Coherence and Dissipation in Nuclear Fusion

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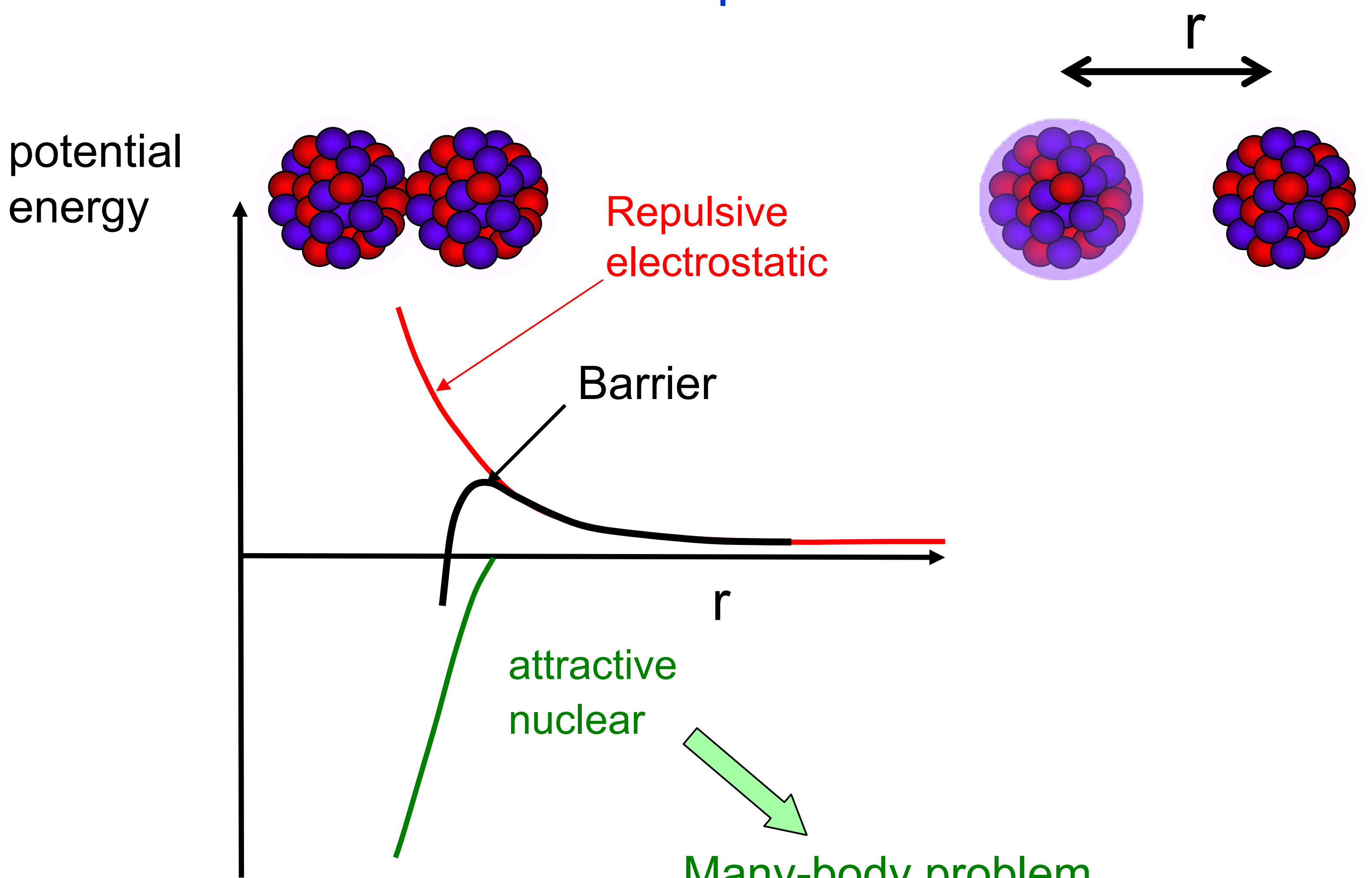
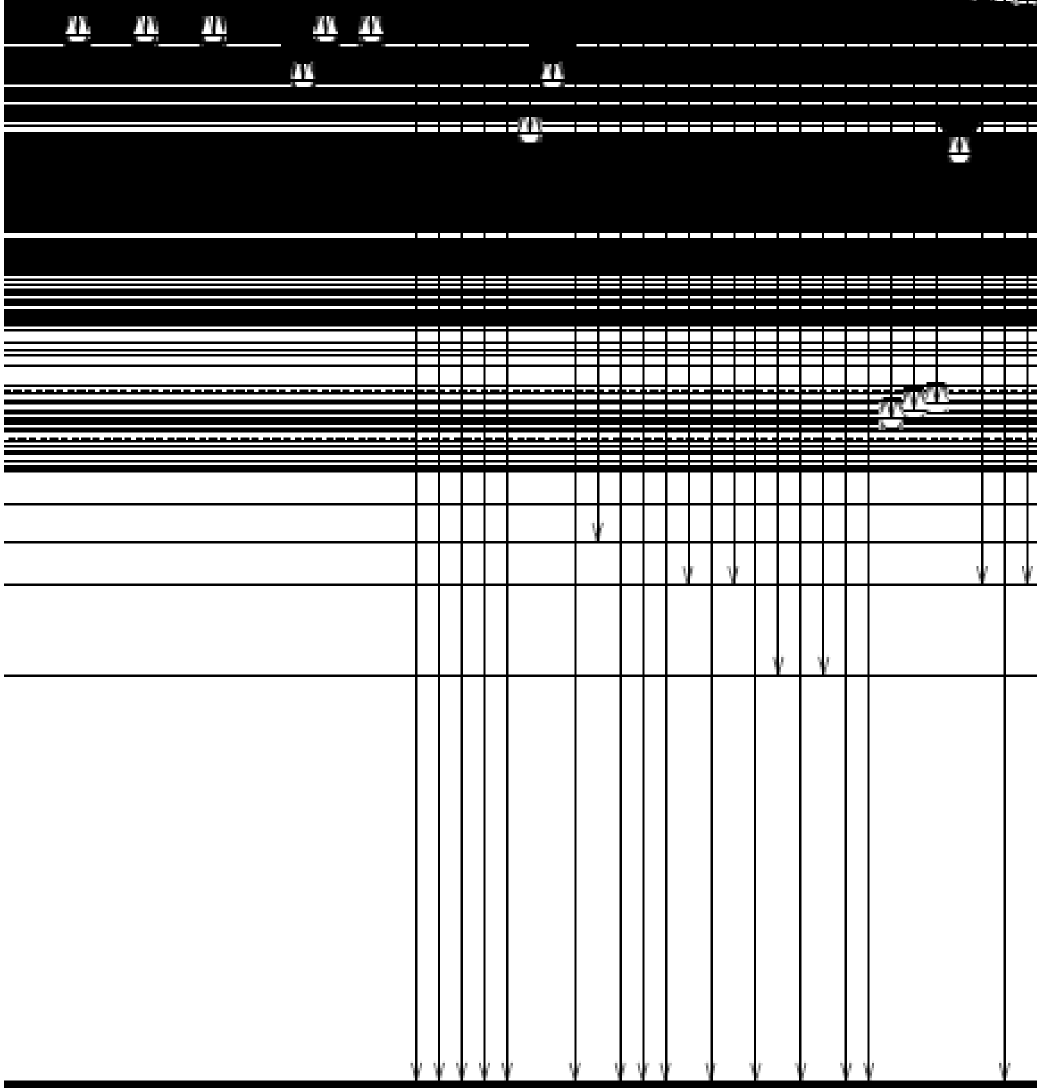
Inter-nuclear potential



