Fusion and other reaction channels in the $^{16}O+^{208}Pb$ reaction at near-barrier energies

D.J. Hinde, M. Dasgupta

Department of Nuclear Physics and Accelerator Applications,
Australian National University

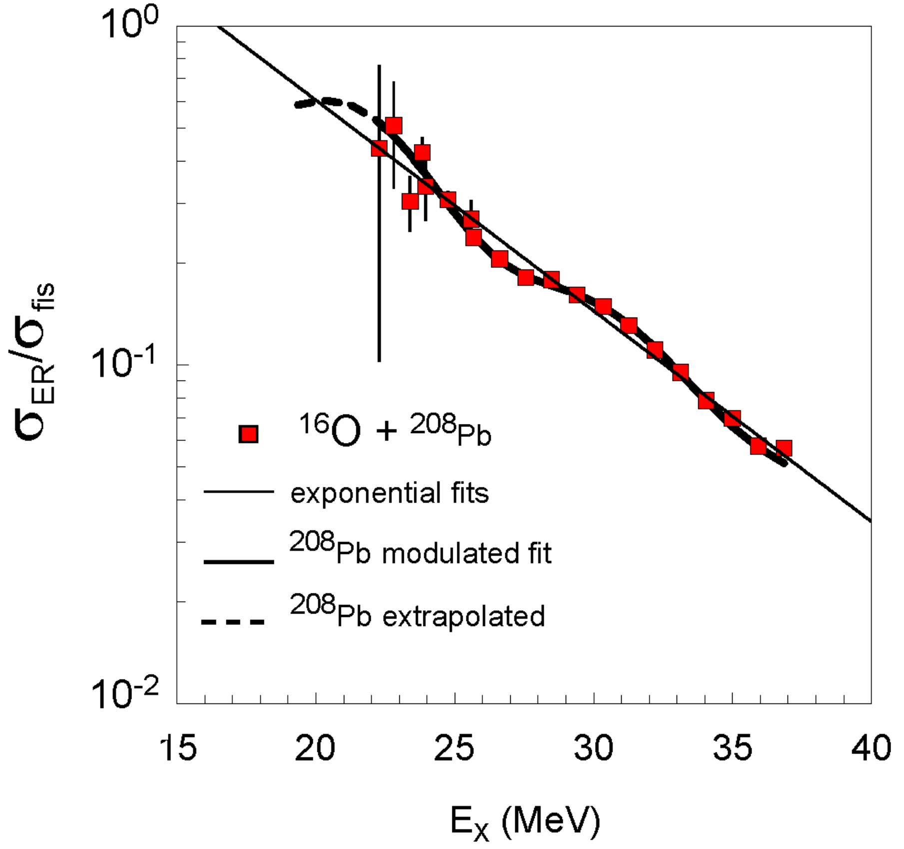
Capture	Fission following capture + ER Cross sections σ_{cap} vs. E, vs. 1/E
$<J^2>$	Map fission angular dist. to $<J^2>$ Map $E\sigma_{cap}$ vs. E to $<J^2>$
QE	Deep-sub-barrier quasielastic scattering: V_{nuc}
D(E)	Fusion barrier distribution D(E) Coupled channels calculations Require transfer couplings in C.C. calculations
Transfer	Sub-barrier transfer yields excitation energy spectra: energy dissipation?

PRL **99,** 192701 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2007

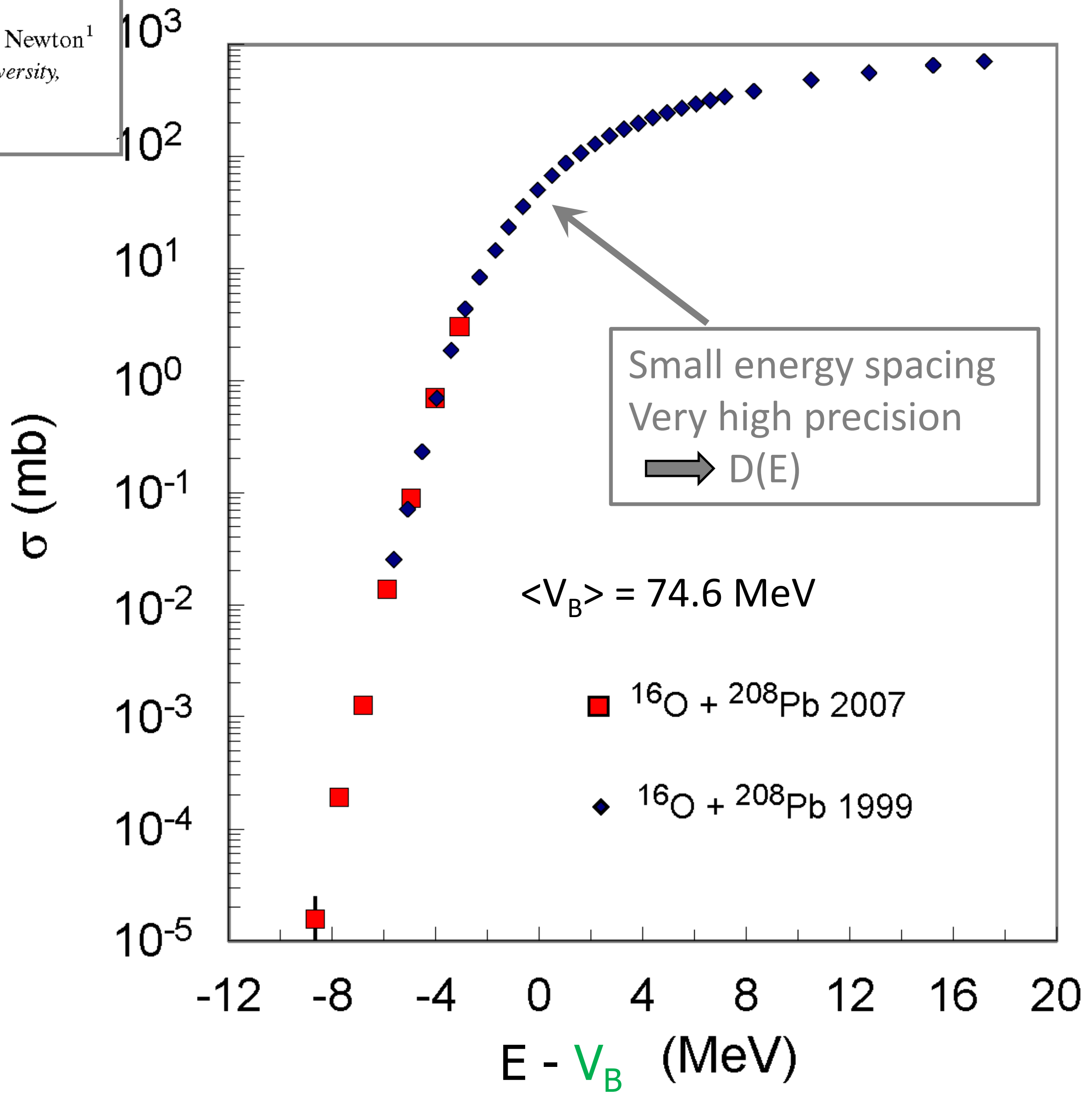
Beyond the Coherent Coupled Channels Description of Nuclear Fusion

M. Dasgupta,[1] D. J. Hinde,[1] A. Diaz-Torres,[1] B. Bouriquet,[1,*] Catherine I. Low,[1,†] G. J. Milburn,[2] and J. O. Newton[1]
[1]*Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia*
[2]*Department of Physics, University of Queensland, St. Lucia, QLD 4072, Australia*

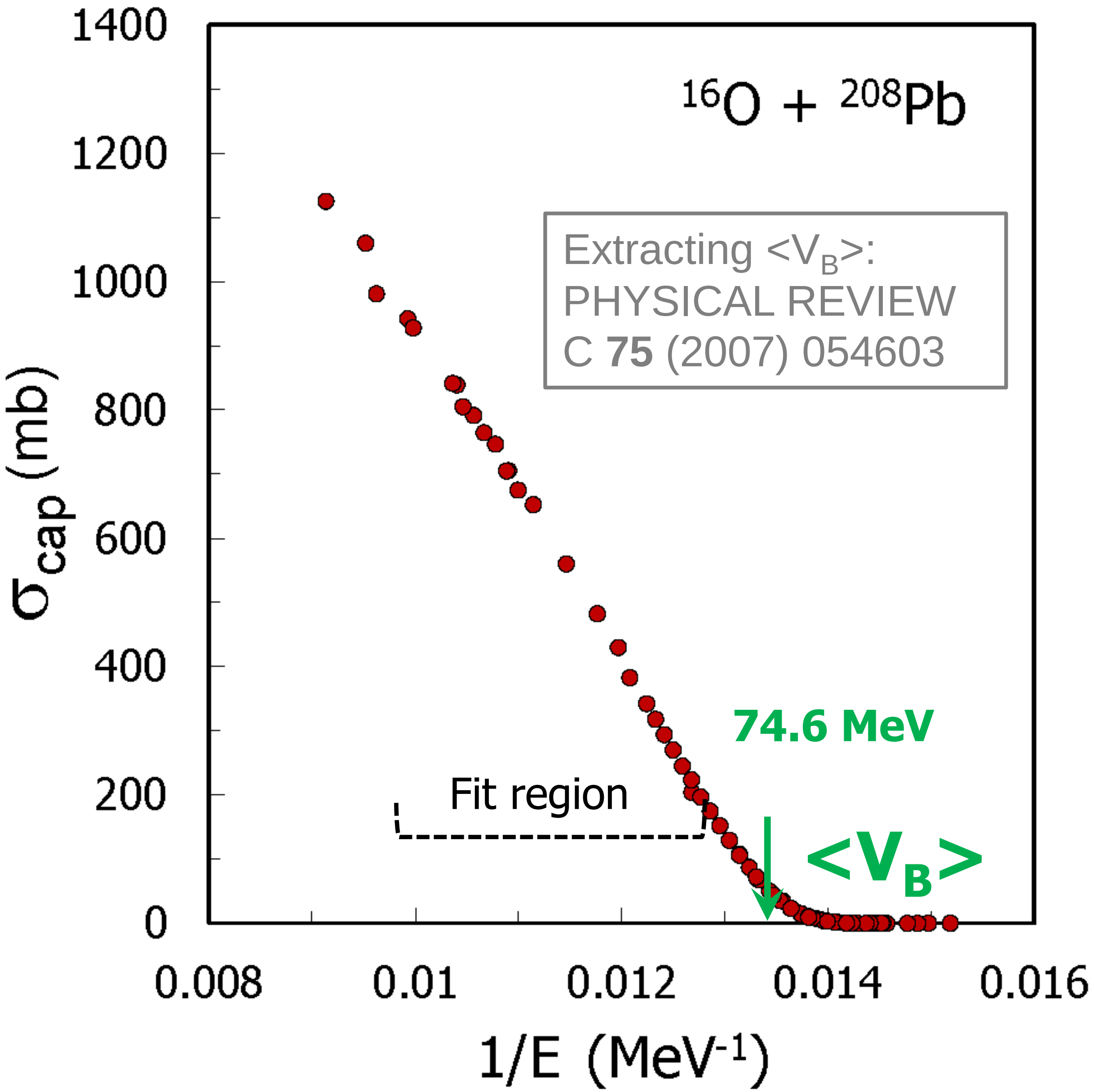
$$\sigma_{capture} = \sigma_{fis} + \sigma_{ER}$$



