The role of nuclear structure in sub-barrier fusion

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Sub-barrier fusion

Why the interest ? - there's not much fusion happening there!

1) Sensitive to physics of interaction (σ ~ exponential with energy)

   - coupling-enhanced tunnelling – many o.o.m. enhancement

     • (c.f. above-barrier σ ~ linear with beam energy)

2) Want to form CN at low E_X – "below-barrier"

How to define sub-barrier? (below which barrier?)

Linear σ with energy ➡ B_0 ~ independent of "detail" (couplings)

$E\sigma = \pi R^2(E-B_0)$ – fit to above-barrier data gives "empirical" B_0

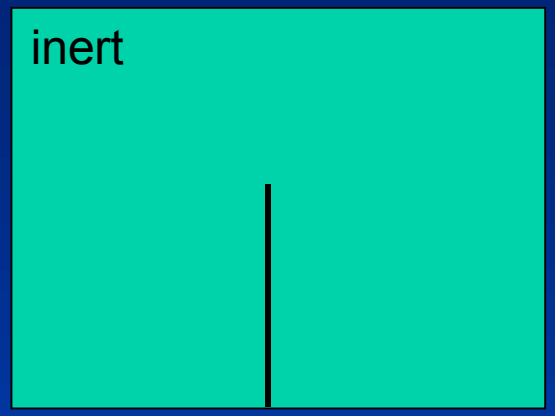
Simplest physical picture explaining enhancement:

Coulomb, nuclear potentials + **static deformation** ➡ enhancement!

Fusion Barrier Distributions

$P(B_i)$

$D(E)$



B_0

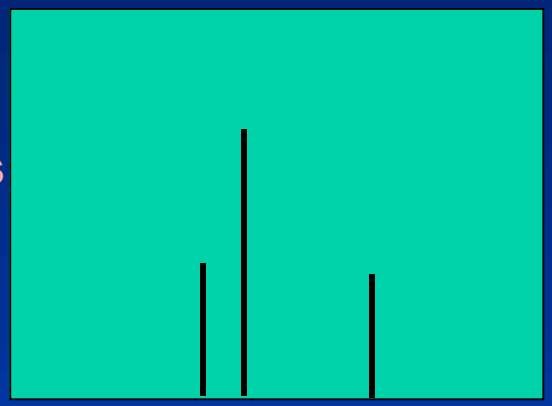
internal structure

excite collective states

approx.coupled channels

Coupling α Z_1Z_2

Vibrational nuclei

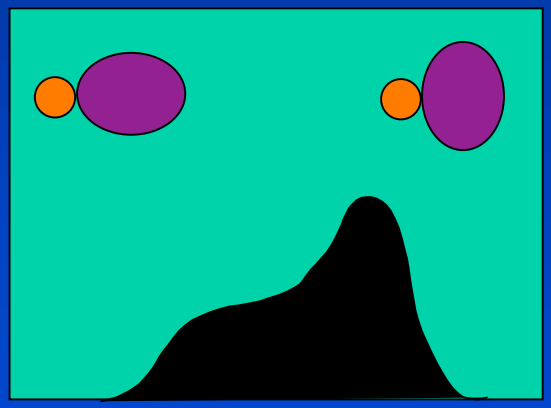


B_1B_2 B_3

Quantum tunnelling – smooths distribution
~ independent of Z_1Z_2

Distribution of barrier energies from experimental data (based on $E_{_fus} = \pi R^2 (E-B)$)

$D(E) = d^2(E_{_fus})/dE^2$

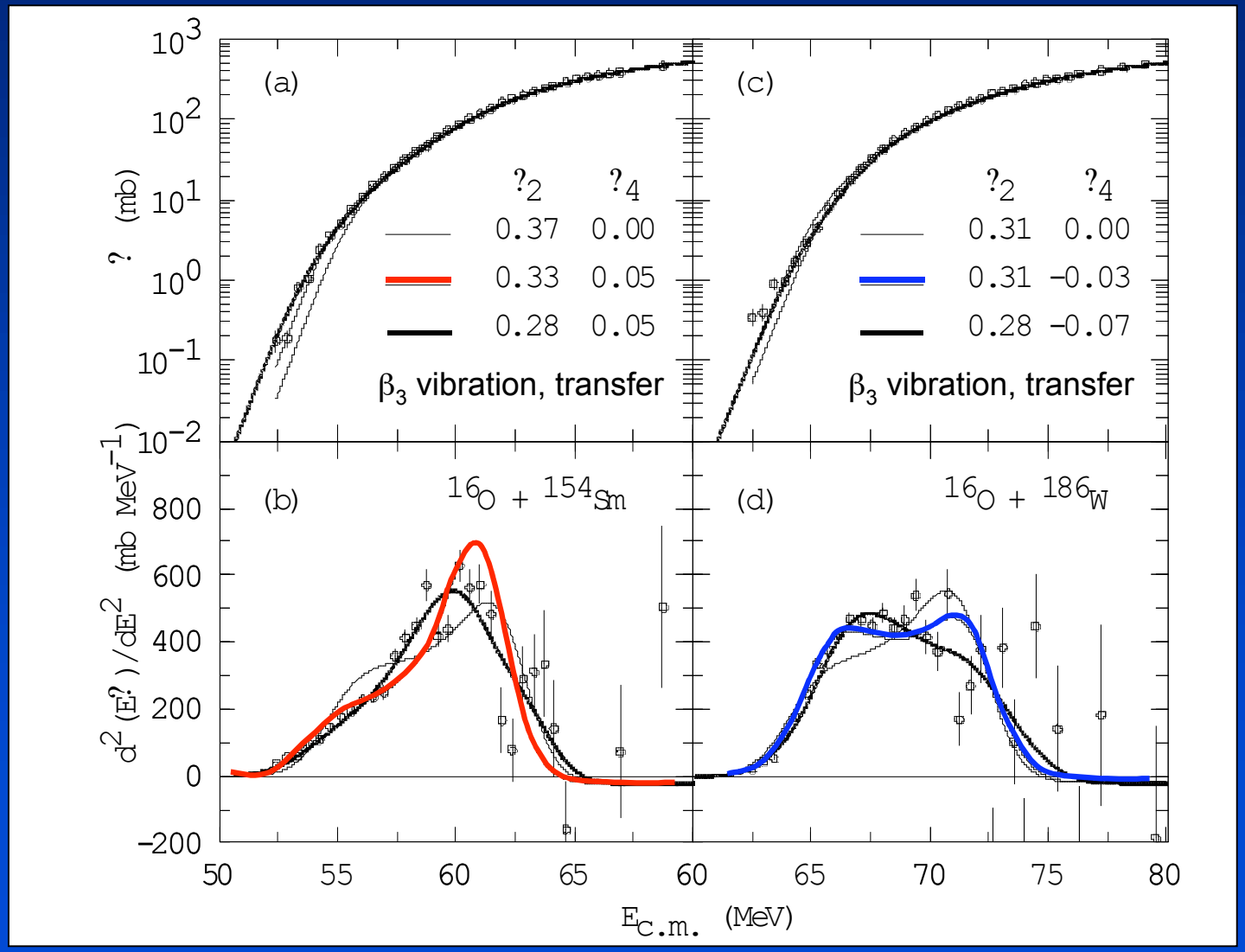


Deformed nuclei

Rowley et al., Phys. Lett. B25 (1991)25

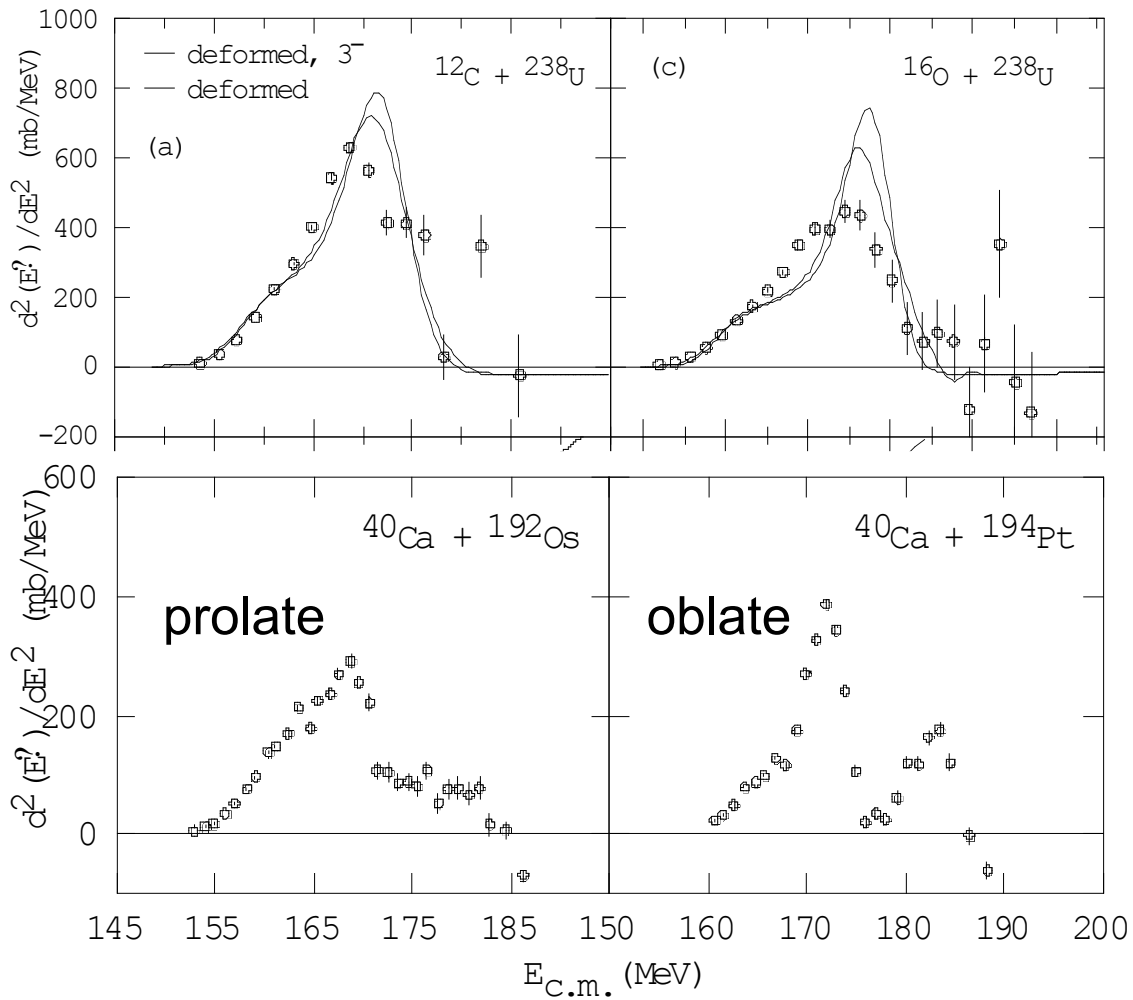
Review: Dasgupta et al., Annu. Rev. Nucl. Part. Sci 48 (1998) 401

- Measurement of ERs: 5 energies ang. dist, 2° exc. func. ΔE 0.5 MeV
- Static Deformation: results sensitive to β_2, and β_4 (prolate)
- ^{16}O seems to play no role – inert?



