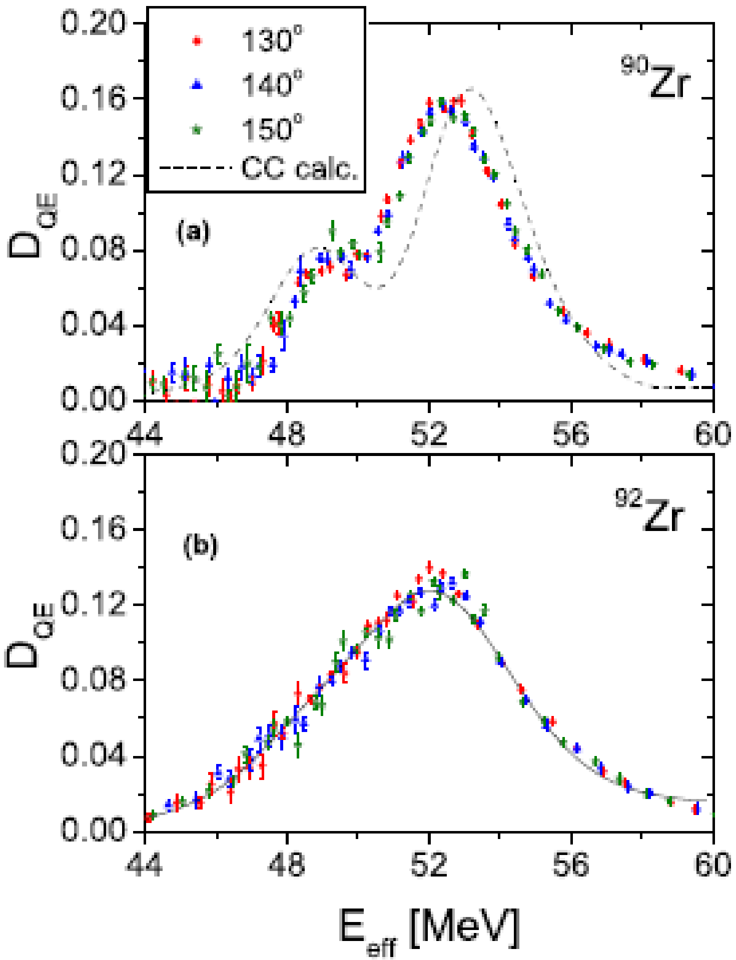


112 levels up to 4.1 MeV
(93 single-particle levels)
nearly "complete" level scheme

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



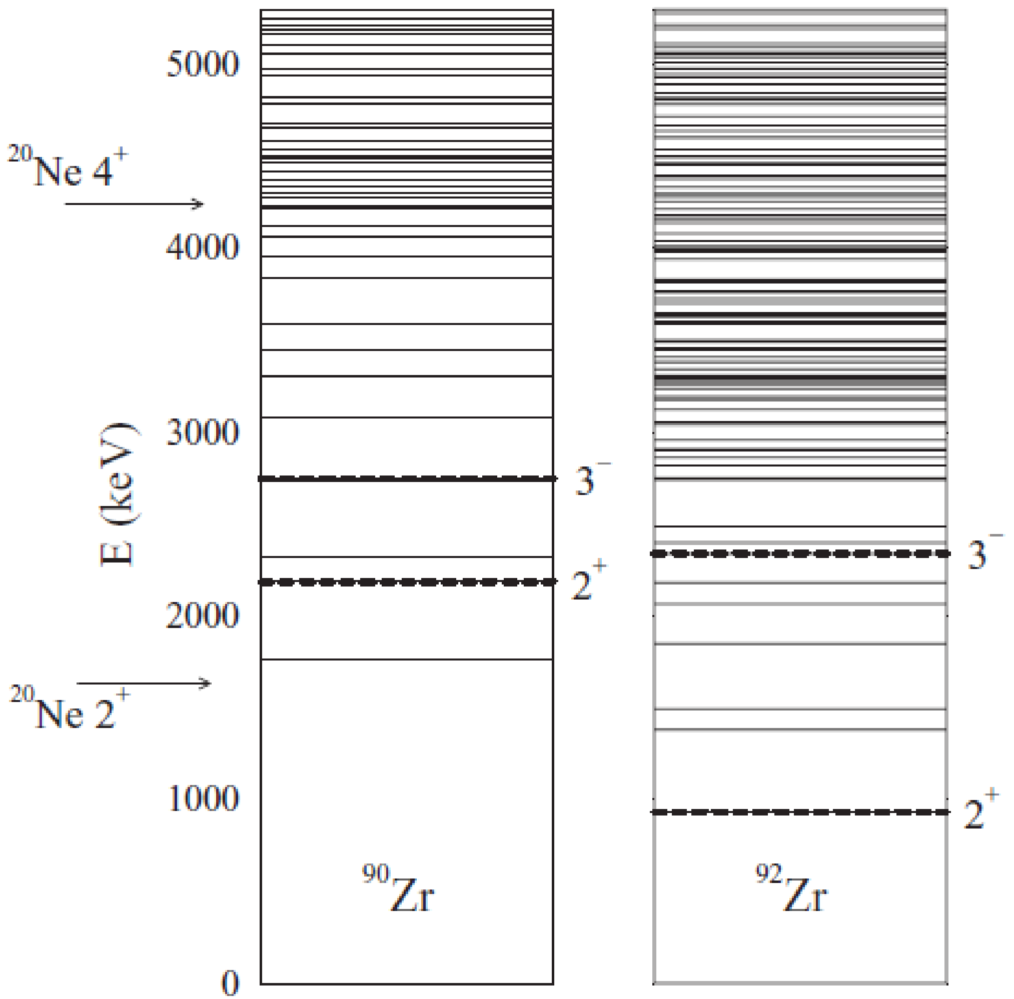
E. Piasecki et al., PRC80('09)054613

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

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:

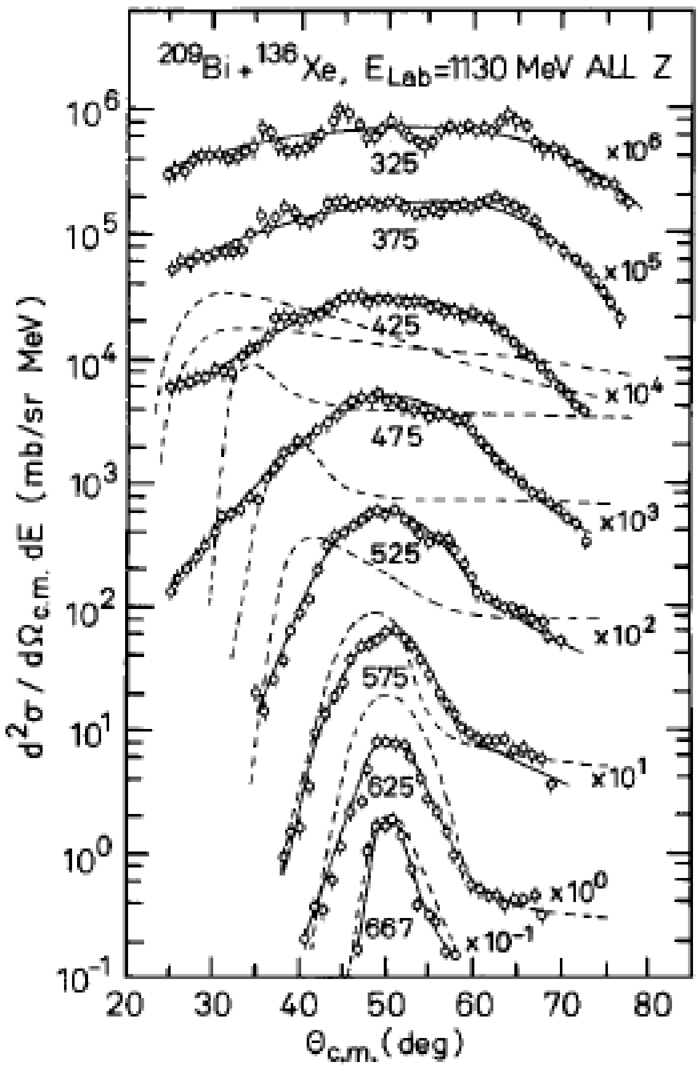
$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V_0(r) + \epsilon_k - E\right]\psi_k(\boldsymbol{r}) + \sum_{k'}\langle\phi_k|V_{\rm coup}|\phi_{k'}\rangle\psi_{k'}(\boldsymbol{r}) = 0$$

$|\phi_k\rangle$: 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:

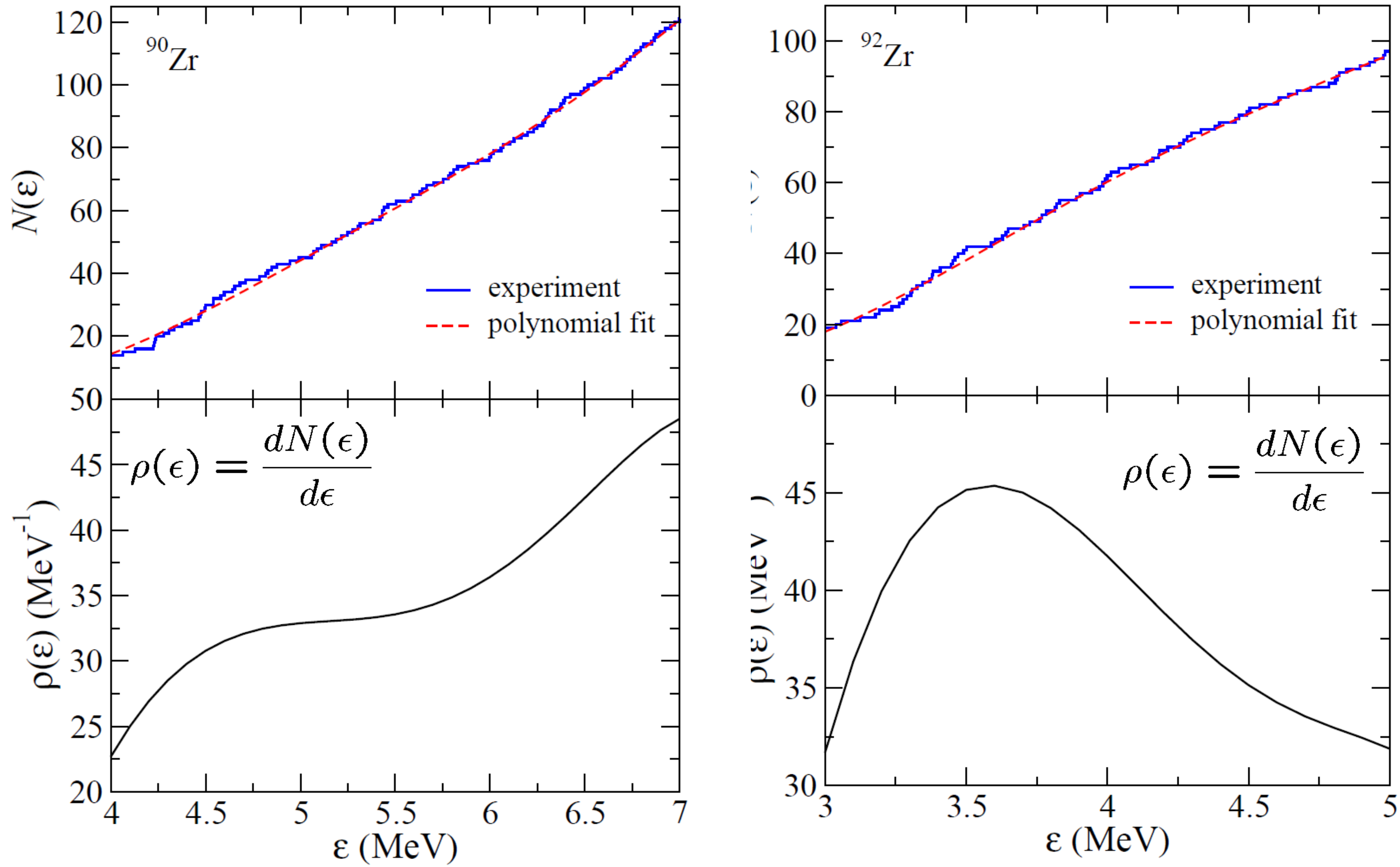
✓originally developed by Weidenmuller et al. to analyze DIC

