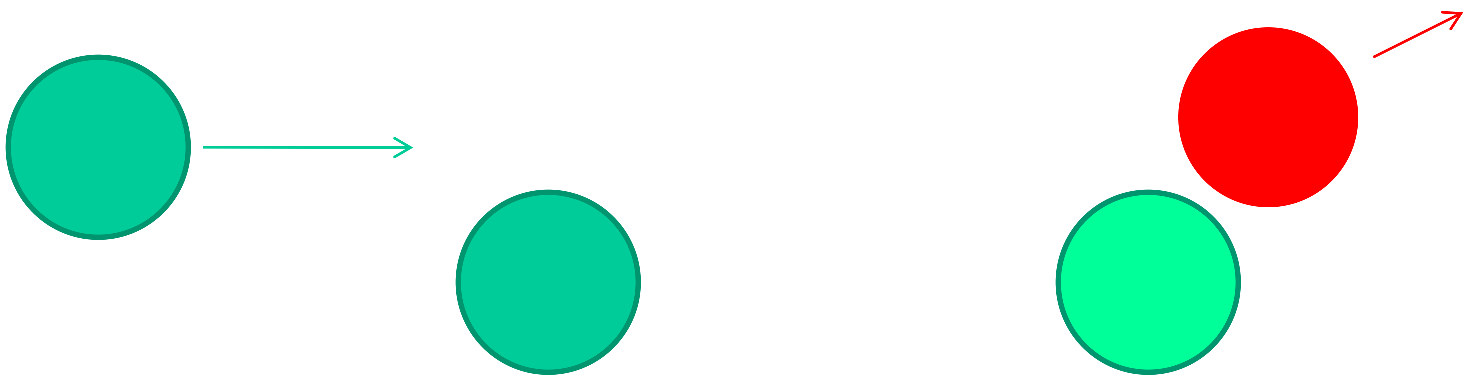
Subbarrier fusion reactions with dissipative couplings

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

Kouichi Hagino (Tohoku University)



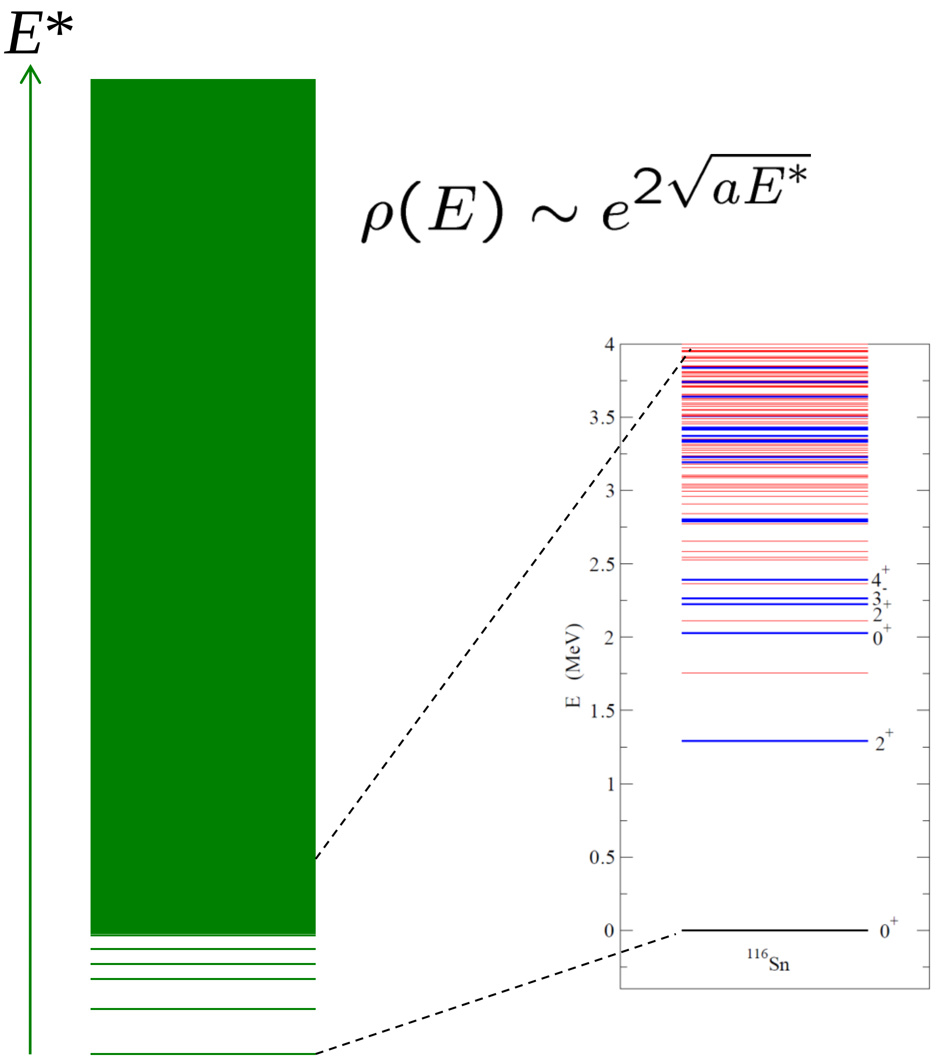
1. *Introduction: Environmental Degrees of Freedom*
2. *Mott Scattering and Quantum Decoherence*
3. *Application of RMT to subbarrier fusion and scattering*
4. *Summary*

Introduction

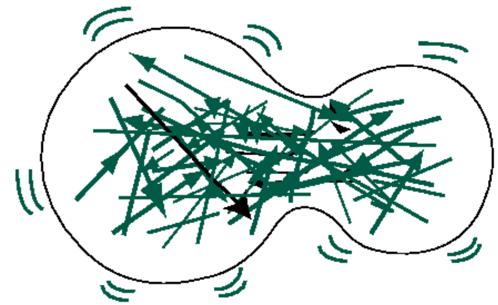
atomic nuclei: microscopic systems

⟶ little effect from *external* environment

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



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"

How have "internal excitations" been treated in nuclear physcs ?

1. Optical potential

elimination of "environmental" d.o.f. $\longrightarrow$ effective potential

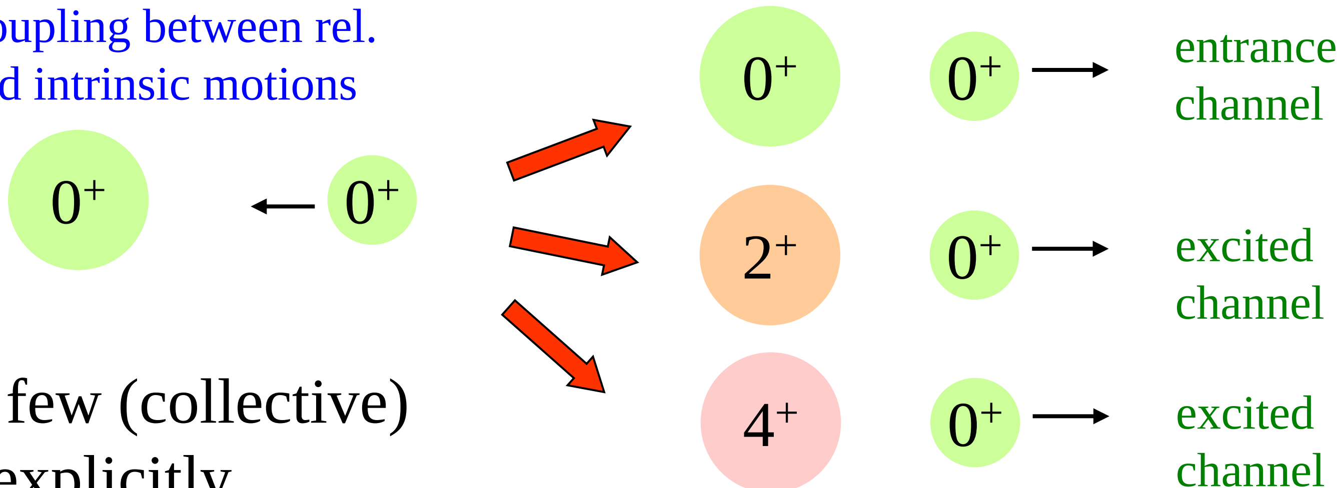
$$V_{\rm opt}(r) = V(r) - iW(r)$$

✓Feschbach formalism
✓Phenomenological potential

absorption of flux

2. Coupled-channels method (Close coupling method)

Coupling between rel.
and intrinsic motions

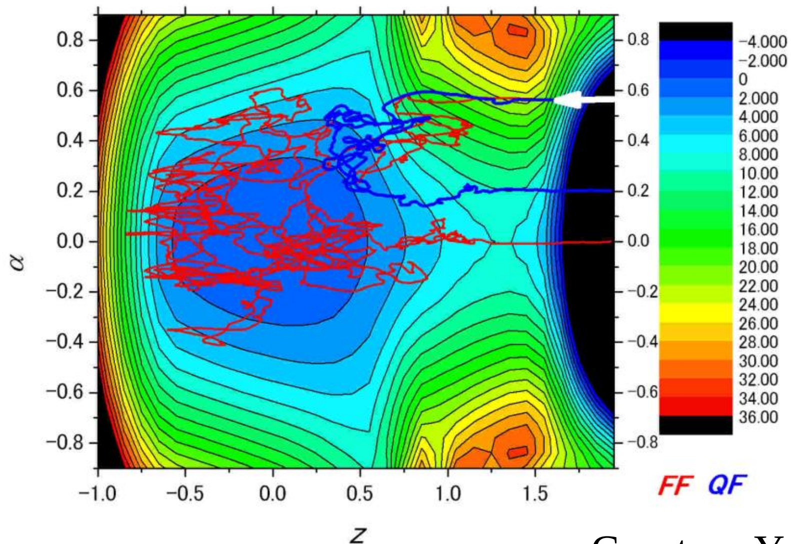


treat a few (collective)
states explicitly

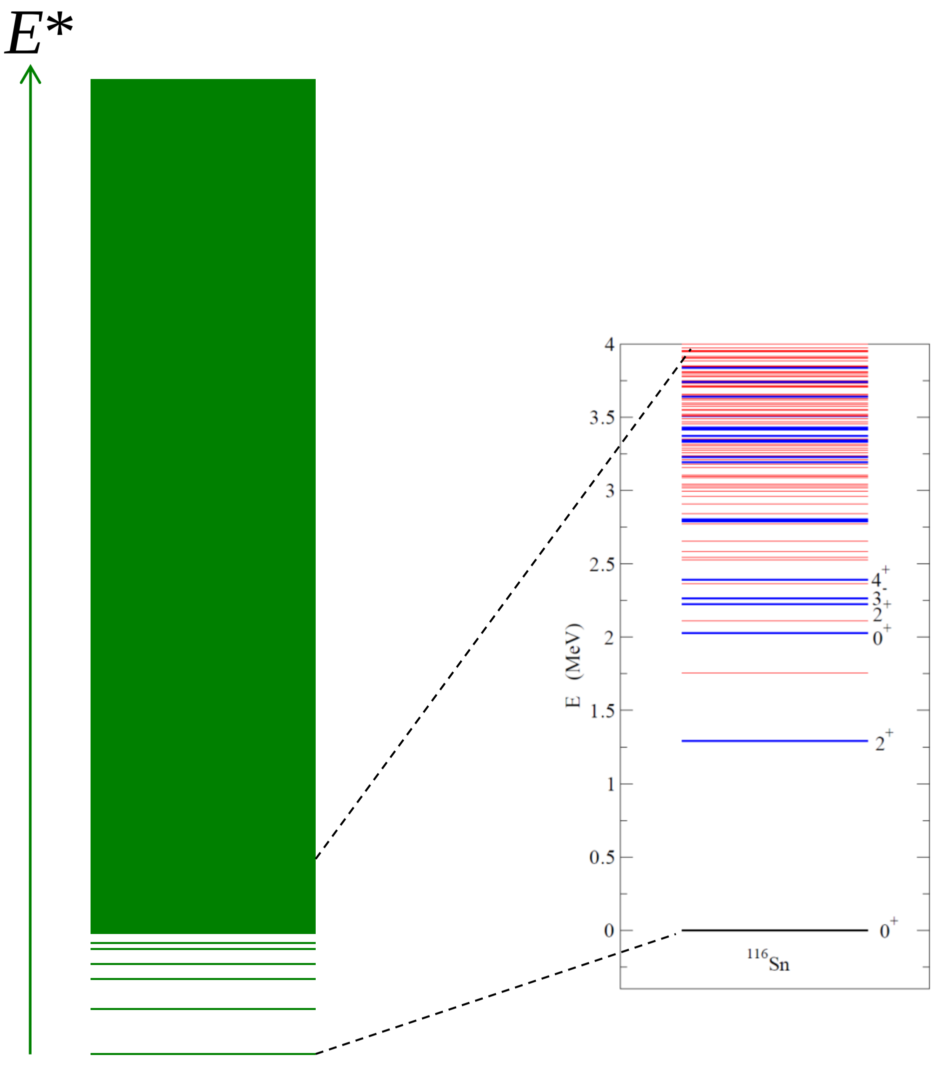
3. Classical treatment

e.g., Langevin calculations for superheavy elements

$$\dot{p}_i = -\partial_i V - \frac{1}{2}\partial_i (m^{-1})_{jk}\, p_j p_k - \gamma_{ij} (m^{-1})_{jk}\, p_k + g_{ij} R_j(t)$$



Courtesy Y. Aritomo (JAEA)



nuclear spectrum

nuclear excitations

⇕

"*intrinsic* environment"

In this talk:

- Mott scattering and quantum decoherence

- Role of s.p. excitations in quantum tunneling

  c.f. Random Matrix Model

Mott scattering and quantum decoherence

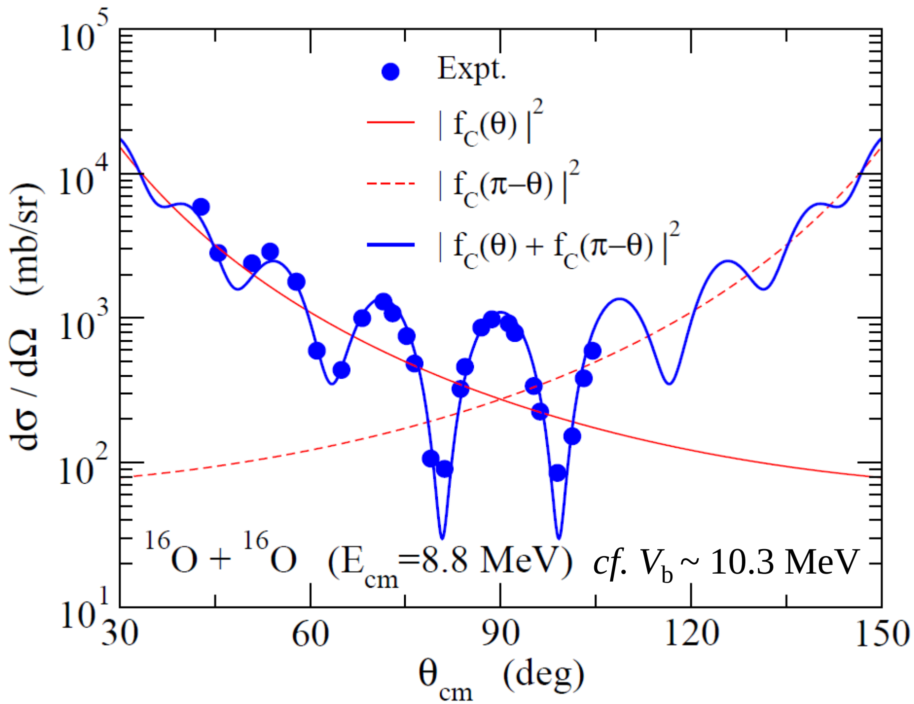
Kouichi Hagino (Tohoku University)
M. Dasgupta (ANU)
D.J. Hinde (ANU)
R. McKenzie (Queensland)
C. Simenel (ANU)
M. Evers (ANU)

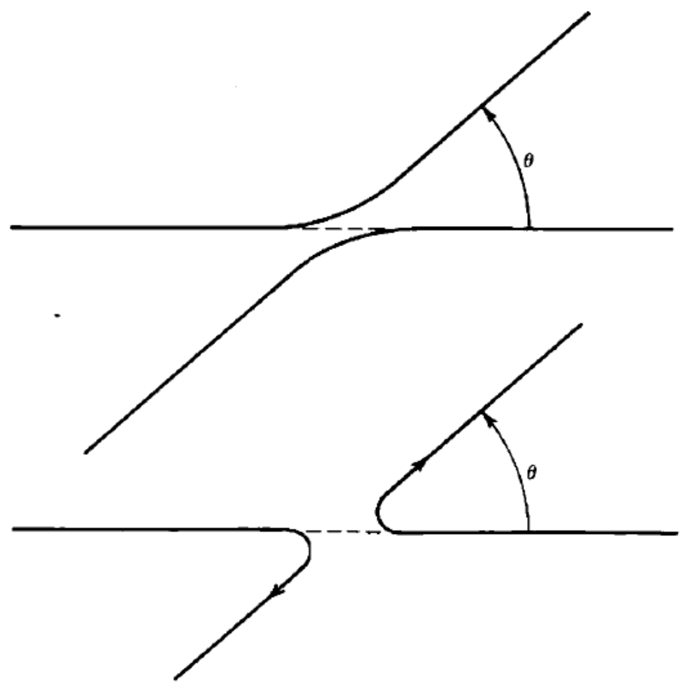
on-going work

Mott Oscillation

scattering of two identical particles

$$\frac{d\sigma}{d\Omega} = |f(\theta) \pm f(\pi-\theta)|^2$$
$$= |f(\theta)|^2 + |f(\pi-\theta)|^2 \pm f^*(\theta)f(\pi-\theta) \pm f(\theta)f^*(\pi-\theta)$$