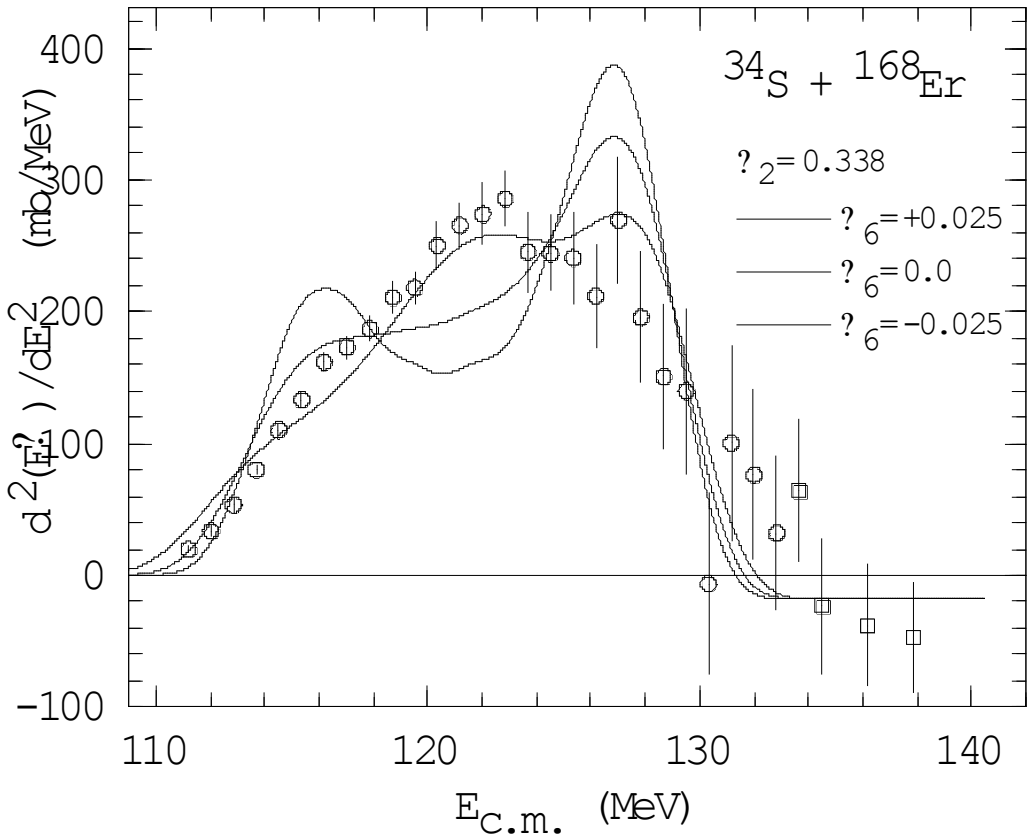
J.R. Leigh et al., PRC52(1995)3151

- Measurement of fission: ANU: ang. dist at each energy
- FMT fission should be distinguished from transfer fission (2 FF)

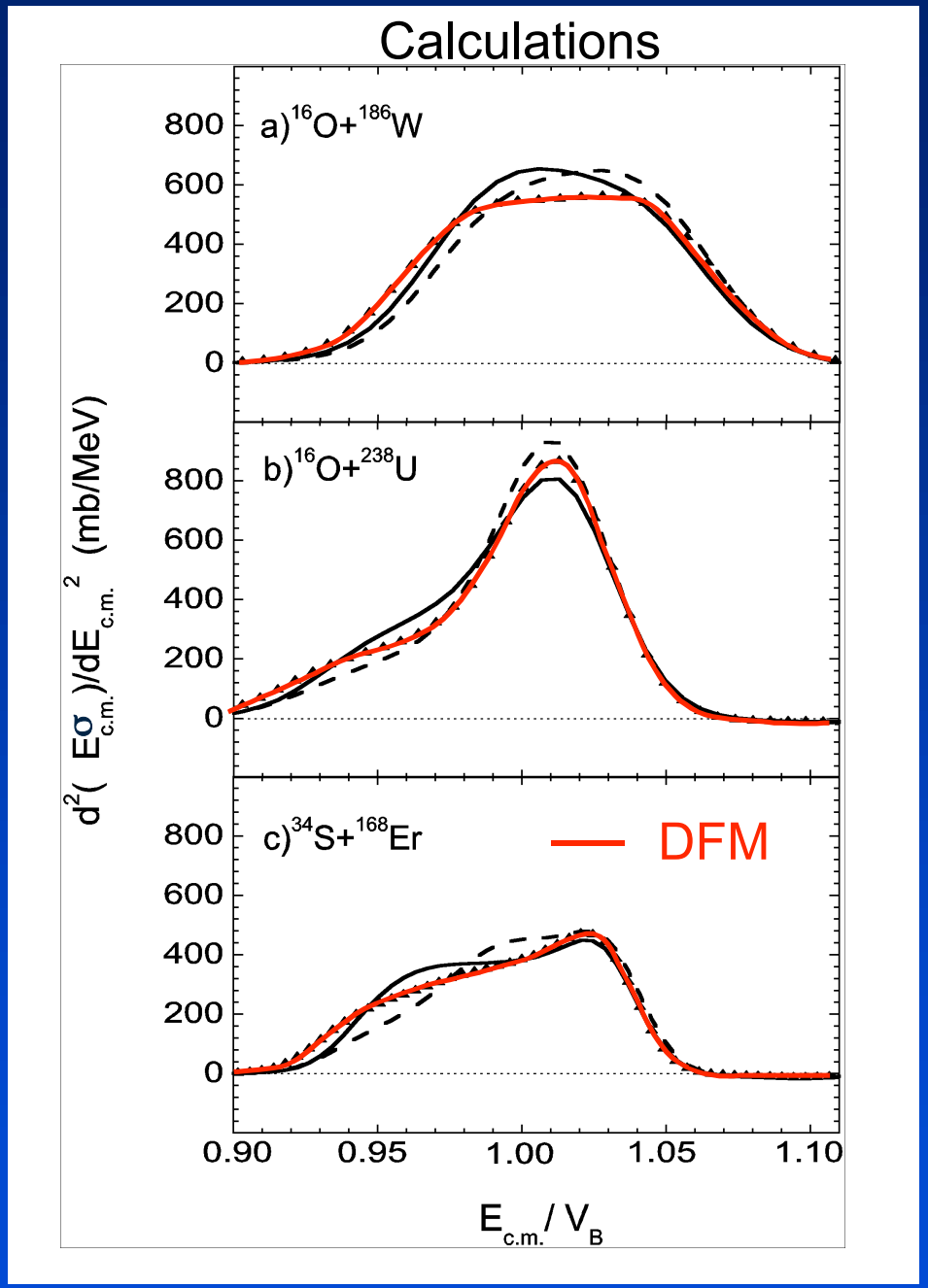


J.D. Bierman et al., PRL66(1996)1587

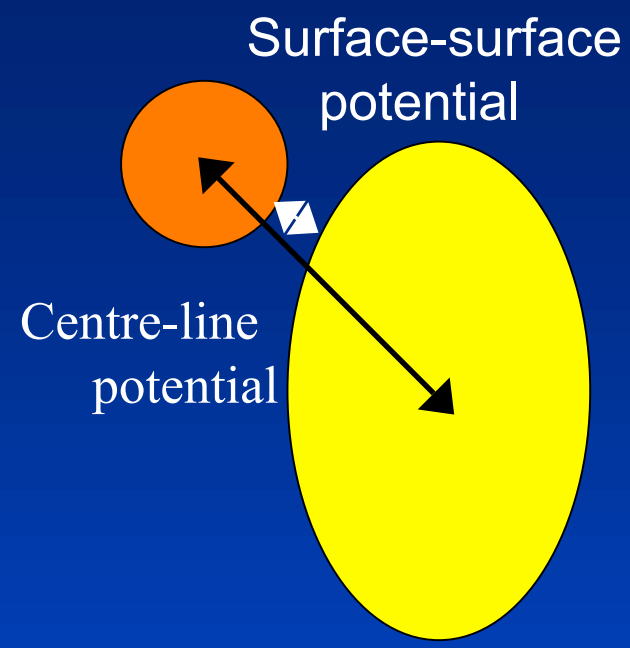
- Measurement of both ER and fission:
- No transfer fission – sufficient to measure 1 FF
- Calculated D(E) sensitive even to β_6 (β_4~0 for ^{168}Er)
- [Also sensitive to coupling to excited states in ^{34}S]