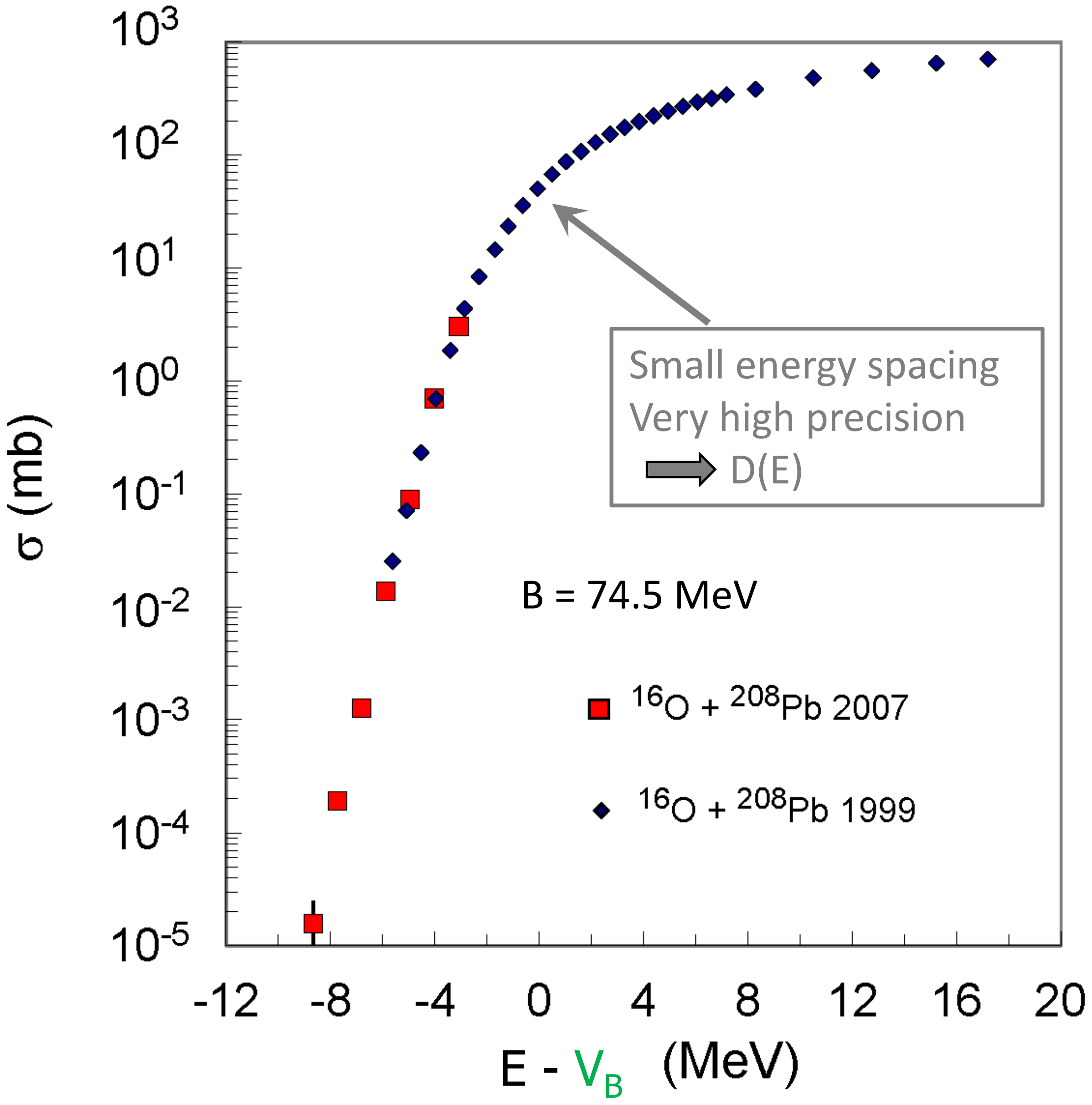
Cross sections σ_{cap} vs. E



Cross sections σ_{cap} vs. 1/E ➡ $<V_B>$



Cross sections σ_{cap} vs. E

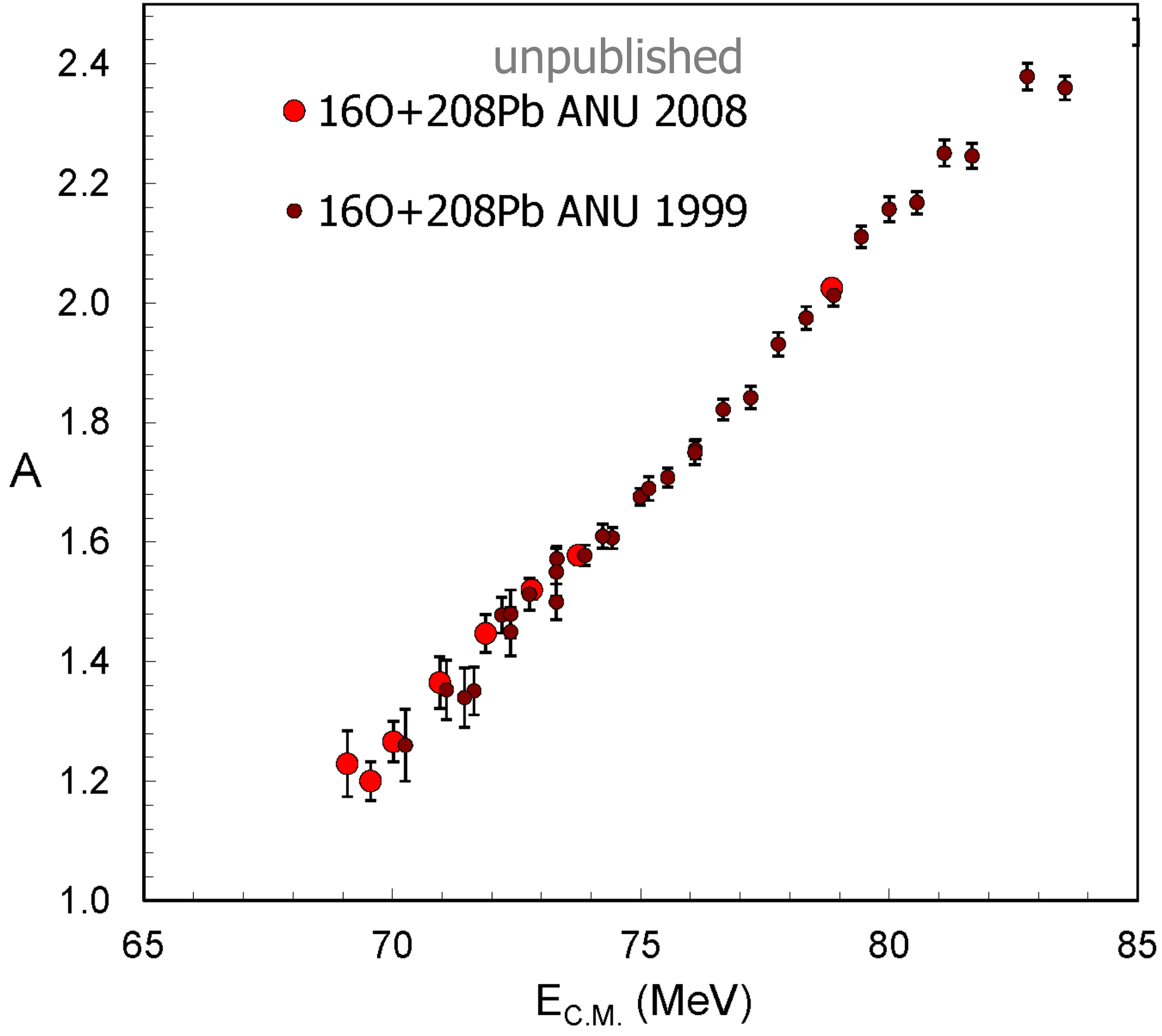


$\langle J^2 \rangle$ from fission A

PHYSICAL REVIEW C, VOLUME 60, 054602

Limiting angular momentum for statistical model description of fission

D. J. Hinde, A. C. Berriman, M. Dasgupta, J. R. Leigh, J. C. Mein, C. R. Morton, and J. O. Newton
Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia



$$A = W(180°)/W(90°) \approx 1 + \frac{\langle J^2 \rangle}{4K_0^2} = 1 + \frac{\langle J^2 \rangle \hbar^2}{4T\mathcal{J}_{\mathrm{eff}}}$$

Don't use approximate expression:
Use q.m. d-functions

<u>TSM uncertainties:</u>

$\mathcal{J}_{\mathrm{eff}}$ (Models: LDM, FRDM)

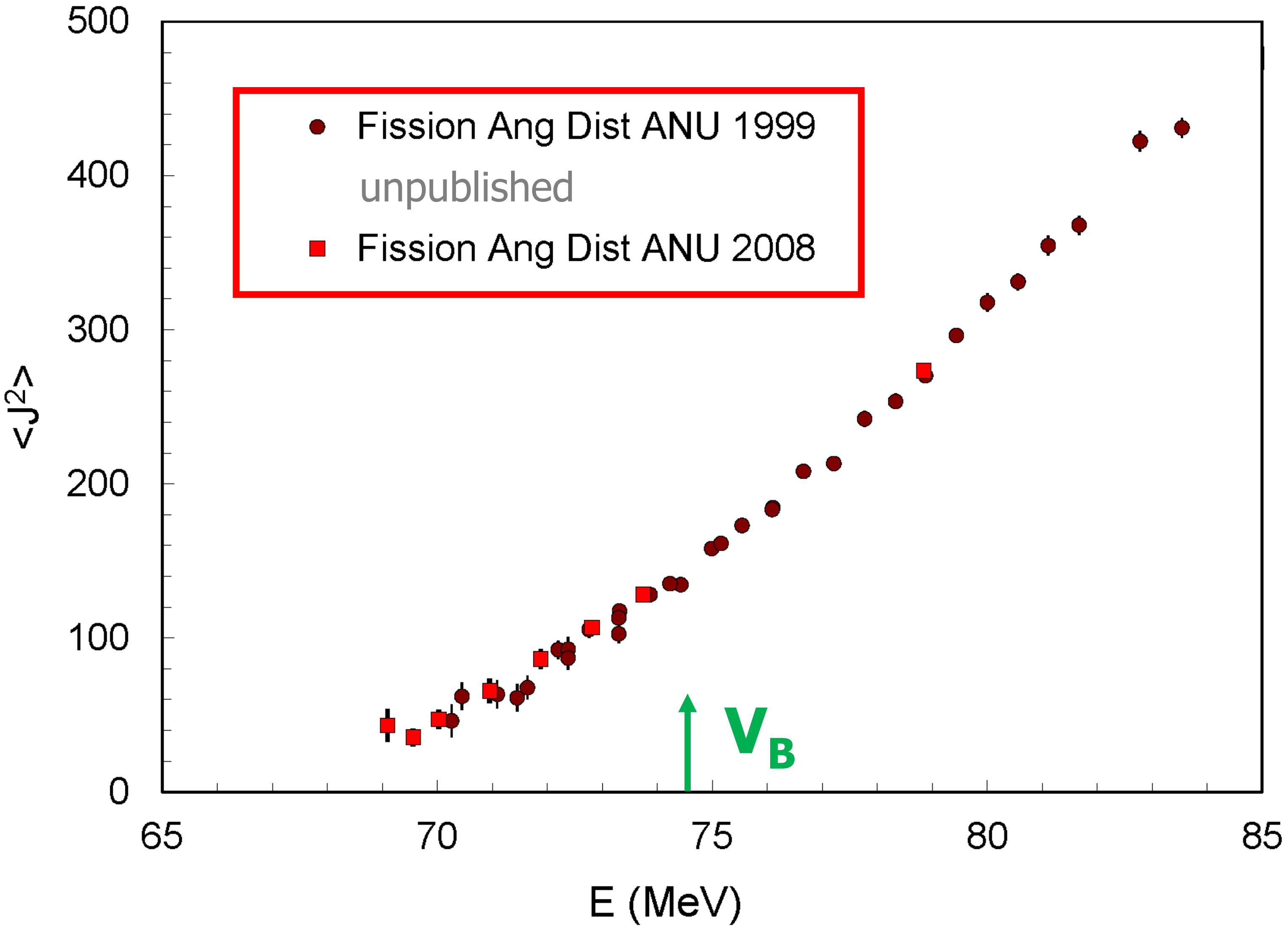
T (a_f, ν_{pre} distribution)
Use statistical model
(No light ion calibration reaction)

$$A = W(180°)/W(90°) \approx 1 + \frac{\langle J^2 \rangle}{4K_0^2} = 1 + \frac{\langle J^2 \rangle \hbar^2}{4T\mathcal{J}_{\text{eff}}}$$

PHYSICAL REVIEW C, VOLUME 60, 054602

Limiting angular momentum for statistical model description of fission

D. J. Hinde, A. C. Berriman, M. Dasgupta, J. R. Leigh, J. C. Mein, C. R. Morton, and J. O. Newton
Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia



$\langle J^2 \rangle$ from fission A

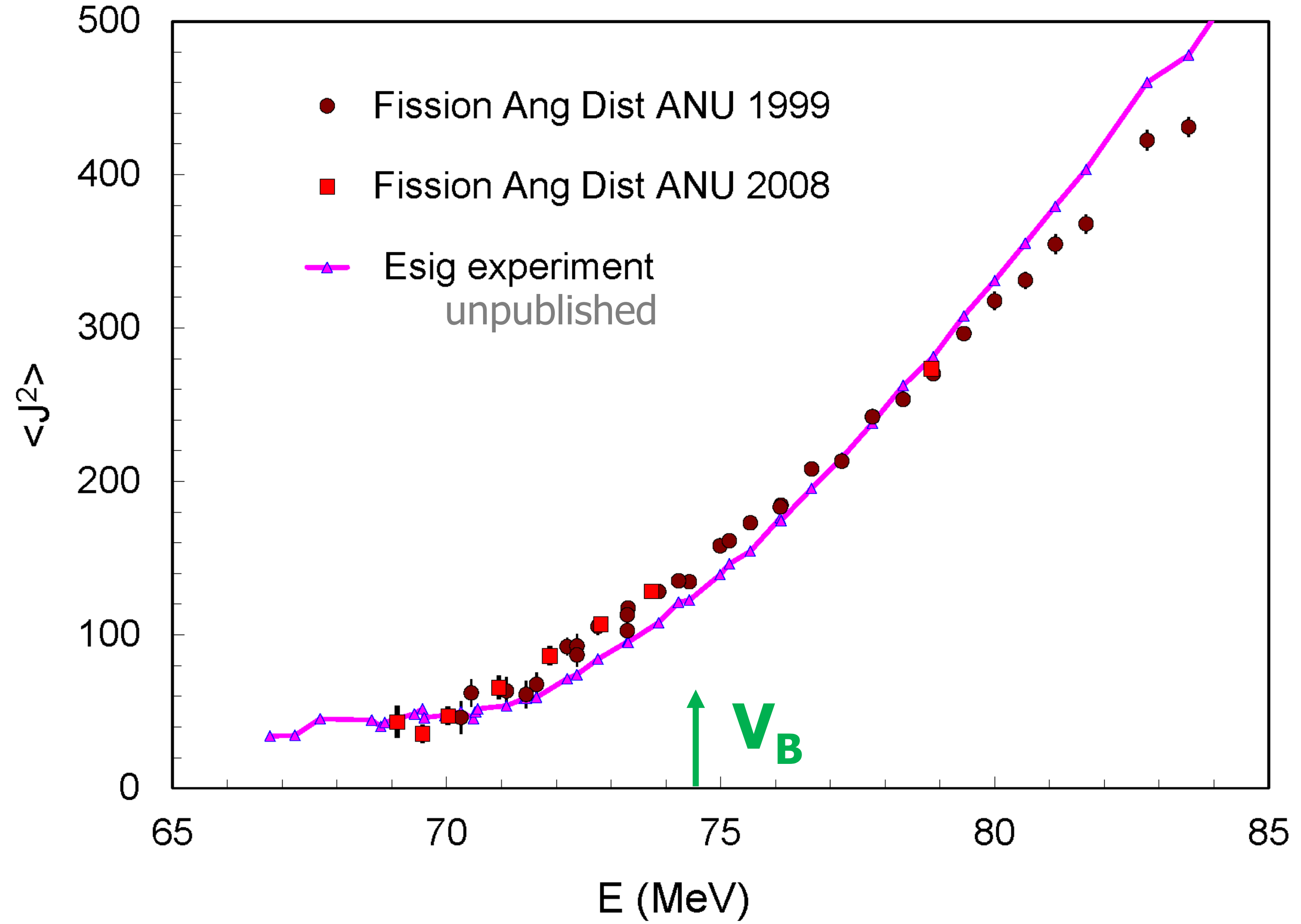
<u>TSM uncertainties:</u>

$\mathcal{J}_{\text{eff}}$ (Models: LDM, FRDM)