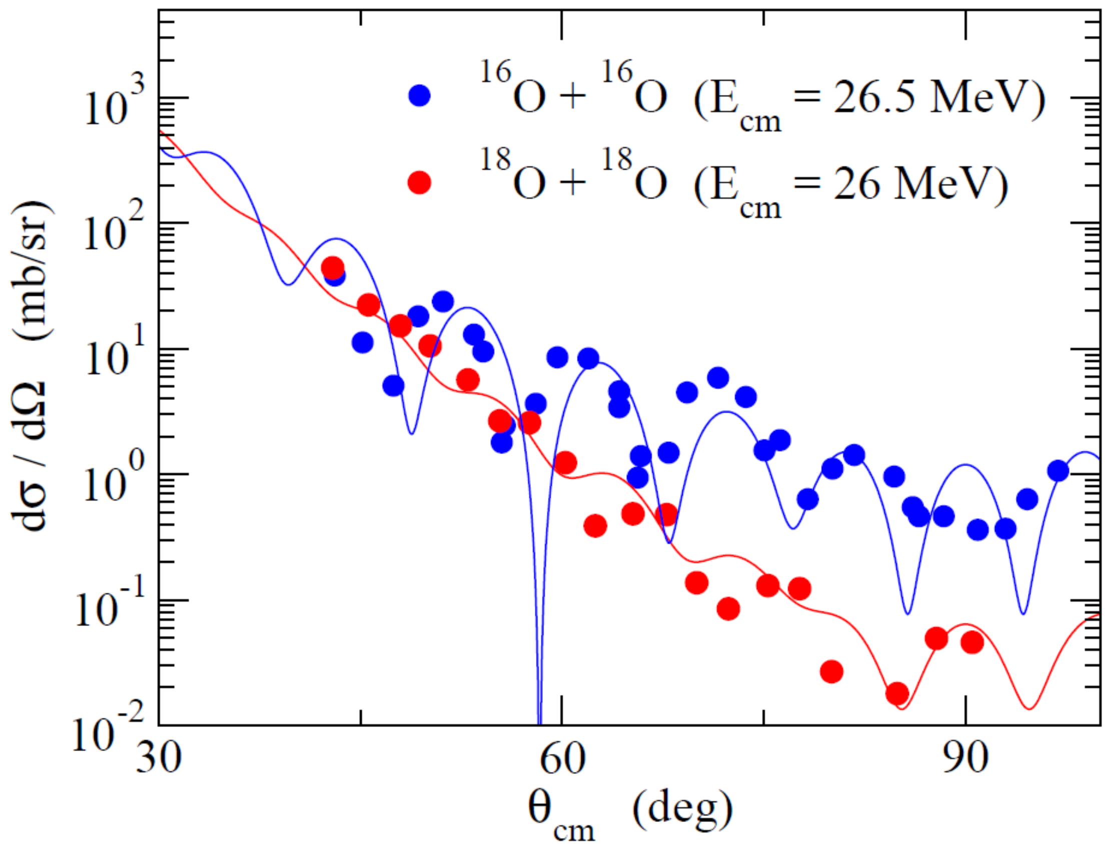




expt: D.A. Bromley et al., Phys. Rev. 123 ('61)878

"Quantum Physics", S. Gasiorowicz

Comparison between $^{16}O+^{16}O$ and $^{18}O+^{18}O$



^{16}O, ^{18}O: I^{π} (g.s.) = 0^+
(both are bosons)

$V_b \sim 10.3$ MeV

$\longrightarrow$ $E_{cm} \sim 2.5\, V_b$

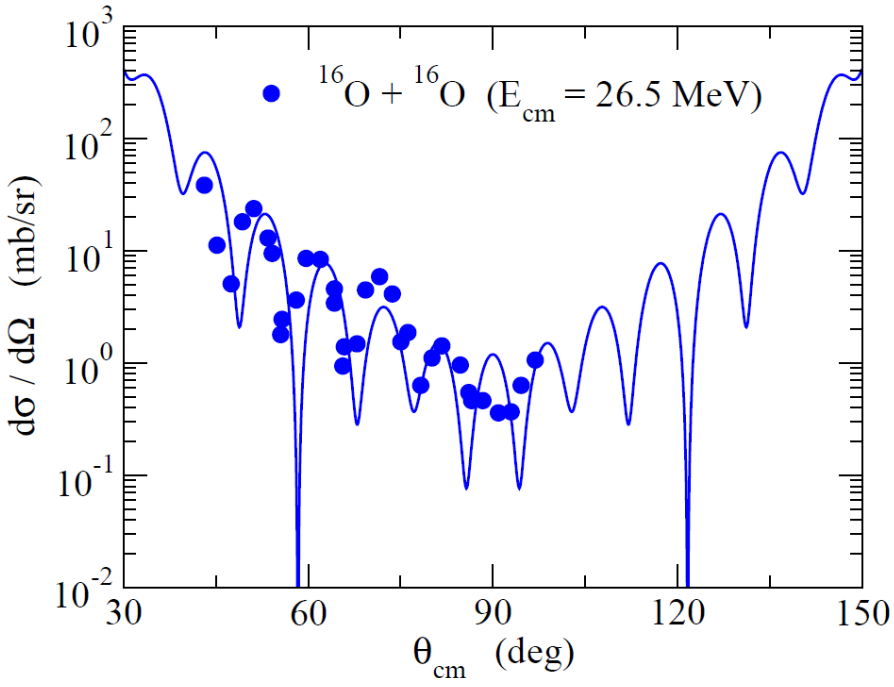
$^{18}O+^{18}O$: much less pronounced interference pattern

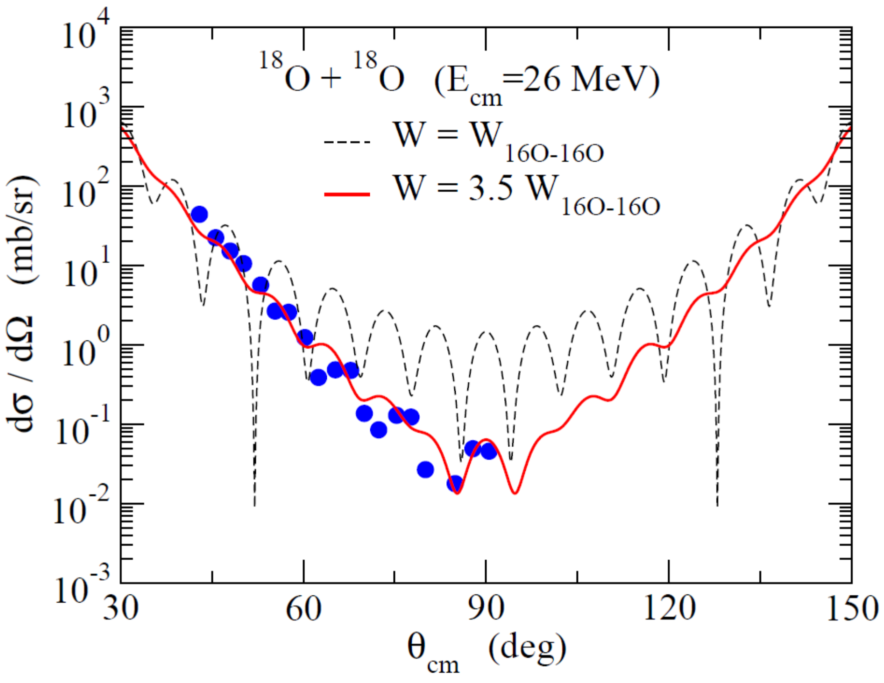
$^{18}O = ^{16}O$ (double closed shell) + 2n

$\longrightarrow$ stronger coupling to environment

➡ manifestation of environmental decoherence?

Optical potential model calculation





The data can be fitted with an opt. pot. model calculation.

$$W = 0.4 + 0.1\,E_{cm} \quad \text{(MeV)}$$

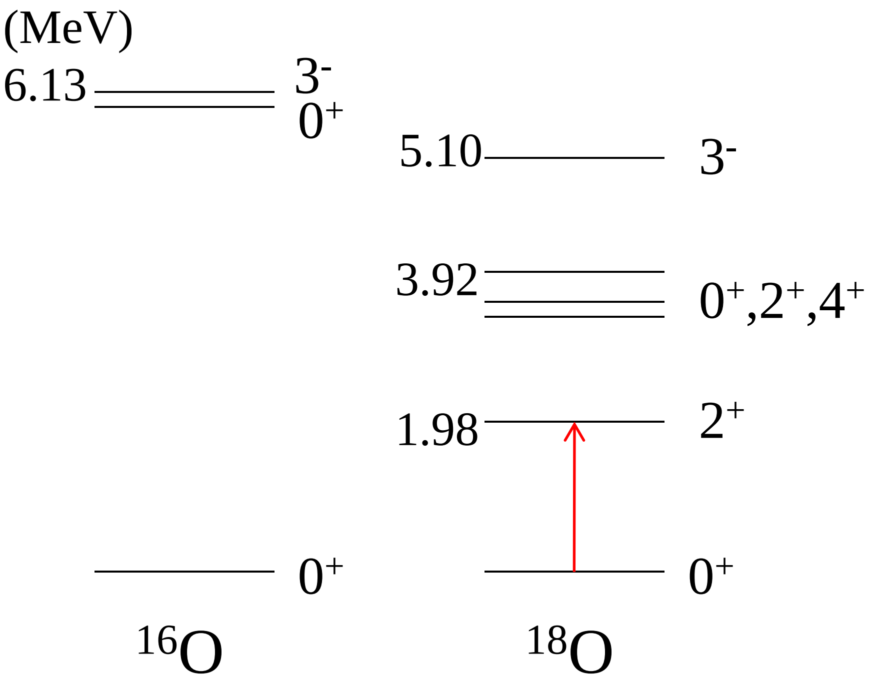
R.H. Siemssen et al., PRL19 ('67) 369

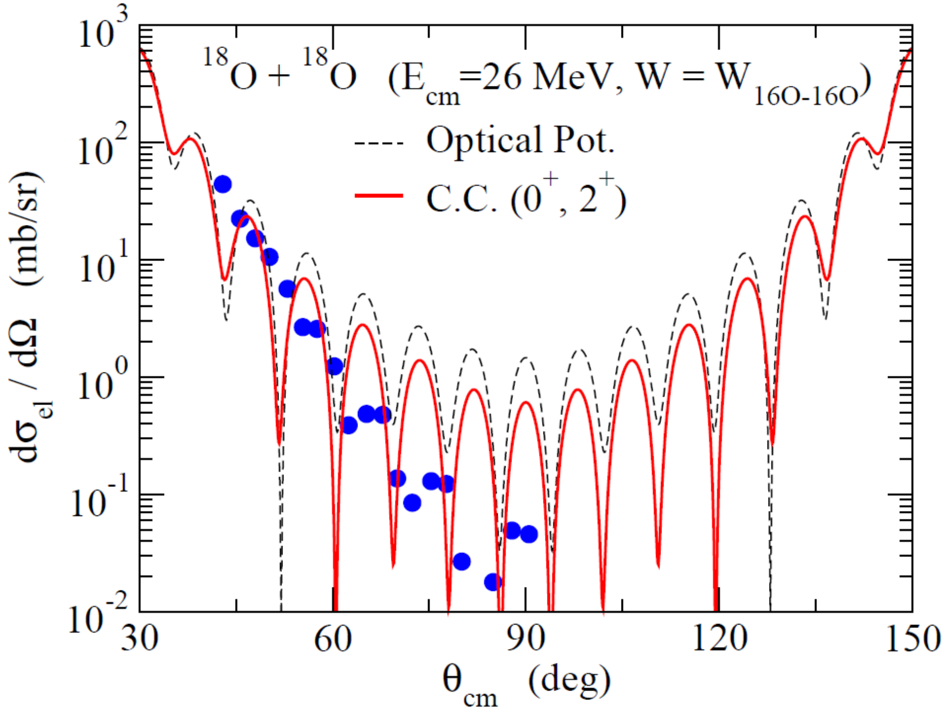
However, the same opt. pot. does not fit $^{18}O+^{18}O$

↓

need to increase *W* by a factor of 3.5

The origin of stronger absorption?

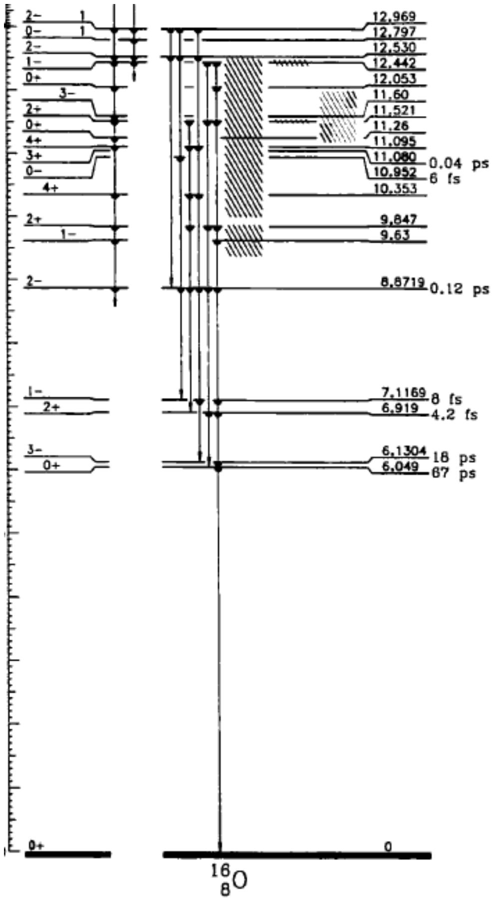




Coupling to low-lying 2^+ state: *insufficient* to damp the oscillation

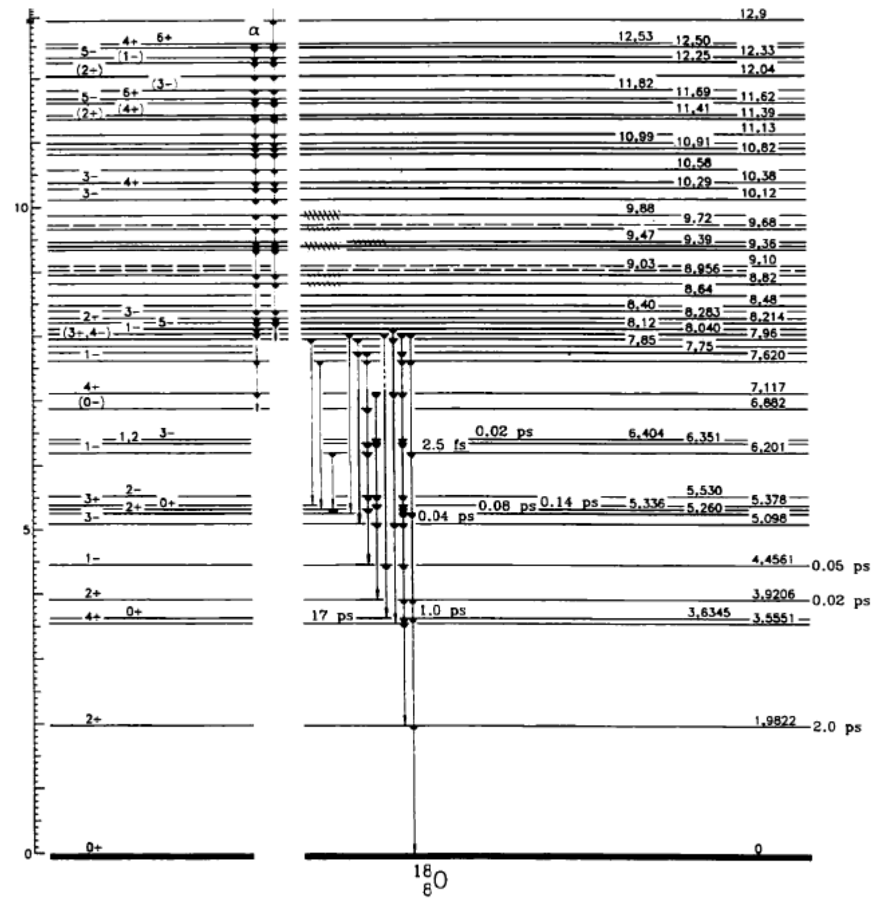
⟶ role of single-particle (non-collective) excitations

Spectra up to E* = 13 MeV



^{16}O

20 levels



^{18}O

56 levels

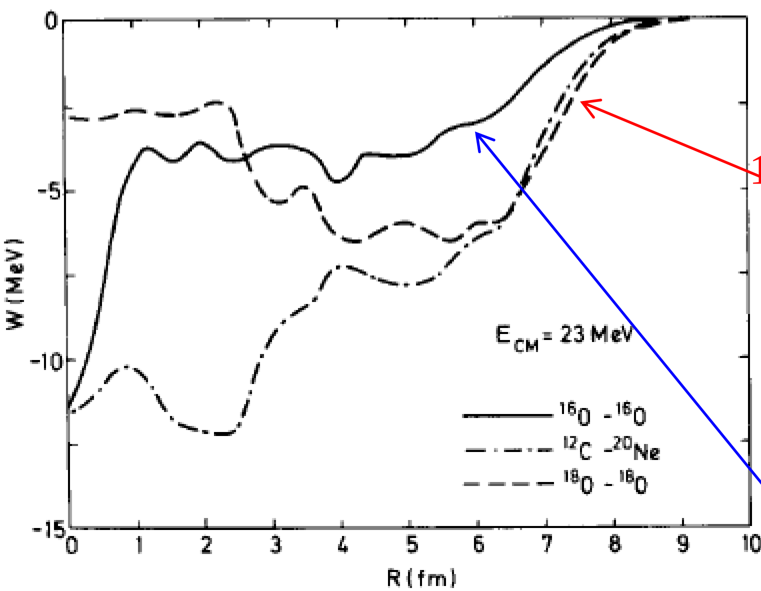
C. Von Charzewski, V. Hnizdo, and C. Toepffer, NPA307('78)309