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

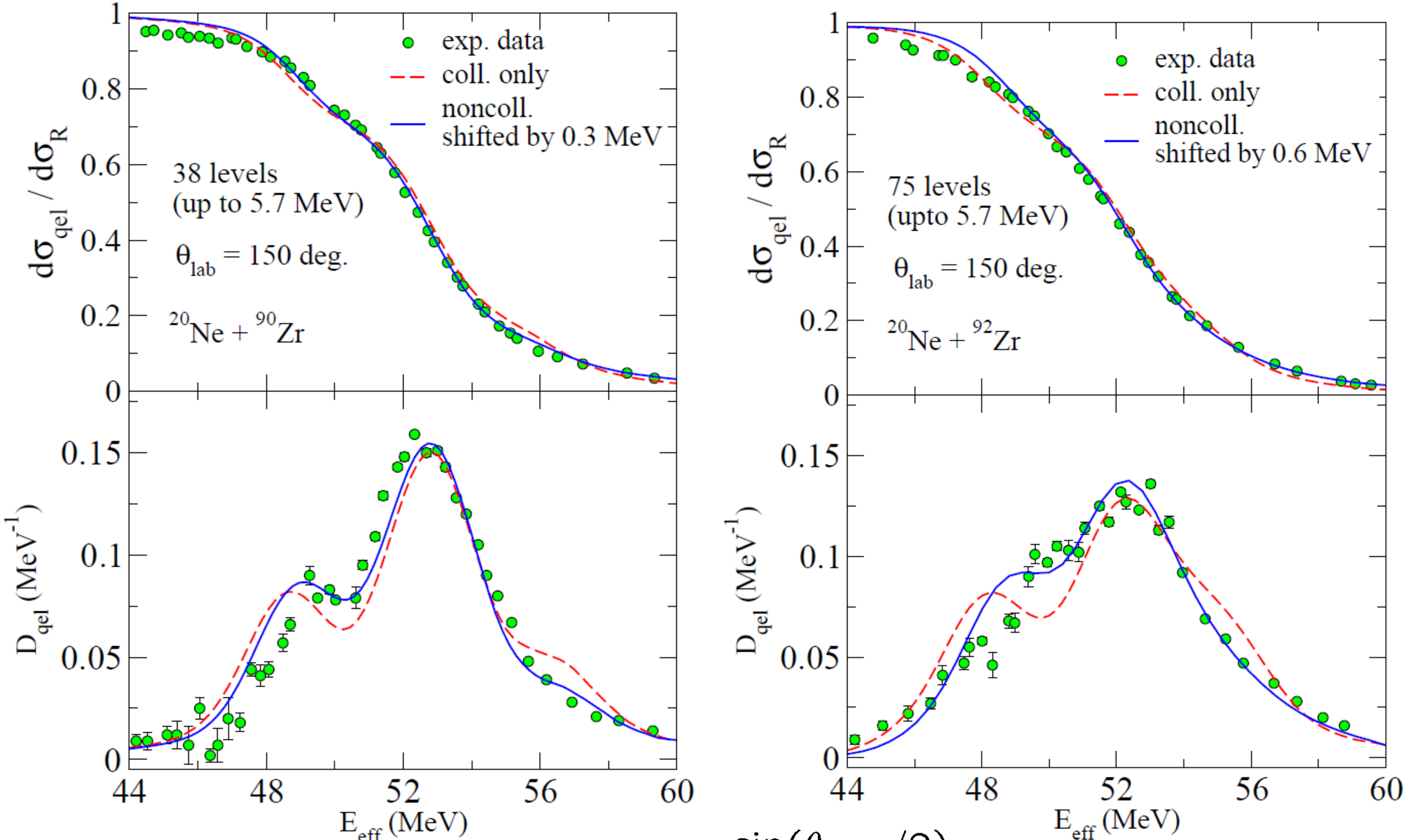
- M. Wilkinson, PRA41('90)4645
- A. Bulgac, G.D. Dang, and D. Kusnezov, PRE54('96)3468
- S. Mizutori and S. Aberg, PRE56('97)6311