T (a_f, ν_{pre} distribution)
Use statistical model
(No light ion calibration reaction)

<J^2> from Eσ_{cap}

$$\langle l^2 \rangle = \{(2\mu R_B^2)/[\sigma_f(E)E\hbar^2]\} \int_{-\infty}^{E} dE' E' \sigma_f(E').$$



Indirect, some assumptions

Annu. Rev. Nucl. Part. Sci. 42(1992)447

ANGULAR MOMENTUM DISTRIBUTIONS IN SUBBARRIER FUSION REACTIONS[1]

Robert Vandenbosch

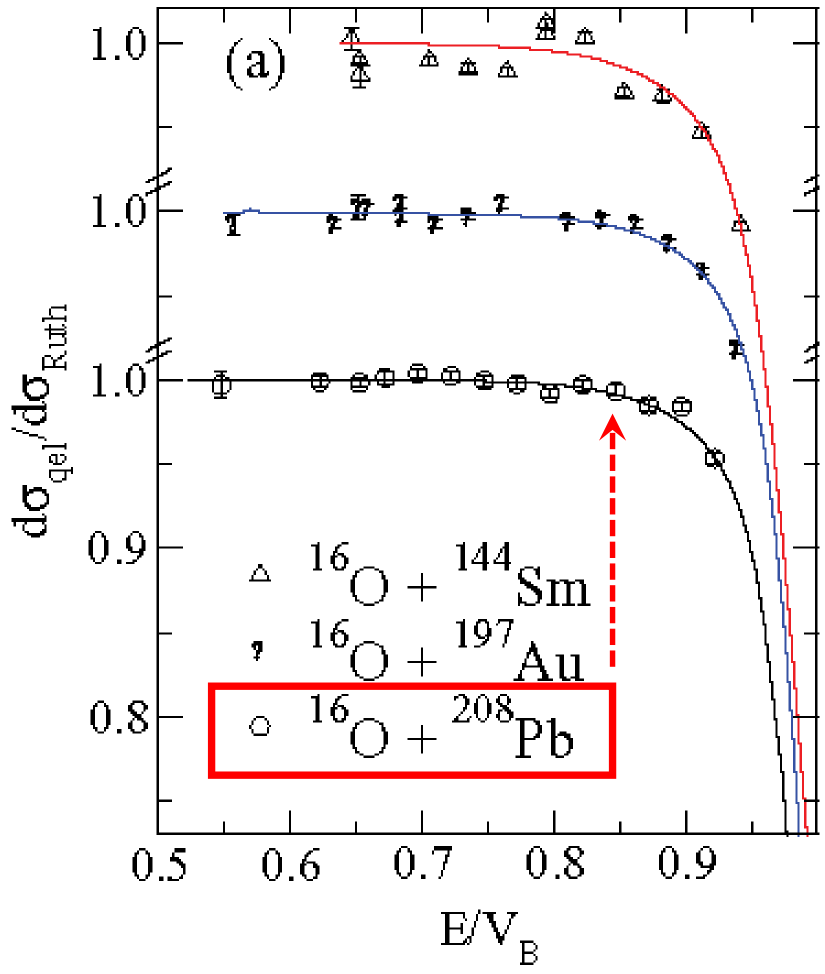
Department of Chemistry and Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195

Agreement of independent methods is quite good.

(Similar deviations seen for $^{19}F+^{208}Pb$)

<J^2> not as sensitive as σ_{cap}

V_{nuc} (for C.C. calculations): deep-sub-barrier quasielastic scattering



Concept
K. Hagino, T. Takehi, A. B. Balantekin, and N. Takigawa,
Phys.Rev. C **71**, 044612 (2005).

PHYSICAL REVIEW C **78**, 034614 (2008)

Systematic study of the nuclear potential diffuseness through high precision back-angle quasi-elastic scattering

M. Evers, M. Dasgupta, D. J. Hinde, L. R. Gasques,* M. L. Brown, R. Rafiei, and R. G. Thomas†
Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

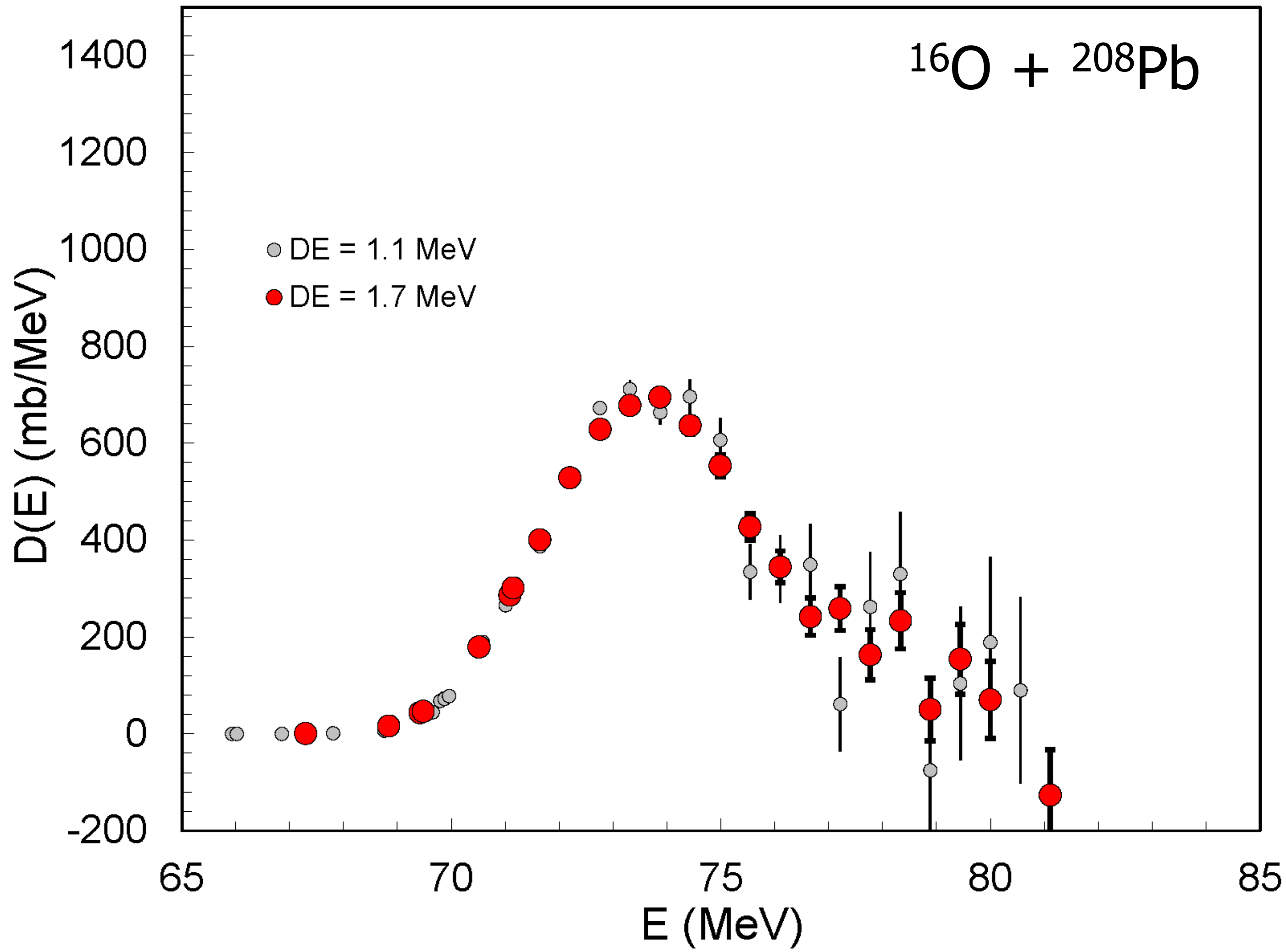
$^{16}O + ^{208}Pb$: (and many other systems)

Nuclear potential diffuseness *a* = 0.67 +- 0.02

Agree with optical model analyses of above-barrier elastic scattering

Fusion barrier distribution D(E)

$$D(E) = d^2(E\sigma_{cap})/dE^2$$



Annu. Rev. Nucl. Part. Sci. 1998. 48:401–61

MEASURING BARRIERS TO FUSION

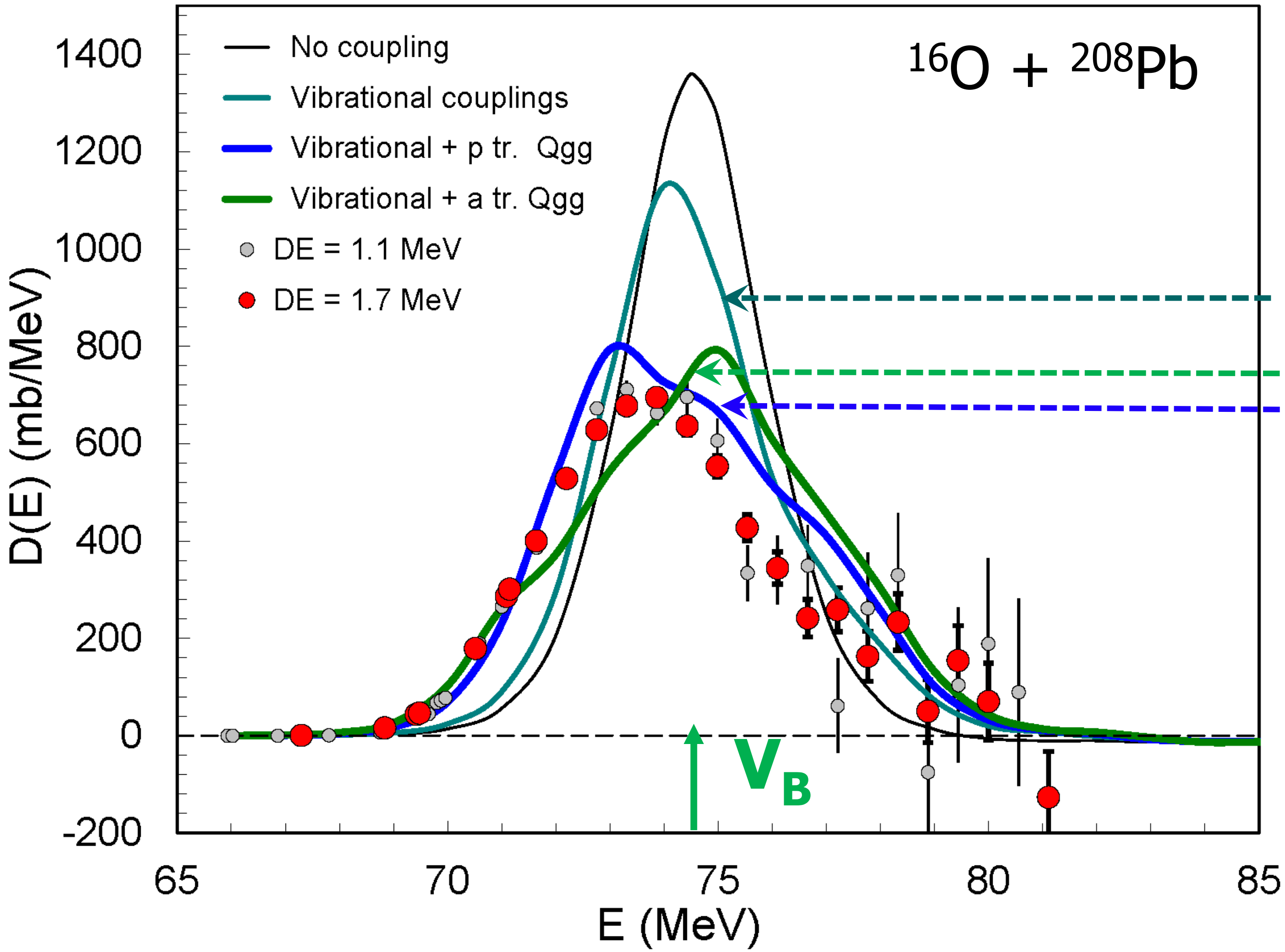
M. Dasgupta and D. J. Hinde
Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

N. Rowley
Institut de Recherches Subatomiques (IReS), UMR 7500, CNRS-IN2P3 and Université Louis Pasteur, F-67037 Strasbourg Cedex 2, France

A. M. Stefanini
Instituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Padova, Italy

Fusion barrier distribution D(E)

$D(E) = d^2(E\sigma_{cap})/dE^2$



Coupled channels calculations using CCFULL:

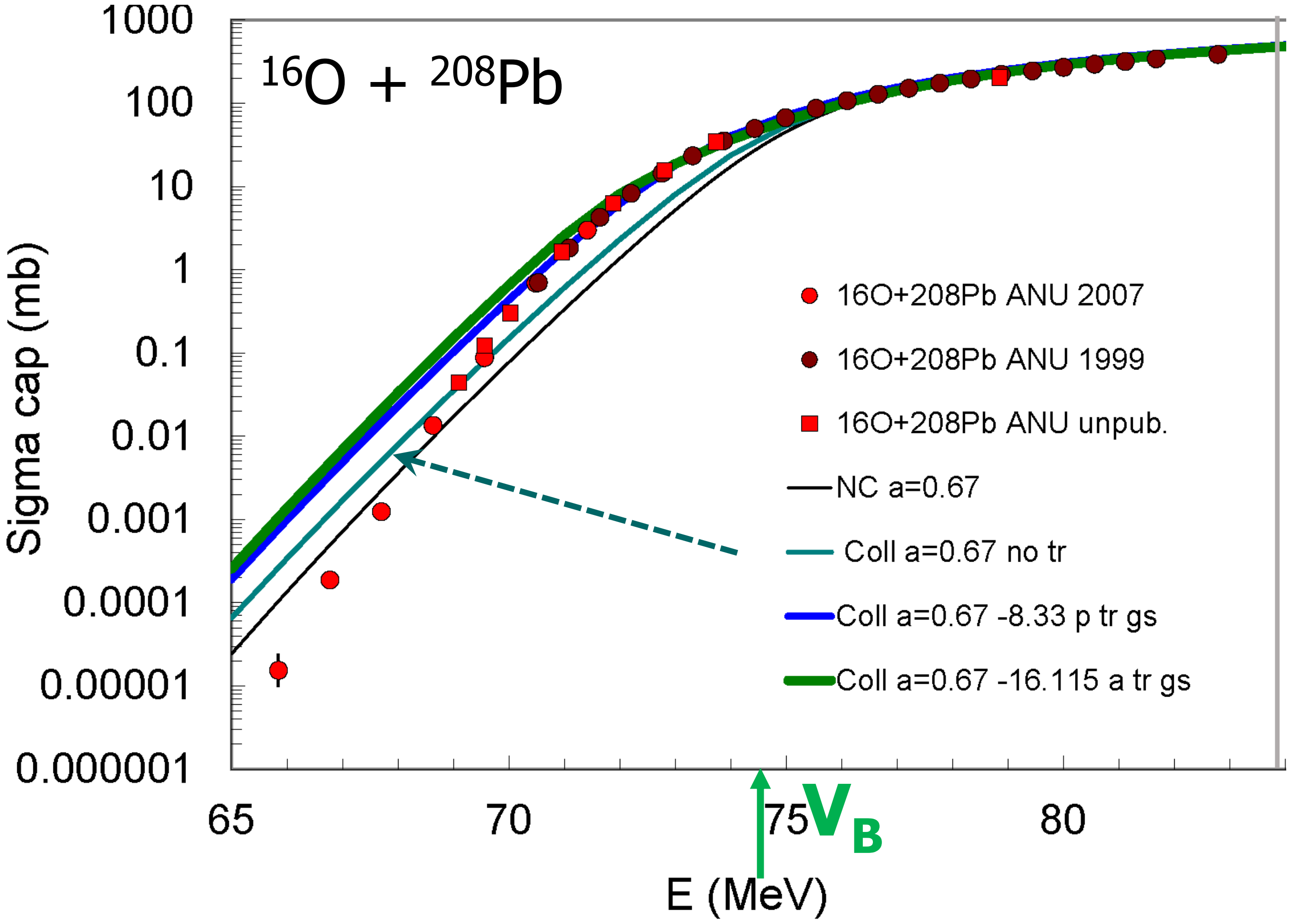
Nuclear potential diffuseness *a* = 0.67

Vibrational couplings: 3^-, 3^-x3^-, 5^-

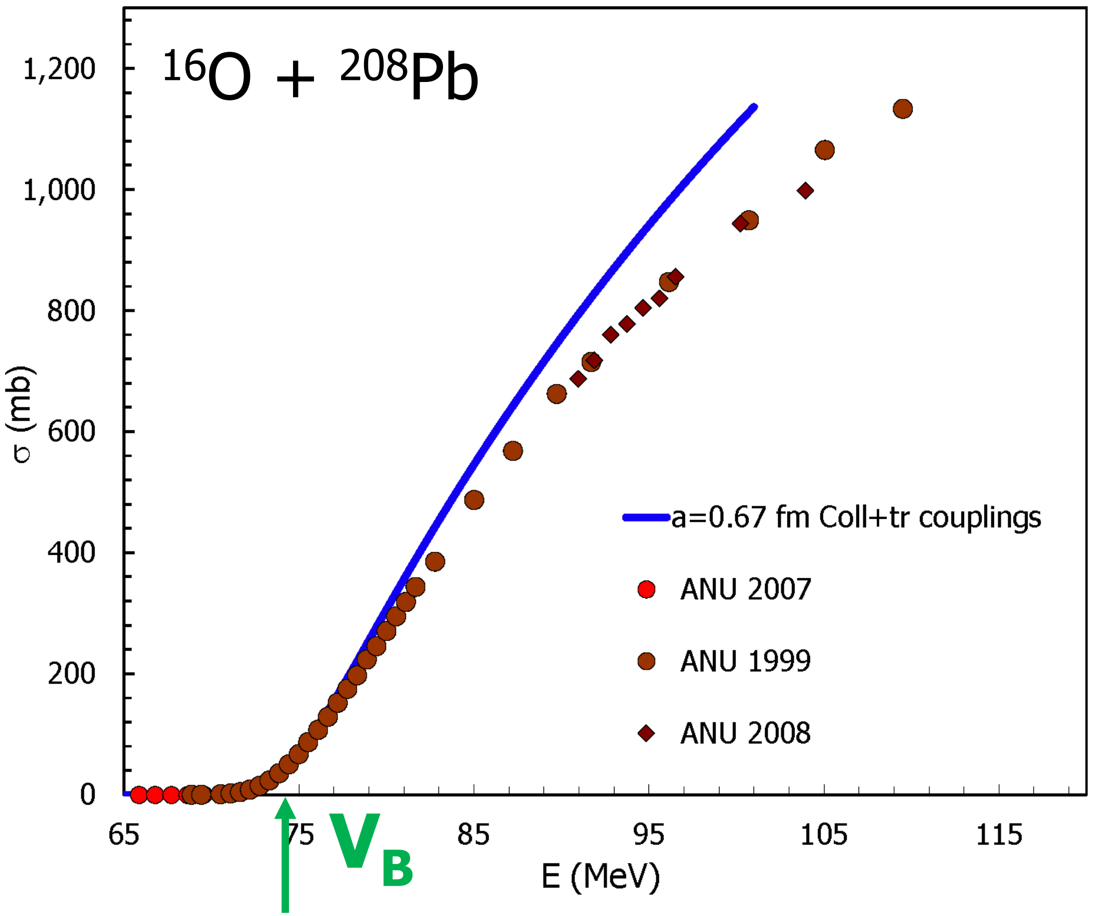
Transfer channels: assumed g.s. transfers, optimised coupling strengths

With transfer, barrier distribution shape not bad

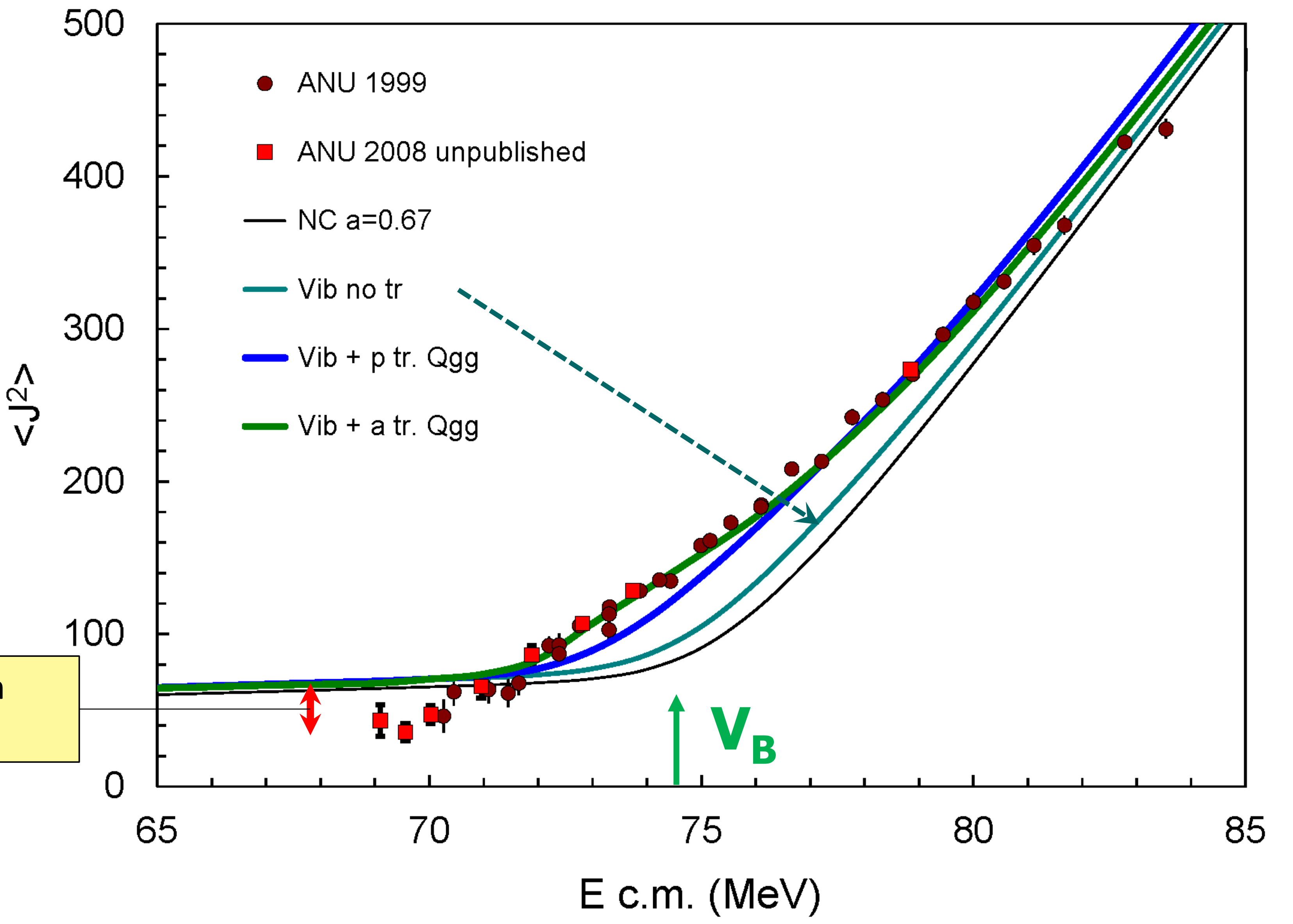
Below-barrier: no good!



Above-barrier: no good!