F. Haas and Y. Abe, PRL46('81)1667

The number of *open channels*

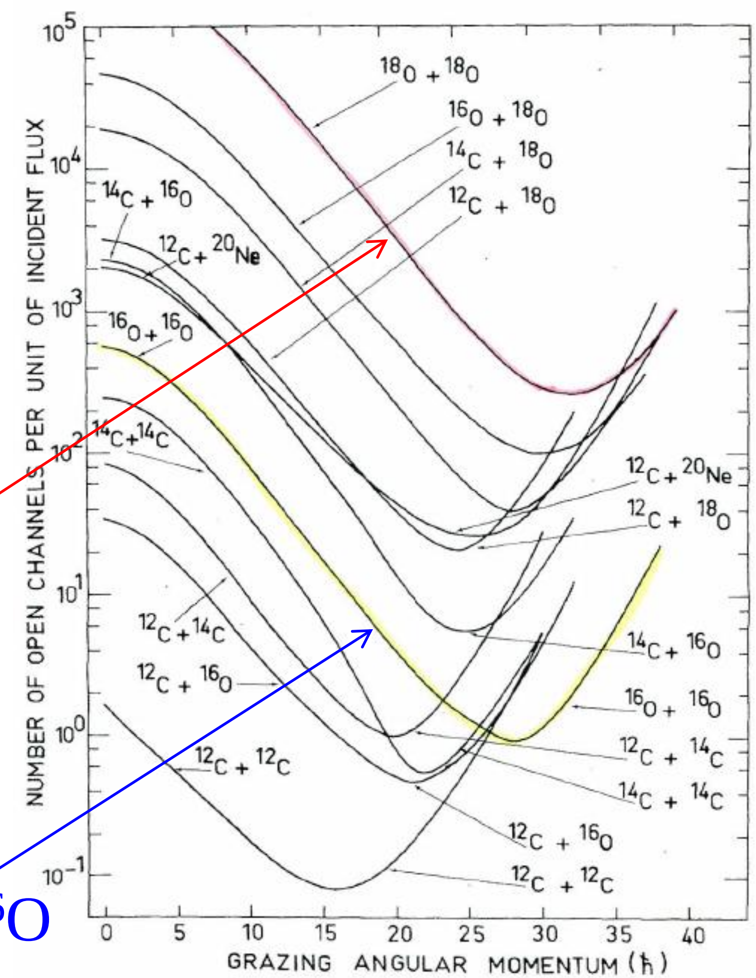
$$W(E,R) = -W_0 f(R) \times \int_0^{E-V(R)} \frac{dN(E^*,R)}{dE^*} e^{-E^*/\Delta E} dE^*$$

N(E*,R): the density of accessible 1p1h states (TCSM)

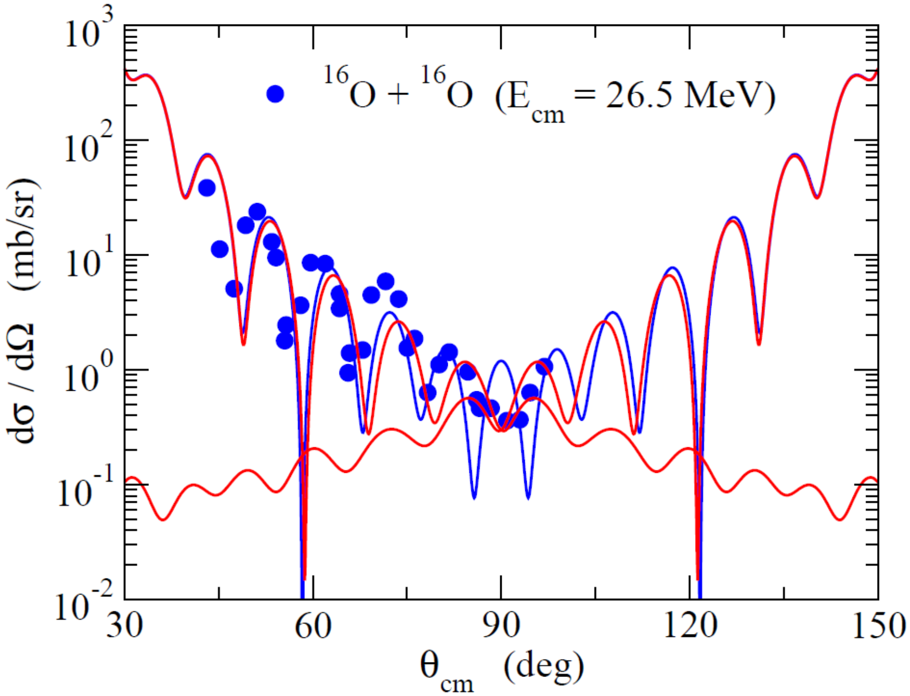


$^{18}O + ^{18}O$

$^{16}O + ^{16}O$



Mechanisms of the oscillatory structure



The unsymmtrized cross sections already show strong oscillations

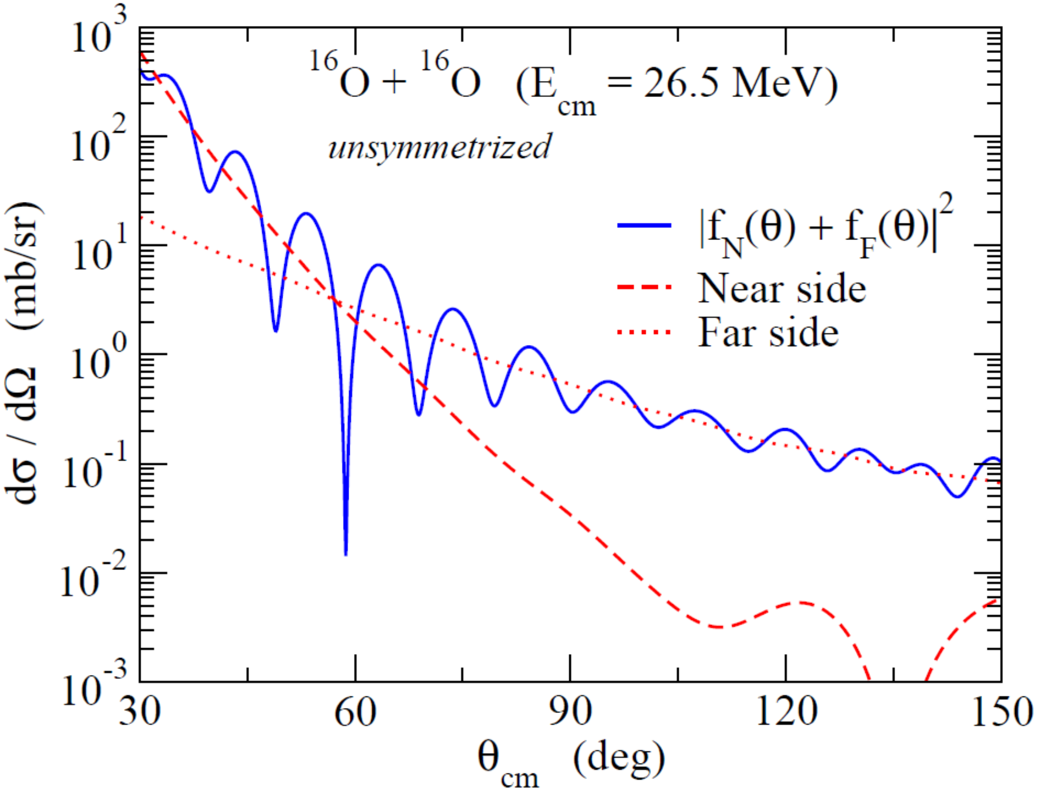
interference due to:

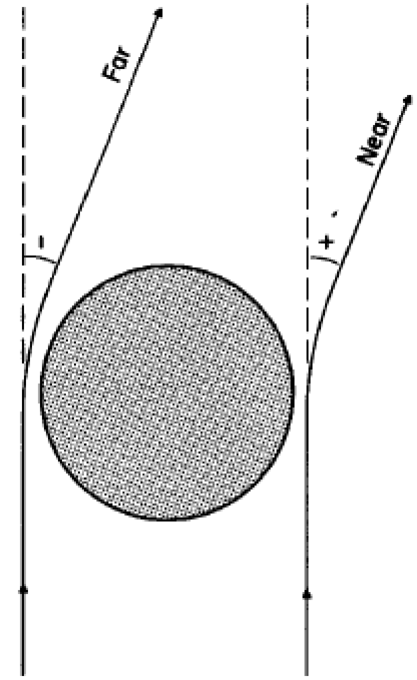
✓symmetrization of wave function ($\theta \sim 90$ deg.)

\+

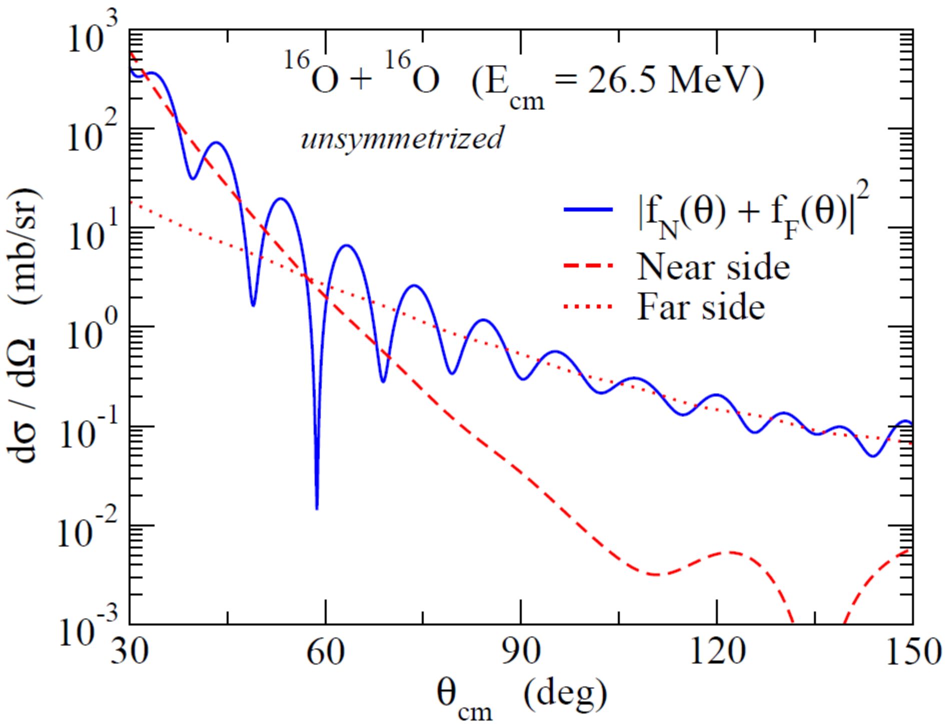
✓another mechanism

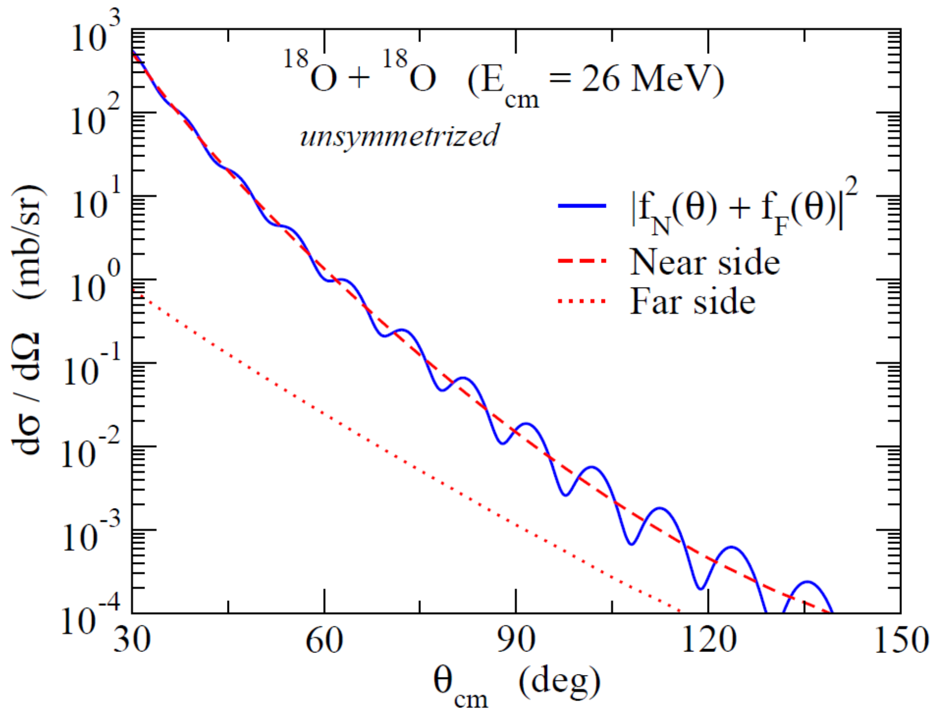
near side-far side interference





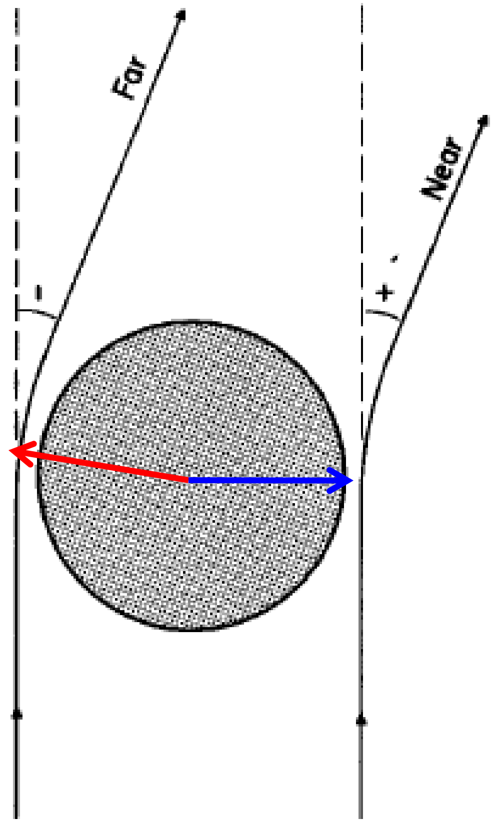
R.C. Fuller, PRC12(‘75)1561
N. Rowley and C. Marty, NPA266(‘76)494
M.S. Hussein and K.W. McVoy, Prog. in Part. and Nucl. Phys. 12 (‘84)103

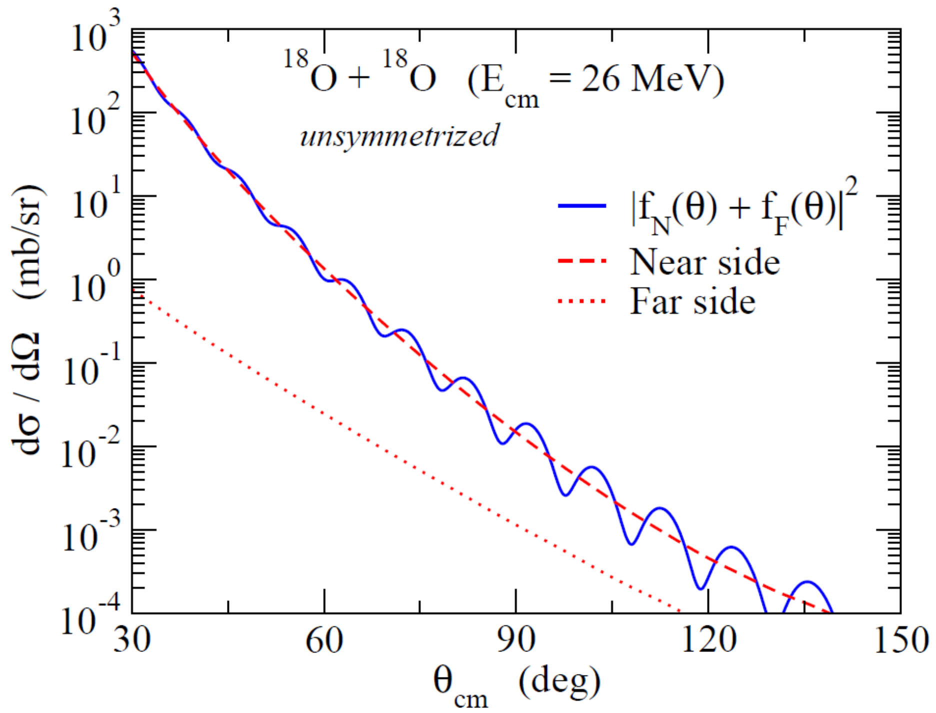




The far-side component is largely damped in ^{18}O+^{18}O due to the strong absorption.

