Reactions with heavy nuclei

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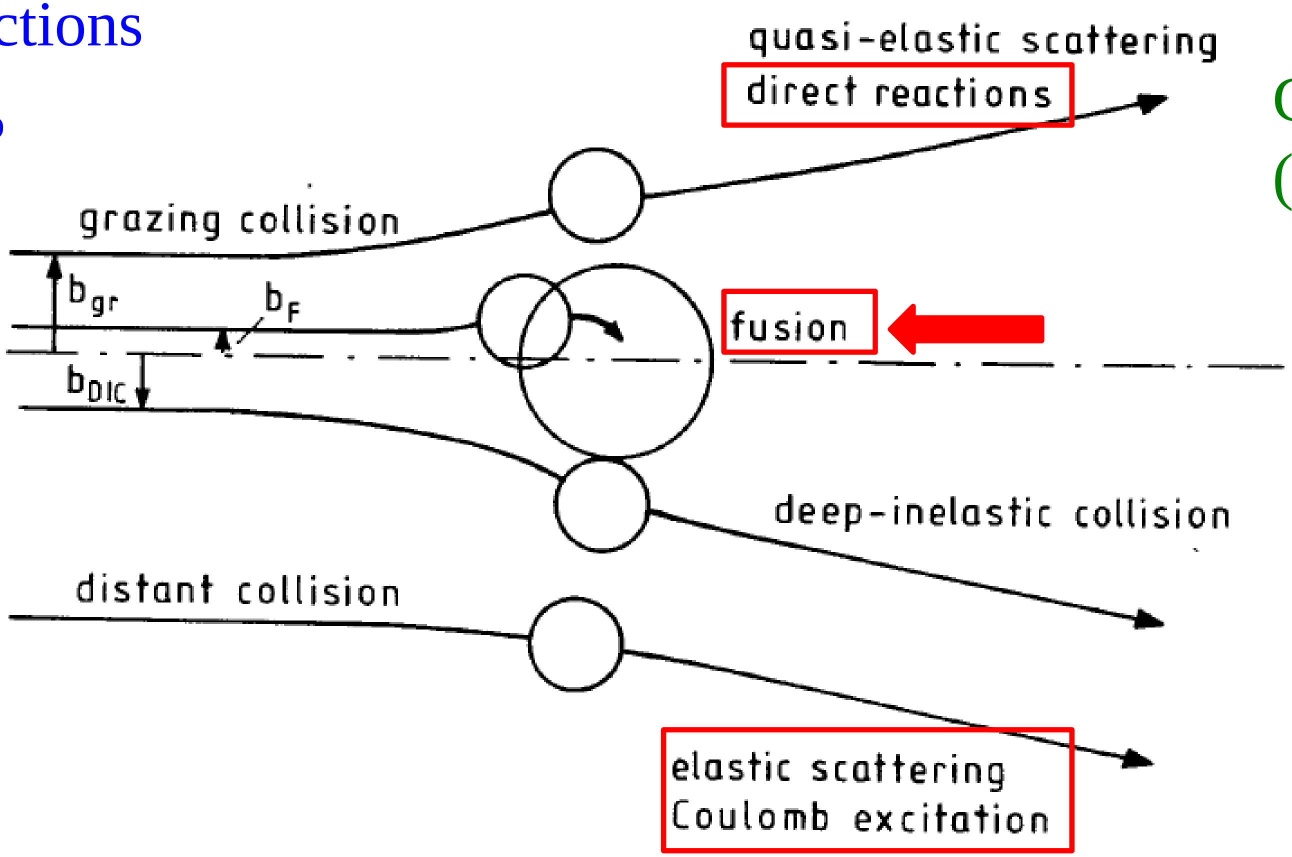
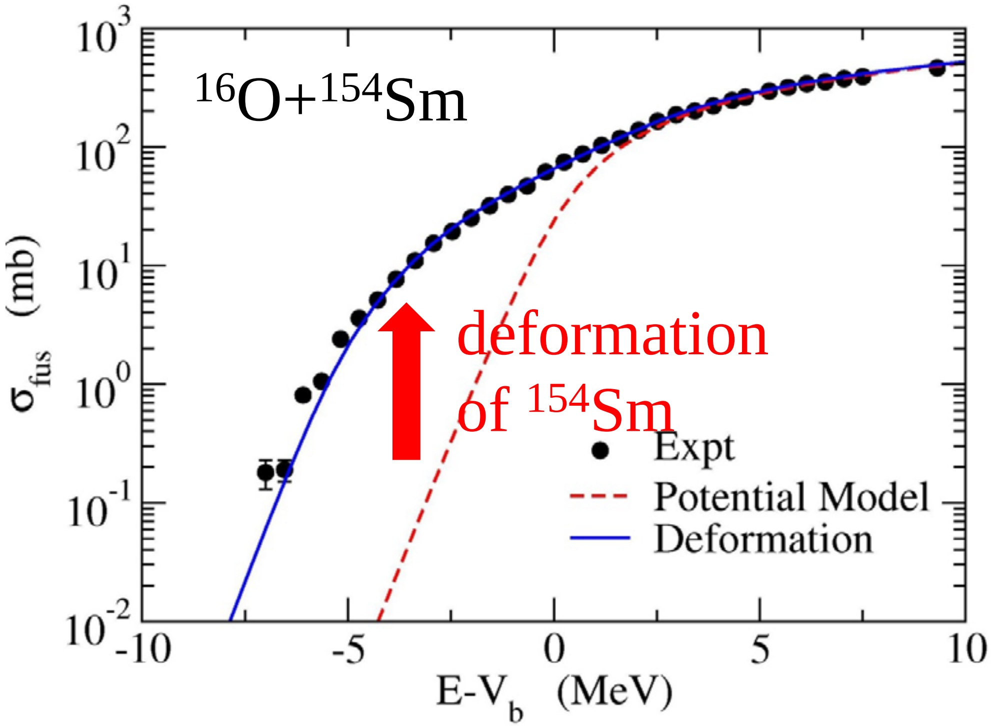
H.I. Reactions
at $E > V_b$



CDCC
(break-up)

"Theory of Nuclear Reactions" Frobrich and Lipperheide

◆ H.I. Sub-barrier fusion reactions ($Z_P * Z_T < 1600$)