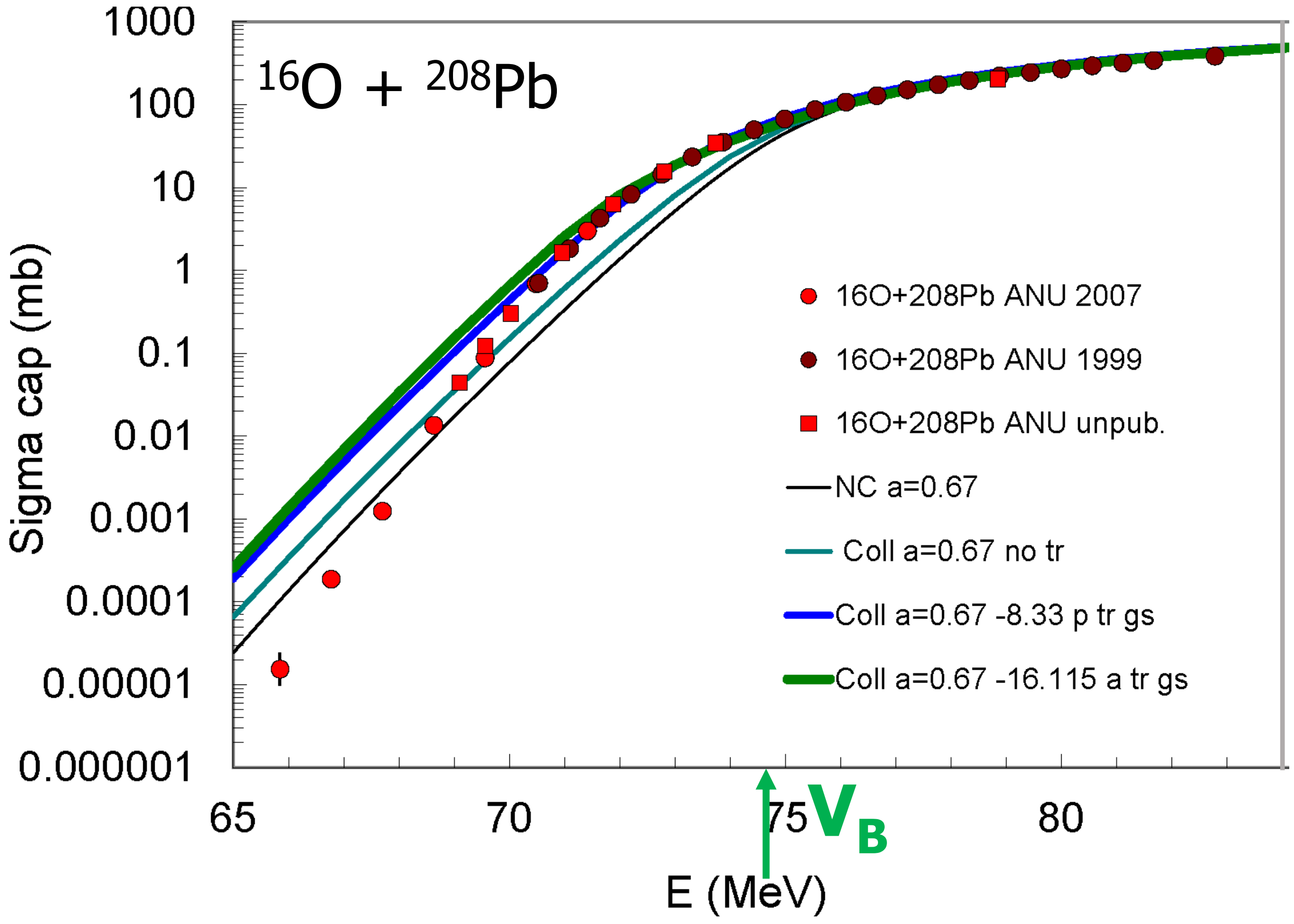


<J^2> compared with C.C. calculations: a = 0.67 fm

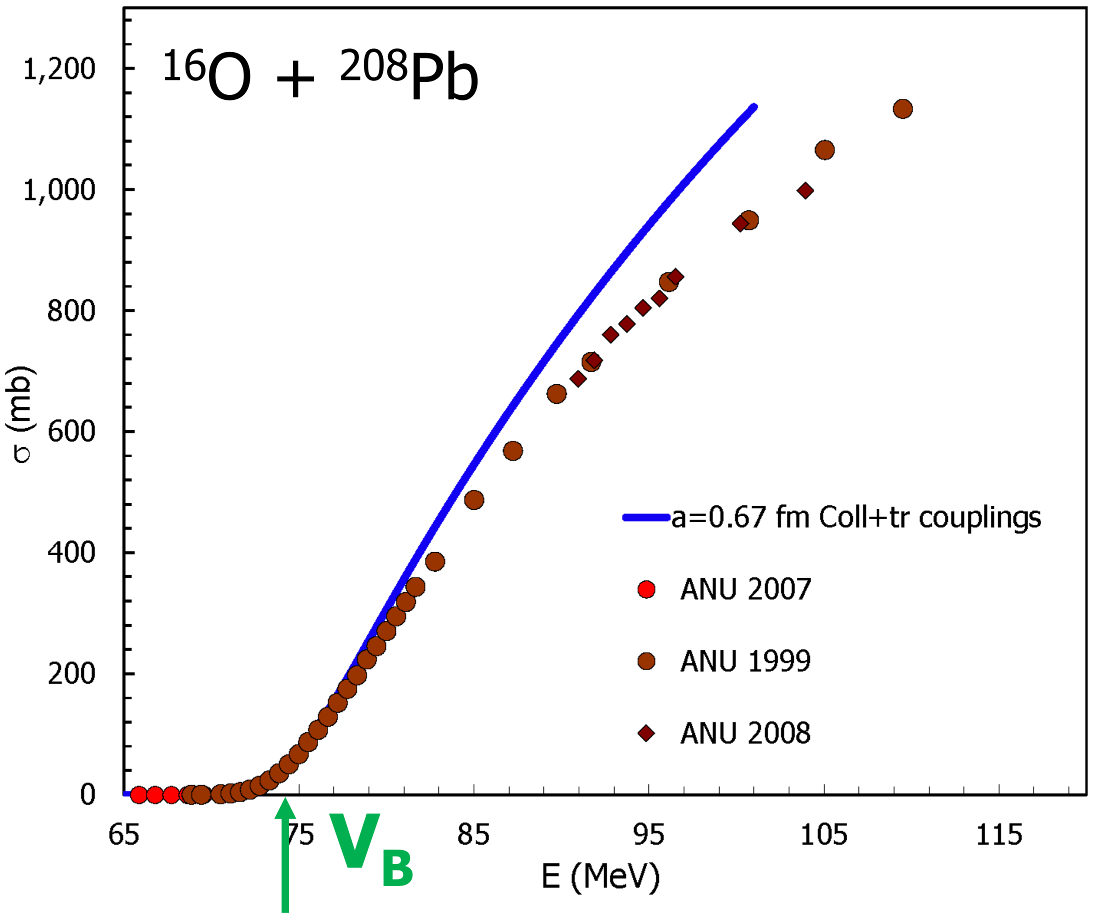


x 5 cross section mismatch

Below-barrier: no good!



Above-barrier: no good!



Coupled channels formalism is really a model to describe scattering:
What are the scattering characteristics at near-barrier energies?

Non-elastic backscattered events

PHYSICAL REVIEW C **78**, 034614 (2008)

Systematic study of the nuclear potential diffuseness through high precision back-angle quasi-elastic scattering

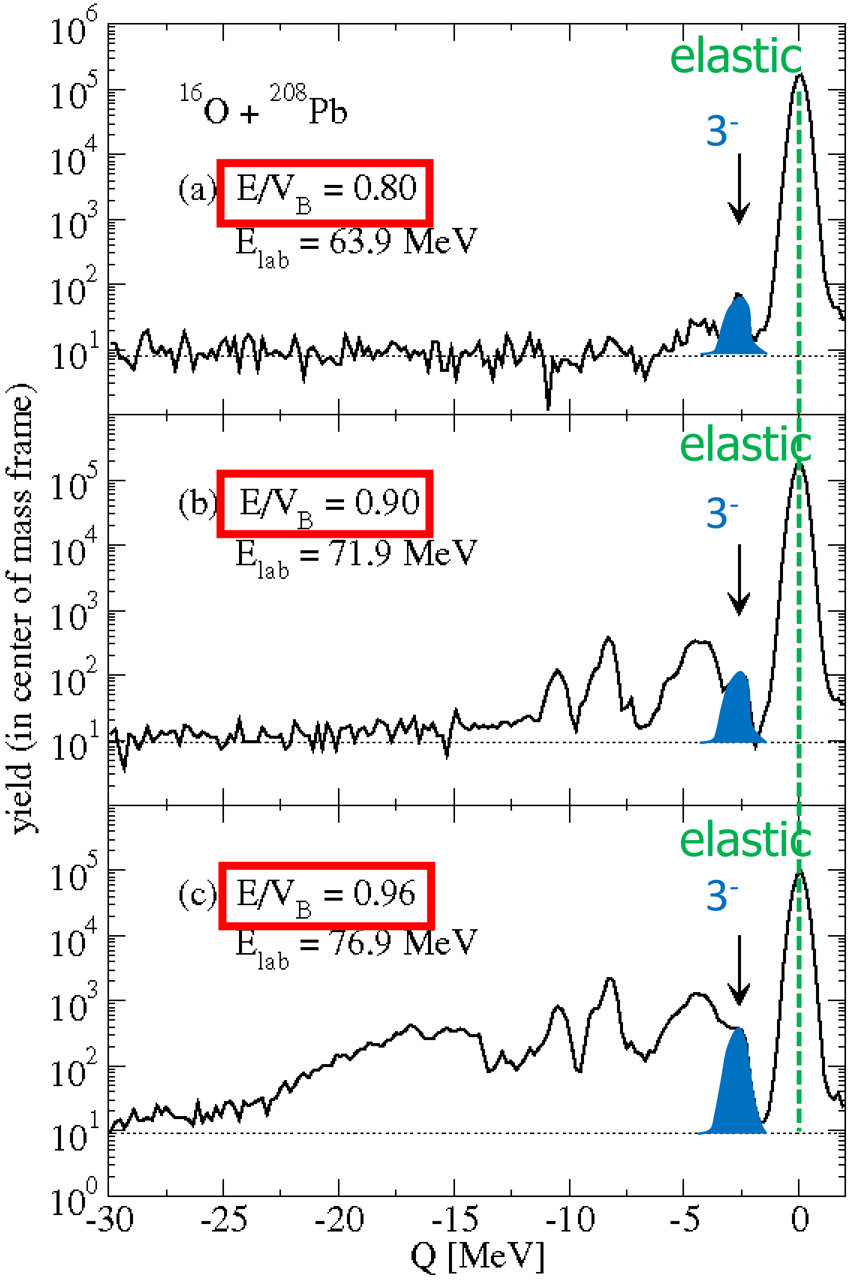
M. Evers, M. Dasgupta, D. J. Hinde, L. R. Gasques,* M. L. Brown, R. Rafiei, and R. G. Thomas†

Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

At E/V_B = 0.80, 3- state comprises most of the non-elastic yield (only ~4×10^{-4} of elastic yield)

At E/V_B = 0.96, 3- state comprises <5% of the non-elastic yield

What is all the rest? Transfer?

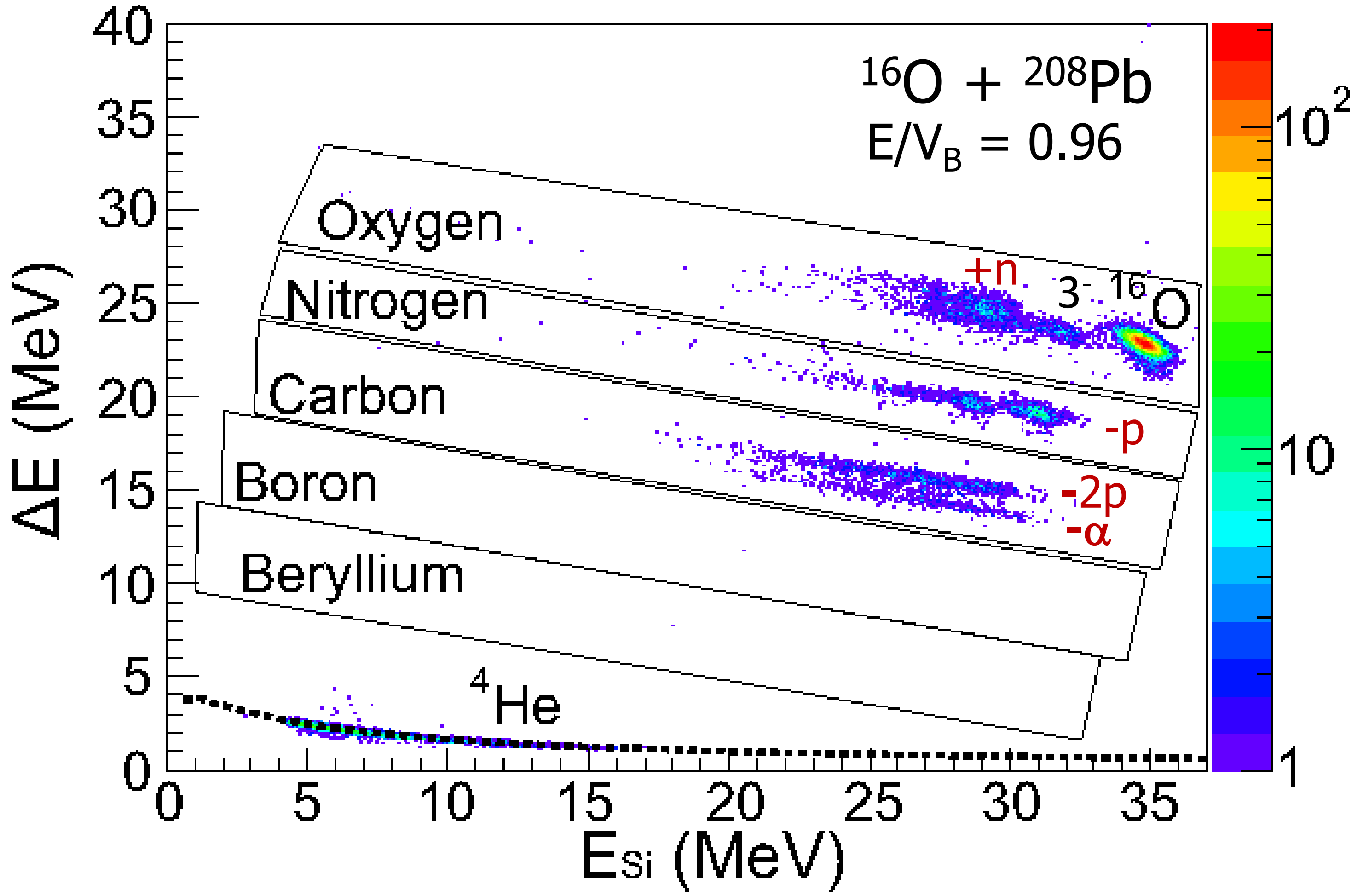


Transfer channels

PHYSICAL REVIEW C **94**, 024607 (2016)

Multinucleon transfer in $^{16,18}O$, ^{19}F + ^{208}Pb reactions at energies near the fusion barrier

D. C. Rafferty,* M. Dasgupta, D. J. Hinde, C. Simenel, E. C. Simpson, E. Williams, I. P. Carter, K. J. Cook, D. H. Luong, S. D. McNeil, K. Ramachandran,† K. Vo-Phuoc, and A. Wakhle‡
Department of Nuclear Physics, Australian National University, Canberra, Australia



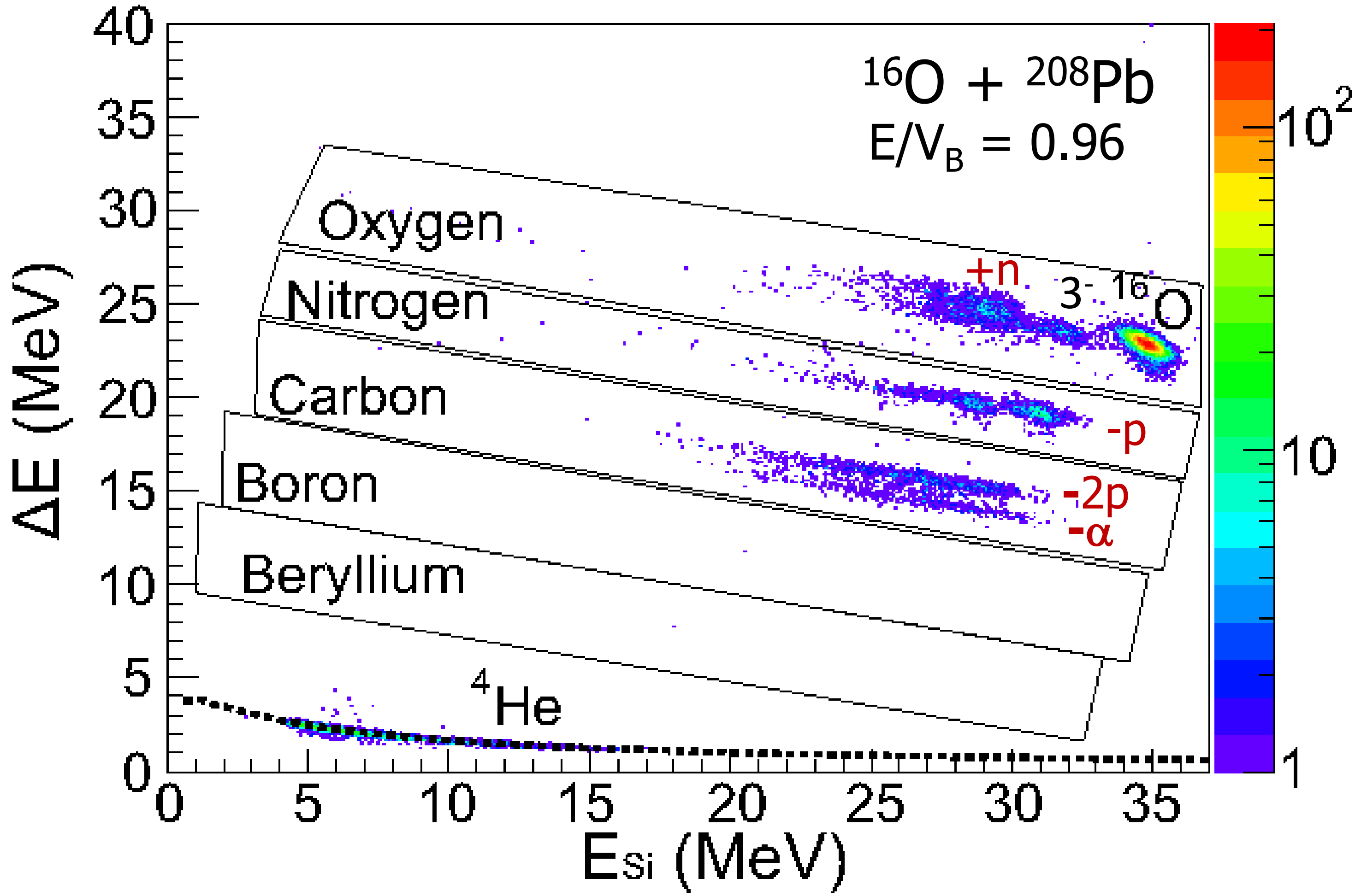
Backscattered non-elastic yield:
most is transfer: +n, -p, -2p, -α