→ less oscillatory pattern



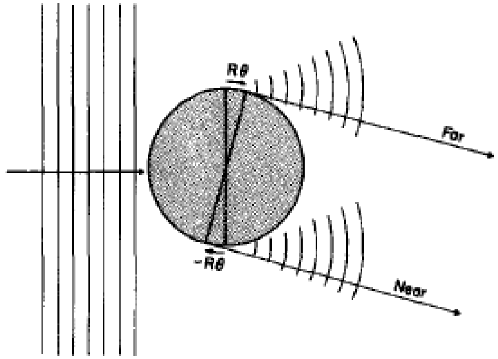


The distance of closest apporach: different between F and N

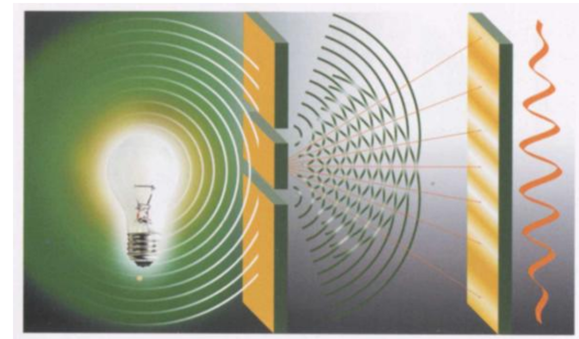
→ F and N are distinguishable (in principle) by looking at how the nuclei get excited

"which-way information"

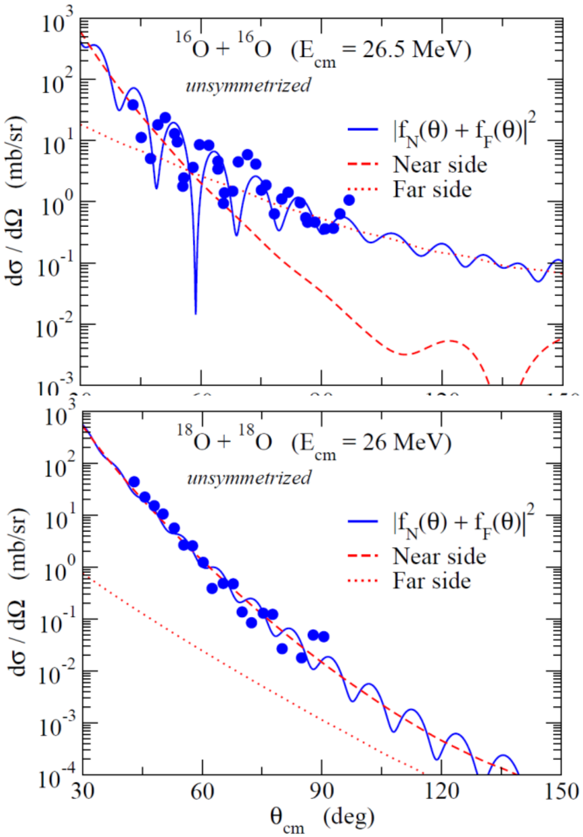
analogy to the double slit problem

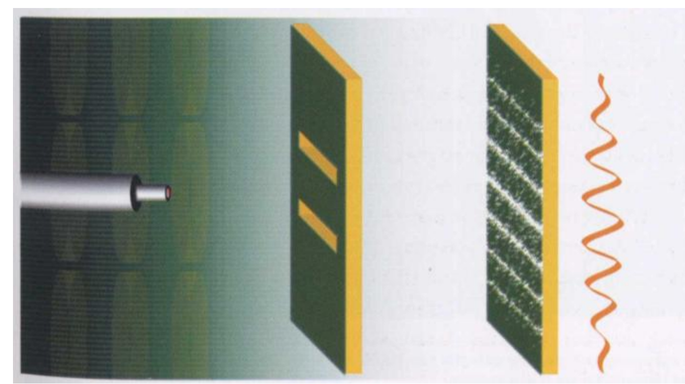


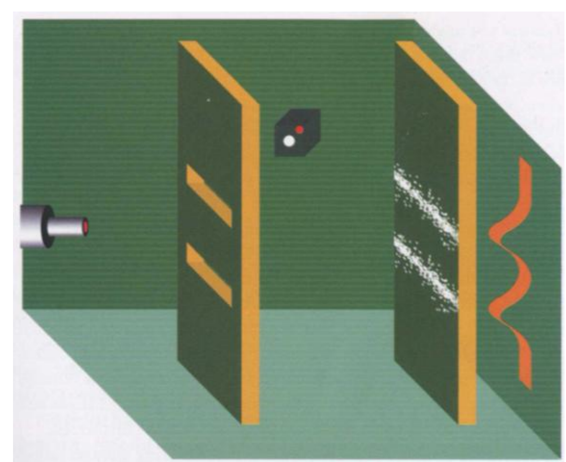
M.S. Hussein and K.W. McVoy,
Prog. in Part. and Nucl. Phys. 12 (‘84)103

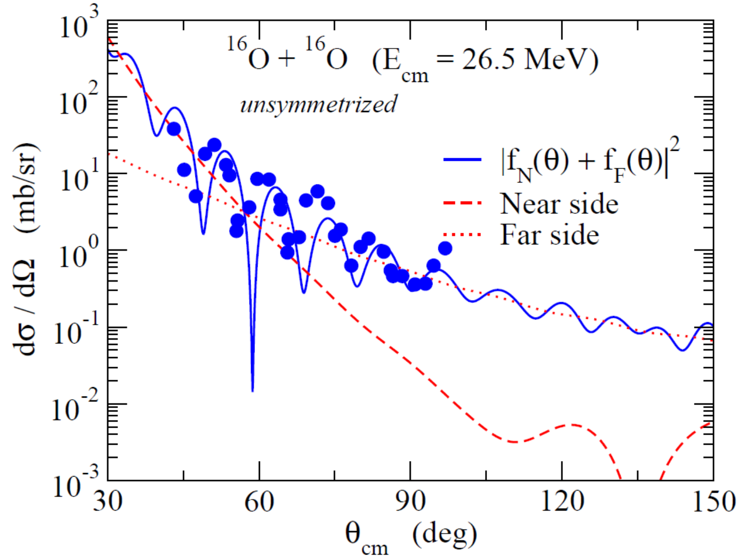


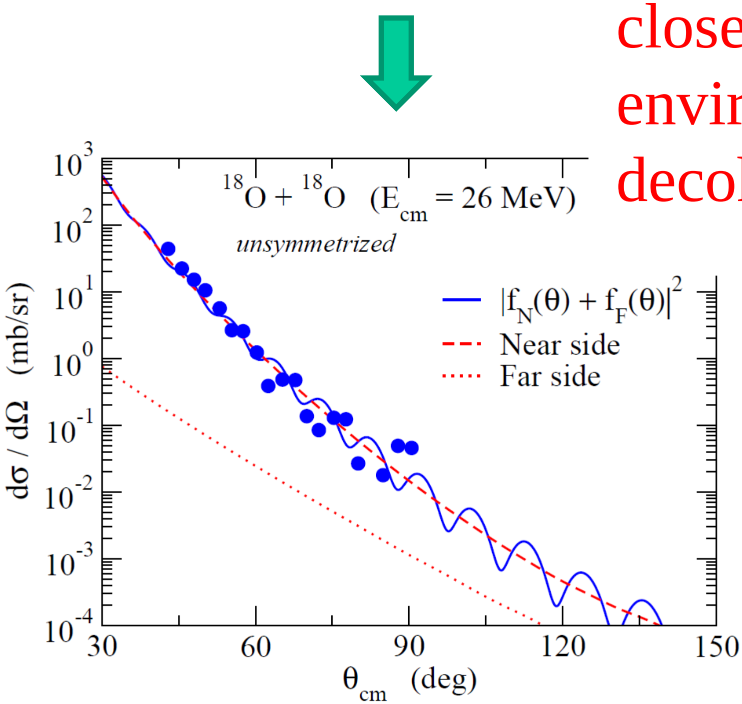
J. Al-Khalili, “Quantum”



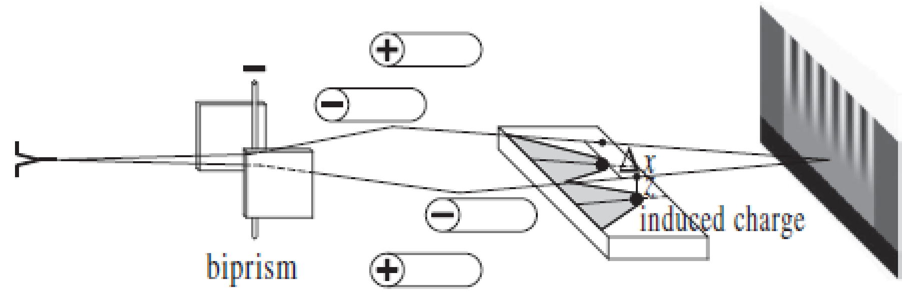


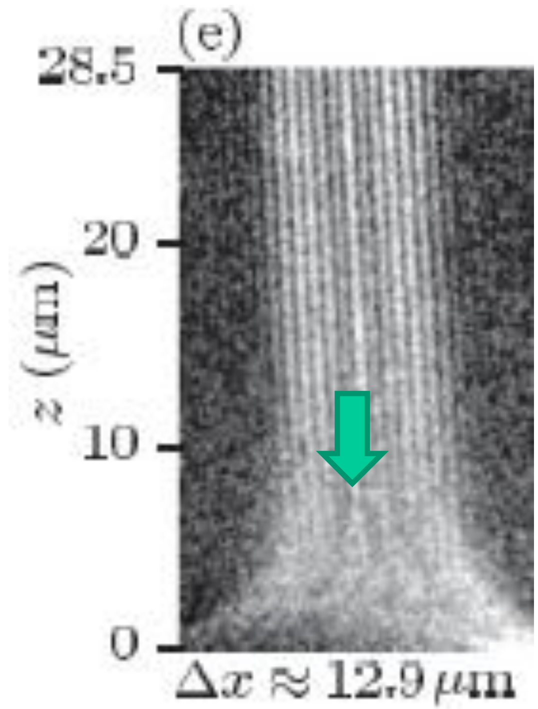






close analogy to environmental decoherence?





P. Sonnentag and F. Hasselbach, PRL98('07)200402

Subbarrier fusion reactions with dissipative couplings

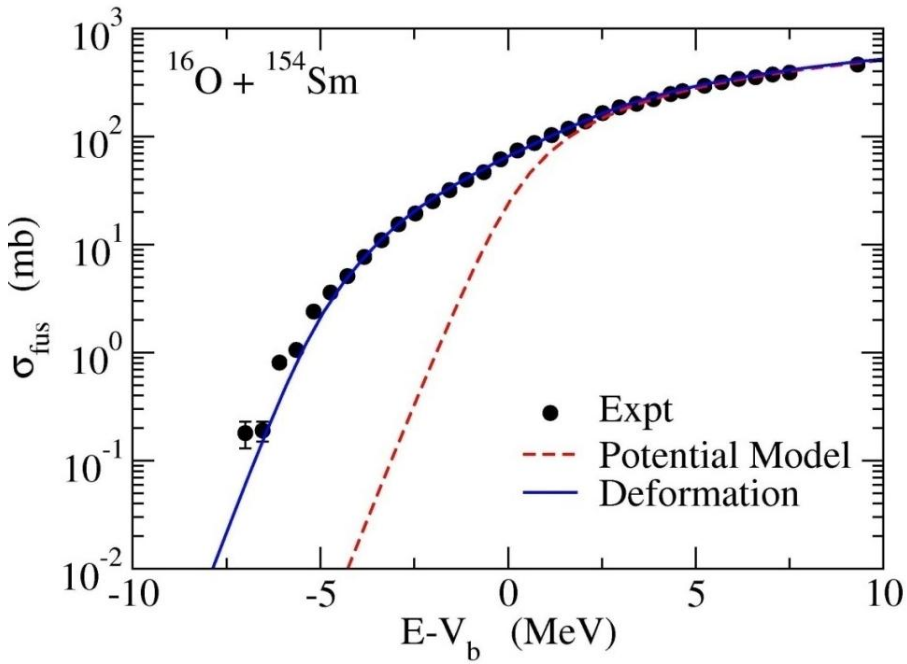
Kouichi Hagino (Tohoku University)
Shusaku Yusa (Tohoku University)
Neil Rowley (IPN Orsay)

in preparation

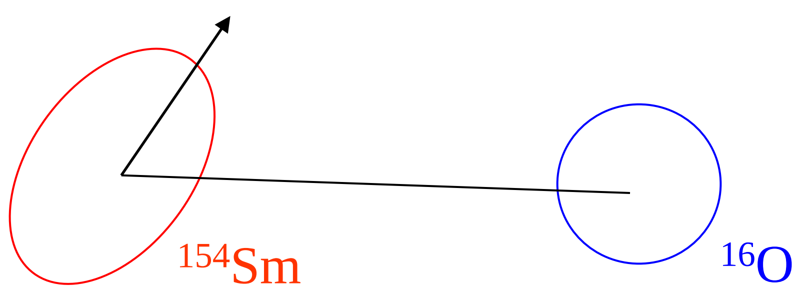
Introduction

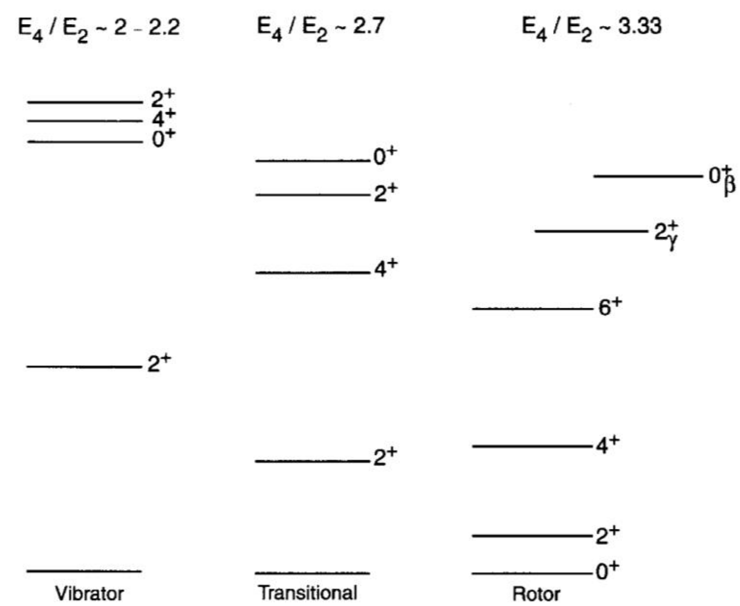
Subbarrier enhancement of fusion cross section

channel coupling effects

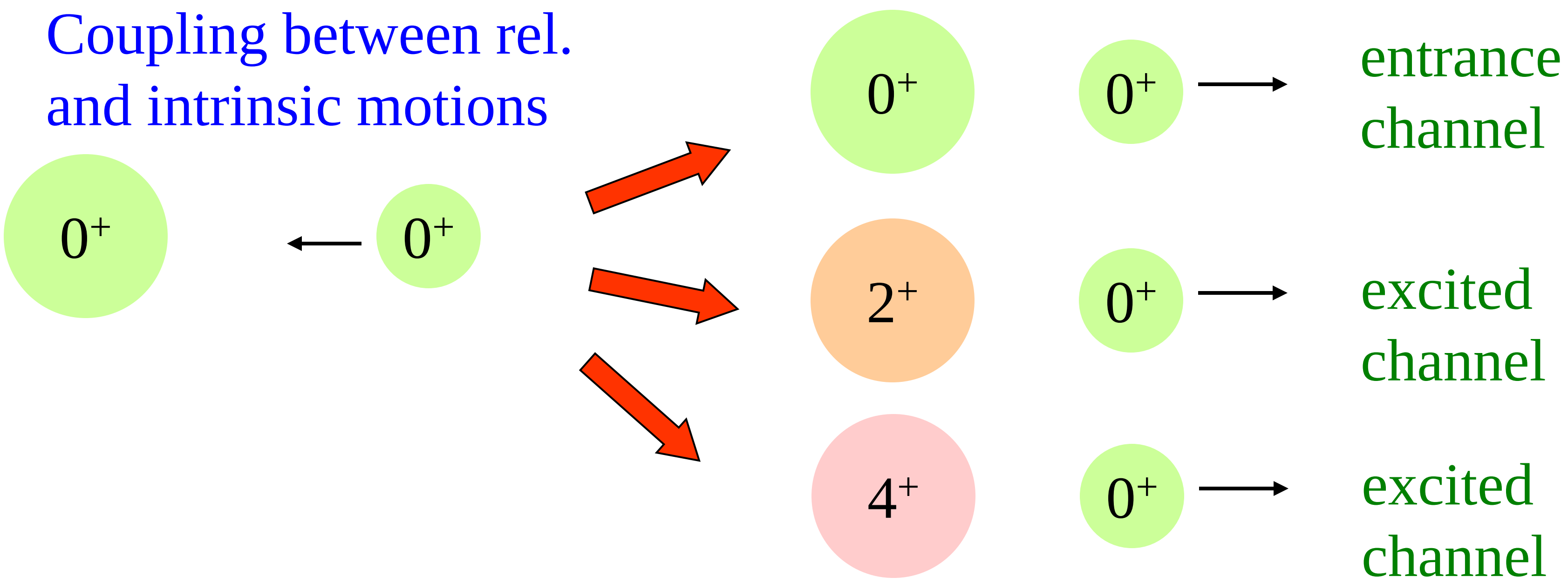


Coupling of the relative motion to collective excitations in the colliding nuclei