C.R. Morton et al., PRC64(2001)034604 + Recent LNL data for ^{48}Ca+^{154}Sm



Finite-size geometry



Matter diffuseness

Finite size geometry

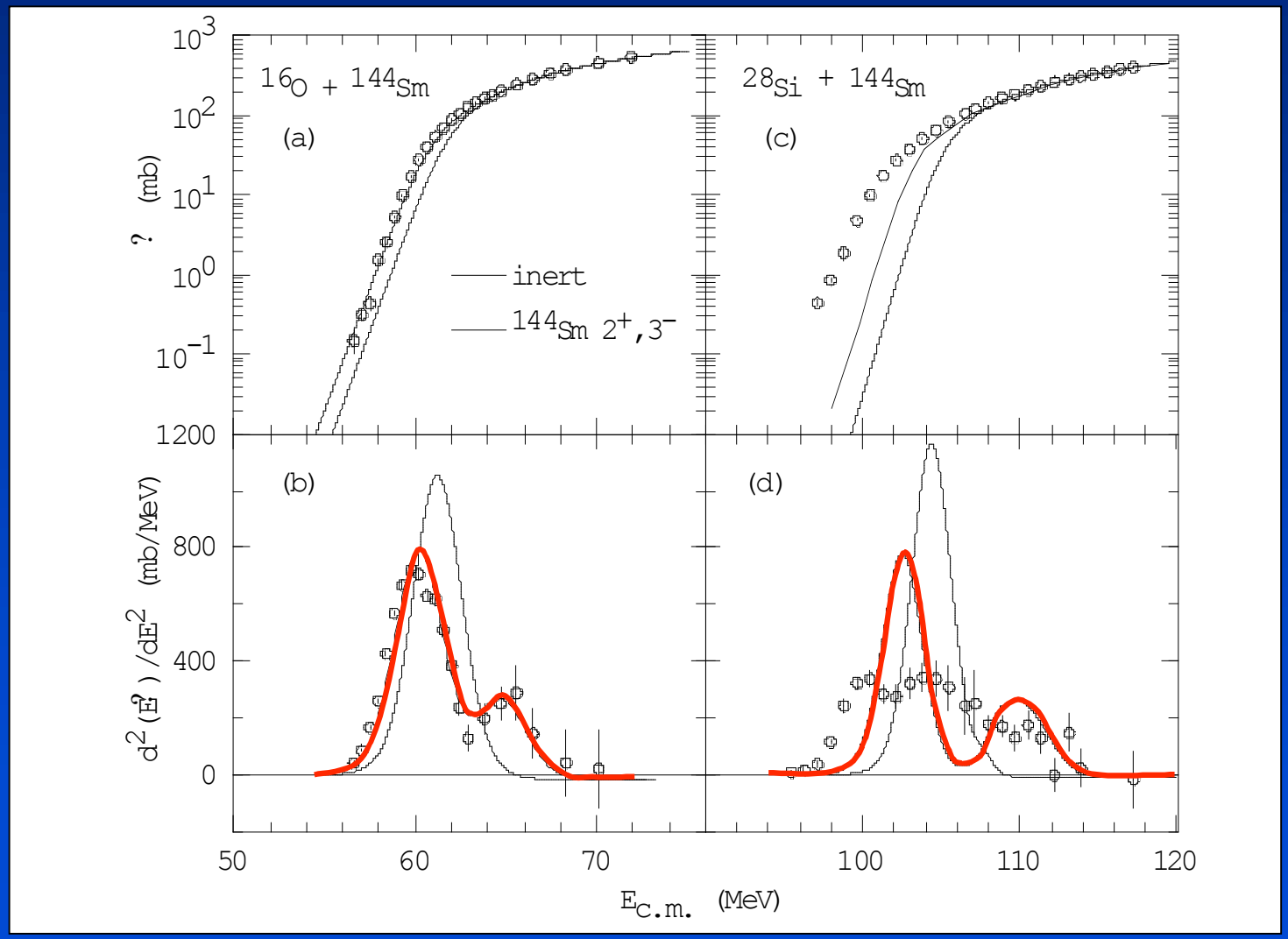
- Deformed DFM

(Semi-classical not Q.M.)

I.I. Gontchar et al., PRC65(2002)034610

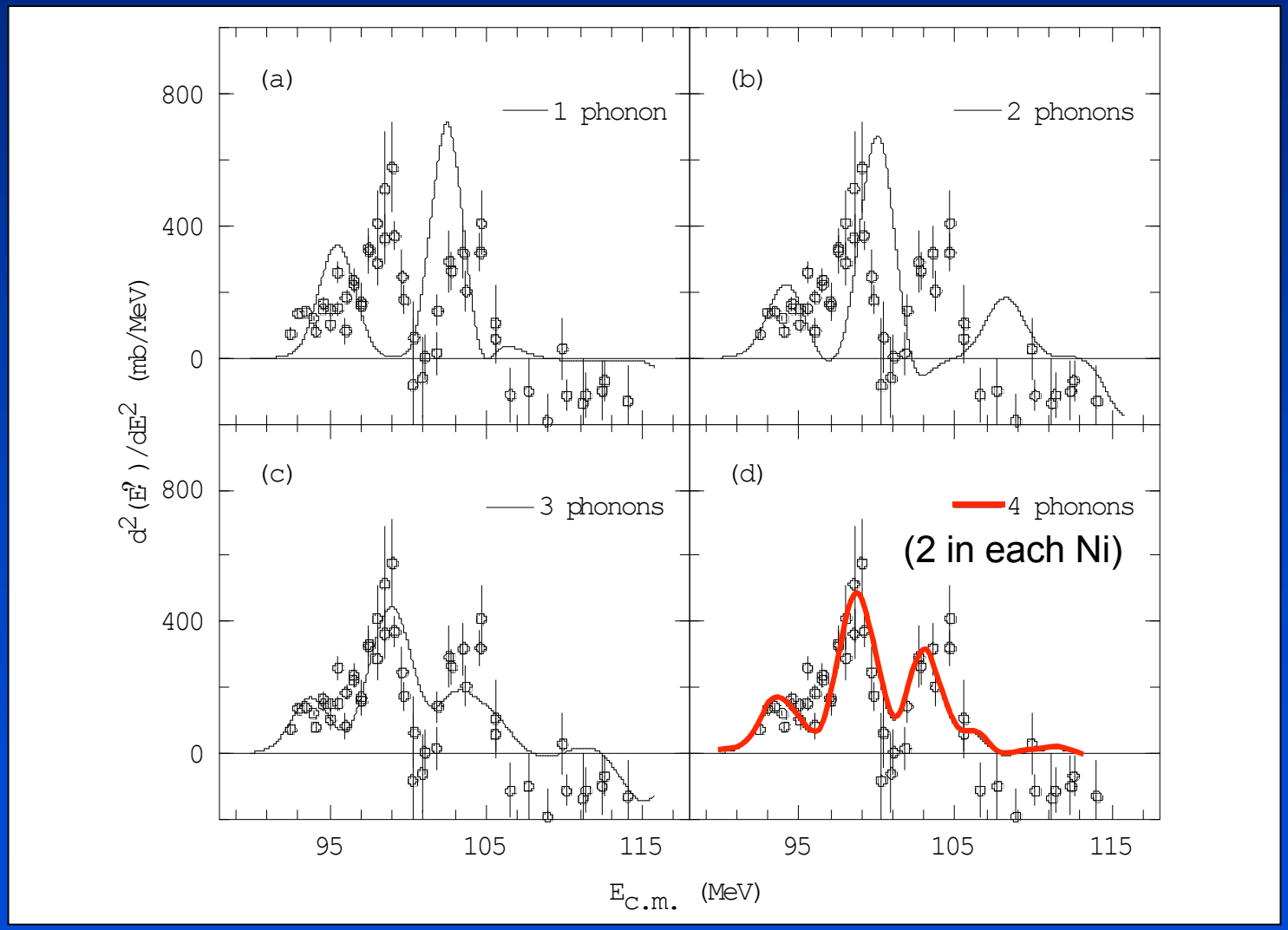
I.I. Gontchar et al., sub. PRC (2005)

- **<u>Surface vibrations</u>** – collective β_2,β_3
- Measurement: ER, or ER and FF
- Single octupole phonon? Yes, and no! (target and projectile)



J.R. Leigh et al., PRC52(1995)3151, M. Dasgupta et al., Pr. Wshop HI Fusion, Padova 1994, World. Sci., p115

- **<u>Multi-phonon</u>** $^{58}Ni + ^{60}Ni$
- Measurement: ER (Looking for effect of zero-Q 2-neutron transfer)
- (Almost) identical nuclei (A.M. Stefanini et al., PRL74(1995)864)



- **Multi-phonon** $^{32}S + ^{208}Pb$

(D.J. Hinde et al., unpublished)

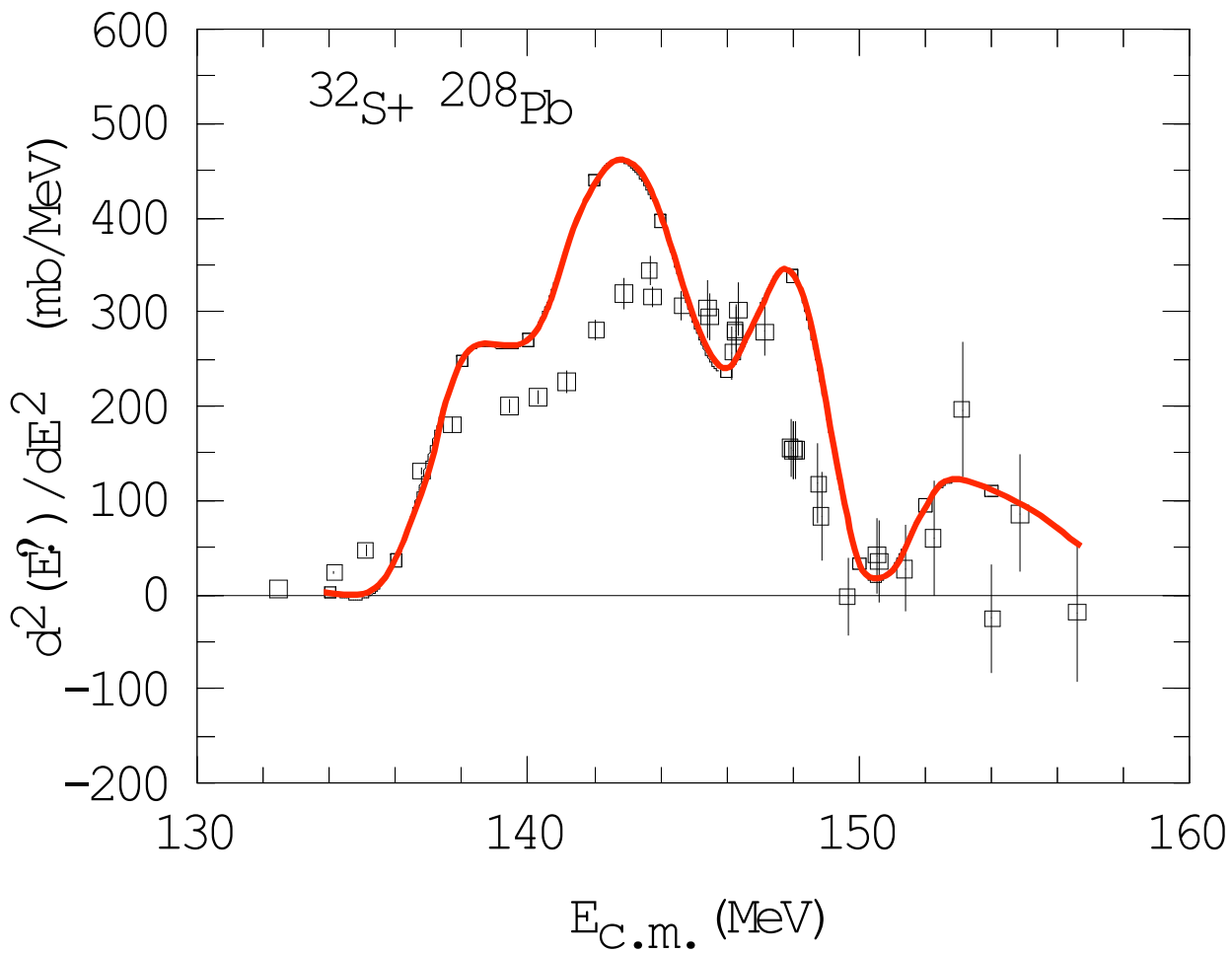
- Measurement: FF
- Doubly-magic ^{208}Pb: poor reproduction

$^{16}O + ^{208}Pb$

(Morton et al., PRC60(1999)044608)