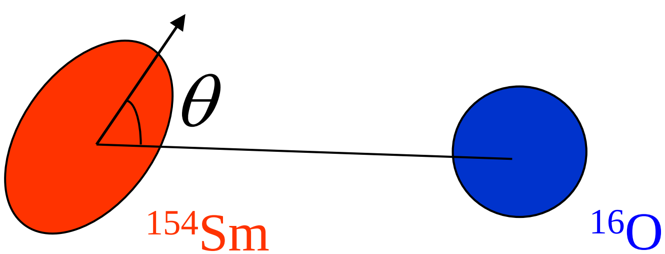
collective excitations during fusion

⇓

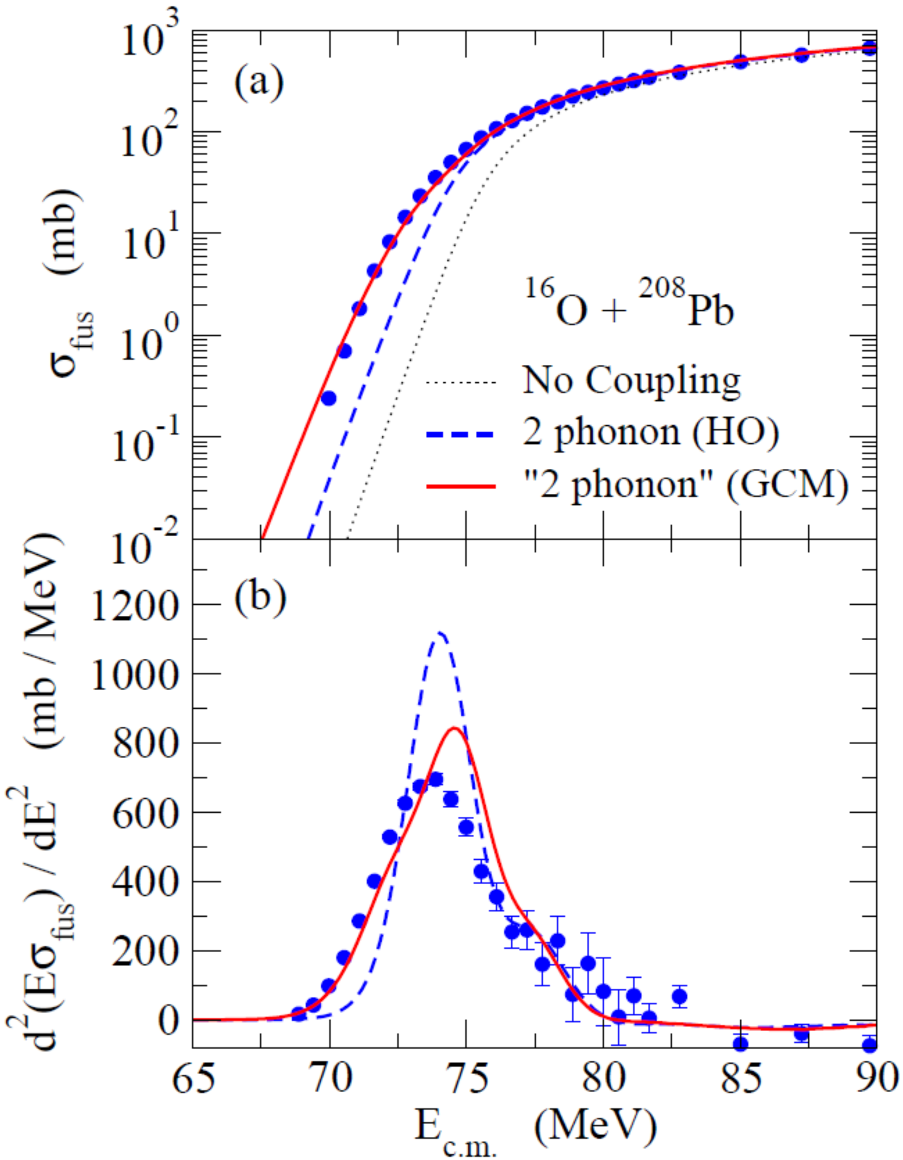
coupled-channels method

- ✓excitation energies
- ✓transition strengths
- ✓multi-phonon excitations or g.s. rotational band

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

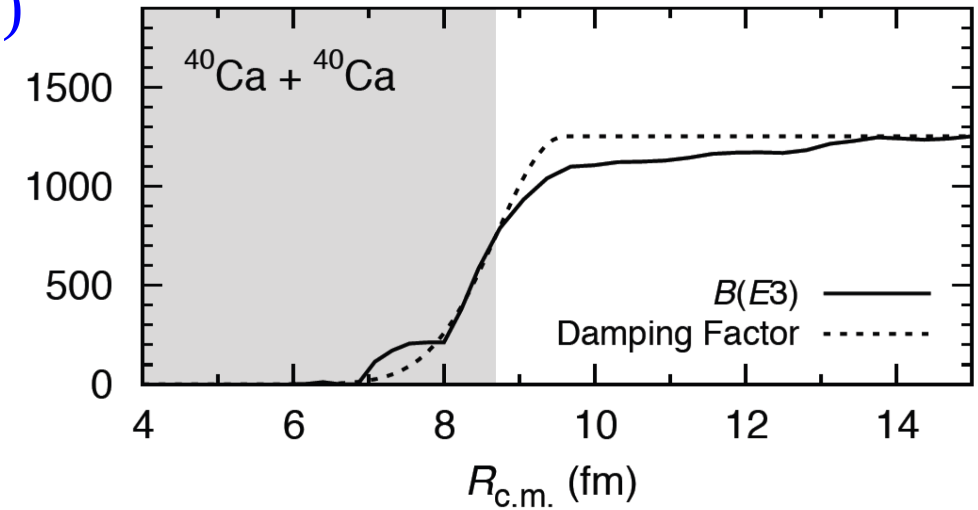


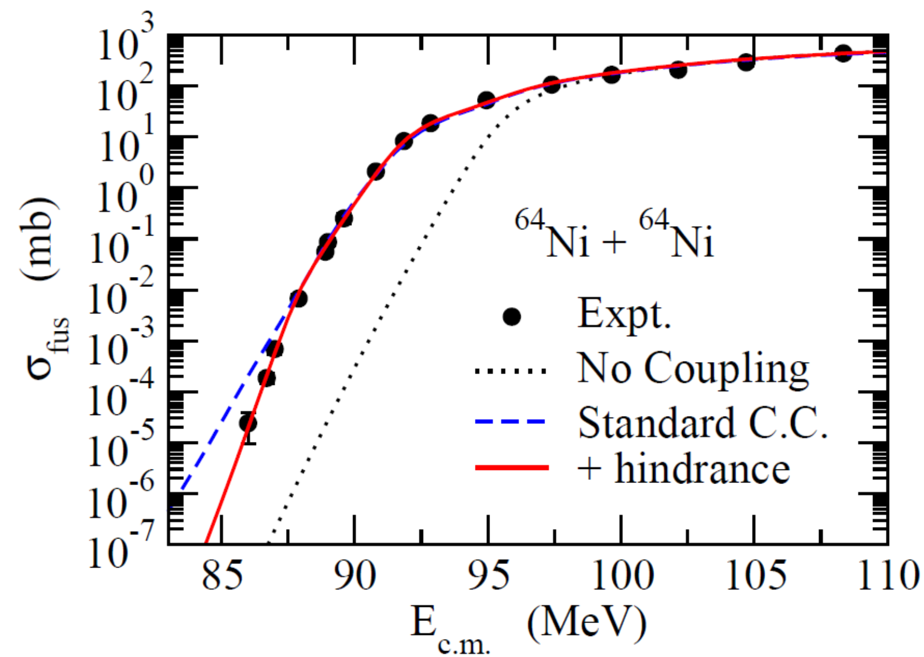
✓C.C. with a state-of-the-art nuclear structure calculation (beyond-MF)