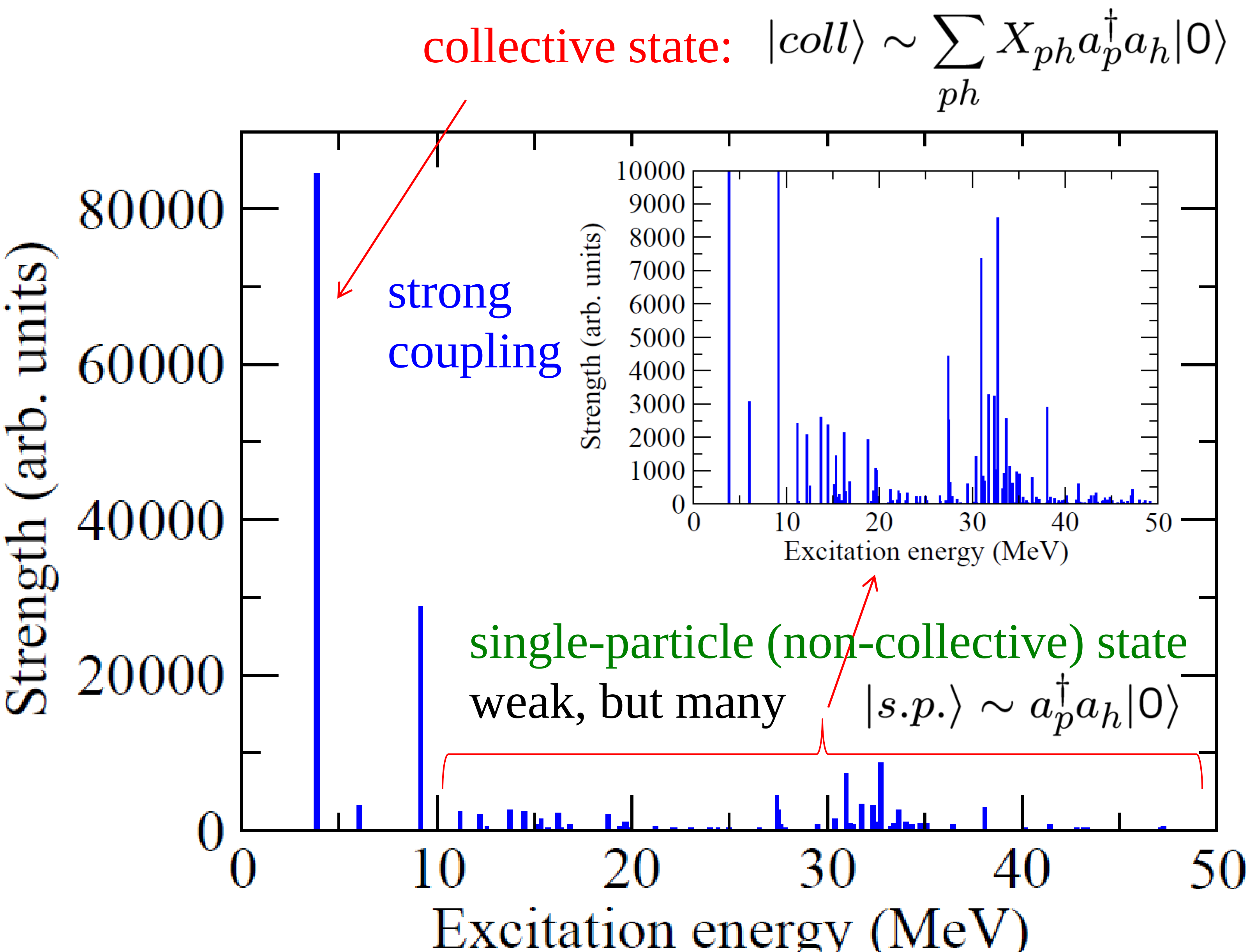


Coupled-channels framework

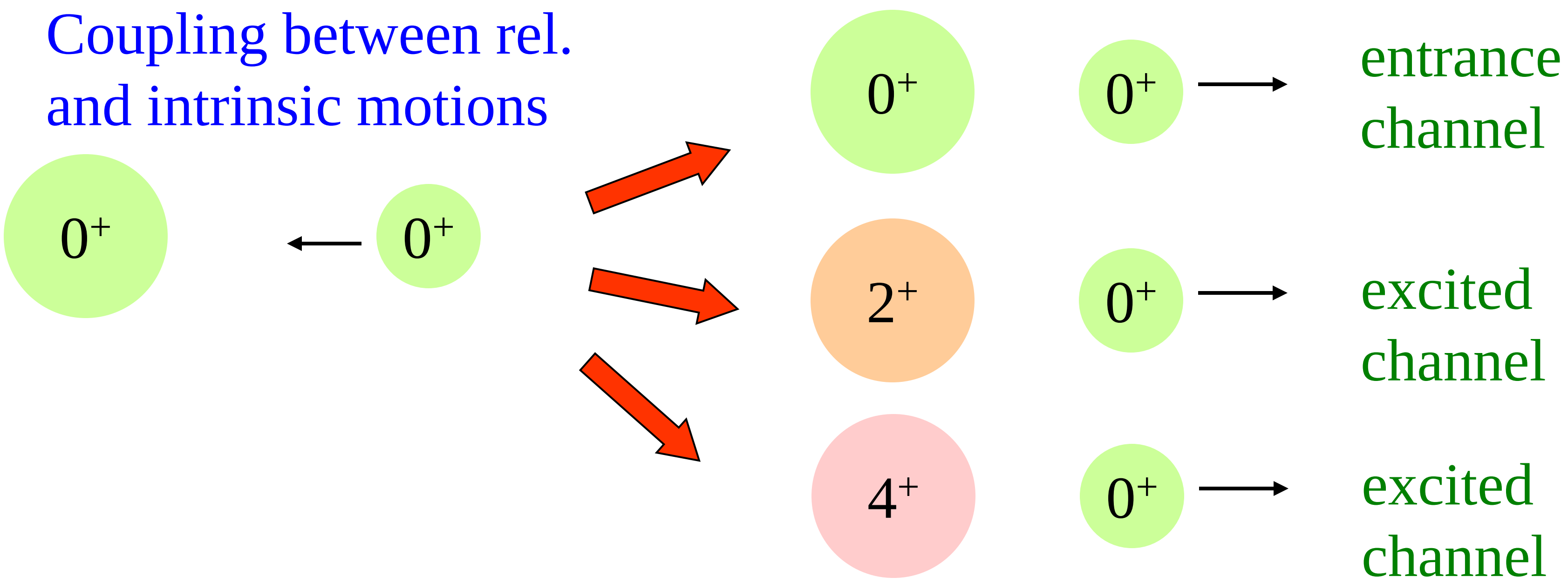


- Quantum theory which incorporates excitations in the colliding nuclei
- a few collective states (vibration and rotation) which couple strongly to the ground state + transfer channel

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



Coupled-channels framework

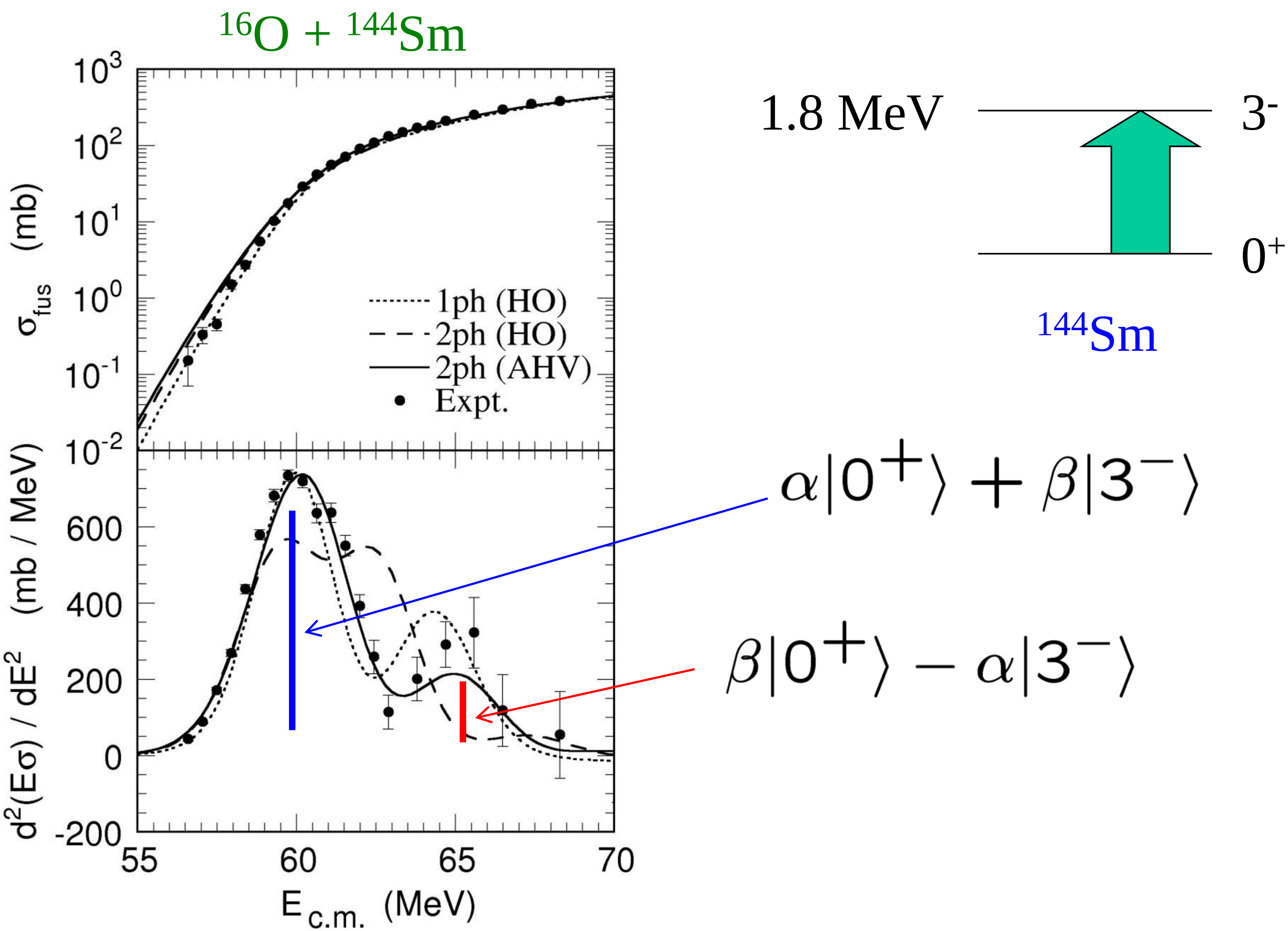


- Quantum theory which incorporates excitations in the colliding nuclei
- a few collective states (vibration and rotation) which couple strongly to the ground state + transfer channel
- several codes in the market: ECIS, FRESCO, CCFULL……

→ has been successful in describing heavy-ion reactions

However, many recent challenges in C.C. calculations!

Barrier distribution



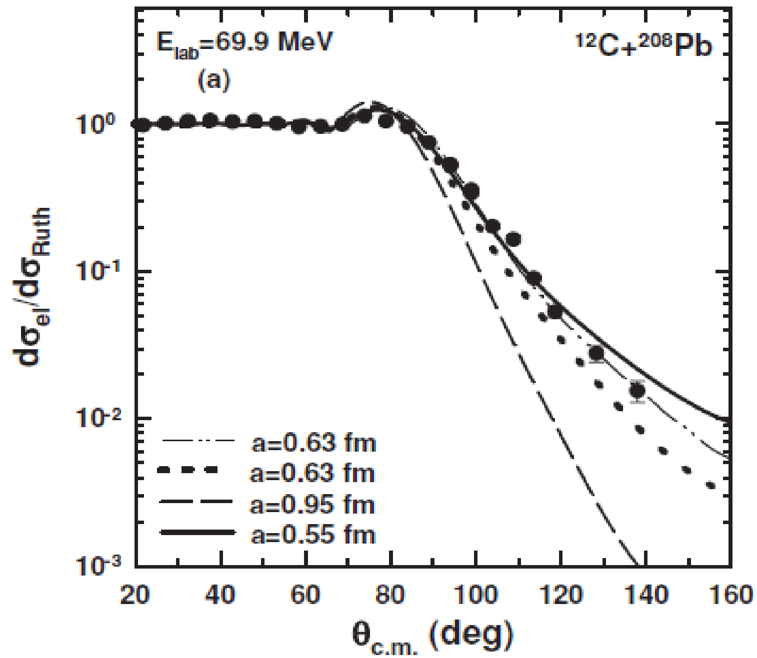
K.Hagino, N. Takigawa, and S. Kuyucak, PRL79('97)2943

surface diffuseness anomaly

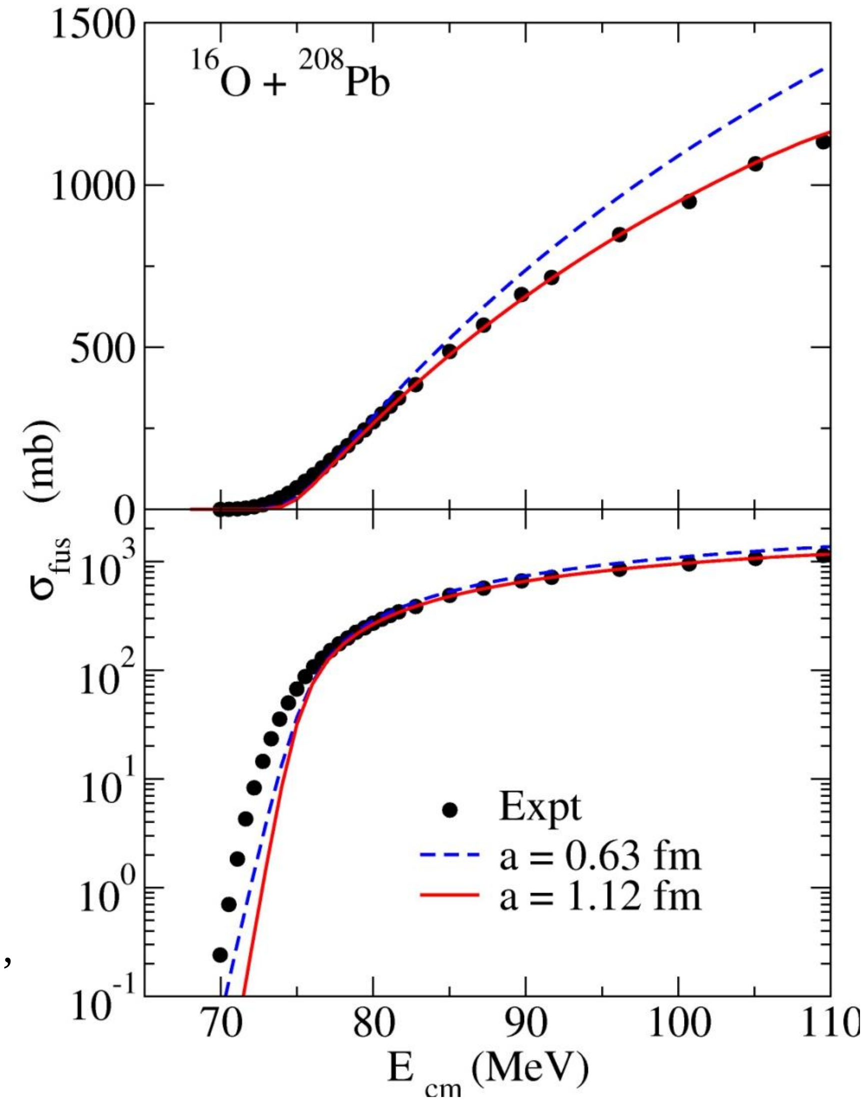
Scattering processes:

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

→ successful



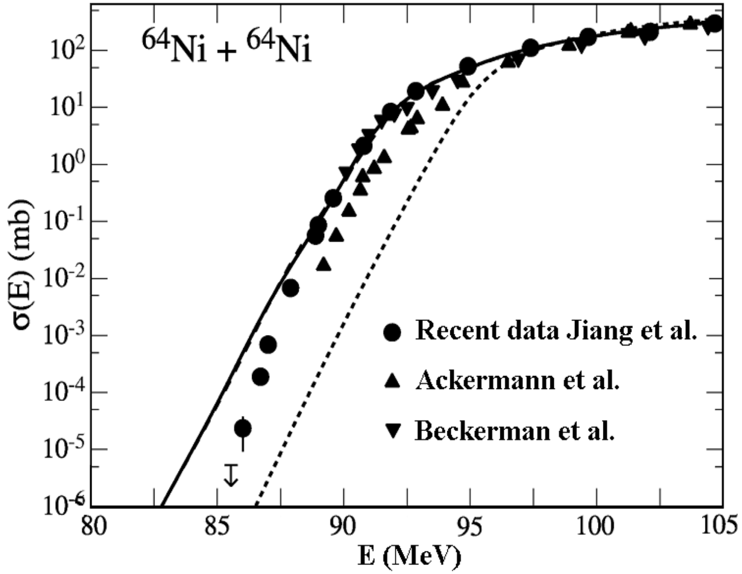
A. Mukherjee, D.J. Hinde, M. Dasgupta, K.H., et al., PRC75('07)044608



Fusion process: not successful

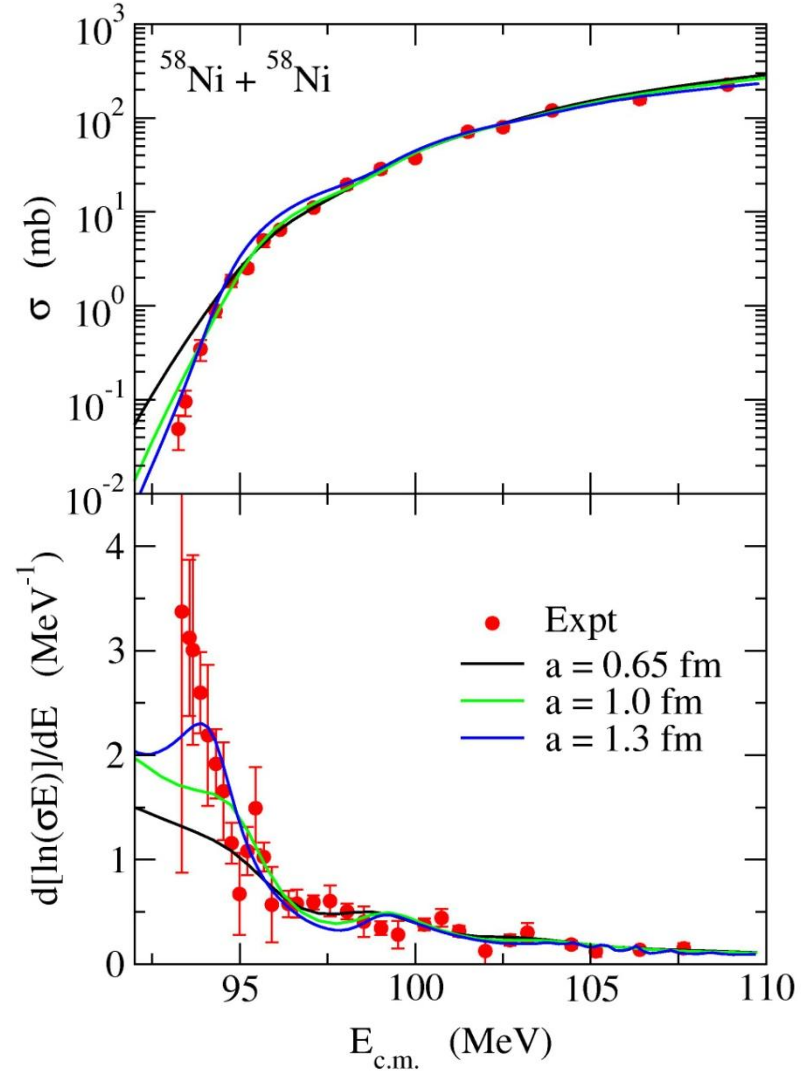
→ *a* ~ 1.0 fm required (if WS)

Deep subbarrier fusion data

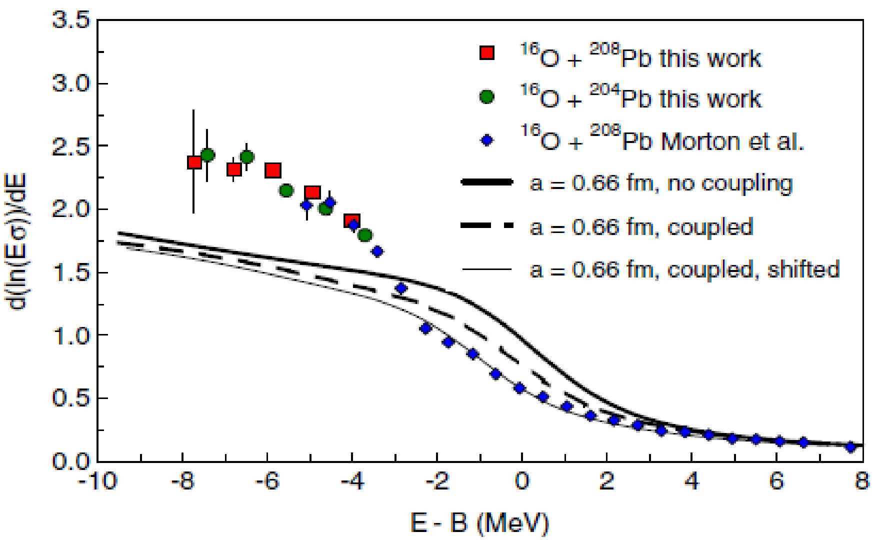


C.L. Jiang et al., PRL93('04)012701

"steep fall-off of fusion cross section"