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

of levels



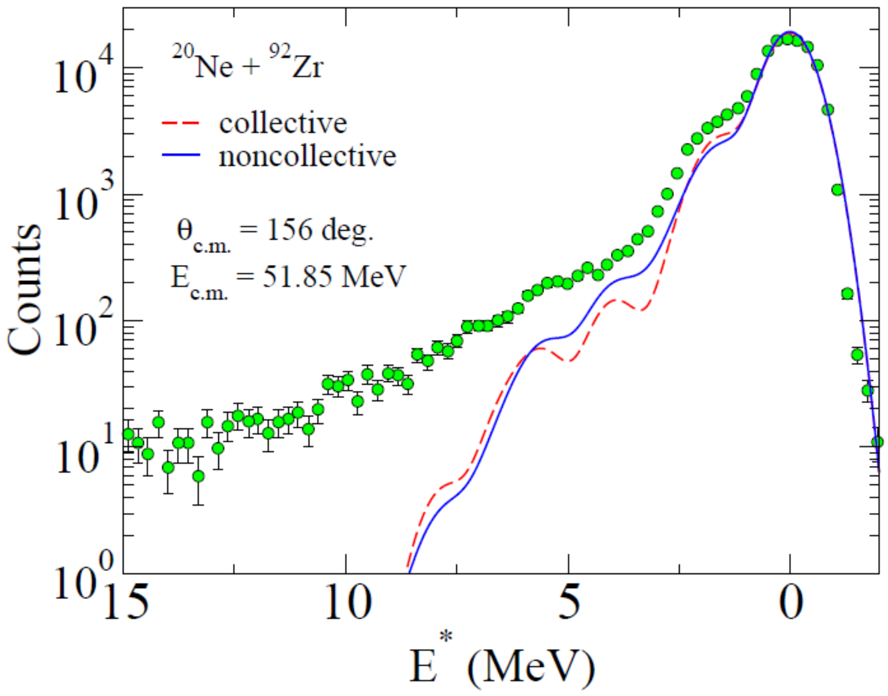
Quasi-elastic cross sections

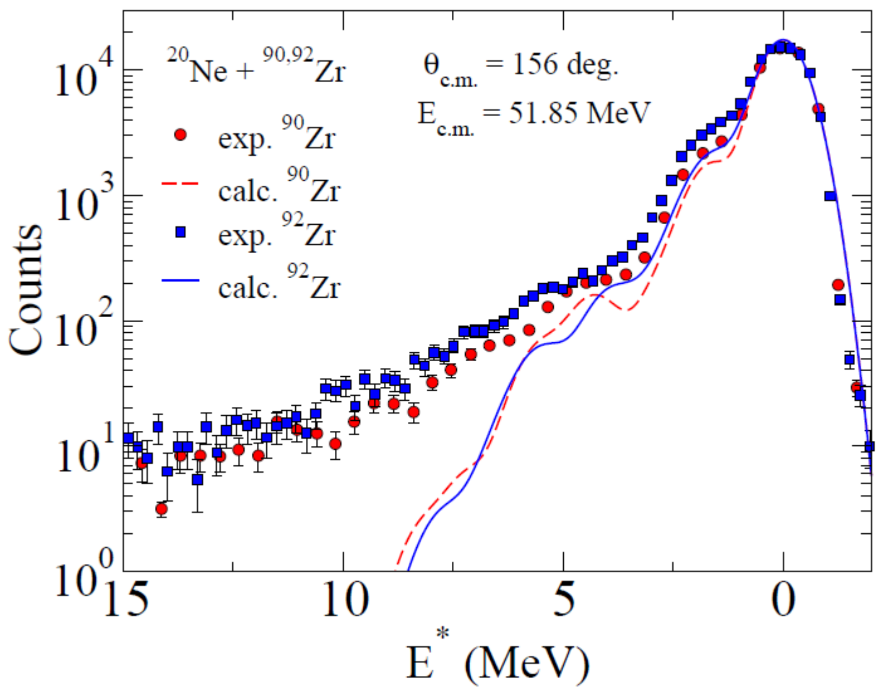


$$E_{\mathrm{eff}} = 2E\frac{\sin(\theta_{\mathrm{c.m.}}/2)}{1+\sin(\theta_{\mathrm{c.m.}}/2)}$$