J.M. Yao and K.H. (2016)

✓C.C. with RPA

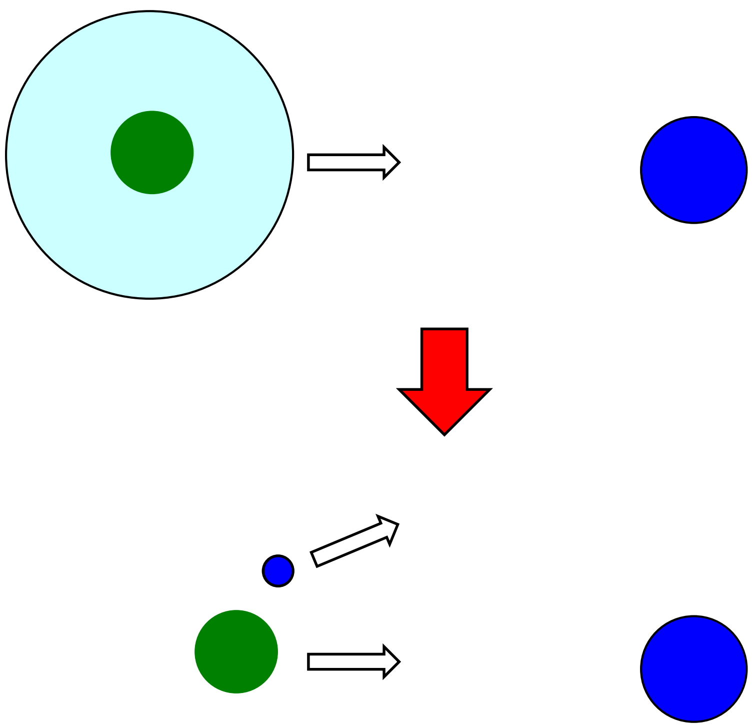


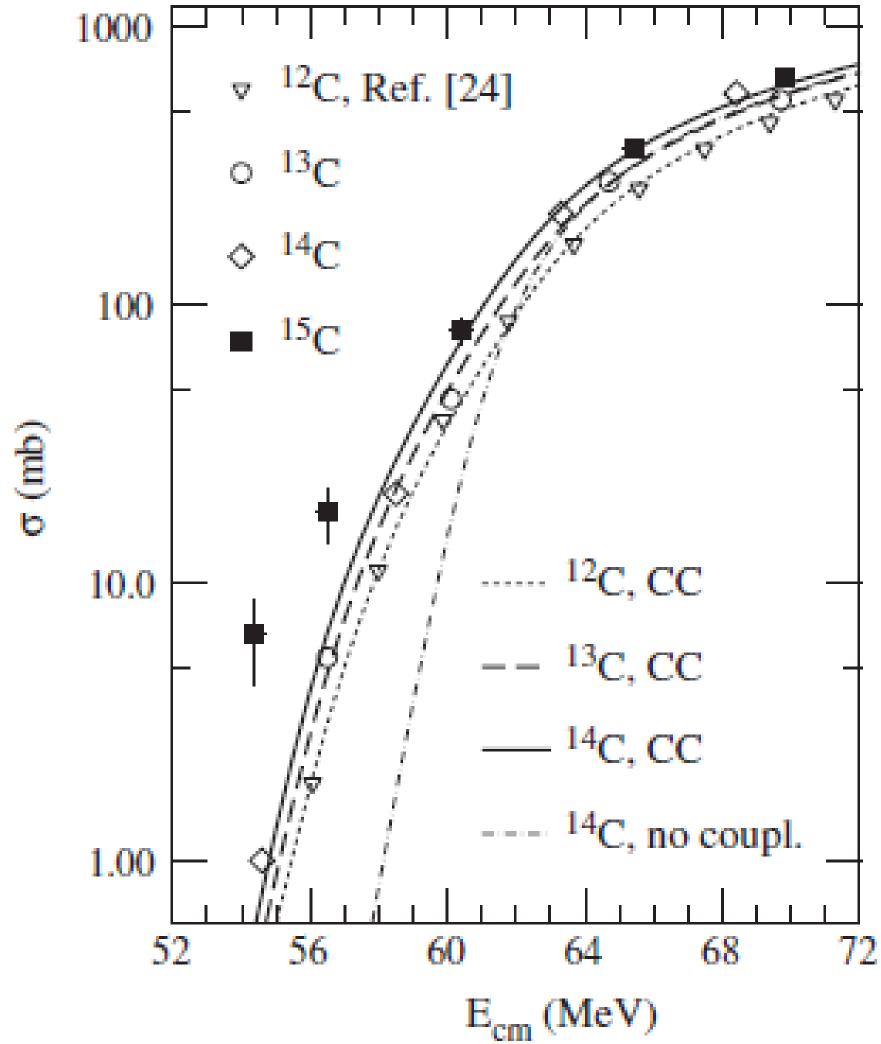


T. Ichikawa and K. Matsuyanagi
PRC88('13) 011602(R)

Fusion of halo nuclei

$^{12,13,14,15}C + ^{232}Th$



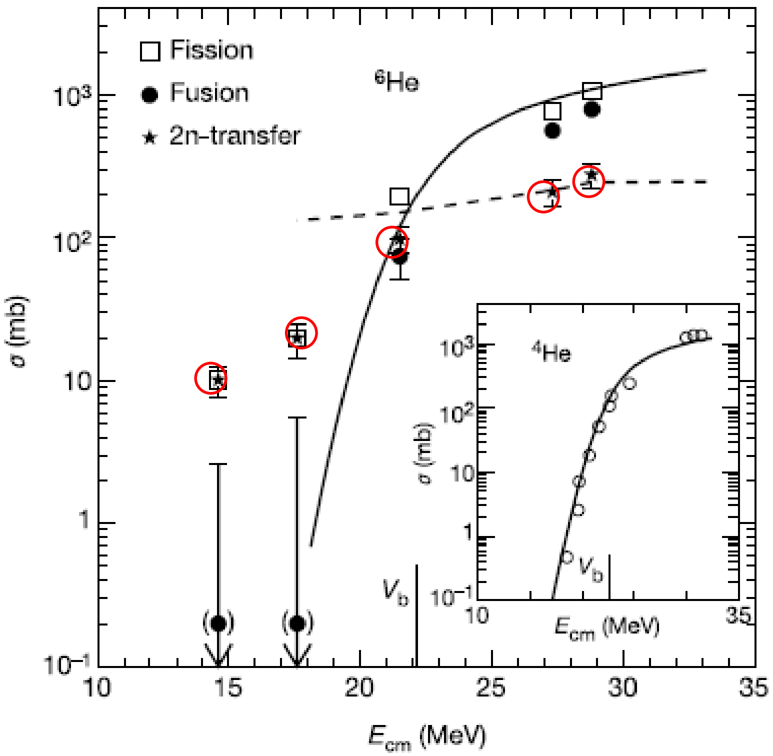


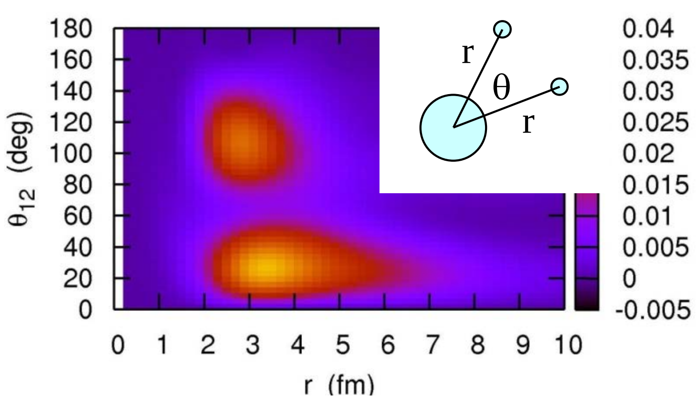
1. Lowering of potential barrier
   due to a halo structure