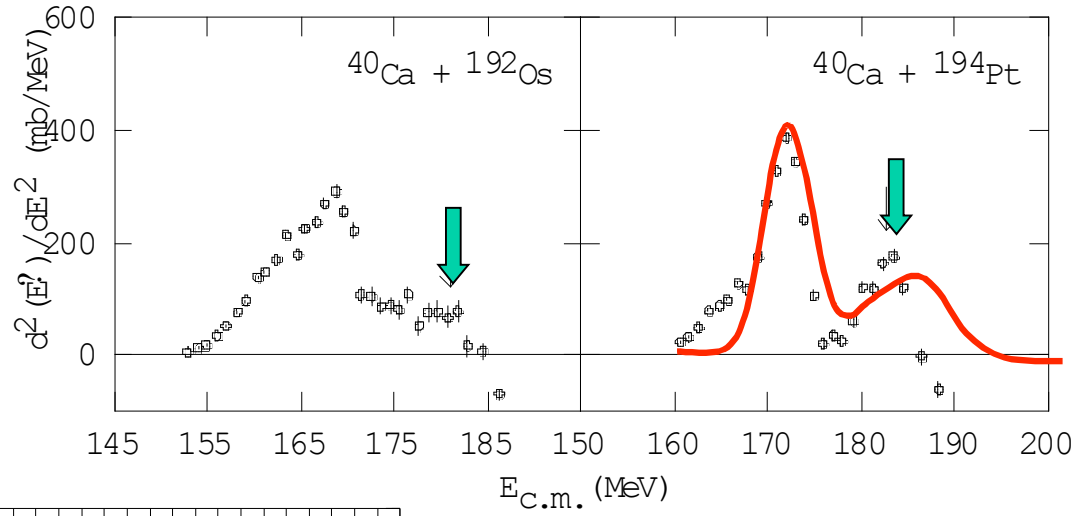
Measurement: FF, ER

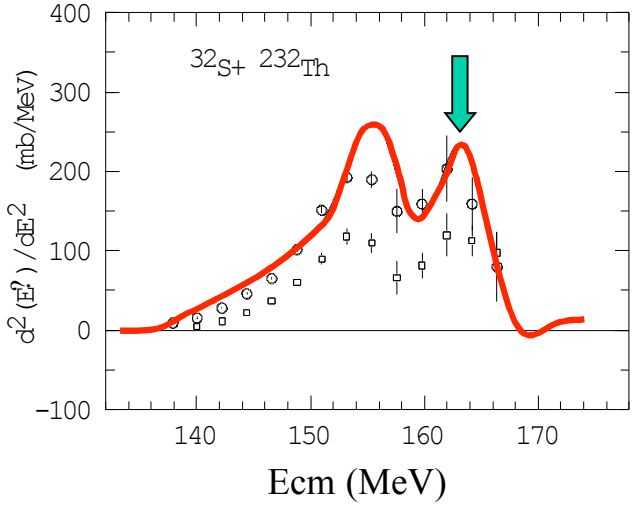
Can't reproduce D(E), σ(E)



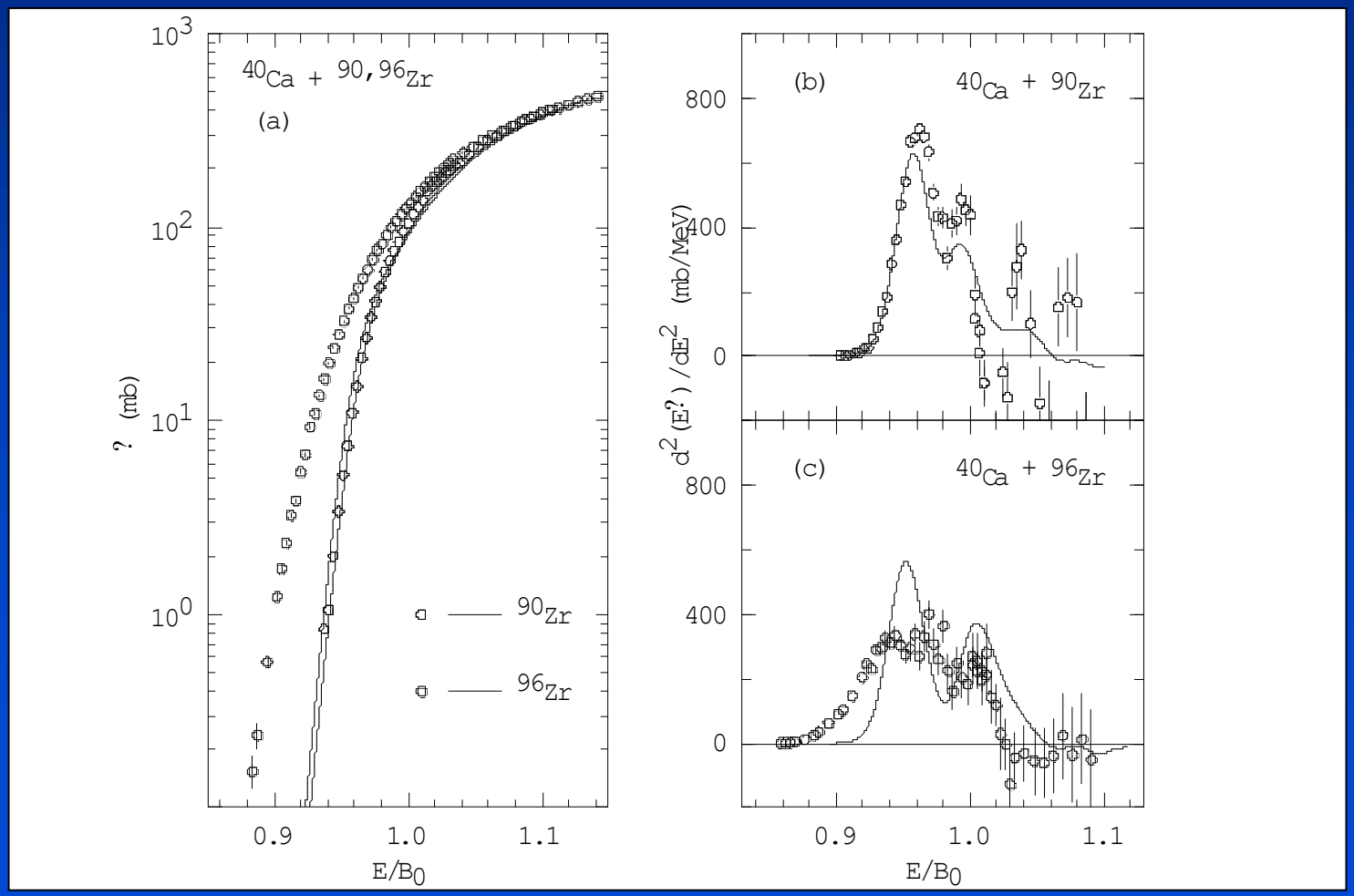
- **Static deformation + phonons**
- Measurement: FF
- $^{40}Ca+^{192}Os, ^{194}Pt$, $^{34}S+^{232}Th$ (J.D. Bierman et al., PRL66(1996)1587)

(D.J.. Hinde et al., unpublished)





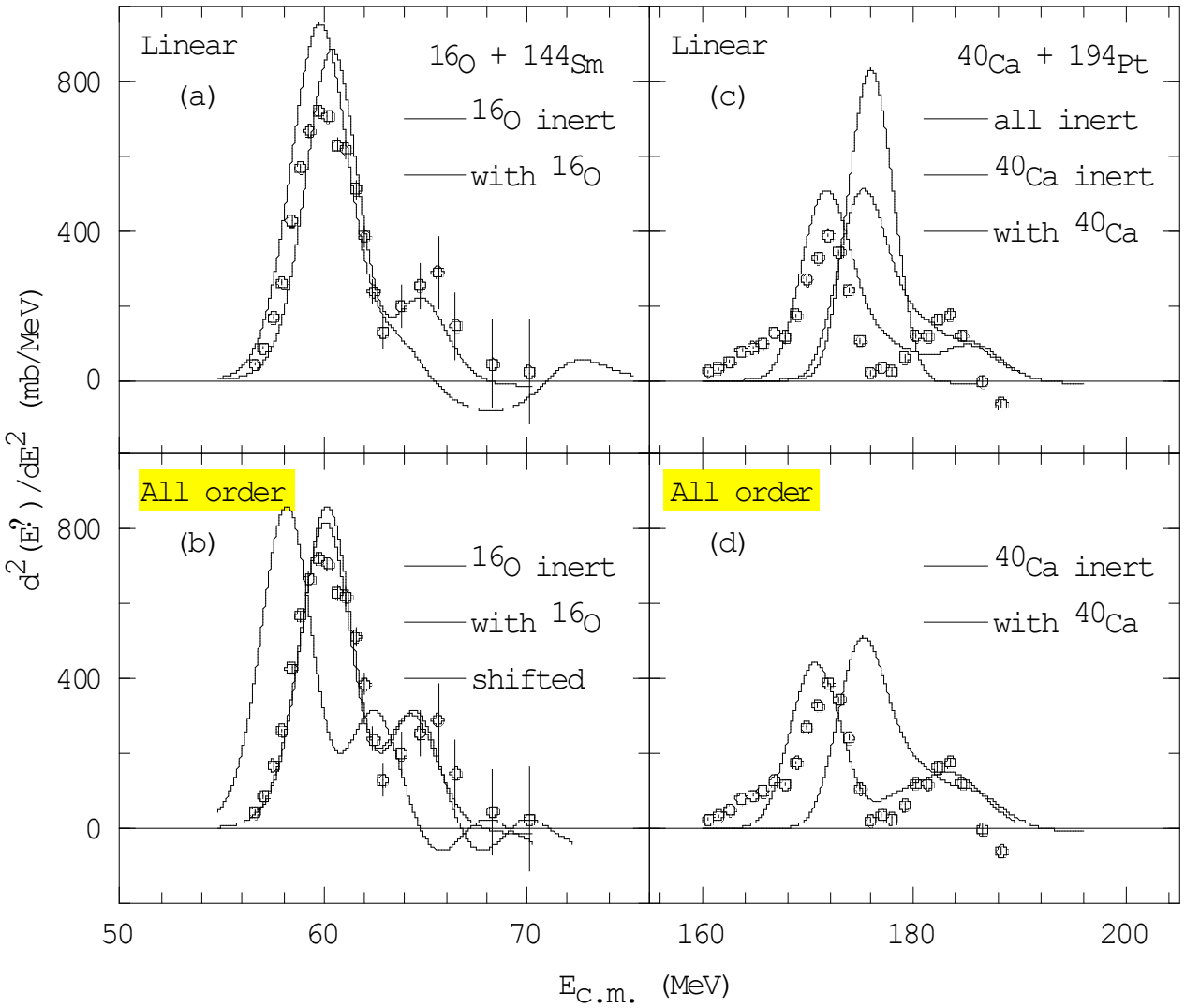
- **<u>Effects of (positive Q-value) transfer</u>**
- Measurement: ER (FF)
- ^{58,64}Ni+^{58,64}Ni (M. Beckermann et al., PRC25(1982)837 and ref. therein)
- ^{40}Ca+^{90,96}Zr (H. Timmers et al., Phys. Lett. B399(1997)35, + recent LNL ^{48}Ca+Zr)



What should be used as a bare potential?