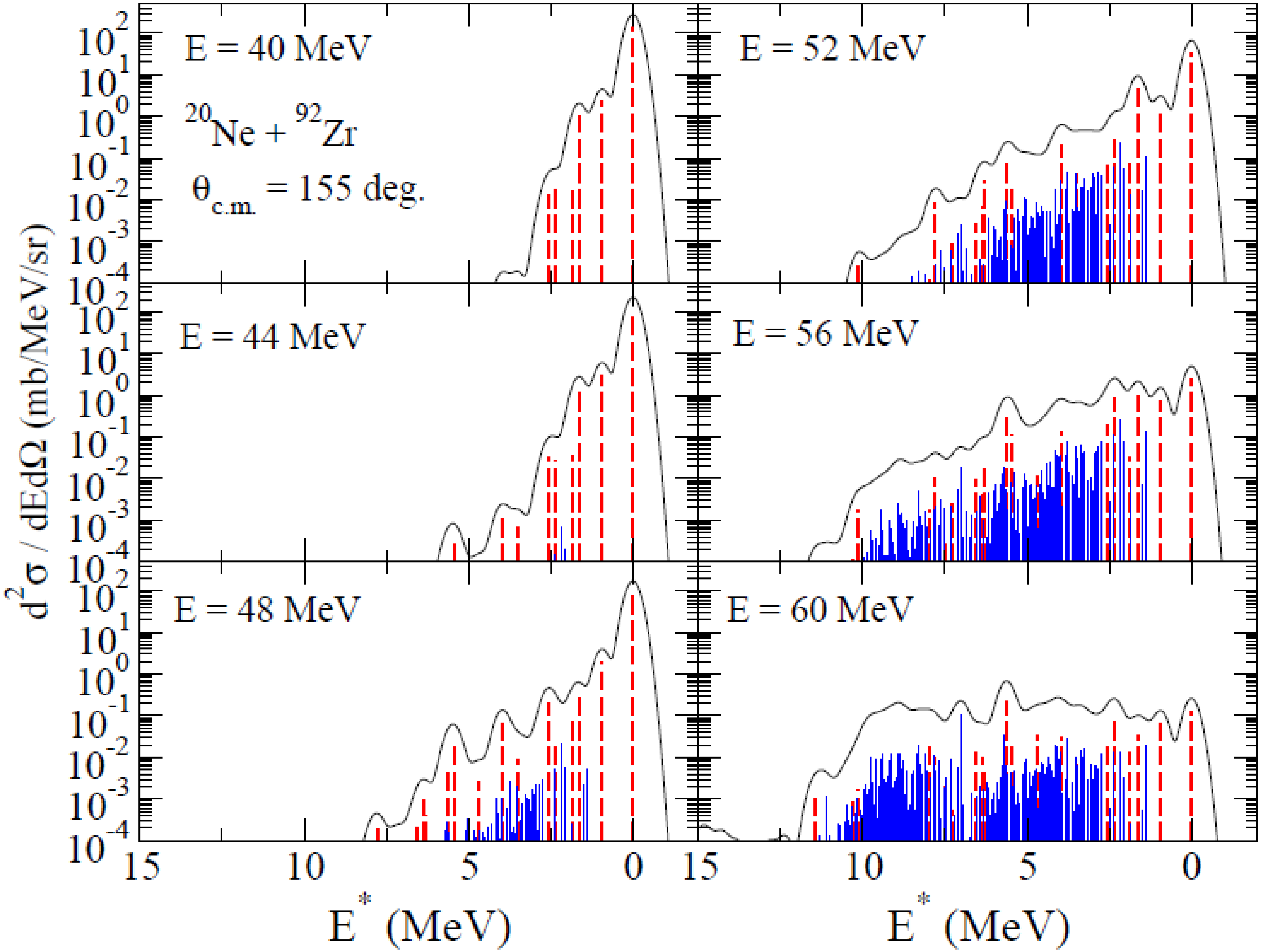
S. Yusa, K.H., and N. Rowley, arXiv:1309.4674