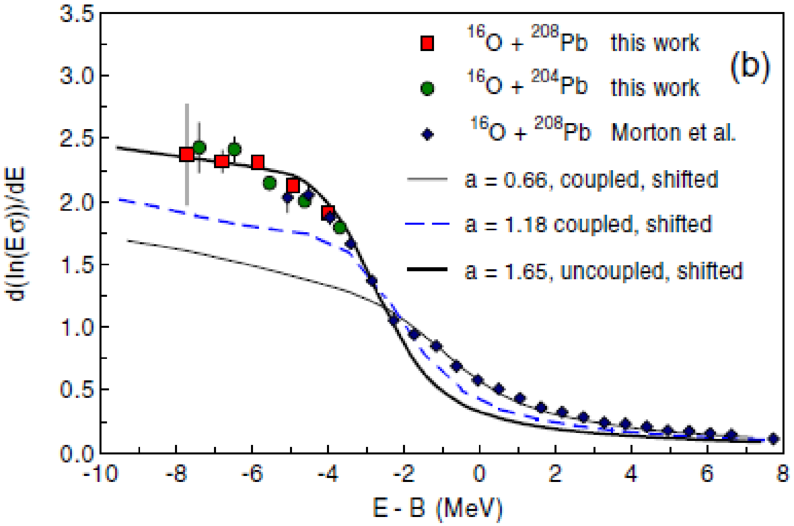


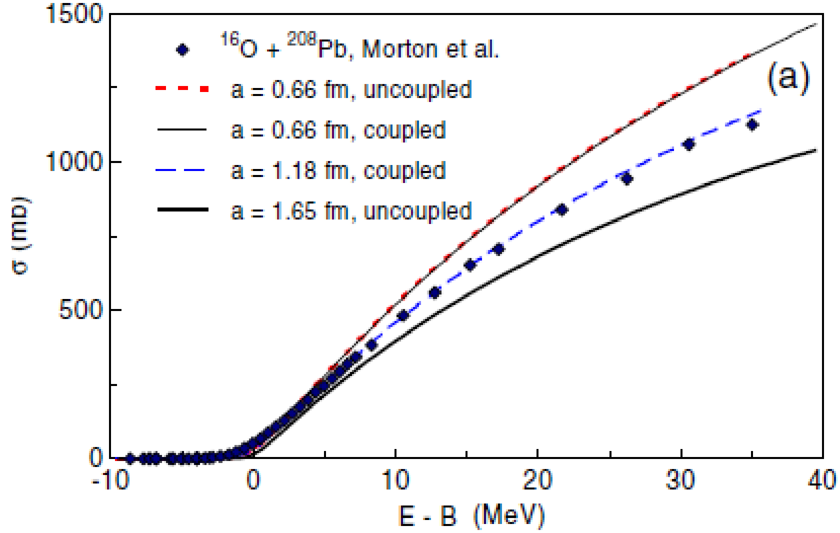
K. H., N. Rowley, and M. Dasgupta, PRC67('03)054603



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

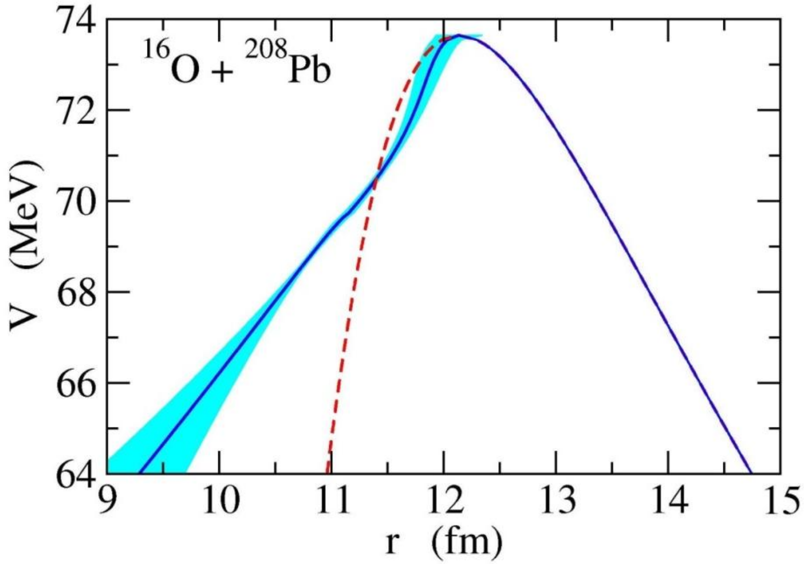
energy dependence of surface diffuseness parameter

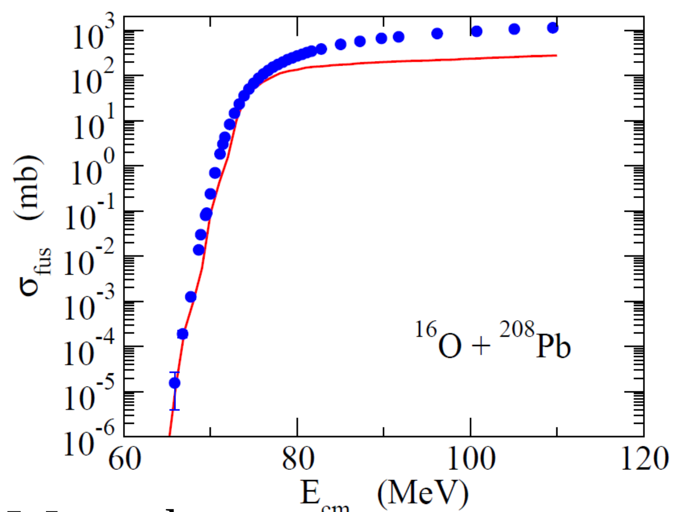




M. Dasgupta et al., PRL99('07)192701

potential inversion with deep subbarrier data

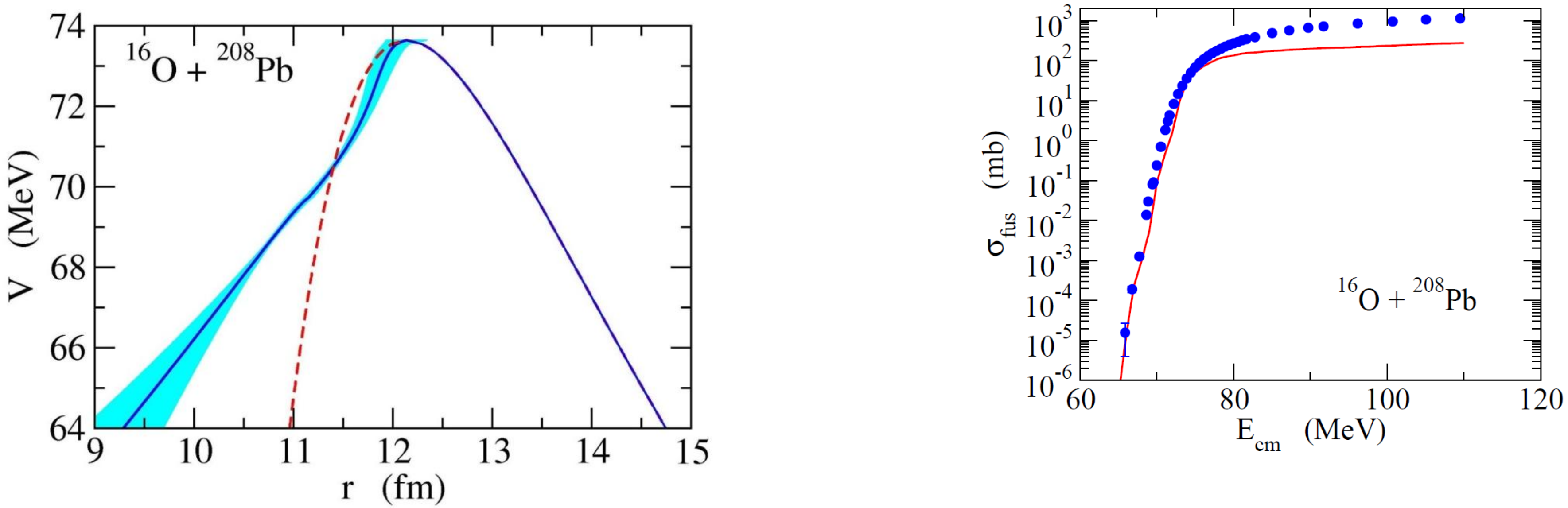




K.H. and Y. Watanabe,
PRC76 ('07) 021601(R)

energy dependence of surface diffuseness parameter

potential inversion with deep subbarrier data

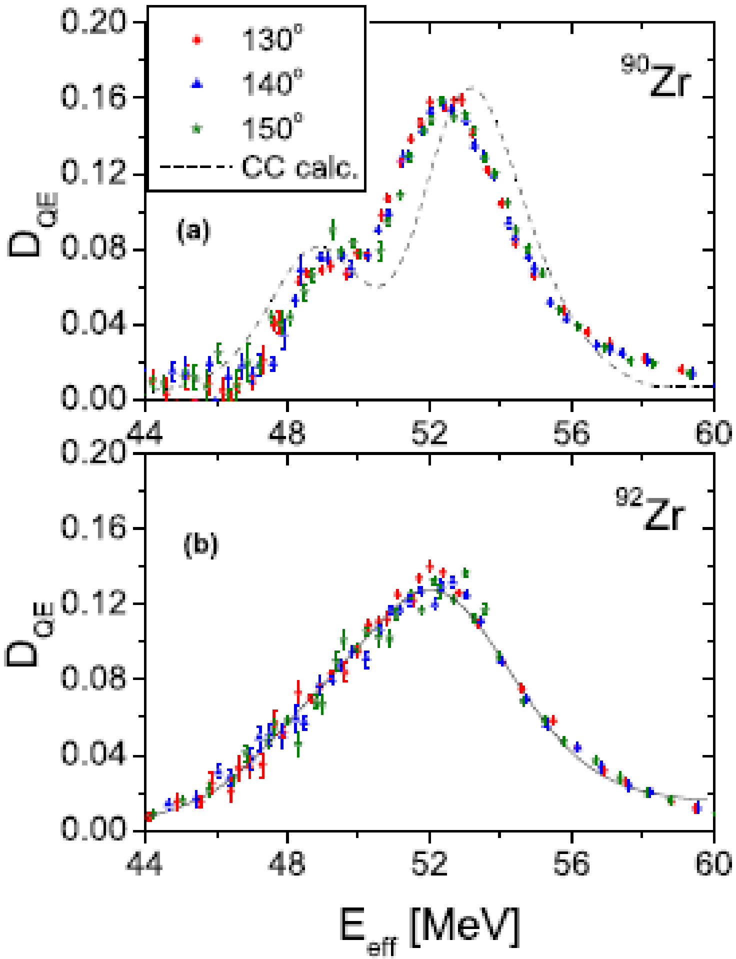


K.H. and Y. Watanabe,
PRC76 ('07) 021601(R)

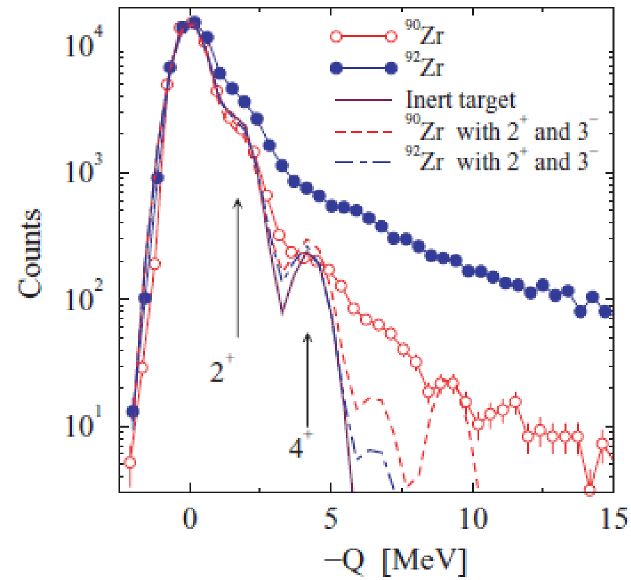
- dynamical effects not included in C.C. calculation?
- energy and angular momentum dissipation?
- weak channels?

A hint: comparison between ^{20}Ne+^{90}Zr and ^{20}Ne+^{92}Zr

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



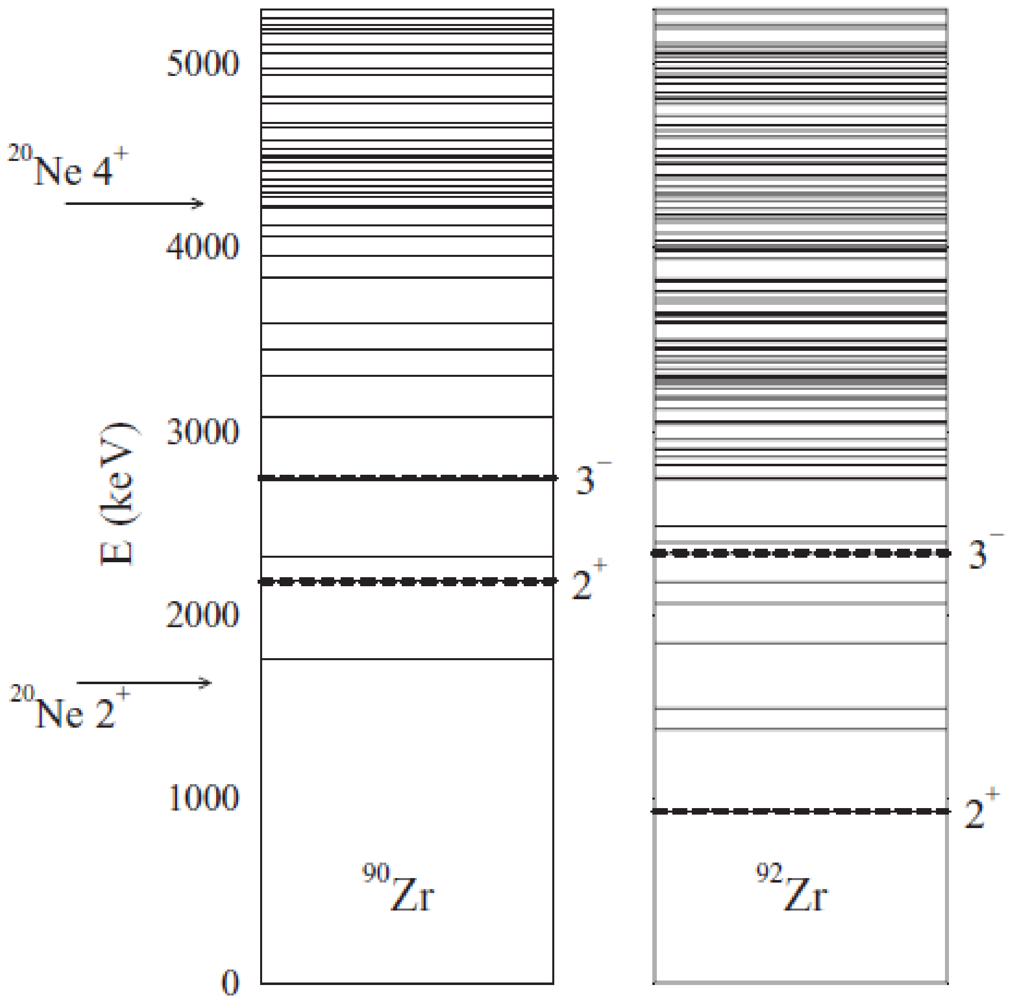
E. Piasecki et al.,
PRC80 ('09) 054613



($E_{\rm eff}$ = 50 MeV)

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

single-particle excitations??

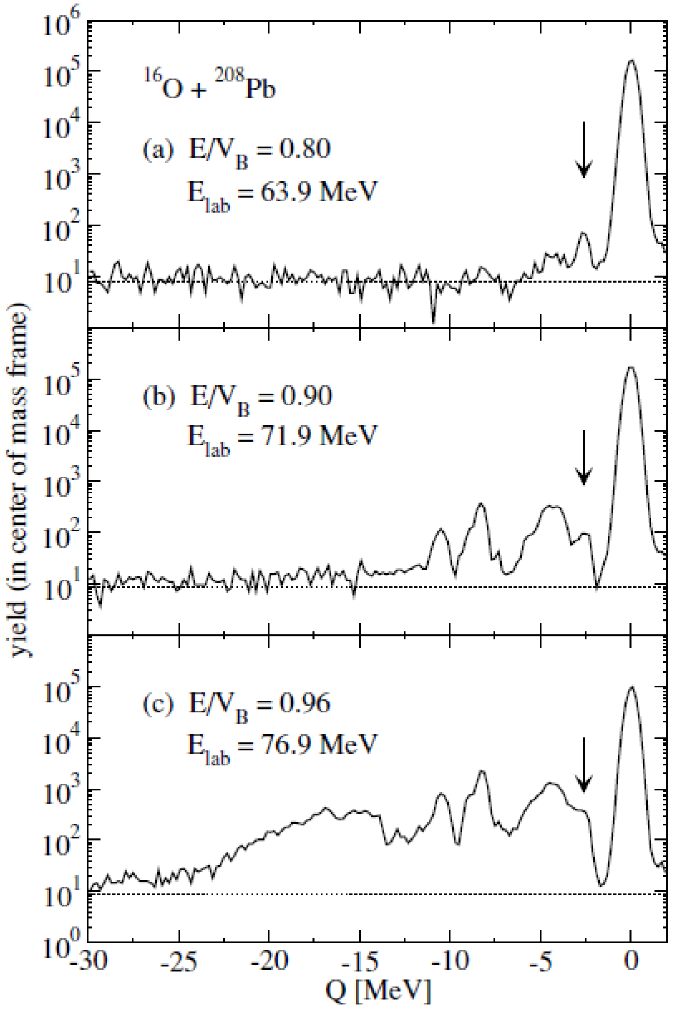


role of these s.p. levels in barrier distribution and Q-value distribution?