Transfer channels

PHYSICAL REVIEW C **94**, 024607 (2016)

Multinucleon transfer in $^{16,18}O$, ^{19}F + ^{208}Pb reactions at energies near the fusion barrier

D. C. Rafferty,* M. Dasgupta, D. J. Hinde, C. Simenel, E. C. Simpson, E. Williams, I. P. Carter, K. J. Cook, D. H. Luong, S. D. McNeil, K. Ramachandran,† K. Vo-Phuoc, and A. Wakhle‡
Department of Nuclear Physics, Australian National University, Canberra, Australia



Backscattered non-elastic yield:
most is transfer: +n, -p, -2p, -α

Effective Q-value for charged transfers:
$Q_{eff} = Q_{gg} + E_X + \Delta V_{Coulomb}$

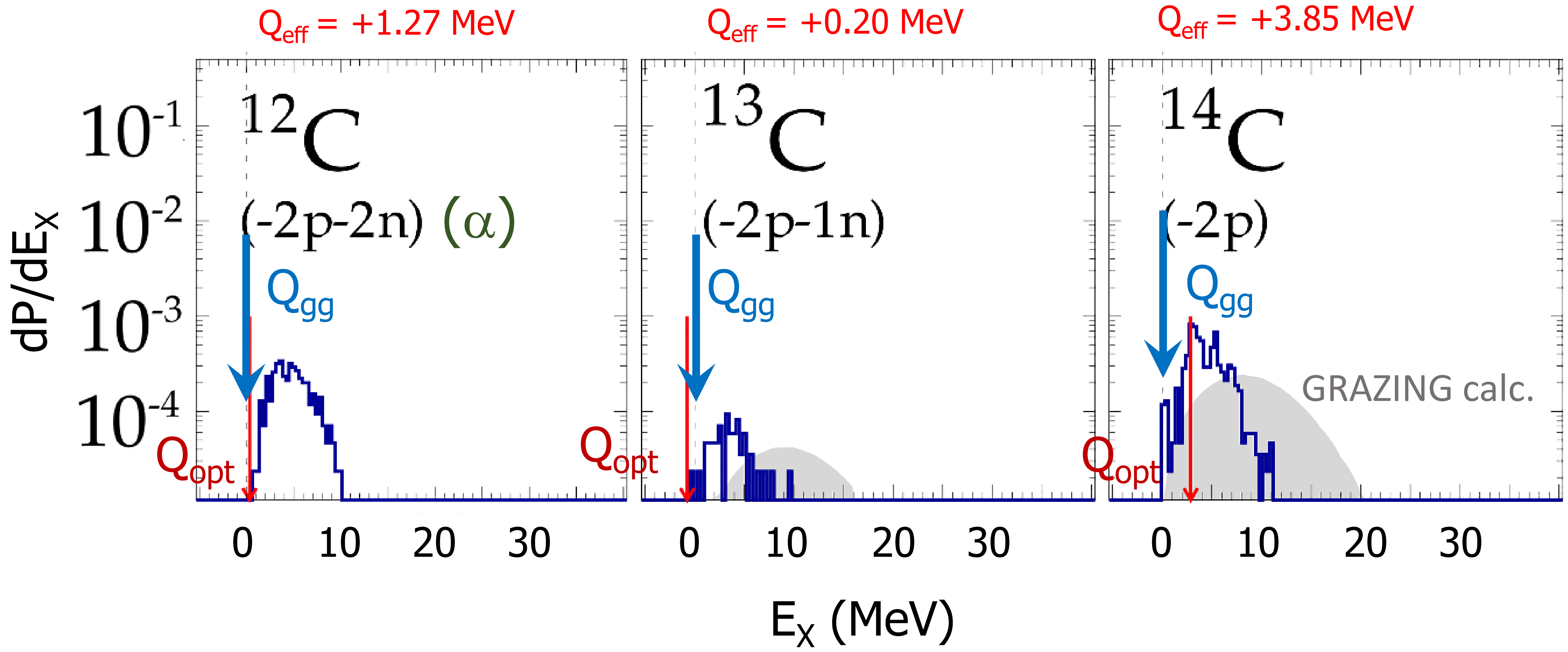
MeV	-p	-2p	-α
Qgg	-8.328	-13.532	-16.116
Qeff	+0.257	+3.848	+1.264

So what is the distribution of E_X ?

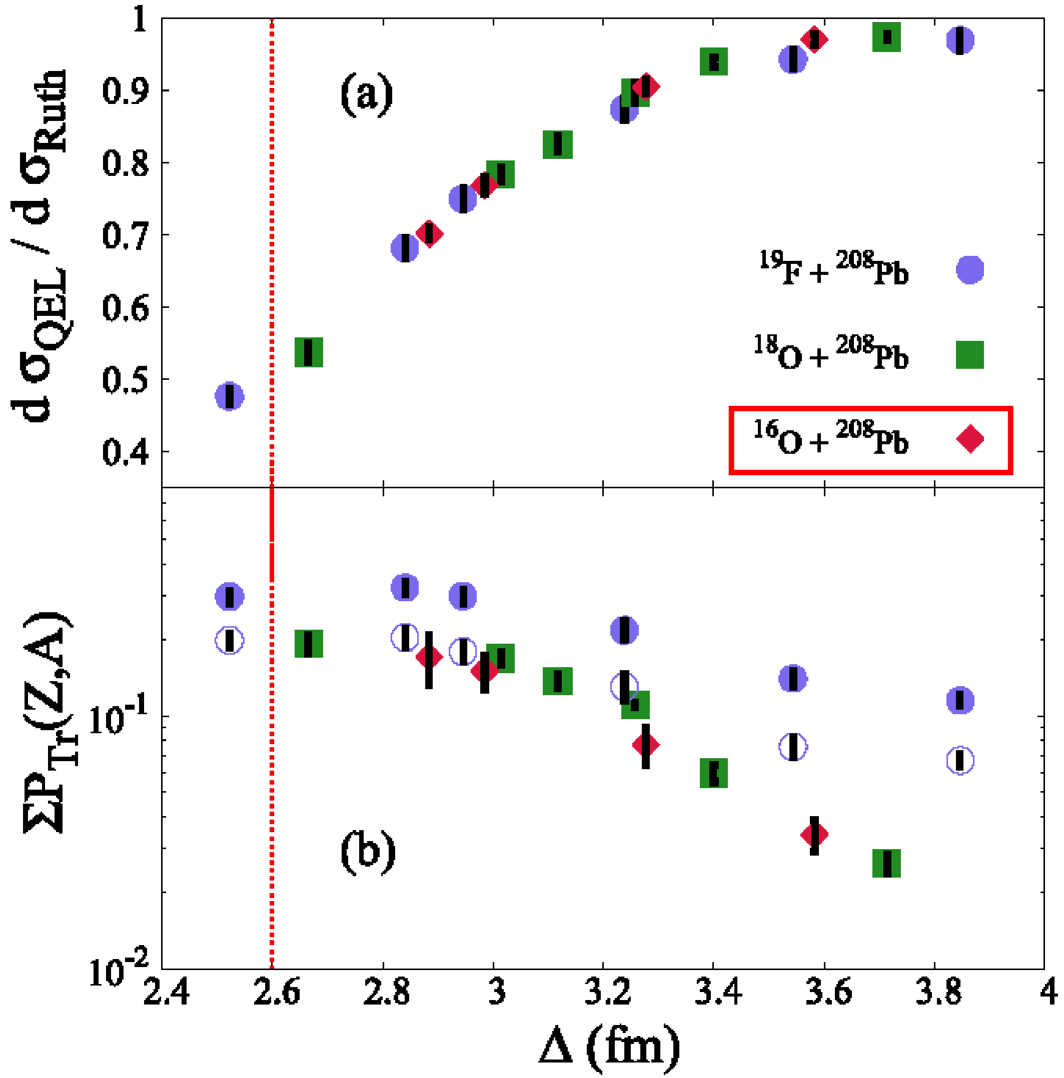
Transfer E_X distributions (Dominic Rafferty PhD thesis ANU 2020)

C isotopes: average E_X = 5 MeV, most likely in heavy transfer product ?

little Q_{gg} transfer



Sub-barrier transfer probabilities (Rafferty PRC 2016)



Δ ~ separation of nuclear surfaces

At the average barrier radius R_B (red line)

$d\sigma_{QEL}/d\sigma_{Ruth} = P_{reflected} = 0.5$

At R_B $P_{Tr} = 0.2$ to 0.3

- Reflected flux ~ 50% transfer
- E_X up to 10 MeV

At R_B+1 fm, $P_{Tr} = 0.03$

At R_B - 1 fm, P_{Tr} = ?? ….very large….

First conclusion:

Including only the 3-, 5- vibrational states and g.s. transfer channels in CC calculations misses >95% of the non-elastic scattering at the barrier !

Resulting questions:

Should coupling to transfer at E_X around 5 MeV be included in the C.C. framework in the same way as vibrational states?

Is all transfer coherent with the elastic channel? i.e. is all transfer reversible on the timescale of the scattering or tunneling process?

Should some transfers be treated as energy dissipative?

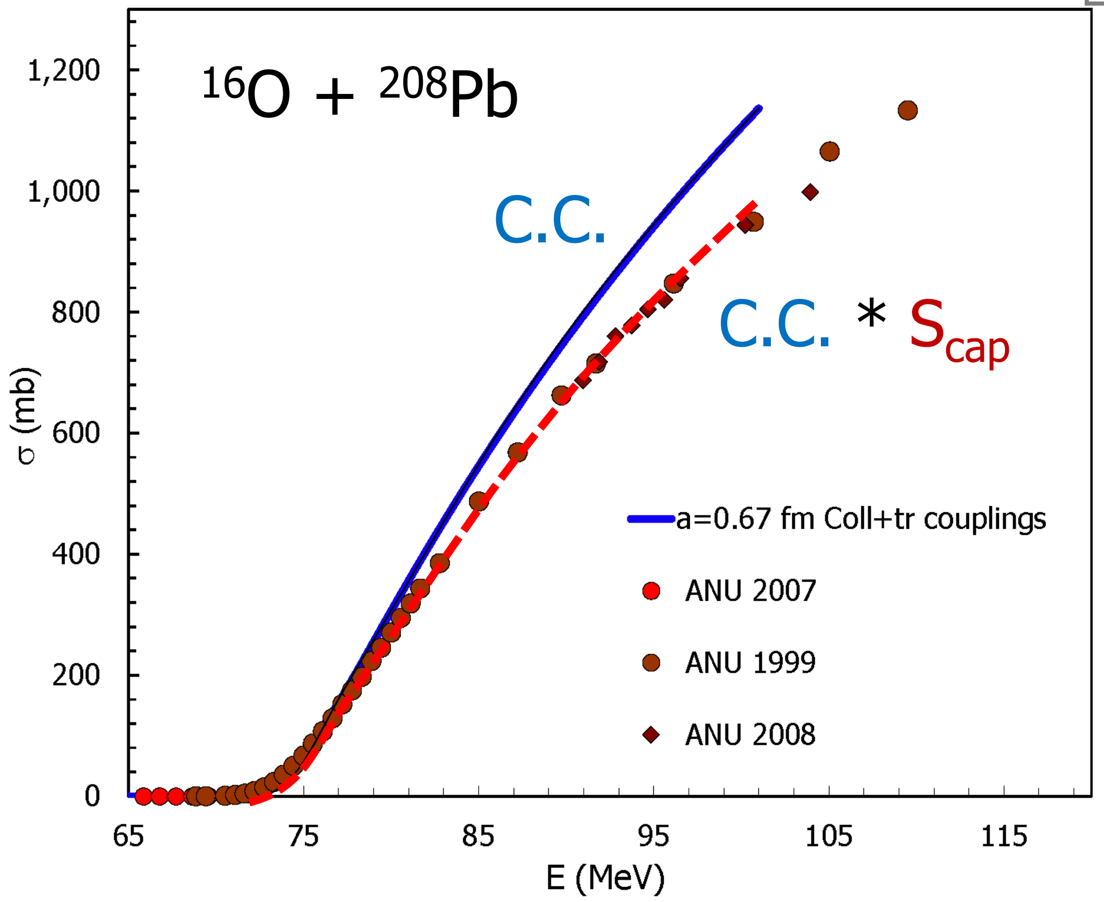
Systematic above-barrier fusion suppression (Newton 2004)