Q-value distributions



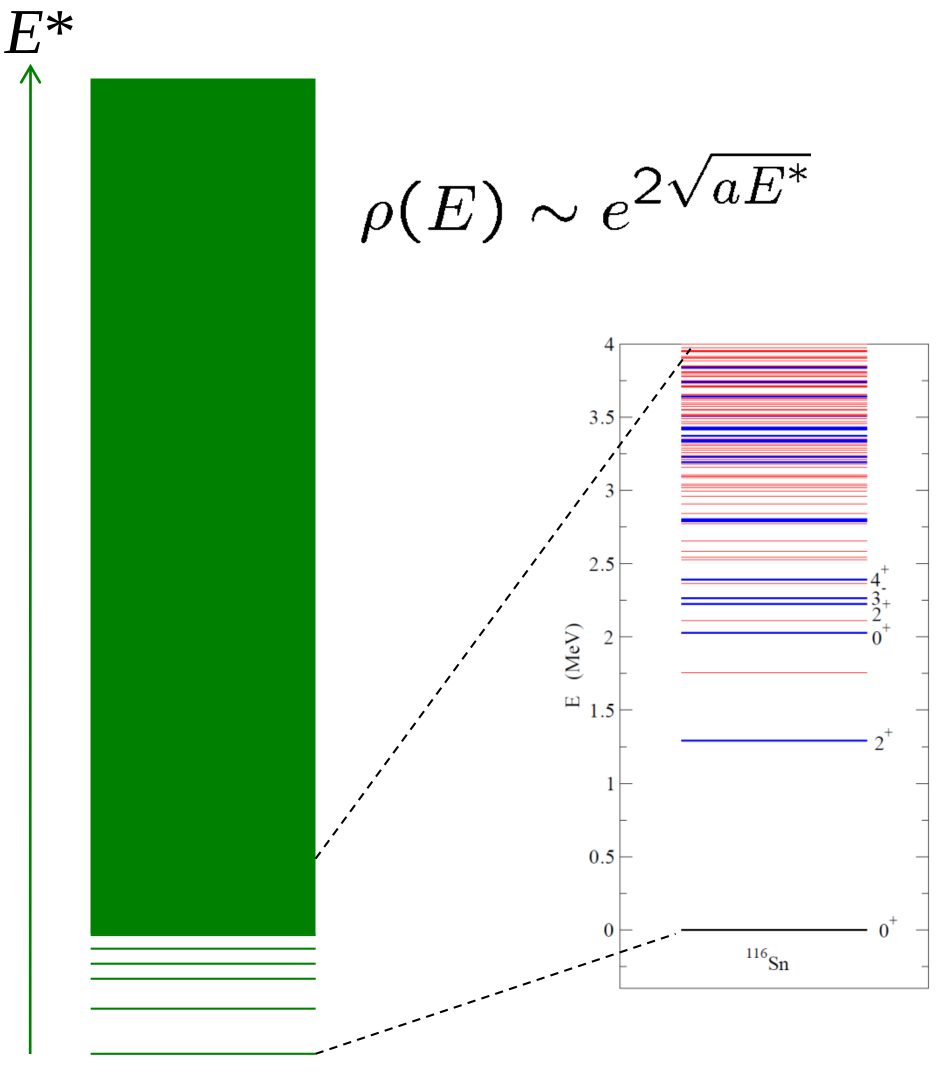


S. Yusa, K.H., and N. Rowley, arXiv:1309.4674



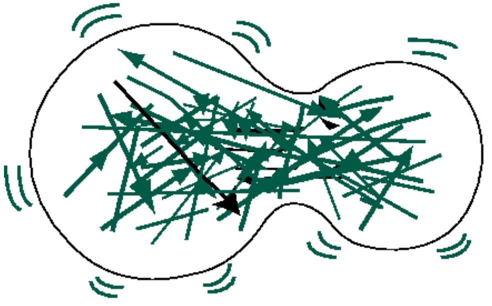
S. Yusa, K.H., and N. Rowley, arXiv:1309.4674

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.

⇩

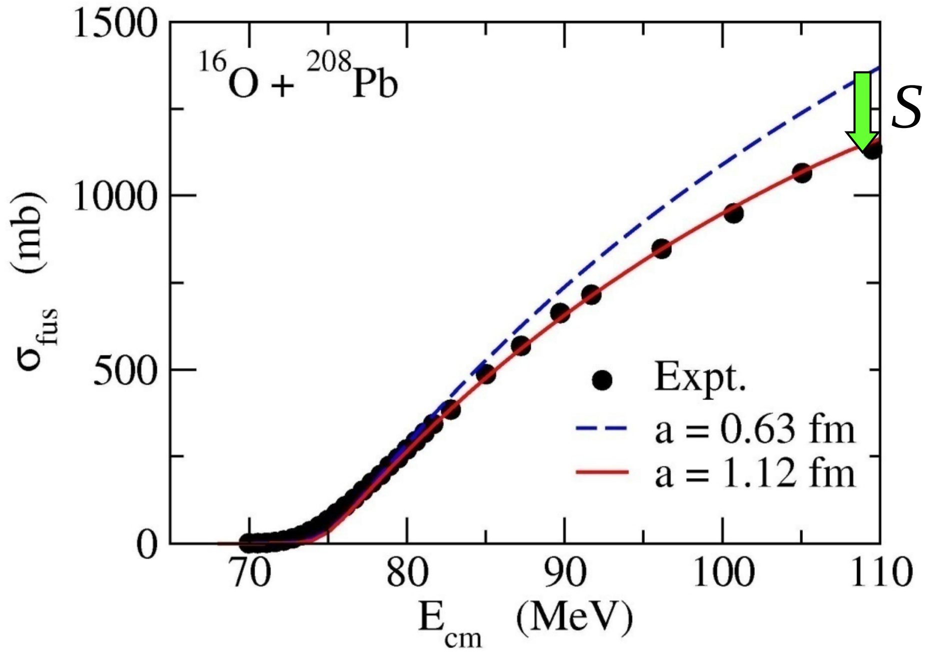
nuclear intrinsic d.o.f. act as environment for nuclear reaction processes

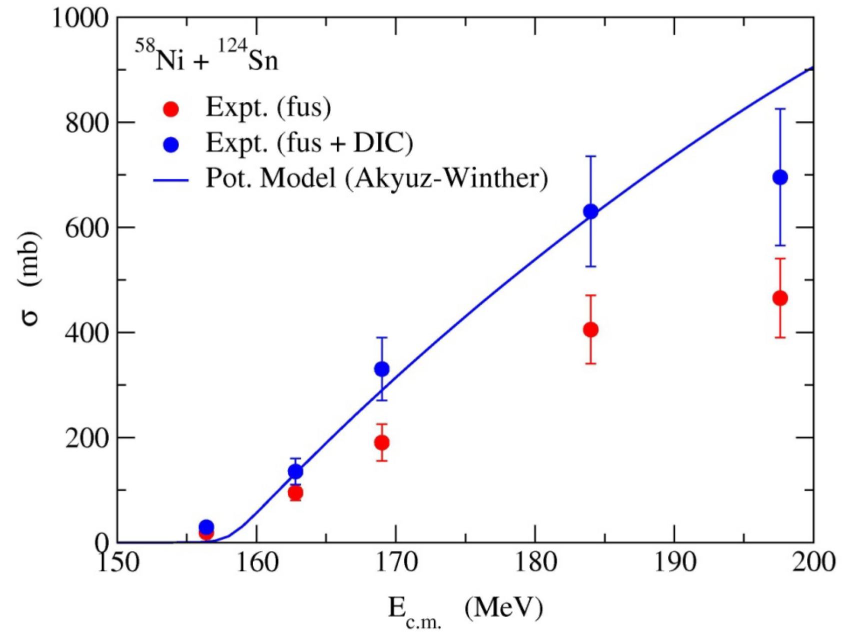
"*intrinsic* environment"

coupling to environment ⟷ dissipation & friction

How much do we know about "friction"?