   ⟶ enhancement
2. effect of breakup
3. effect of transfer

M. Alcorta et al.,
PRL106('11)172701

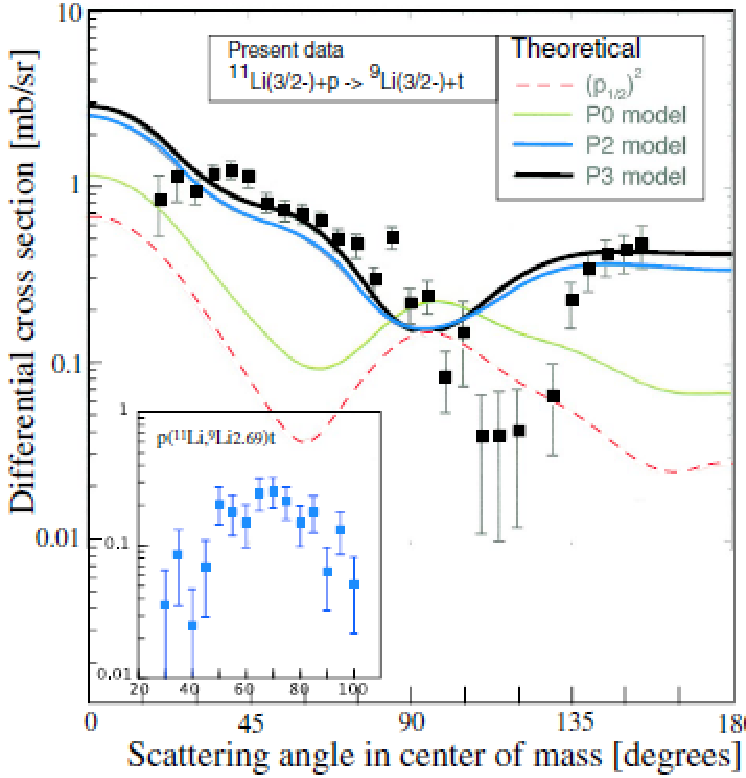
Two-neutron transfer reactions: pairing correlations

$^6He + ^{238}U$





$^1H(^{11}Li,^9Li)^3H$



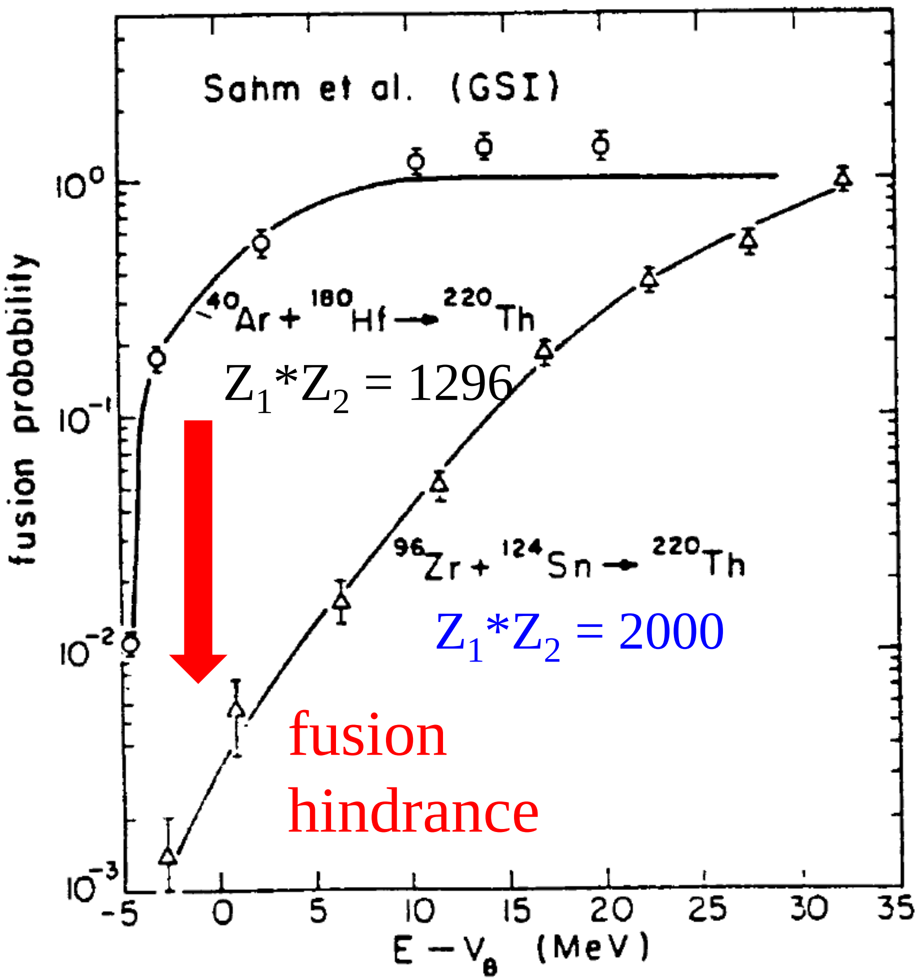
I. Tanihata et al., PRL100('08)192502

✓reaction mechanics?

✓role of unbound intermediate states?