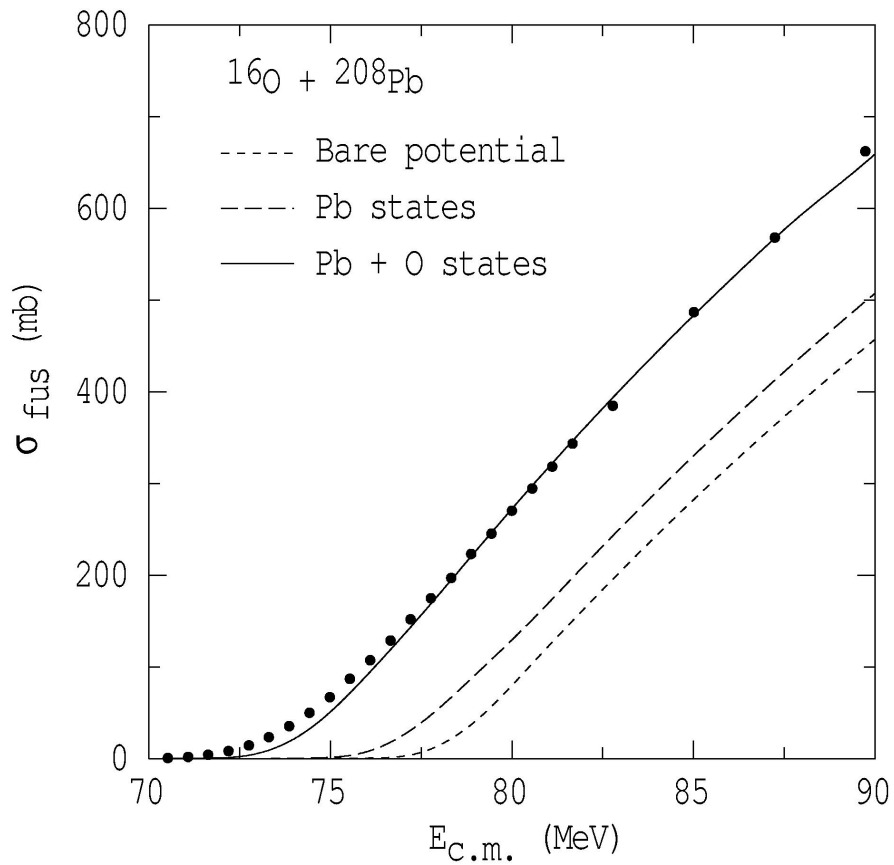
Potential renormalization due to coupling to high energy states

Figure from M. Dasgupta et al., Annu. Rev. Nucl. Part. Sci. 48(1998)401

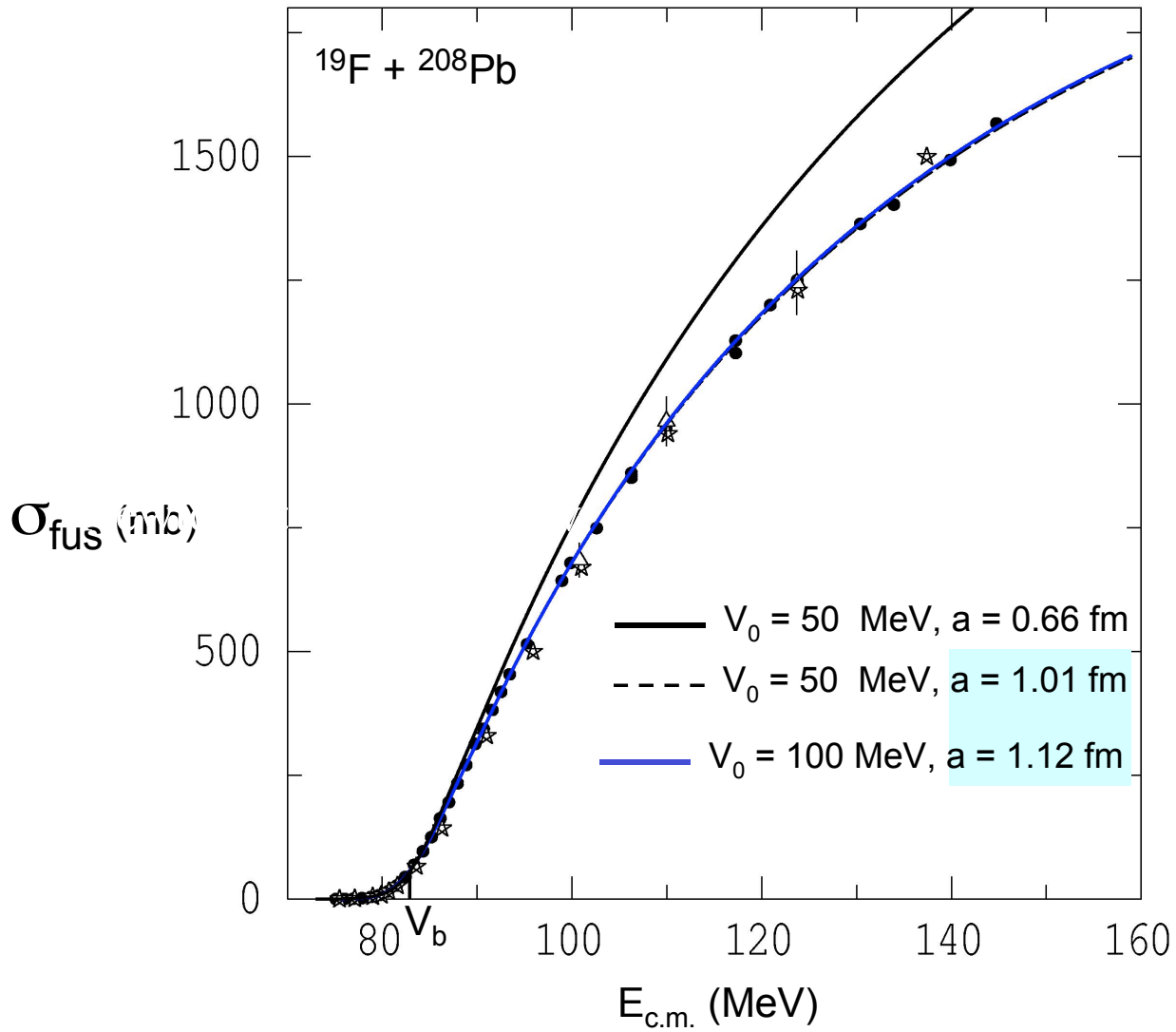


Potential renormalization due to coupling to high energy states

(M. Dasgupta et al., unpublished)



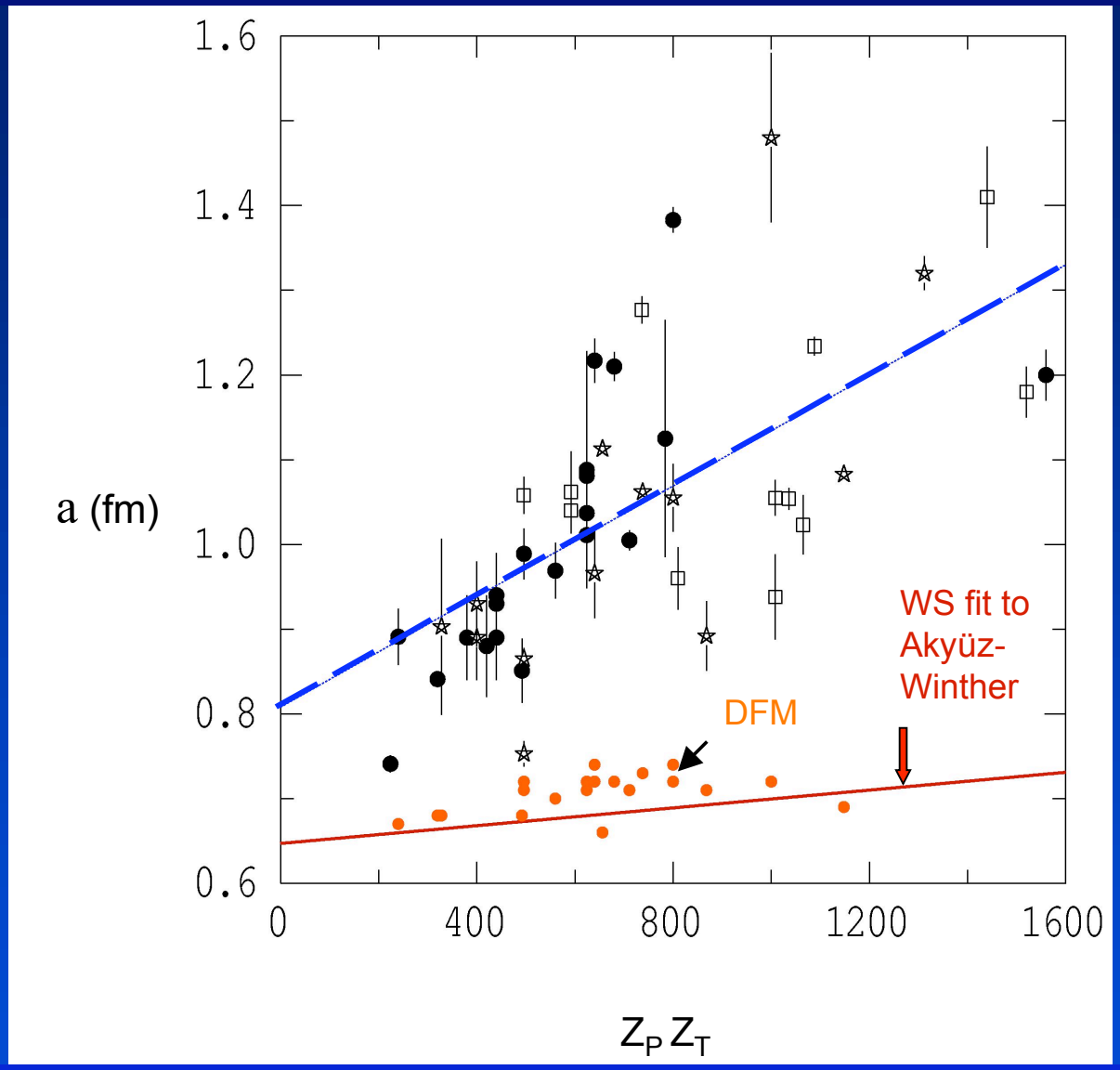
Depth of the nuclear potential and "fitted" diffuseness



a > 0.66 fm irrespective of the depth chosen

('a' depends on the depth of the nuclear potential)