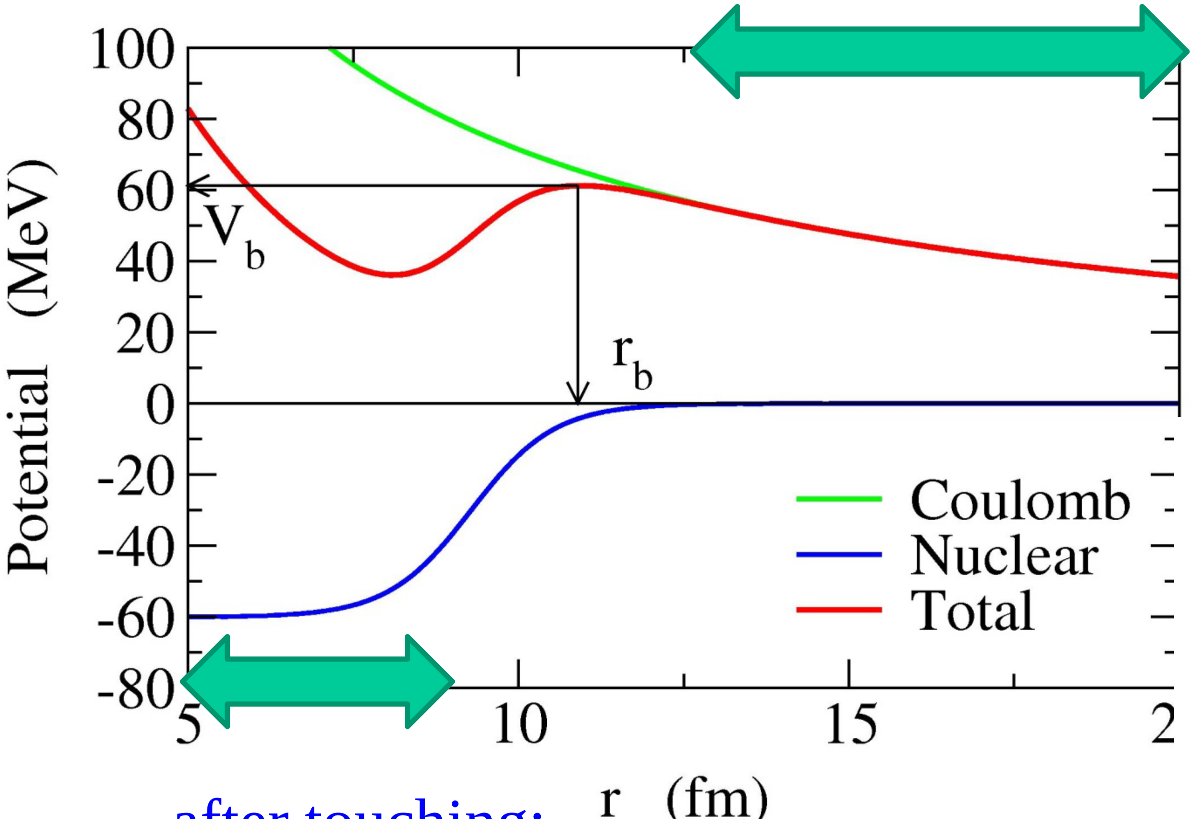
Fusion model ⟶ friction free: strong absorption inside the barrier



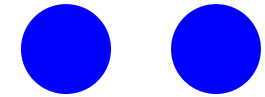


The topic of energy dissipation in fusion should be re-visited

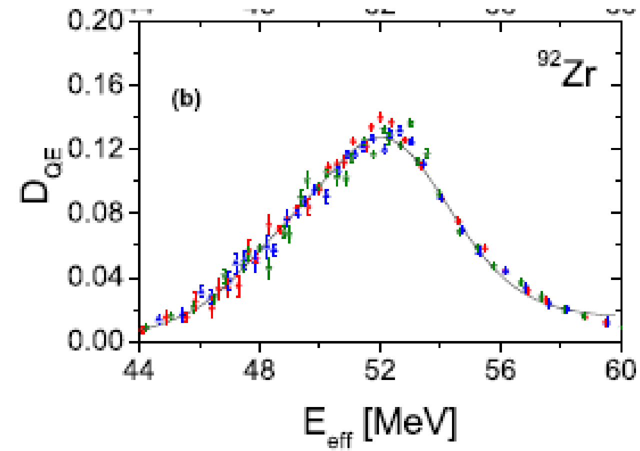
- re-analyses of DIC data: maybe helpful
- Consistent theoretical model (dissipative quantum tunneling)



Non-collective excitations in isolated nuclei

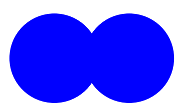


$^{20}Ne + ^{92}Zr$



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, GCM, ASCC ?
imaginary-time TDHF?