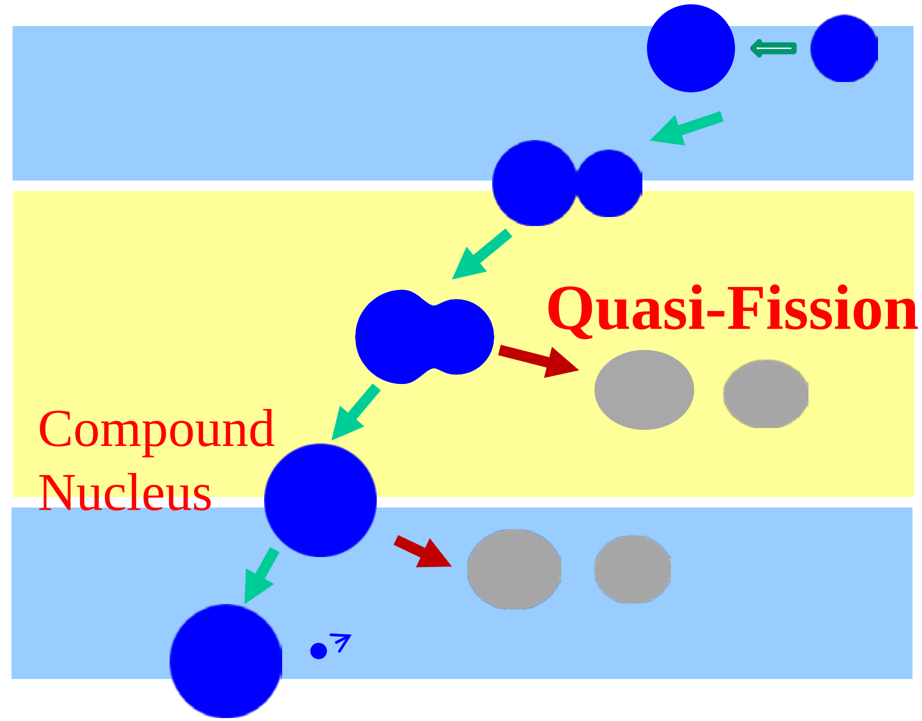
◆H.I. Sub-barrier fusion reactions ($Z_P * Z_T > 1600 \sim 1800$)

fusion hindrance



C.-C. Sahm et al.,
Z. Phys. A319('84)113

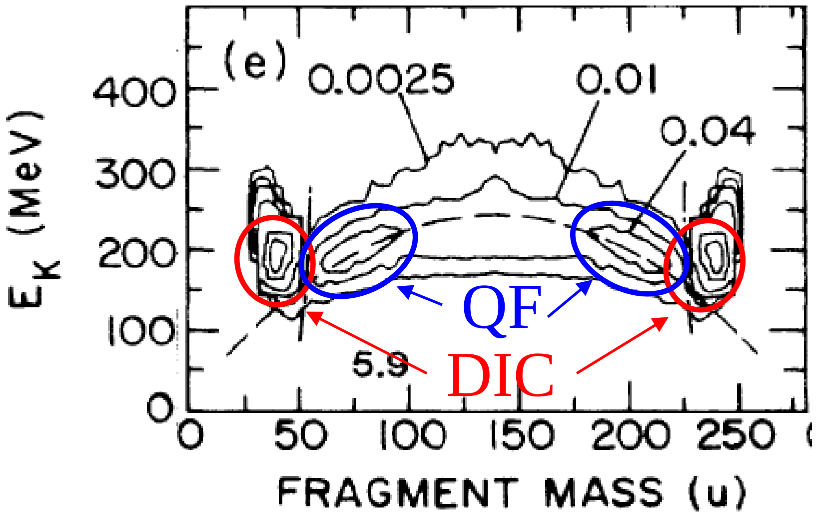
modern understanding



re-separation before CN
= Quasi-Fission

closely related phenomenon: deep inelastic collision (~ 70-80's)

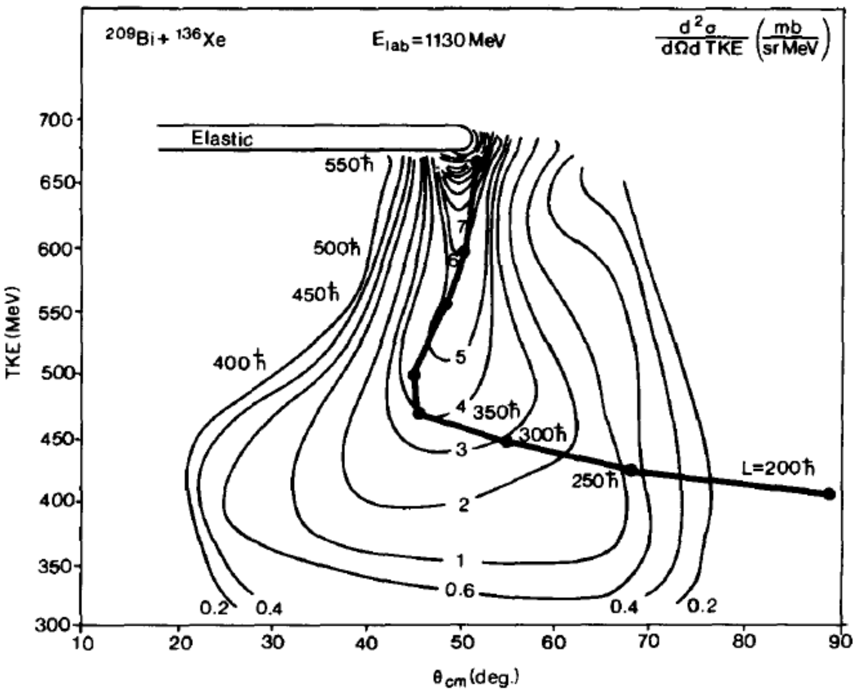
^{40}Ca+^{238}U (E = 5.9 MeV/A)
highly damped reaction



W.Q. Shen et al., PRC36('87)115

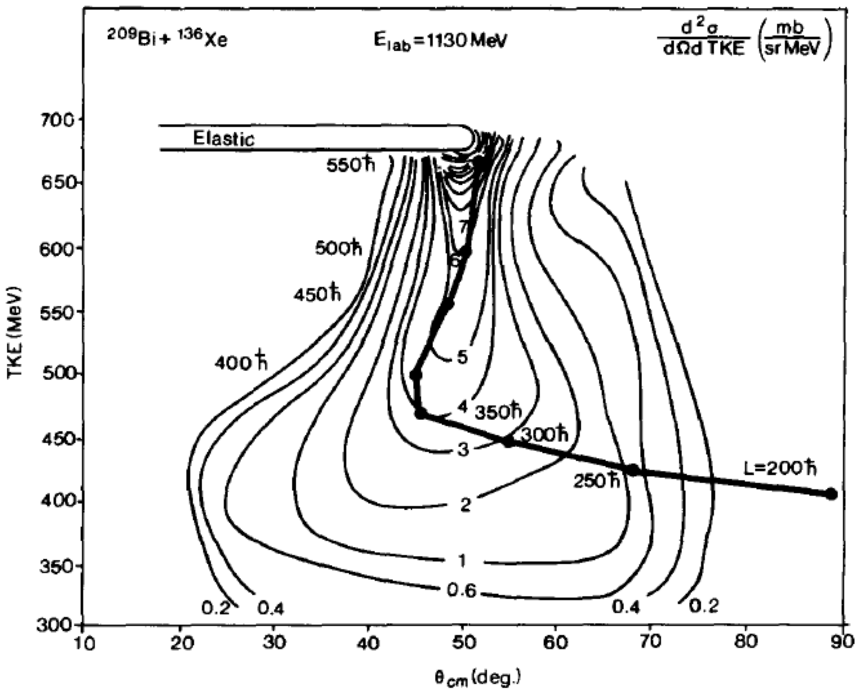
- ✓many phenomenological models
- ✓TDHF

a big success of TDHF:



A.K. Dhar, B.S. Nilsson,
K.T.R. Davies and S.E. Koonin,
NPA364 ('81)105

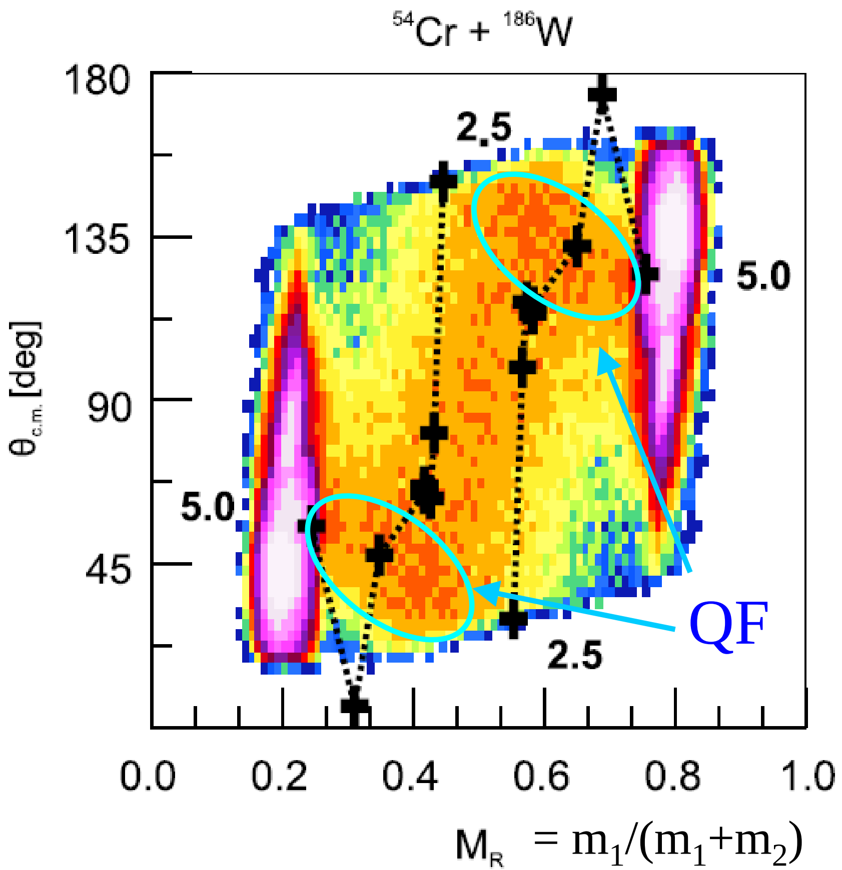
a big success of TDHF for DIC



A.K. Dhar, B.S. Nilsson, K.T.R. Davies and S.E. Koonin, NPA364 (‘81)105

TDHF seems to work for QF as well

mass-angle distribution



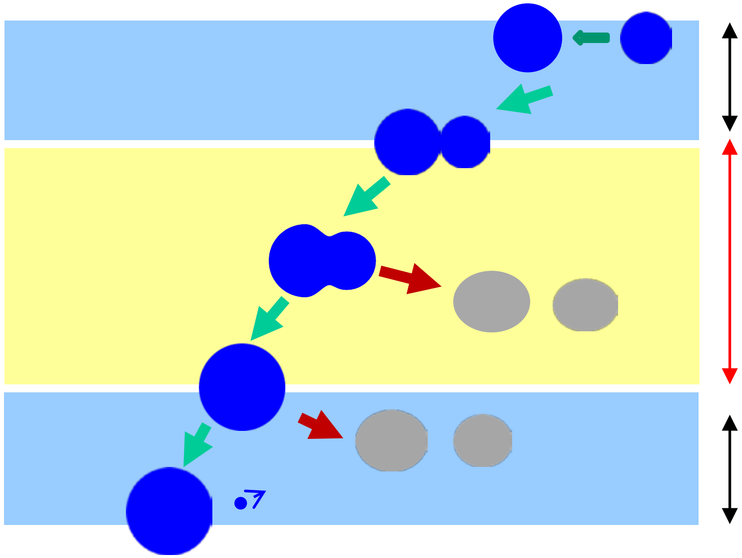
A.S. Umar and V.E. Oberacker, NPA944(‘15)238

c.f. expt.: ANU group (D.J. Hinde et al.)