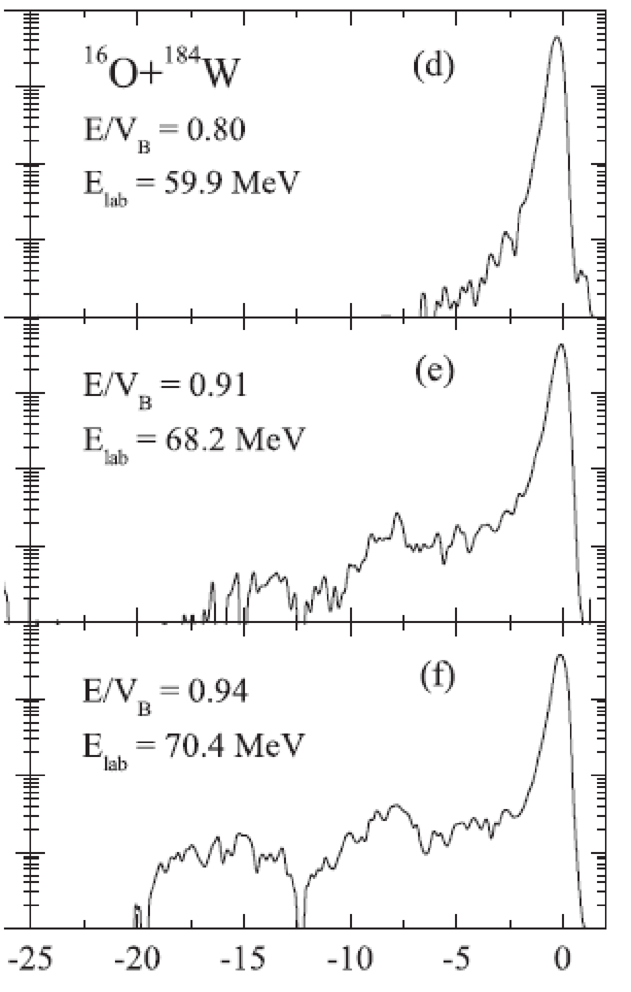
^{90}Zr (Z=40 sub-shell closure, N=50 shell closure)
^{92}Zr = ^{90}Zr + 2n

cf. ^{18}O = ^{16}O + 2n

Energy dependence of Q-value distribution:



M. Evers et al., PRC78('08)034614



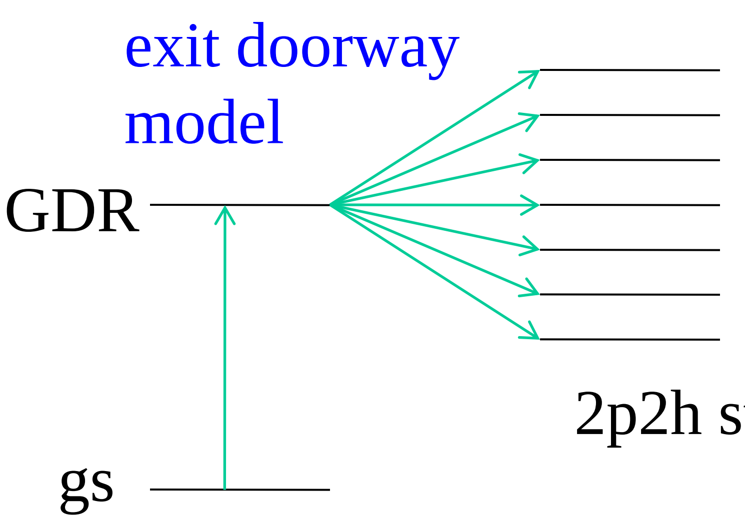
C.J. Lin et al., PRC79('09)064603

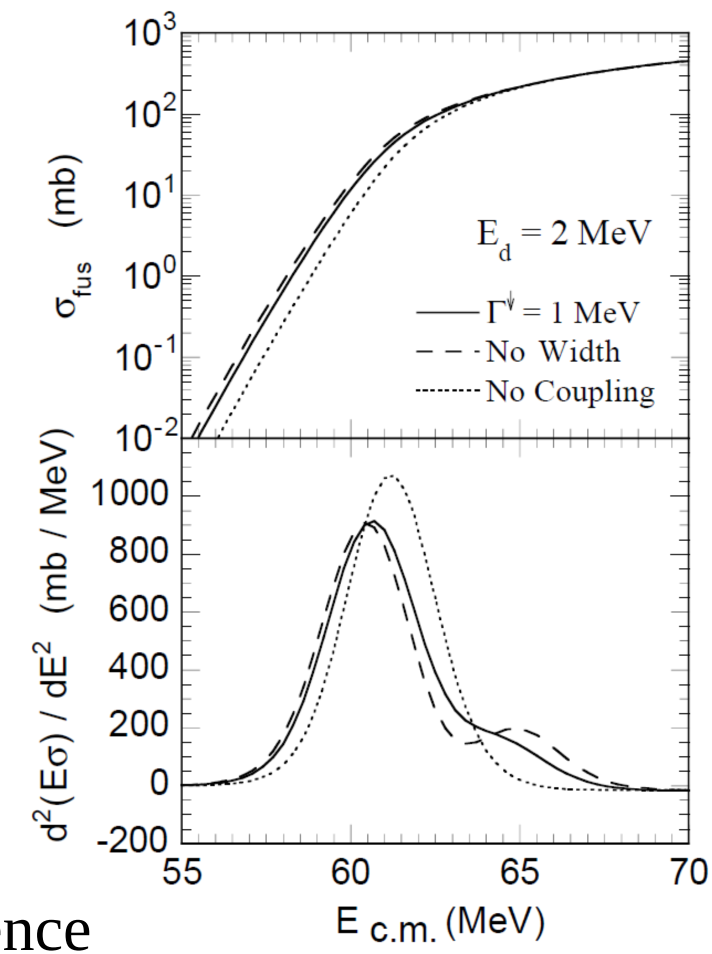
✓relation to the energy dependence of *a* parameter?

C.C. calculation with non-collective levels

Recent experimental data: a need to include non-collective excitations in C.C.

- previous attempt





K.H. and N. Takigawa, PRC58('98)2872

cf. recent application of quantum decoherence (Lindblad) theory:
A. Diaz-Torres et al., PRC78('08)064604

Random Matrix Model

Coupled-channels equations: $\Psi(r,\xi)=\sum_k \psi_k(r)\phi_k(\xi)$

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

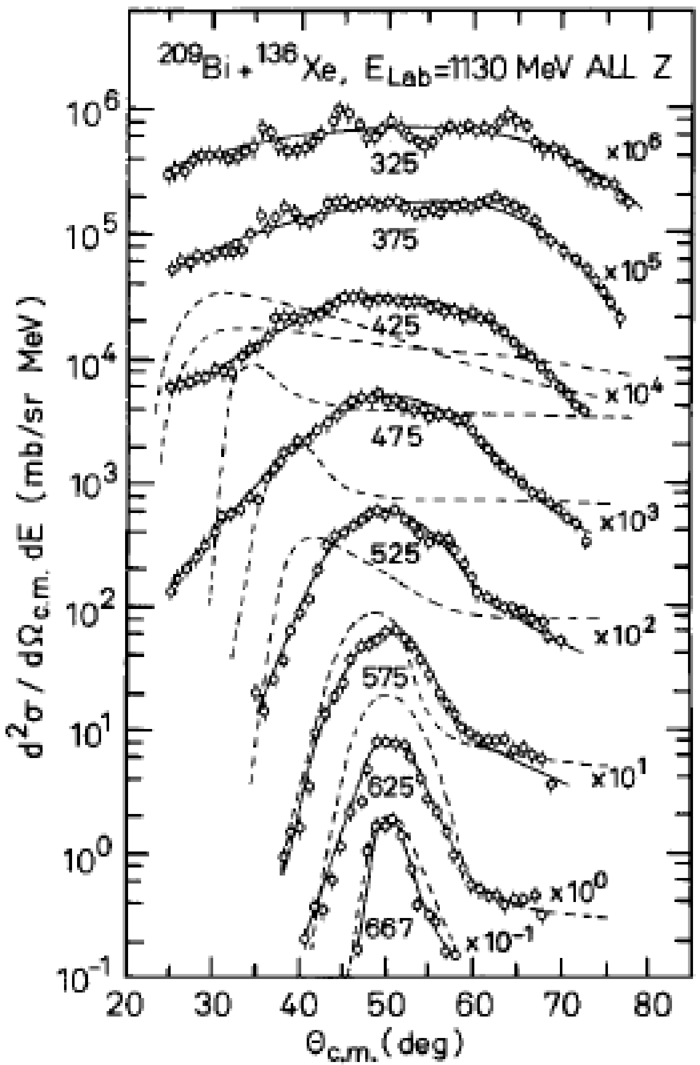
$|\phi_k\rangle$: complicated single-particle states

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

$$\overline{V_{ij}} = 0,$$

$$\overline{V_{ij}V_{kl}} = (\delta_{ik}\delta_{jl}+\delta_{il}\delta_{jk})\frac{w_0}{\sqrt{\rho(\epsilon_i)\rho(\epsilon_j)}}e^{-\frac{(\epsilon_i-\epsilon_j)^2}{2\Delta^2}}$$

D. Agassi, C.M. Ko, and H.A. Weidenmuller, Ann. of Phys. 107('77)140.
M.C. Nunes, Nucl. Phys. A315 ('79) 457.



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

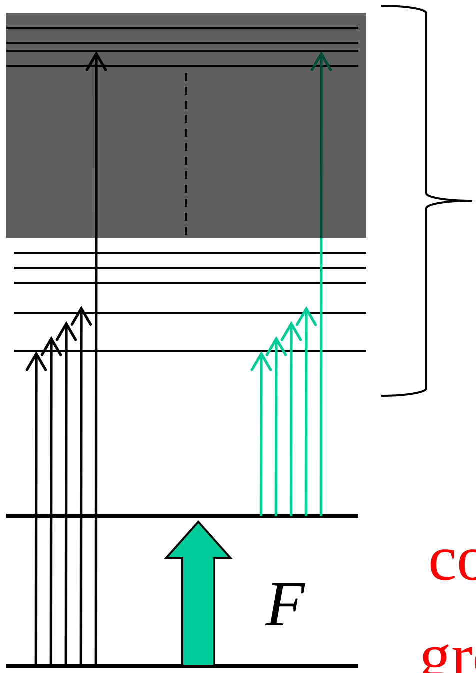
RMT model for H.I. reactions:

✓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 *one dimensional* model:



s.p. states: $\rho(\epsilon) = \rho_0\, e^{2\sqrt{a\epsilon}}$ from 2 to 23 MeV

discretization

$$\sum_{k'} V_{kk'}\psi_{k'}(\boldsymbol{r}) = \int d\epsilon\, \rho(\epsilon) V_{k\epsilon}\psi_\epsilon(x)$$

$$\sim \sum_n \Delta\epsilon\, \rho(\epsilon_n) V_{k\epsilon_n}\psi_{\epsilon_n}(x)$$

$\Delta\varepsilon = 0.02$ MeV ⟶ 1013 channels

collective state: $\varepsilon = 1$ MeV

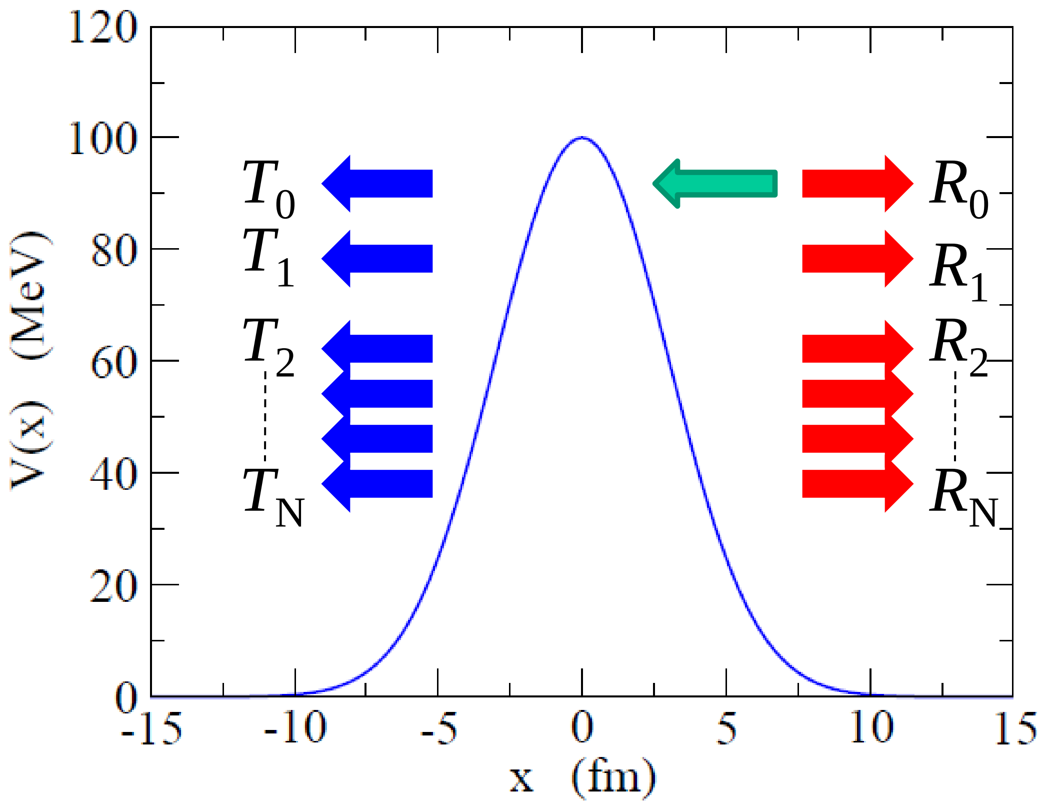
ground state

◆bare potential: $V(x) = V_0\, e^{-\frac{x^2}{2s^2}}$ ($V_0 = 100$ MeV, $s = 3$ fm, $\mu = 29\, m_N$)

constant coupling approximation

◆coupling to coll.: $F = 2$ MeV

◆coupling to s.p. levels: RMT $\overline{V_{ij}^2} = \frac{w_0}{\sqrt{\rho(\epsilon_i)\rho(\epsilon_j)}}\, e^{-\frac{(\epsilon_i-\epsilon_j)^2}{2\Delta^2}}$

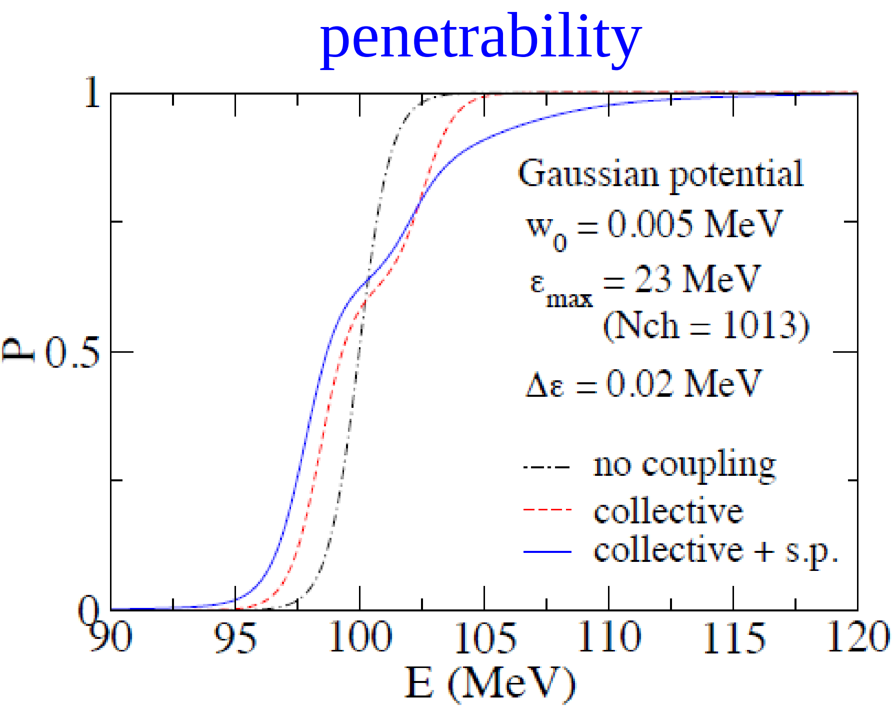


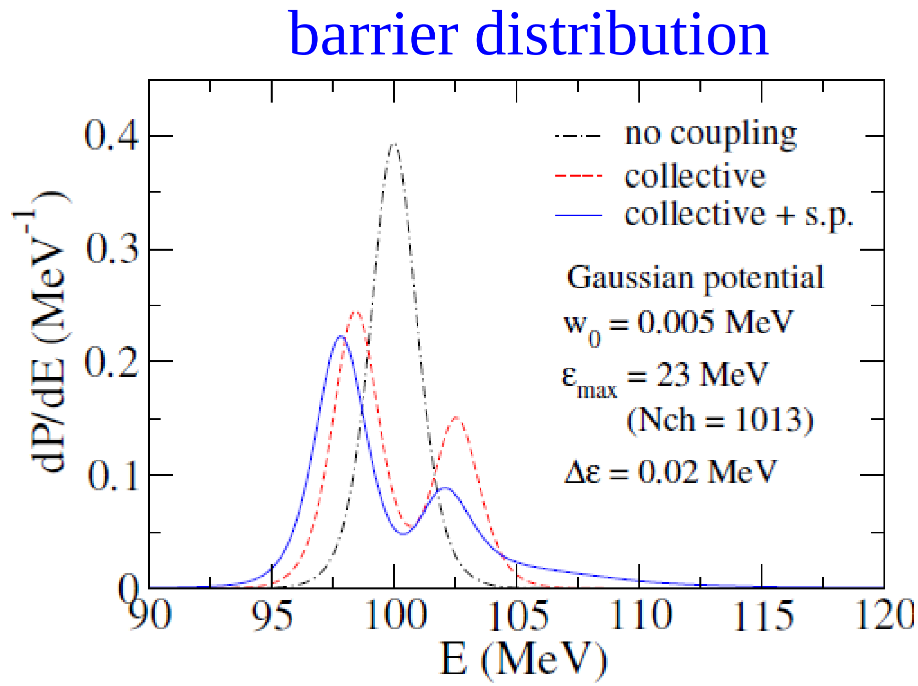
Total penetrability: $P(E) = \sum_n P_n(E) = \sum_n \frac{k_n}{k_0} |T_n|^2$