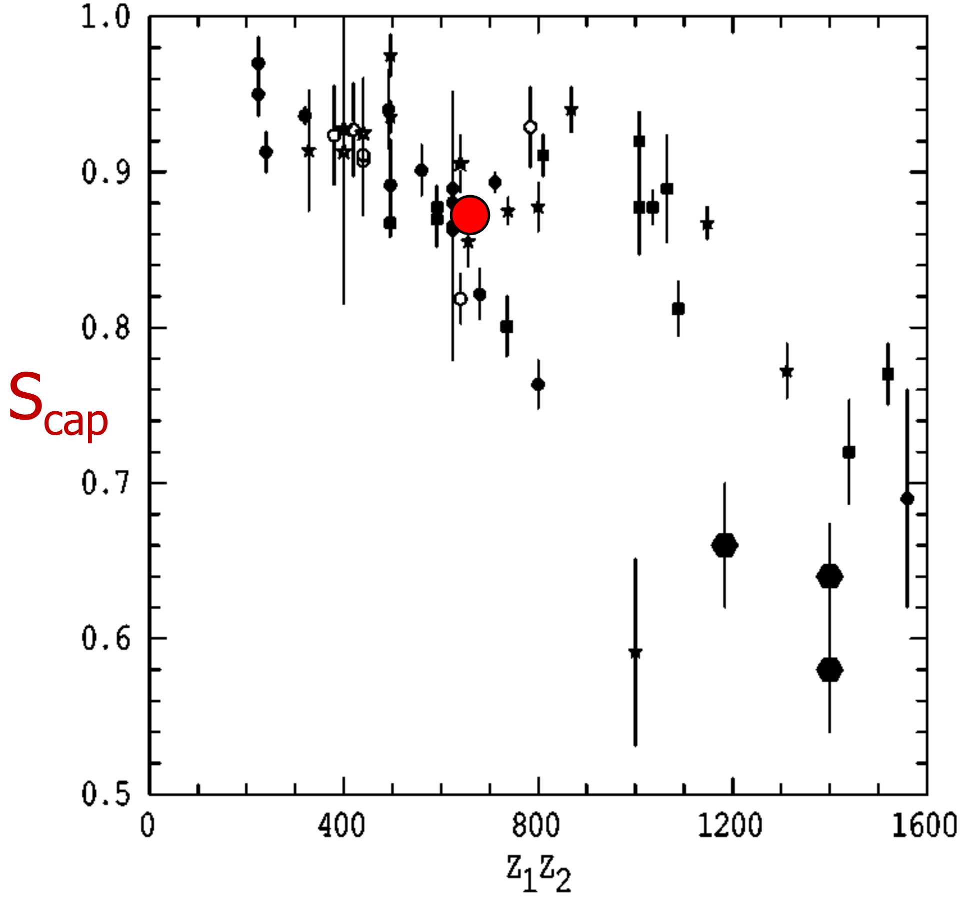
PHYSICAL REVIEW C **70**, 024605 (2004)

Systematic failure of the Woods-Saxon nuclear potential to describe both fusion and elastic scattering: Possible need for a new dynamical approach to fusion

J. O. Newton, R. D. Butt, M. Dasgupta, D. J. Hinde, I. I. Gontchar,* and C. R. Morton
Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

K. Hagino
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan





Systematic above-barrier fusion suppression (Newton 2004)

Capture suppression increases with Z_1Z_2

Matter overlap at V_B increases with Z_1Z_2

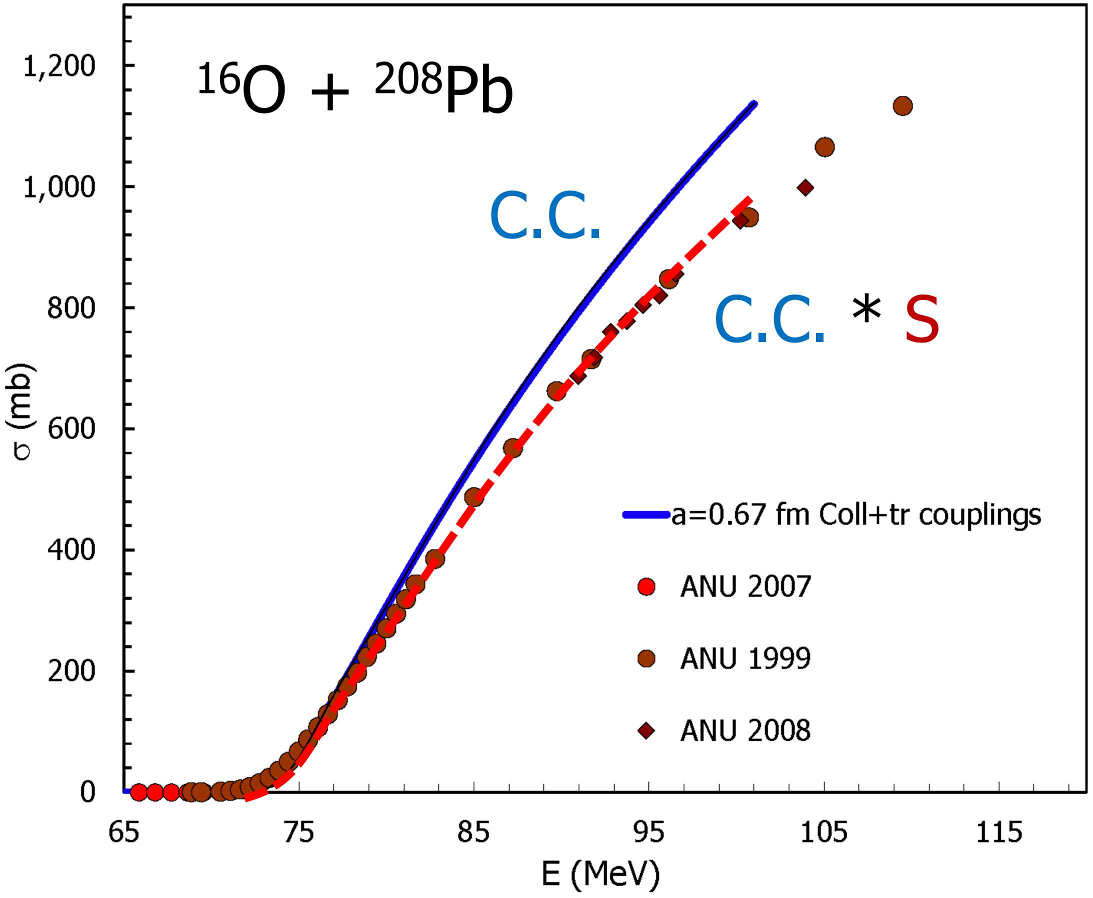
Transfer E_X increases with Z_1Z_2

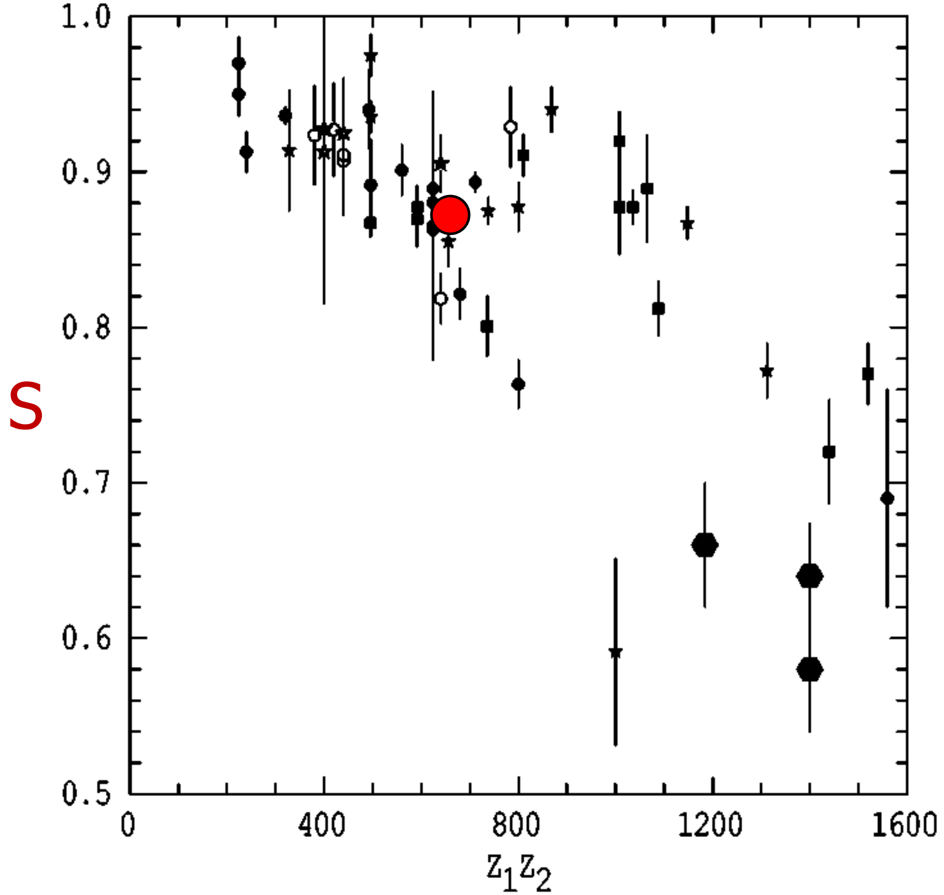
PHYSICAL REVIEW C **70**, 024605 (2004)

Systematic failure of the Woods-Saxon nuclear potential to describe both fusion and elastic scattering: Possible need for a new dynamical approach to fusion

J. O. Newton, R. D. Butt, M. Dasgupta, D. J. Hinde, I. I. Gontchar,* and C. R. Morton
Department of Nuclear Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

K. Hagino
Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan





How to identify thermalised energy loss following transfer

PHYSICAL REVIEW C **103**, 034603 (2021)

Energy dissipation and suppression of capture cross sections in heavy ion reactions

D. Y. Jeung,[*] D. J. Hinde, E. Williams, M. Dasgupta, E. C. Simpson, R. du Rietz,[†] D. H. Luong, R. Rafiei,[‡] M. Evers,[§] I. P. Carter, K. Ramachandran,[‖] C. Palshetkar, D. C. Rafferty, C. Simenel, and A. Wakhle[¶]
Department of Nuclear Physics, Research School of Physics, Australian National University, Canberra, ACT 2601, Australia

Concept:

Use fission to signal thermalised energy following transfer

Implementation:

Reactions with ^{232}Th target ➡ Fission for $E_X > 6$ MeV (B_f)

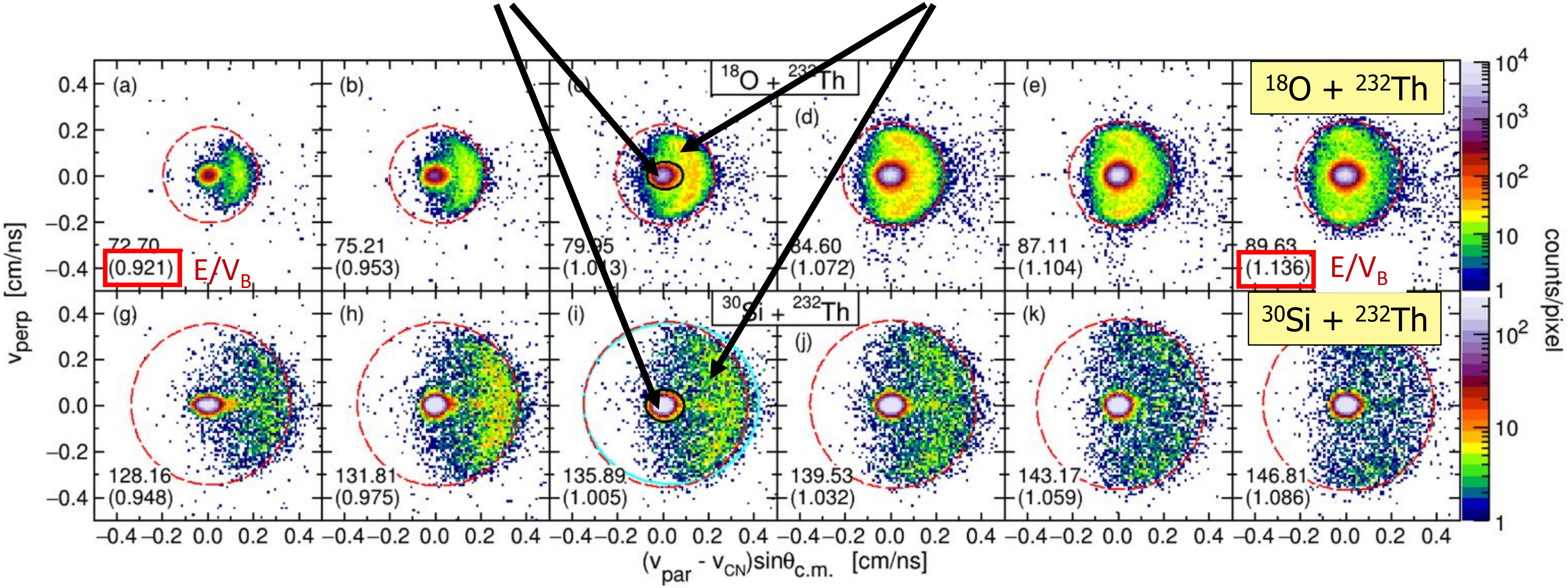
Separation of capture-fission and transfer-fission (Jeung 2021)