Systematics of fitted diffuseness parameter



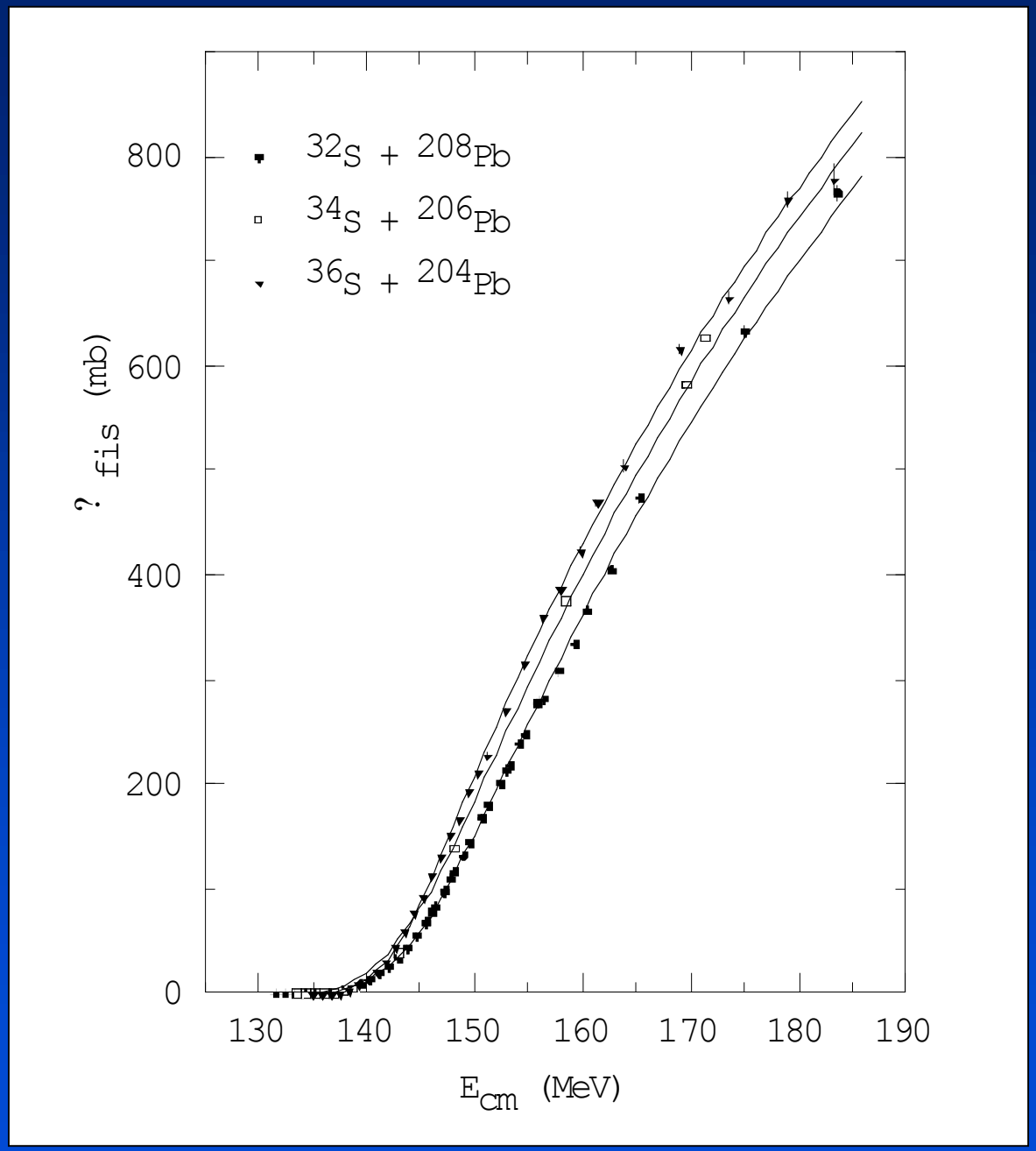
I.I. Gontchar et al. Phys. Rev. C69 (2004)024610

J.O. Newton et al., Phys. Rev. C70 (2004)024605

fits to above barrier fusion data require diffuseness higher than model predictions

1) Potential is more diffuse than DFM

2) Physics is missing (dynamics)

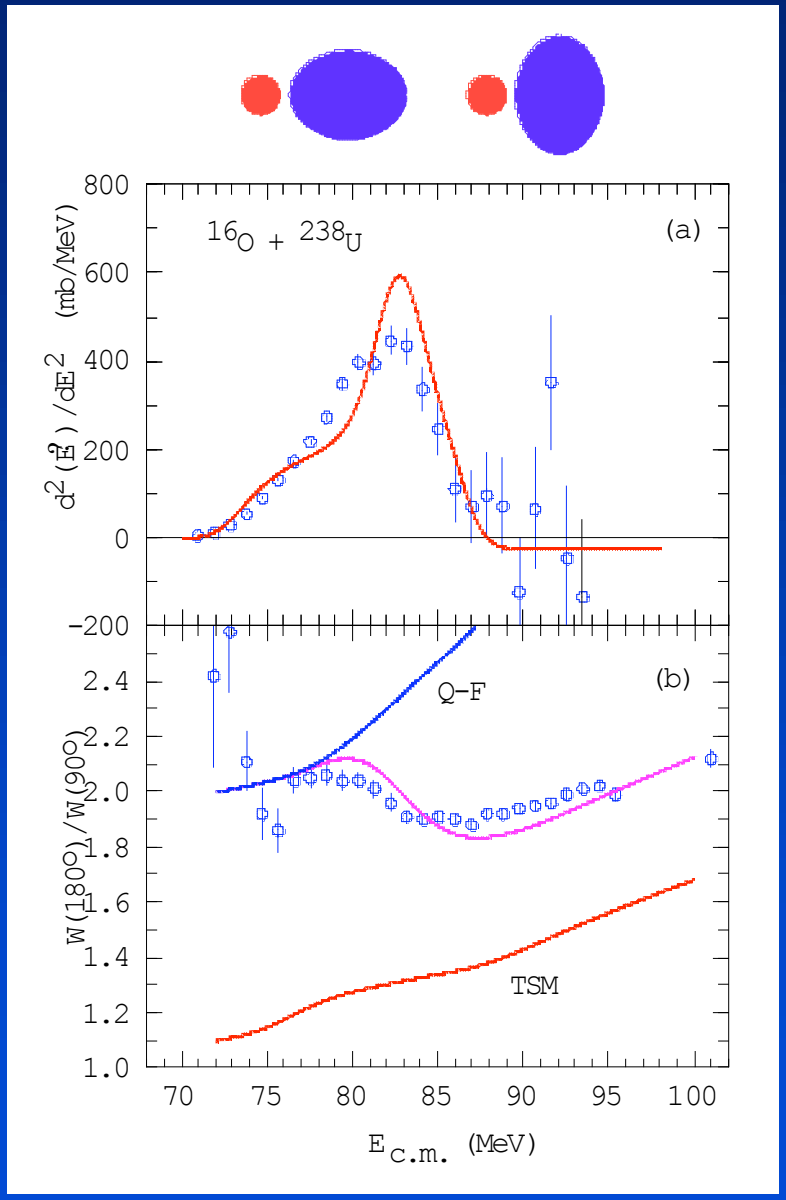


Above-barrier cross sections scale with $A^{1/3}$

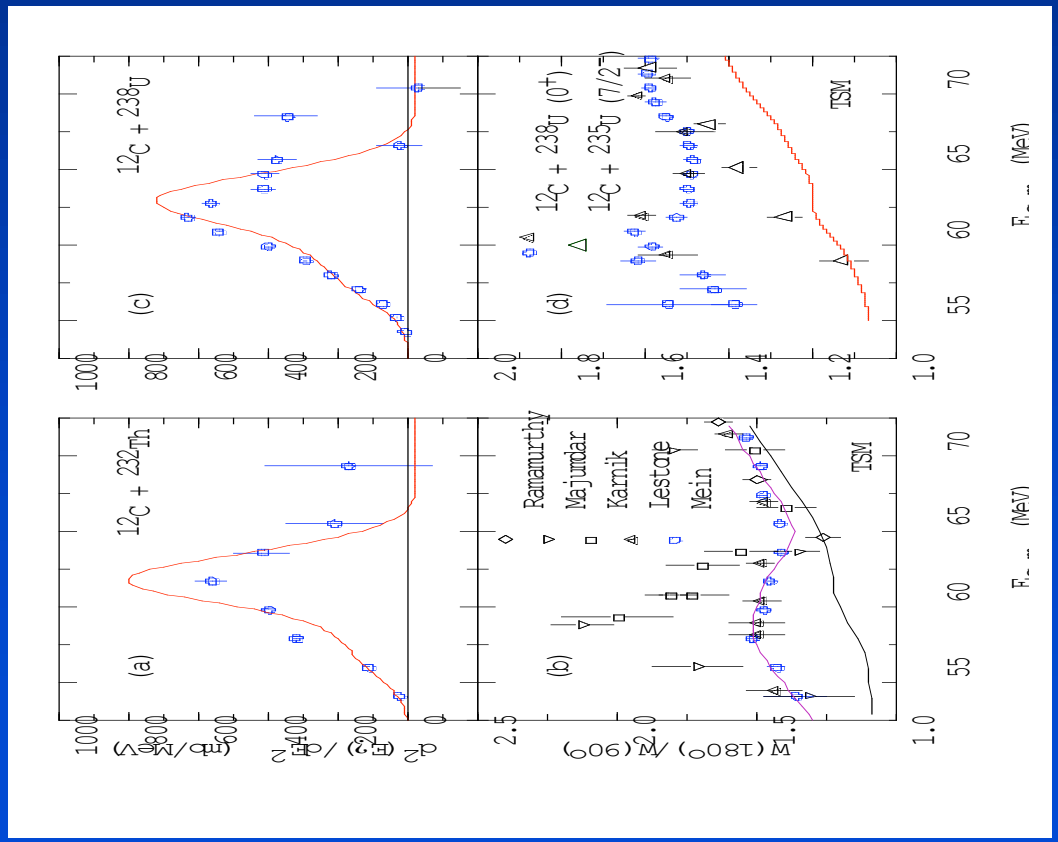
Fitted "a" independent of N/Z imbalance in entrance channel