Barrier distribution: $D(E) = \frac{dP}{dE}$

Q-value distribution: $\frac{dY}{dE} = \mathcal{N} \sum_n \frac{k_n}{k_0} |R_n|^2 \, \delta(E - \epsilon_n)$

Generate 30 coupling matrices $\longrightarrow$ *ensemble average of P(E)*



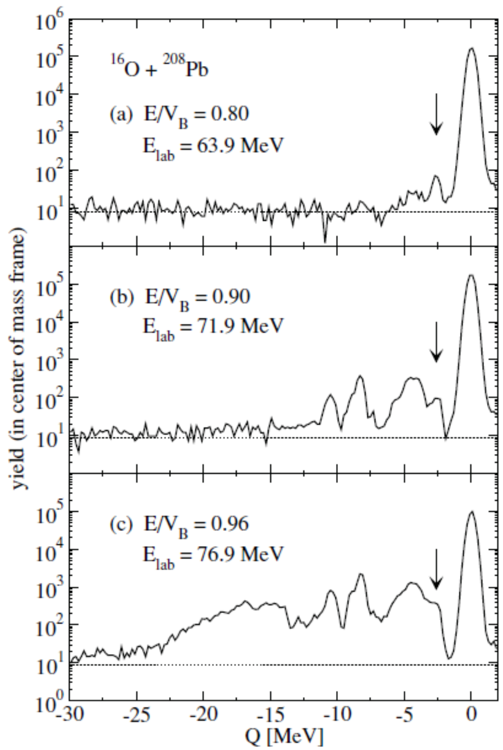


✓Suppression of $P(E)$ at high E due to s.p. excitations

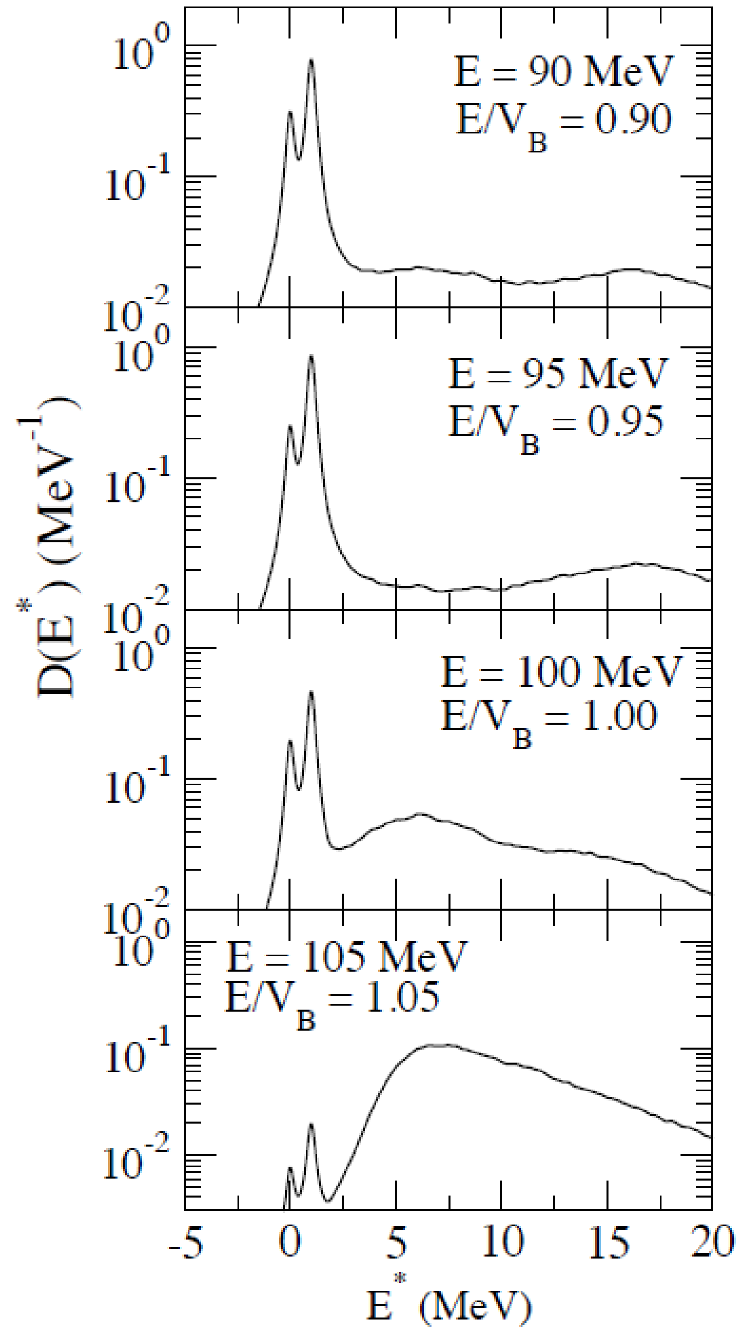
✓The higher peak is smeared due to s.p. excitations while the gross feature remains the same

Q-value distribution

- ✓At subbarrier energies, only elastic and collective channels
- ✓As energies increases, s.p. excitations become important
- ✓consistent with experiments

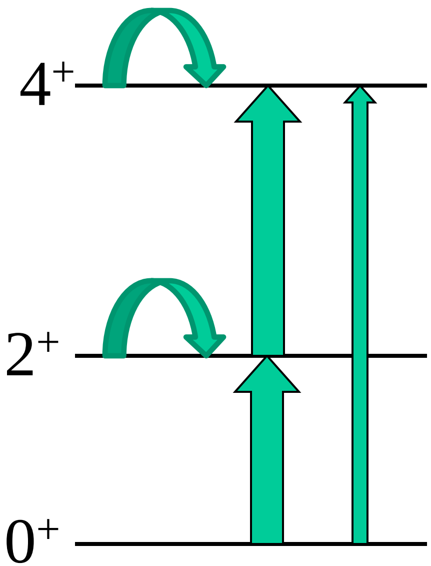


M. Evers et al., PRC78('08)034614



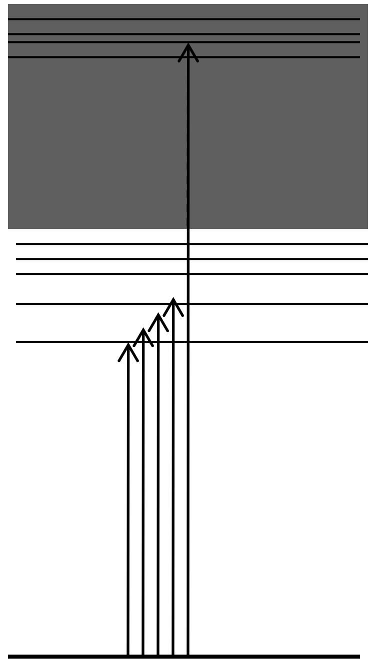
*smeared with $\eta = 0.2$ MeV

Application to ^{20}Ne + ^{92}Zr system



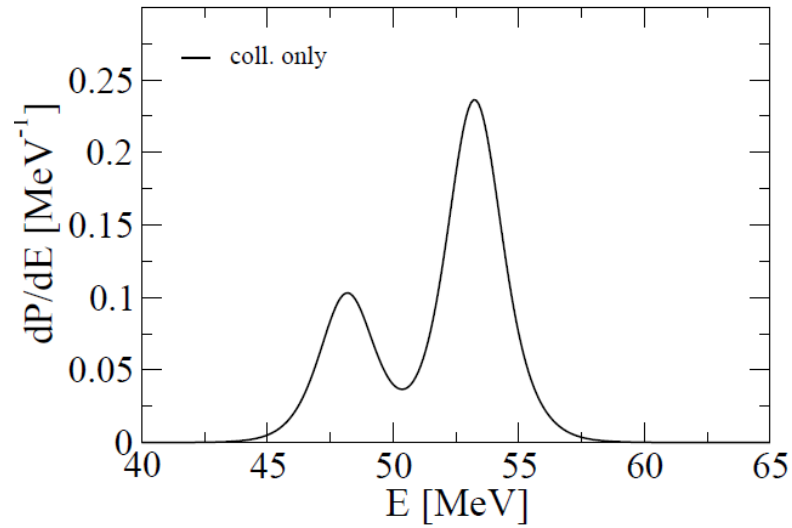
^{20}Ne

rotational coupling

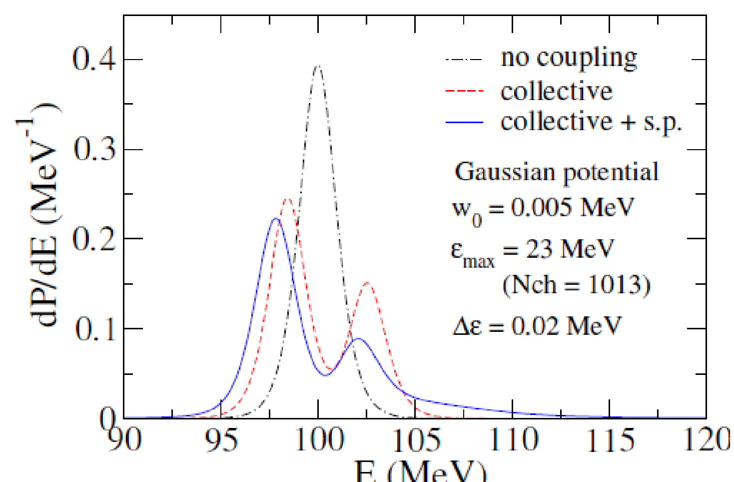


^{92}Zr

non-collective excitations

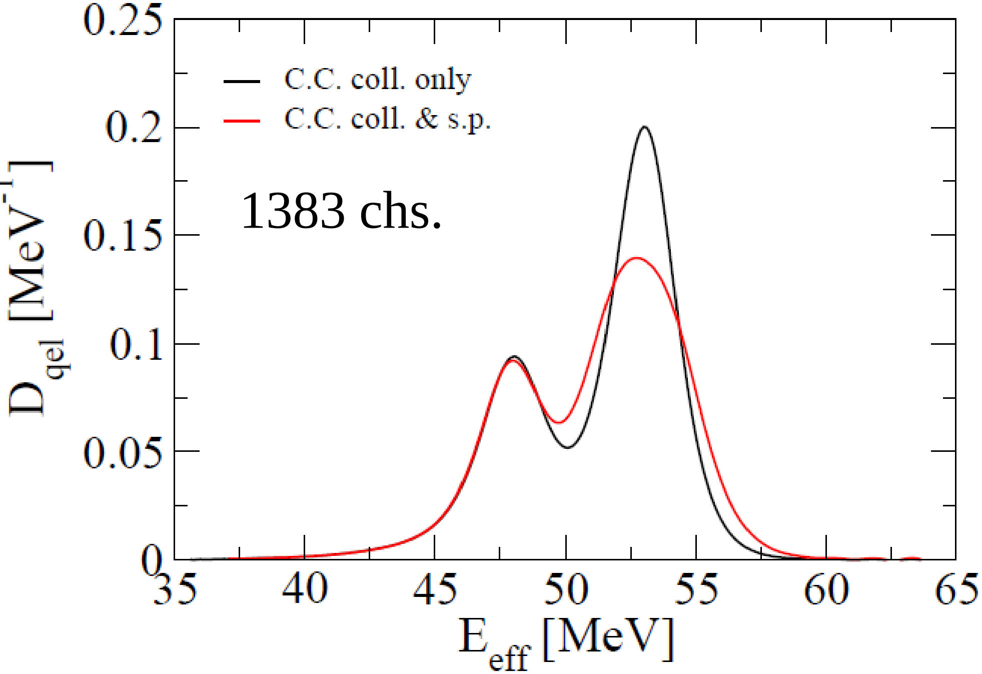


cf. vibrational coupling

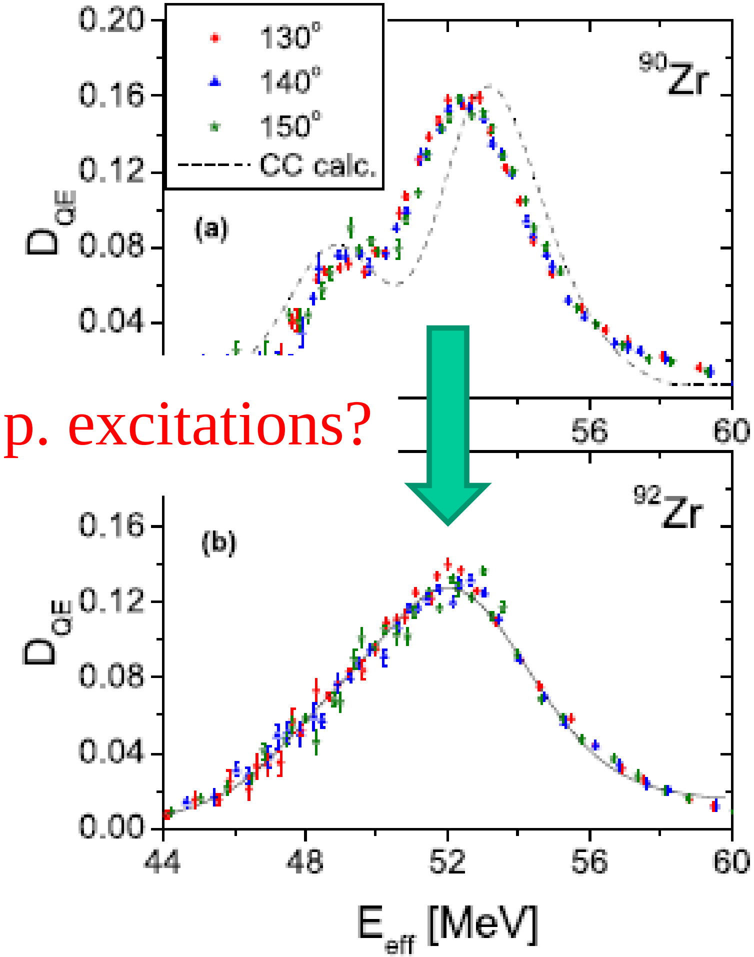


$$\sigma_{\mathrm{qel}}(E,\theta) = \sum_i w_i\,\sigma_{\mathrm{el}}(E-\lambda_i,\theta)$$

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



s.p. excitations?



s.p. excitations: smear the structure

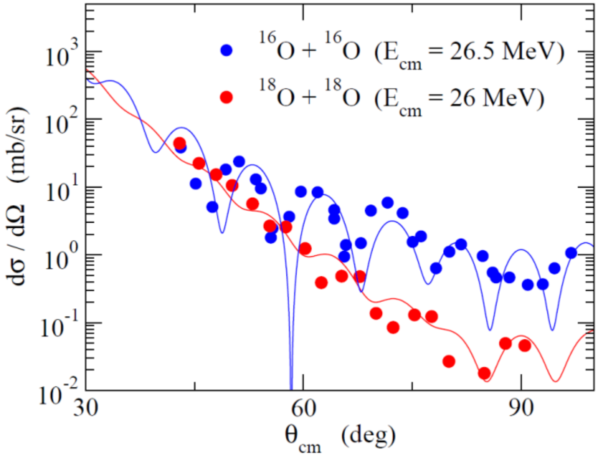
→ consistent with the expt.

Summary

Role of single-particle excitations in low-energy nuclear reactions

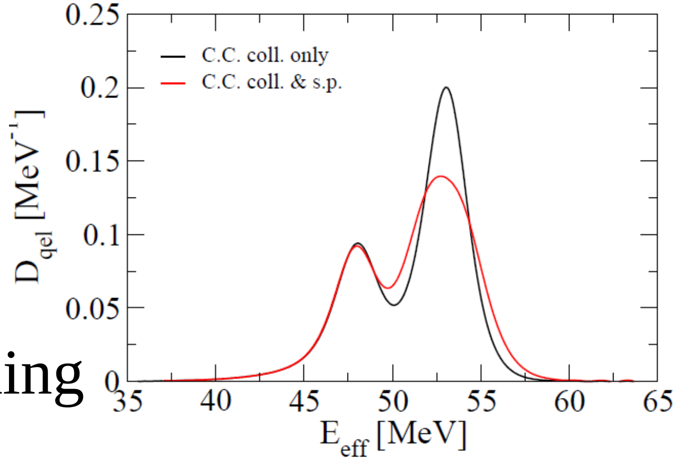
➢ scattering of identical particles

s.p. excitations ⟶
much less pronounced farside-nearside interference in $^{18}O+^{18}O$ than in $^{16}O+^{16}O$



➢ application of RMT to tunneling

s.p. excitations ⟶
smear the barrier distribution



Future problems:

- deep subbarrier fusion hindrance
  - -coupling form factors
  - -excitations of isolated nuclei + after touching
- $^{18}O+^{18}O$ with RMT

Optical potential with RMT:

- D. Agassi, C.M. Ko, and H.A. Weidenmuller,
  Ann. of Phys. 107('77)140
- B.V. Carlson, M.C. Nemes, and M.S. Hussein, PLB91 ('80) 332

Volume 91B, number 3,4 PHYSICS LETTERS 21 April 1980

OPTICAL MODEL DESCRIPTION OF DIC? *

B.V. CARLSON, M.C. NEMES [1] and M.S. HUSSEIN [2]
Department of Physics, University of Wisconsin-Madison, Madison, WI 53706, USA

Received 11 January 1980
Revised manuscript received 6 February 1980

We consider a simple one-dimensional model for a many-channel scattering problem that simulates some aspects of heavy ion deep inelastic collision processes. Applying the statistical considerations of Weidenmüller, we obtain an averaged inelastic cross section given in terms of optical transmission coefficients.