Use fission source velocity relative to C.N. velocity

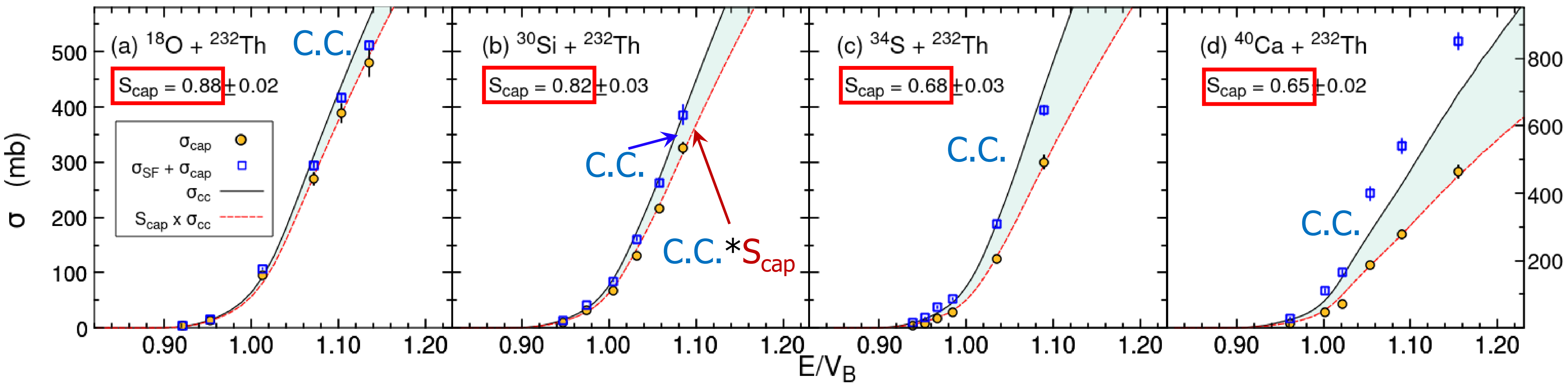
Account for geometrical efficiency

Fusion-fission + quasifission
2-body event: 2 FF (FMT fission)

Transfer-fission (sequential fission)
3-body event: projectile-like nucleus + 2 FF

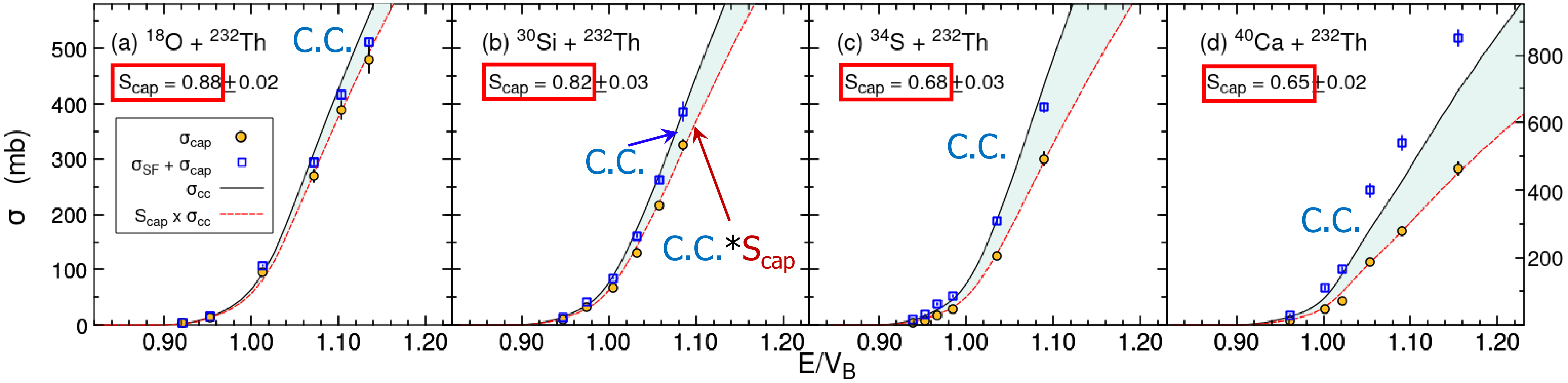


Thermalised energy loss in transfer (Jeung 2021)



Thermalised energy loss in transfer

(Jeung 2021)



(C.C. calculation)

Capture trajectory

No transfer or diss. energy → Capture → 2-body fission : probability $P_f^{cap}(E_X,J)$

Transfer/dissipated energy → Capture

Transfer/dissipated energy → No capture → 3-body fission : probability $P_f^{tr}(E_X,J)$

No capture → 2-body scattering (transfer)

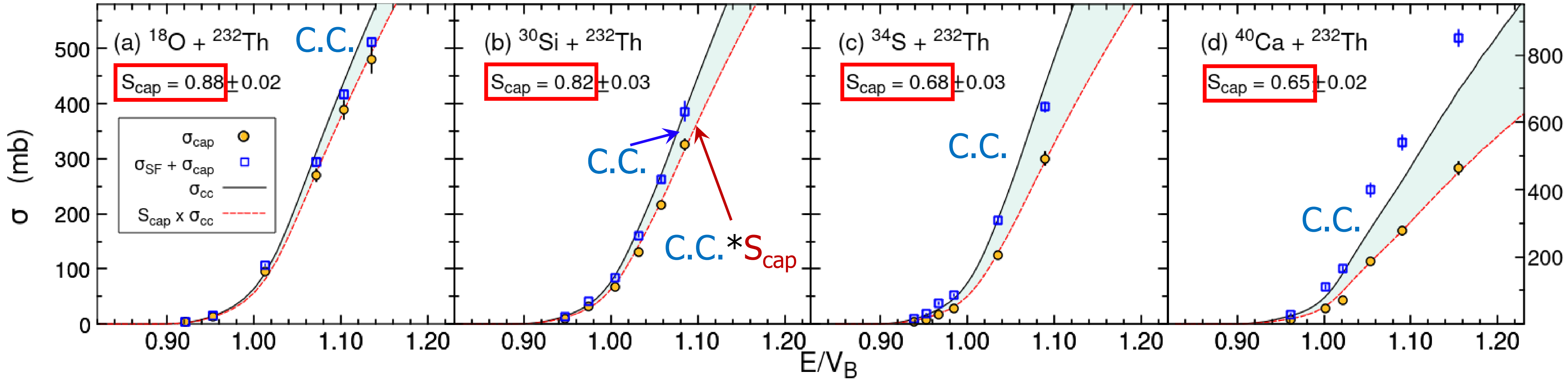
(Classical picture)

Peripheral trajectory → Transfer/dissipated energy — No capture → 3-body fission : probability $P_f^{tr}(E_X,J)$

No capture → 2-body scattering (transfer)

Peripheral trajectory → No transfer or diss. energy — No capture → 2-body scattering (inelastic)

Thermalised energy loss in transfer (Jeung 2021)



(C.C. calculation)
Capture trajectory

No transfer or diss. energy → Capture → 2-body fission : probability $P_f^{cap}(E_X,J)$

Transfer/dissipated energy → Capture

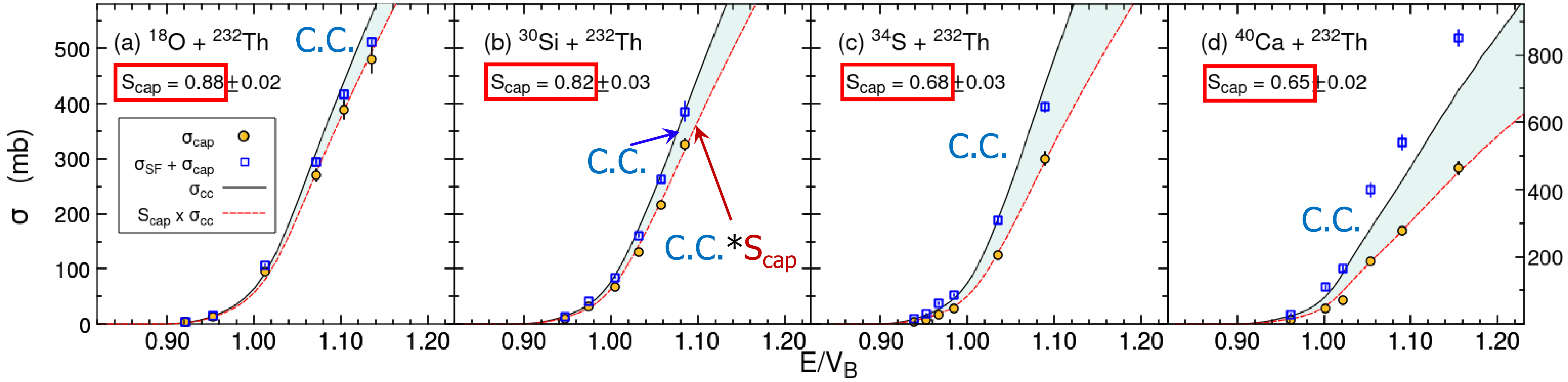
Transfer/dissipated energy → No capture → 3-body fission : probability $P_f^{tr}(E_X,J)$

(Classical picture)

Peripheral trajectory → Transfer/dissipated energy → No capture → 2-body scattering (transfer)

Peripheral trajectory → No transfer or diss. energy → No capture → 2-body scattering (inelastic)

Thermalised energy loss in transfer (Jeung 2021)



(C.C. calculation)
Capture trajectory

No transfer or diss. energy → Capture → 2-body fission : probability $P_f^{cap}(E_X,J)$

Transfer/dissipated energy → Capture

Transfer/dissipated energy → No capture → 3-body fission : probability $P_f^{tr}(E_X,J)$

No capture → 2-body scattering (transfer)

(Classical picture)

Peripheral trajectory

Transfer/dissipated energy — No capture → 3-body fission : probability $P_f^{tr}(E_X,J)$; → 2-body scattering (transfer)

No transfer or diss. energy — No capture → 2-body scattering (inelastic)

Thermalised energy loss (dissipated energy) in transfer reactions:

Correlated with above-barrier suppression of capture
Time scales of thermalisation and fusion?
Above-barrier: classical modelling may be adequate

Effects of transfer on tunneling?

Need quantum model
Need better understanding of nuclear potentials

- inner turning points
- channel-specific potentials

What happens in the tunneling regime?

Approaching the inner turning point, matter overlap increases.
Do transfer channels continue to evolve, taking flux out of energetically favourable channels, reducing the fusion cross section?

Conclusions

Understanding heavy ion capture and fusion:

(i) Capture excitation function: key observable

Logarithmic σ below-barrier, or log derivative

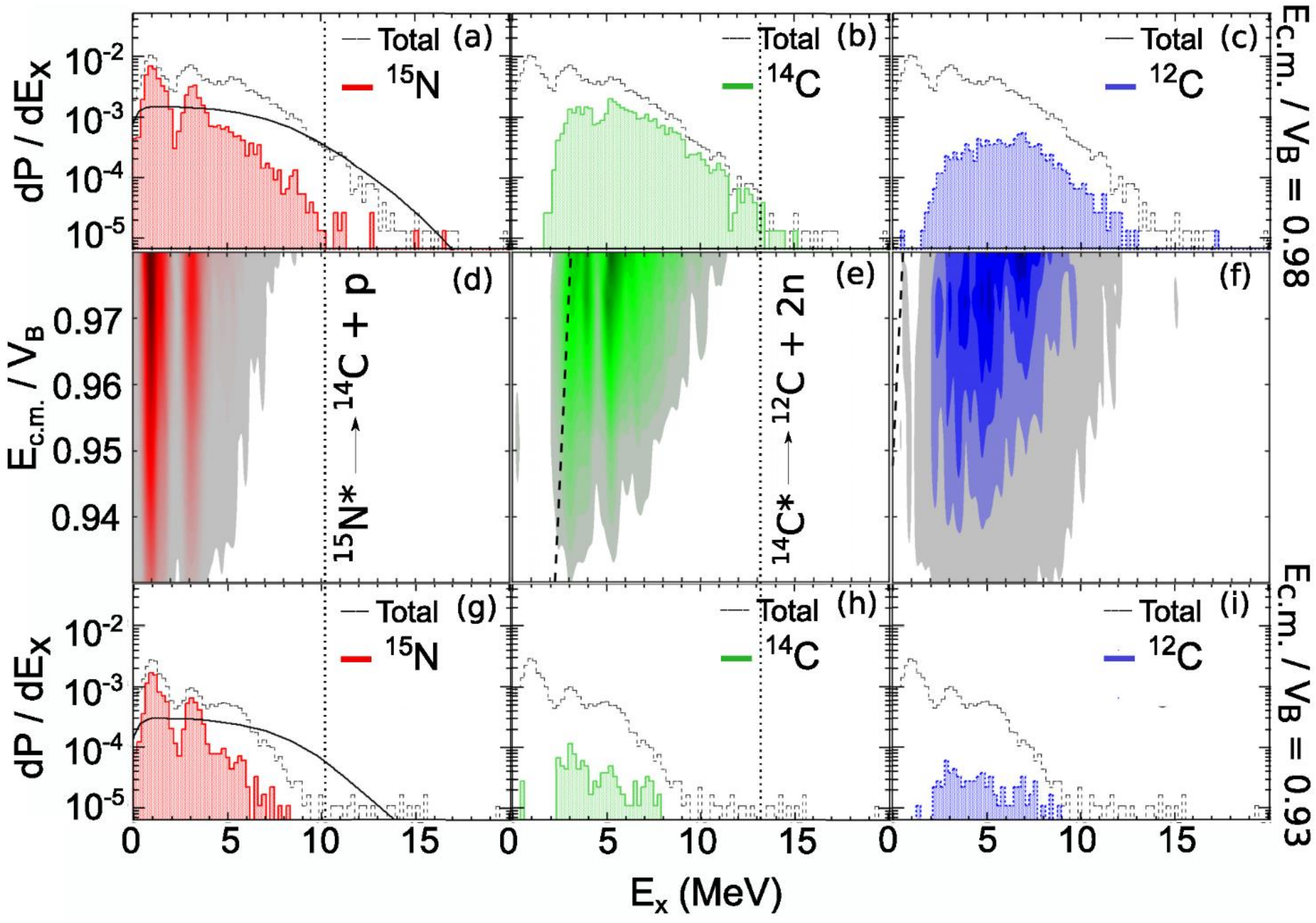
D(E) around the average barrier energy

Linear σ above-barrier, vs. E or 1/E

Not clear whether $\langle J^2 \rangle$ can bring independent information

(ii) Full transfer information and energy dissipation are missing ingredients in understanding capture – E_X distributions

(iii) Q.M. modelling in more dimensions (N,Z,E_X), including transitioning from coherent to irreversible couplings (dissipation)



Total (a)
15N
Total (b)
14C
Total (c)
12C
(d)
15N* → 14C + p
(e)
14C* → 12C + 2n
(f)
Total (g)
15N
Total (h)
14C
Total (i)
12C
dP / dEx
Ec.m. / VB
Ec.m. / VB = 0.98
Ec.m. / VB = 0.93
Ex (MeV)