D.J. Hinde et al., unpublished

Effect of nuclear structure on formation of compact compound nucleus



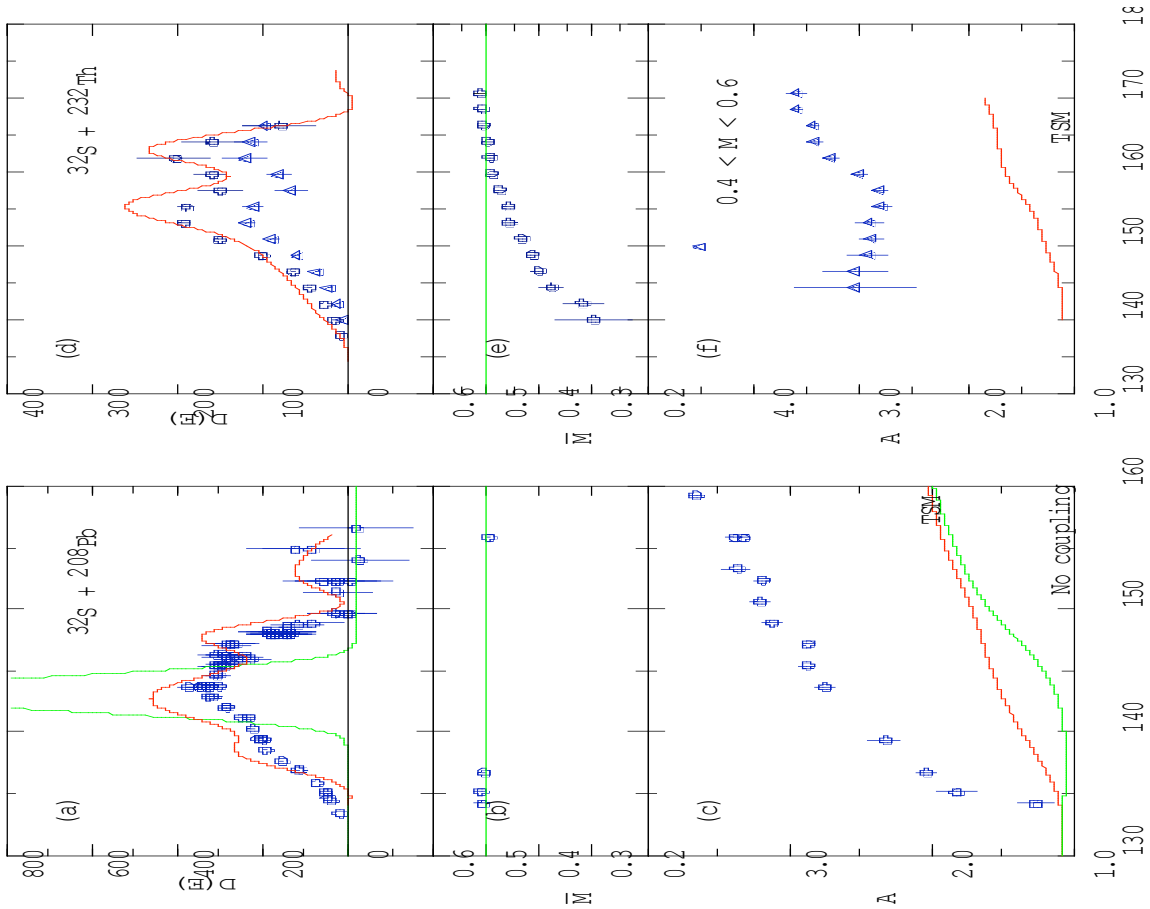
1) Fission angular distributions

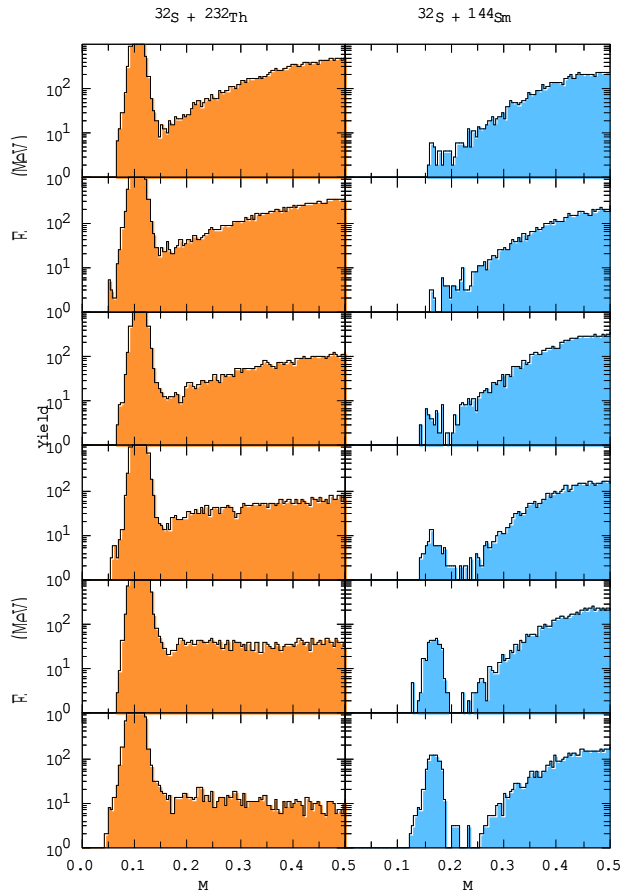


Hinde et al., PRC**53** (1996) 1290

Mein et al., PRC55(1997)R995

2) Quasi-fission mass distributions

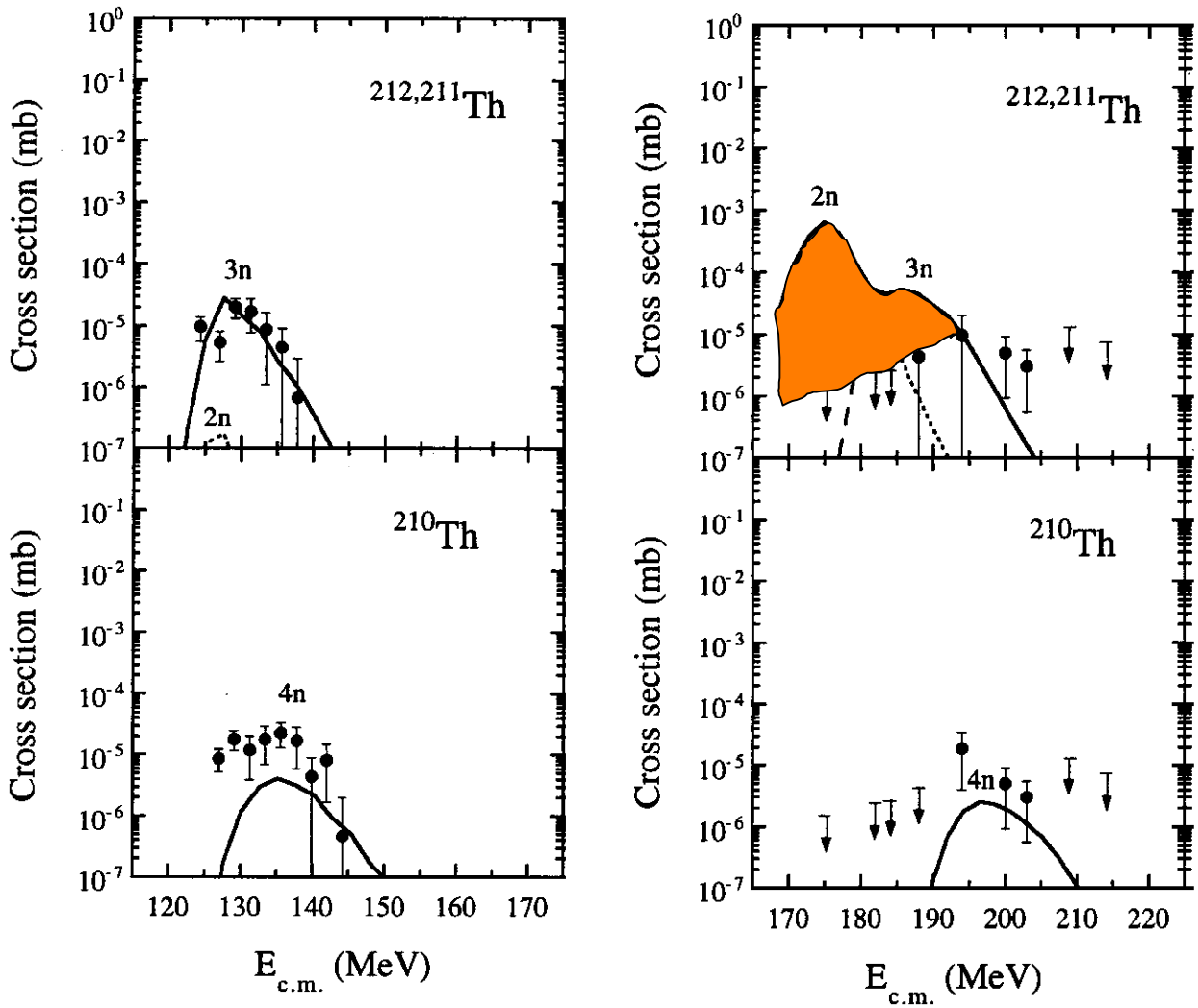




(D.J. Hinde et al., conference proceedings)

3) ER survival

$^{32}S + ^{182}W$ **Reactions forming** ^{214}Th $^{60}Ni + ^{154}Sm$



Mitsuoka et al., Phys. Rev. C 62 (2000) 054603

Fusion is suppressed at below-barrier energies, but not at above-barrier energies for $^{60}Ni+^{154}Sm$

Enhancement?

Compact contact shape enhances ER production ?