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

microscopic nuclear reaction theory

Few-body approach

reduce to a few-body Hamiltonian and solve it as accurately as possible

- time-dependent wave packet approach

  M. Ito, K. Yabana, T. Nakatsukasa, and M. Ueda, PLB637('06)53

- (4-body) CDCC

more particles?
nuclear transfer channel (CDCC)?

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
Resonating Group Method (RGM)

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

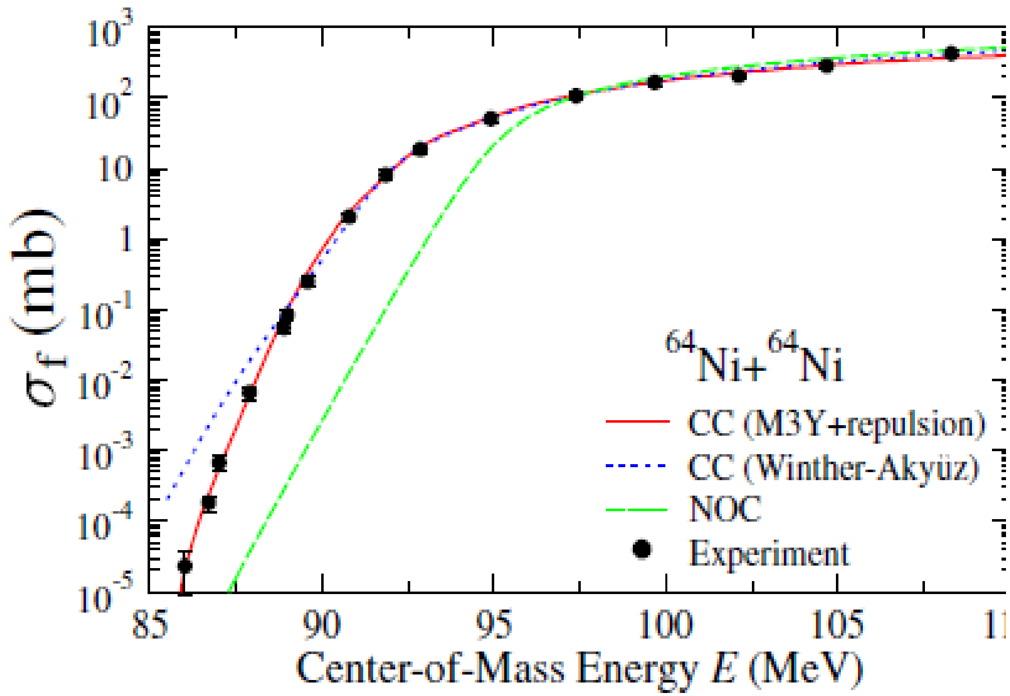
✧Adiabatic approach (slow collision)

Liquid-drop model (+ shell correction)
Adiabatic TDHF

← Coordinate dependent mass μ(r)

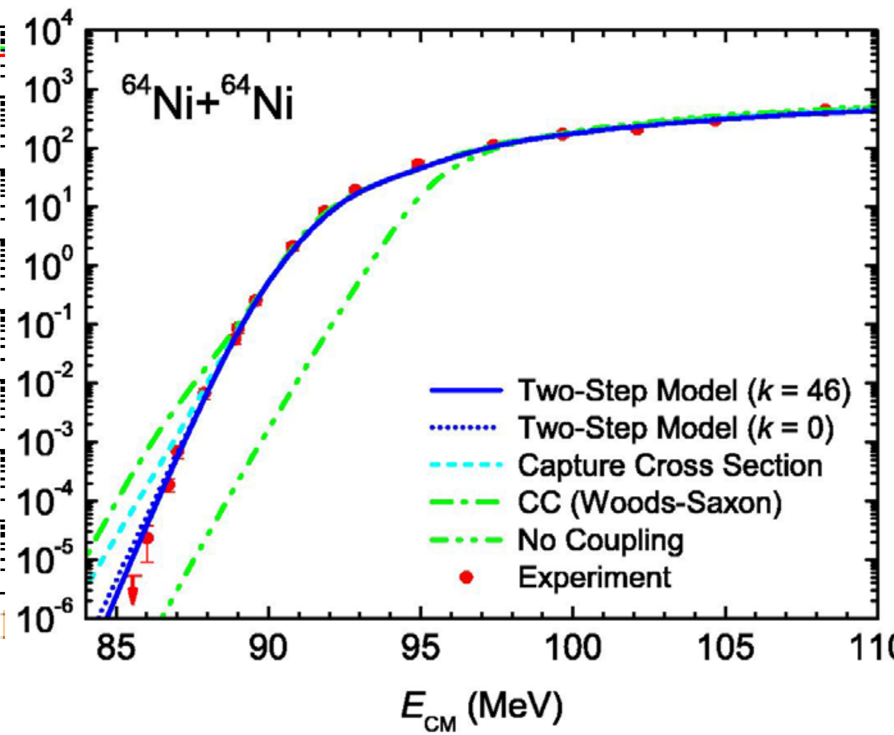
cannot discriminate one of them at present

sudden approach (frozen density)



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

adiabatic approach



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?