- nuclear friction from TDHF

K. Washiyama, D. Lacroix, and S. Ayik, PRC79(‘09)024609

Super-heavy nuclei



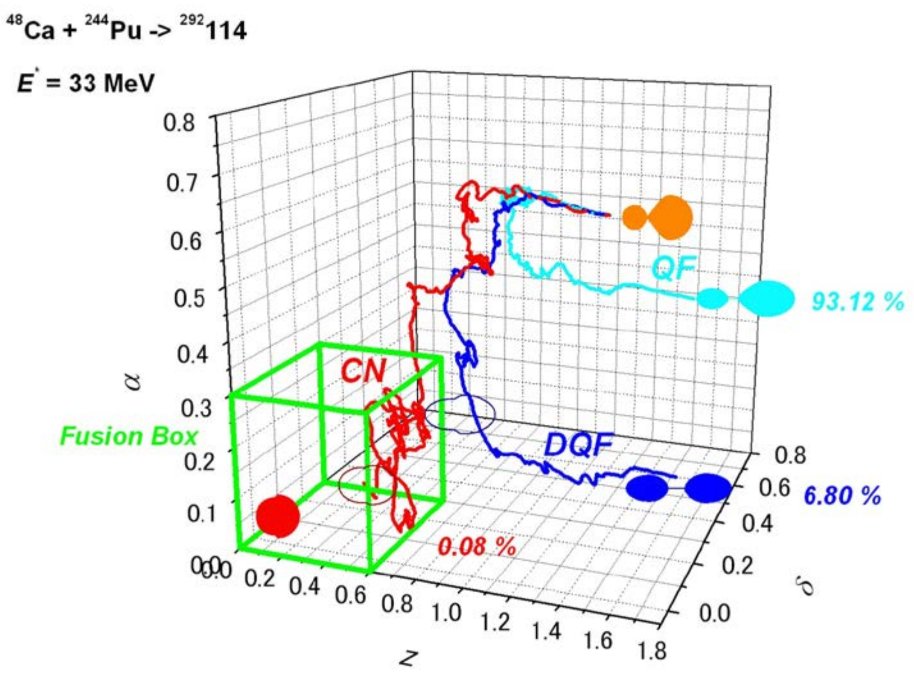
coupled-channels method

Langevin approach

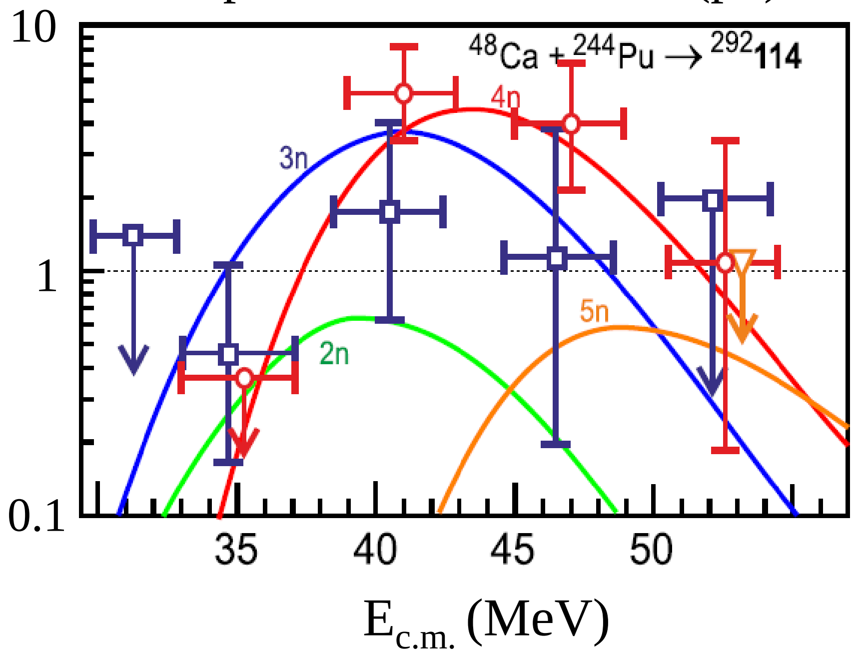
V.I. Zagrebaev and W. Greiner, NPA944('15)257

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

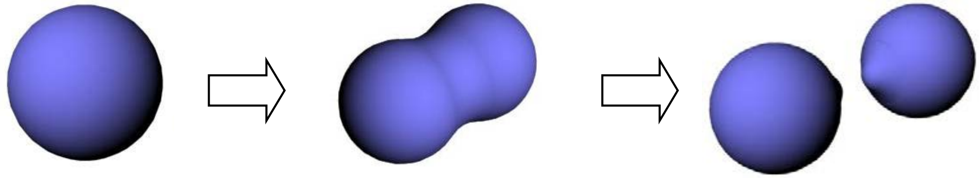
statistical model



Evap. resid. cross section (pb)

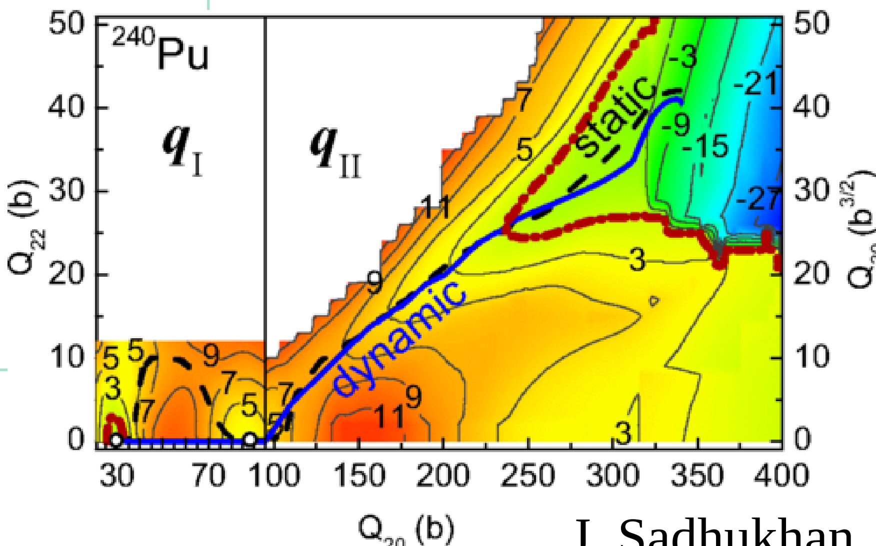


Fission



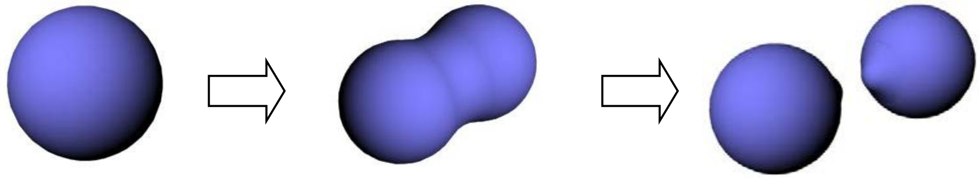
still a very challenging problem for nuclear theory

	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)

Fission



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issues:

- which degrees of freedom? (time-indep. approaches)
- how to deal with many-body tunneling? (time-dep. approaches)

Summary and discussions

- Heavy-ion reactions around the Coulomb barrier
  : strong interplay between structure and reaction
  - sub-barrier fusion reactions (coupled-channels effects)
  - fusion of massive nuclei (nuclear friction)
  - spontaneous and induced fissions
  - two-neutron transfer (pairing correlations)
- From phenomenological models to more microscopic models
  - C.C. with microscopic inputs
  - DFT for spontaneous fission
  - TDHF approach ←
- "Beyond mean-field" approximations

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

  ⟶ many-body tunneling

  cf. "Quantum tunneling using entangled classical trajectories"
  A. Donoso and C.C. Martens, PRL87 ('01) 223202

closely related phenomenon: deep inelastic collision (~ 70-80's)