More exotic nuclear structure effects include:

- Effect of g.s. spin on fission (aligned spin for deformed nuclei)
- Inhibition of quasi-fission for $^{48}Ca+^{208}Pb$ – (magic #)^4 - dissipation
- Breakup of weakly-bound nuclei – stable or unstable
- Interaction of neutron halo for nuclei near the drip-line (J. Kolata)
- Heavy-ion sub-barrier fusion hindrance (C.L. Jiang)

Nuclear Structure in Sub-barrier Fusion:

Determines barrier distributions, breakup, halos

Still uncertainties:

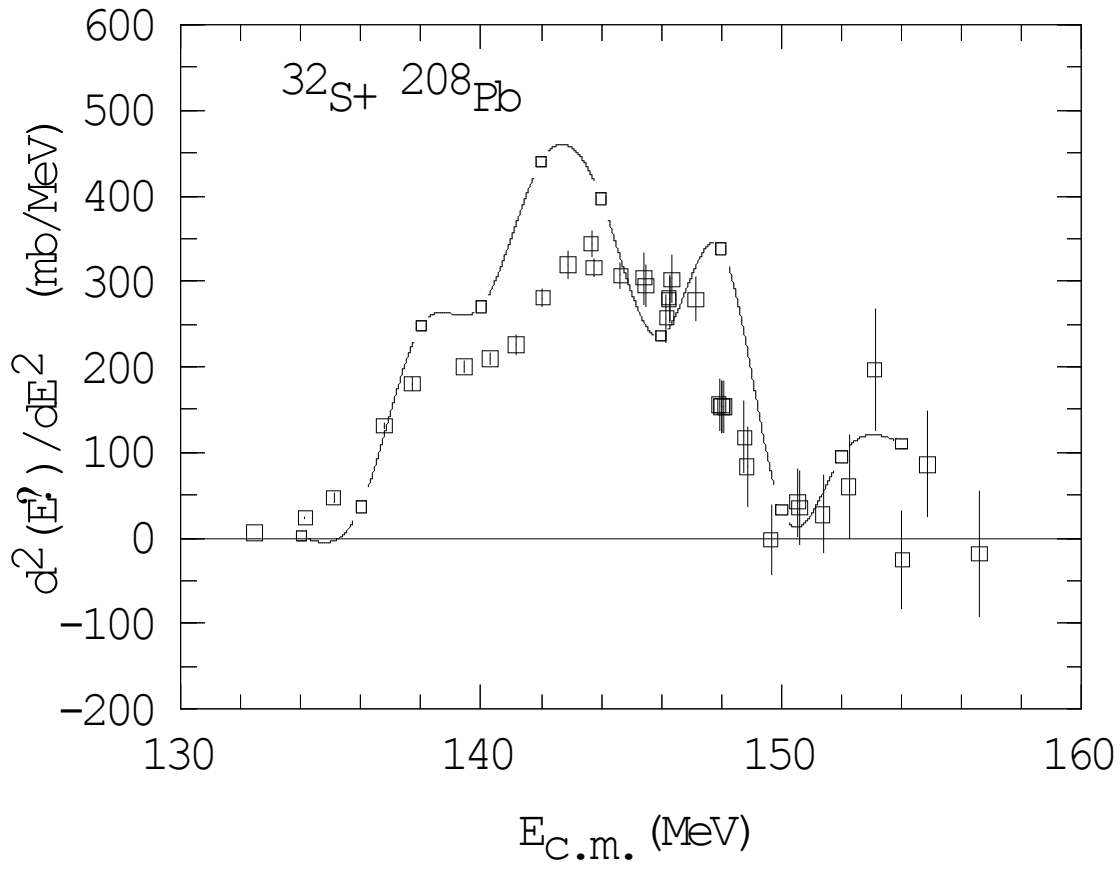
appropriate nuclear potential (form, diffuseness, depth)

pot. renormalization from coupling to giant resonances

dynamical processes after capture (damping)

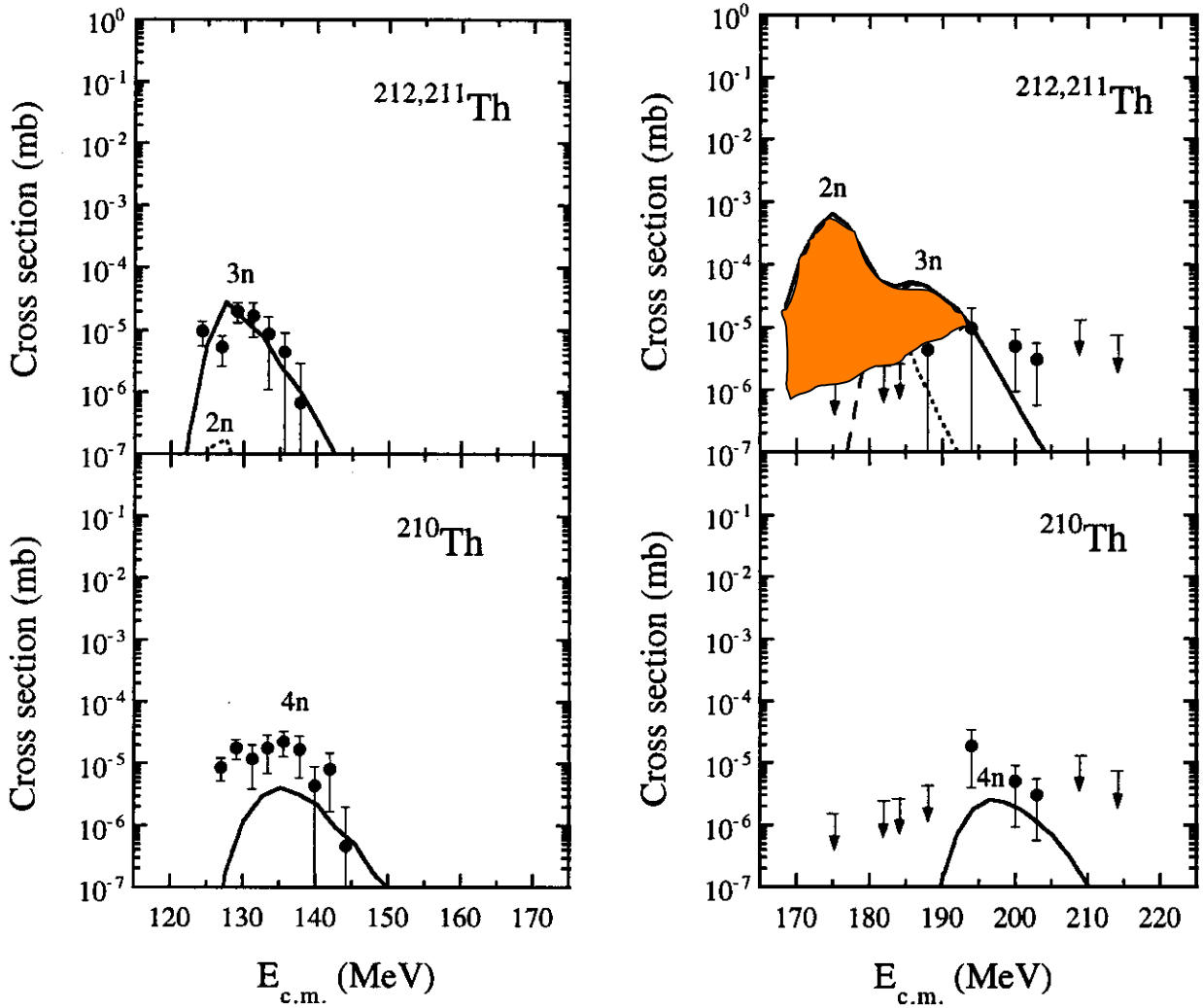
tunnelling at deep sub-barrier energies

fusion of very neutron-rich nuclei (at and after capture)


$^{32}S+\ ^{208}Pb$
600
500
400
300
200
100
0
−100
−200
130
140
150
160
$d^2(E?)/dE^2$ (mb/MeV)
$E_{c.m.}$ (MeV)

ERs

$^{32}S + ^{182}W$ $^{60}Ni + ^{154}Sm$



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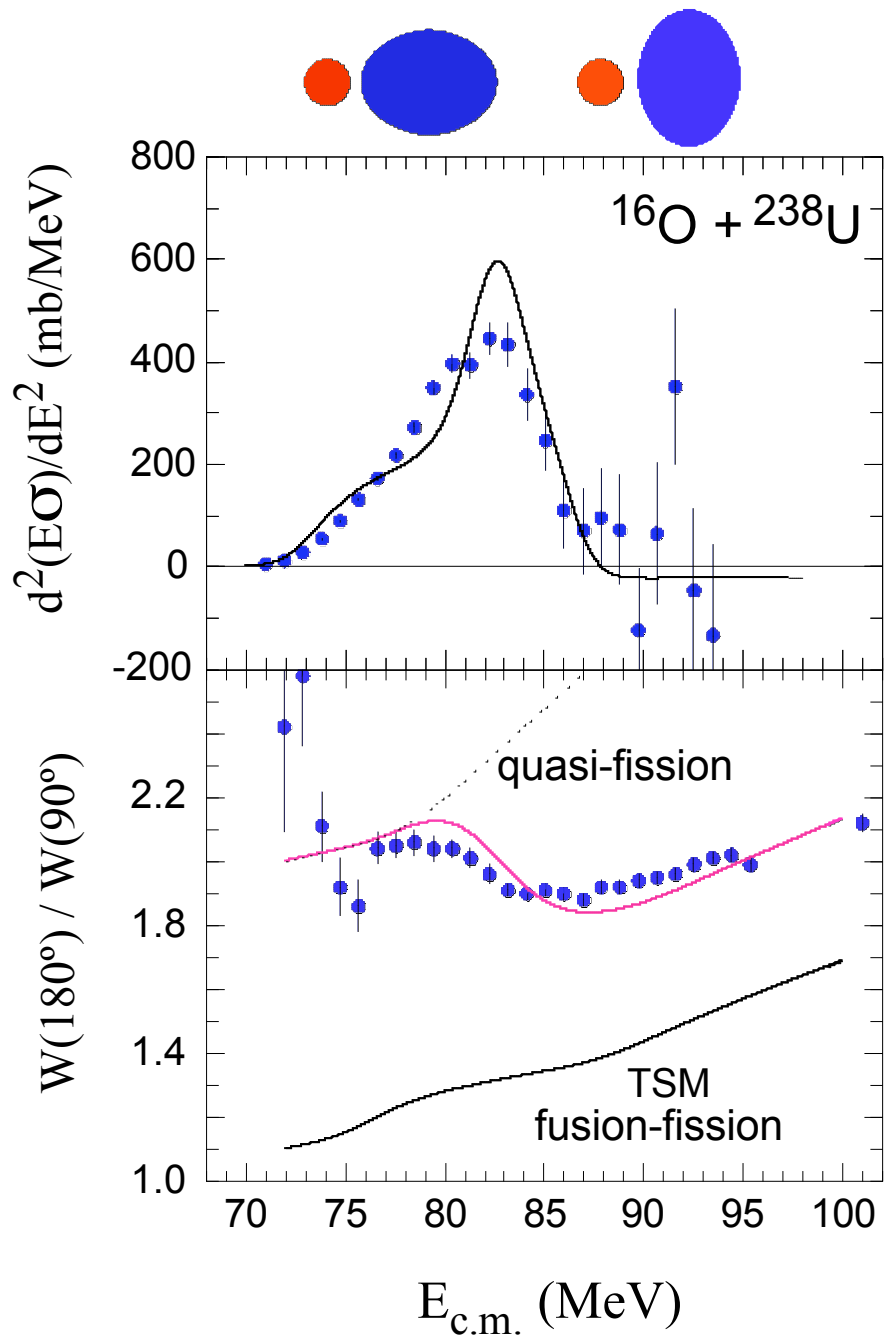

Effect of deformation on quasi fission

- $^{16}O+^{238}U$ (prolate β_2~0.26, β_4~0.05)

  Hinde et al., Phys. Rev. Lett. 74 (1995) 1295

  Phys. Rev. C (1996)

  -QF for collisions with tip

  -Not necessarily 100%

- $^{60}Ni+^{154}Sm$ (prolate β_2~0.30, β_4~0.07)

  Mitsuoka et. al., PRC 62 (2000) 054603

  - no ER formation at low E (i.e. in tip collisions)

elongated configuration

→ low capture barriers

→ Quasi-fission