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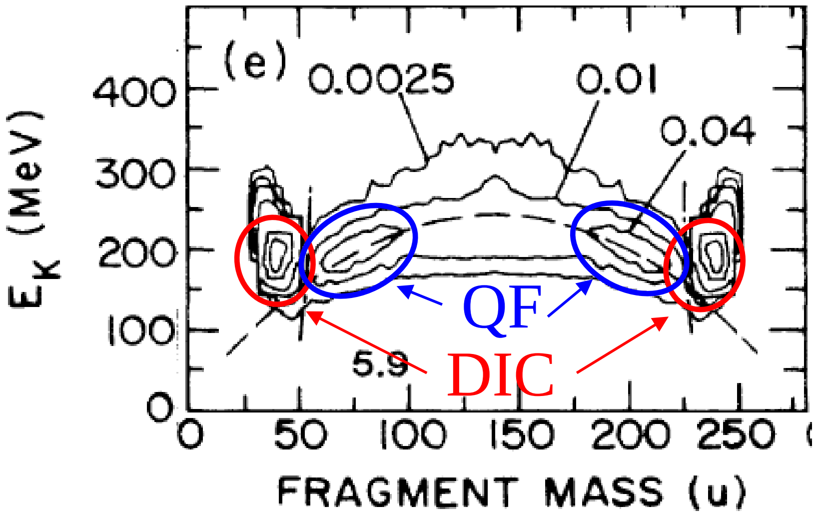
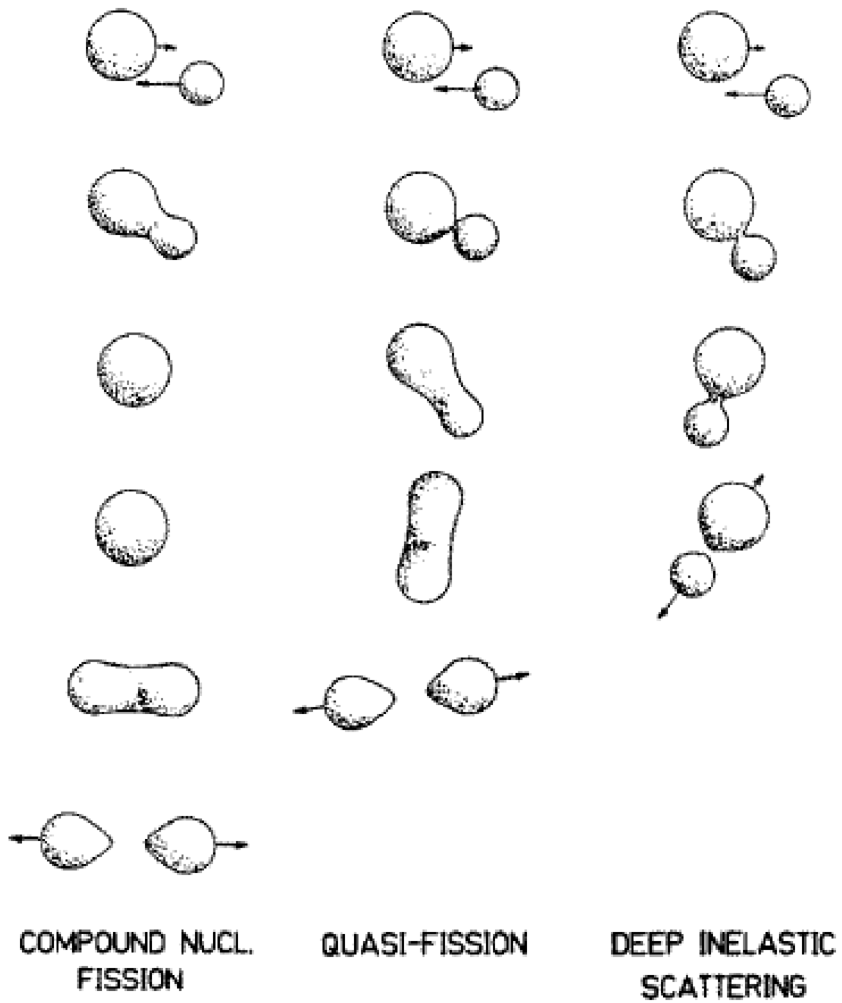


W.Q. Shen et al., PRC36('87)115



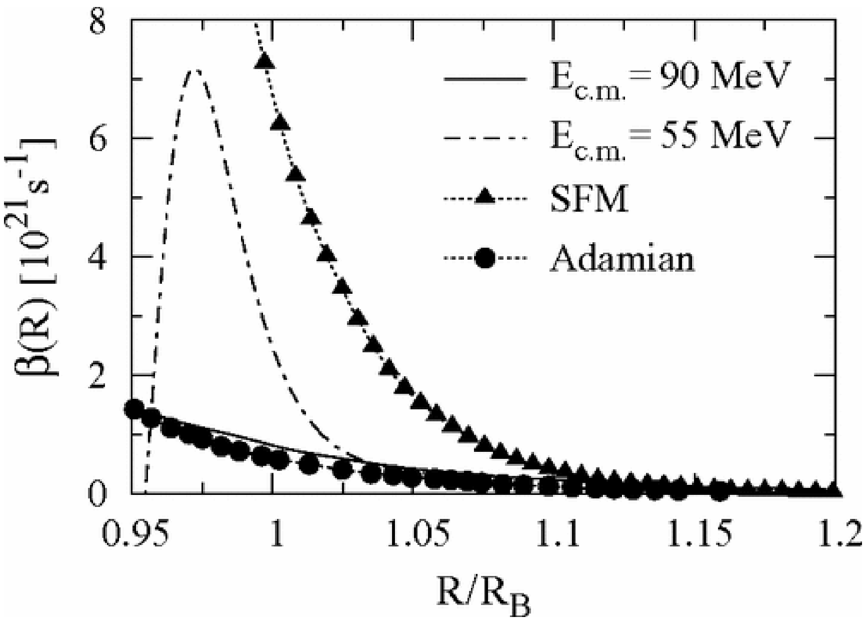
J. Toke et al., NPA440('85)327

nuclear friction

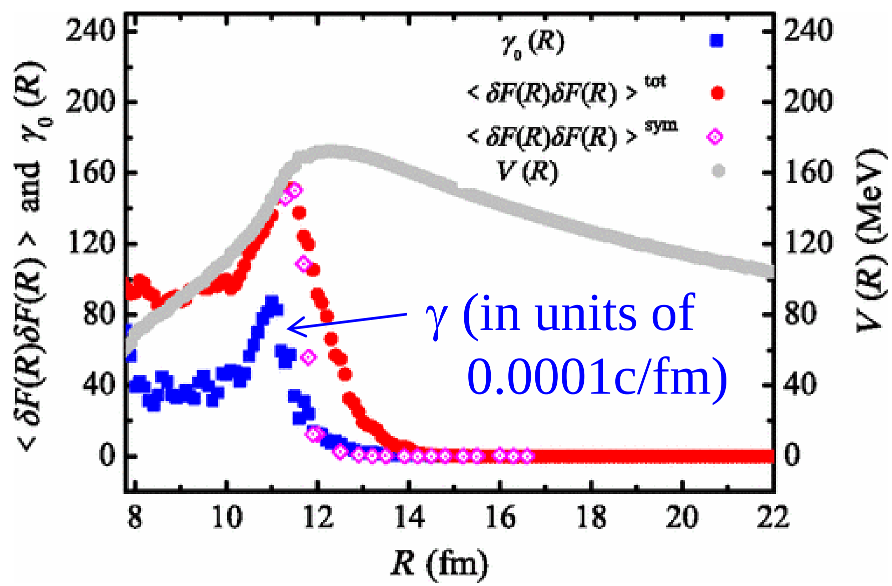
- ➢damping of giant resonances
- ➢neutron induced fission (Kramers factor)
- ➢deep-inelastic collisions and quasi-fission
  - ✓wall-and-window formula
  - ✓linear response theory
  - ✓attempts with TDHF and QMD

$$M\ddot{q} = -V'(q) - \gamma\dot{q}$$

$$\beta = \gamma/M$$



K. Washiyama, D. Lacroix, and S. Ayik, PRC79('09)024609



K. Wen et al., PRL111('13)012501