Many-body problem

- no exact solution

- phenomenological potential



~ 5 MeV

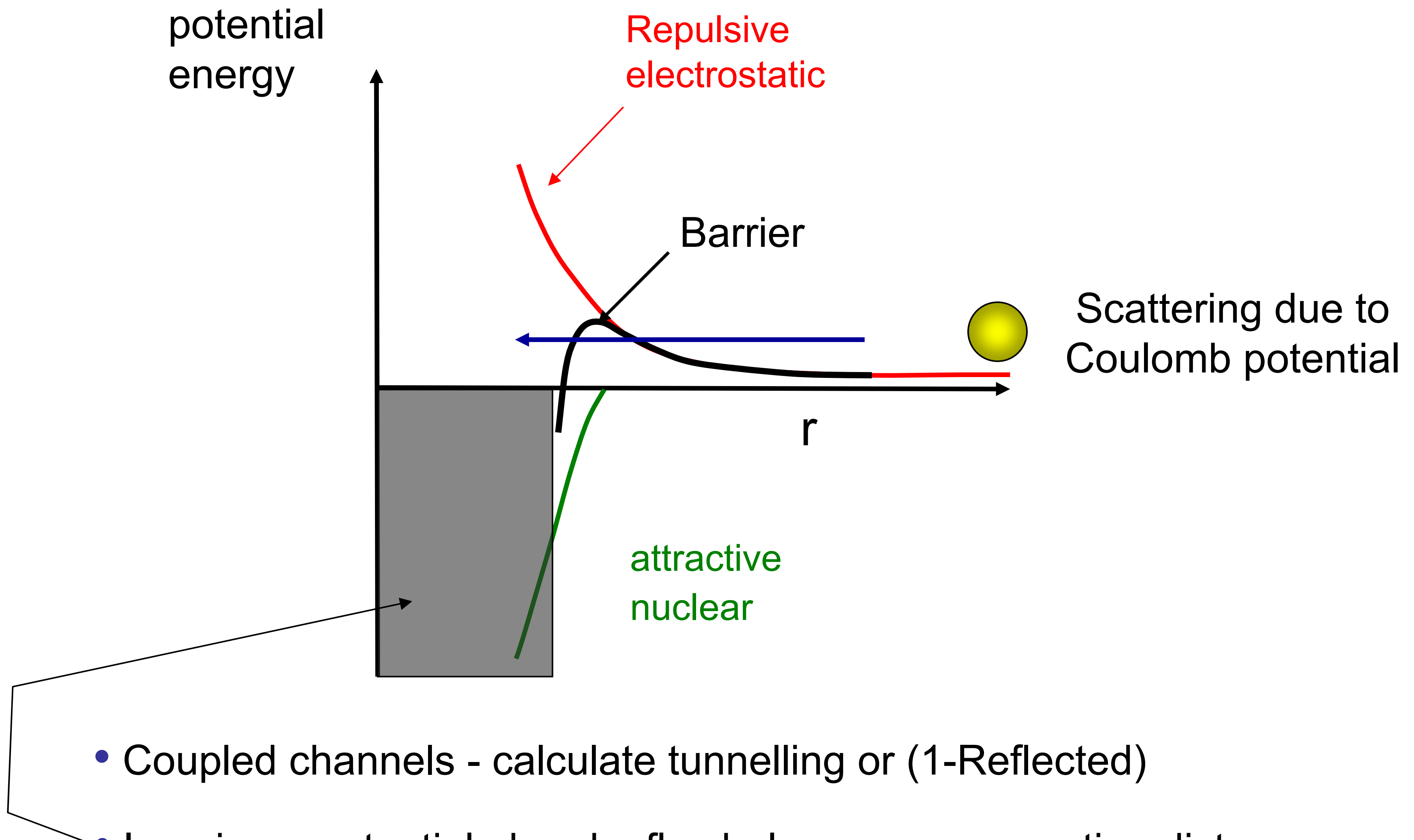
Collective states

~ 0.1 – few MeV

Density of quantum states increases rapidly with excitation energy

$$N \sim \exp\sqrt{2aE^*}$$

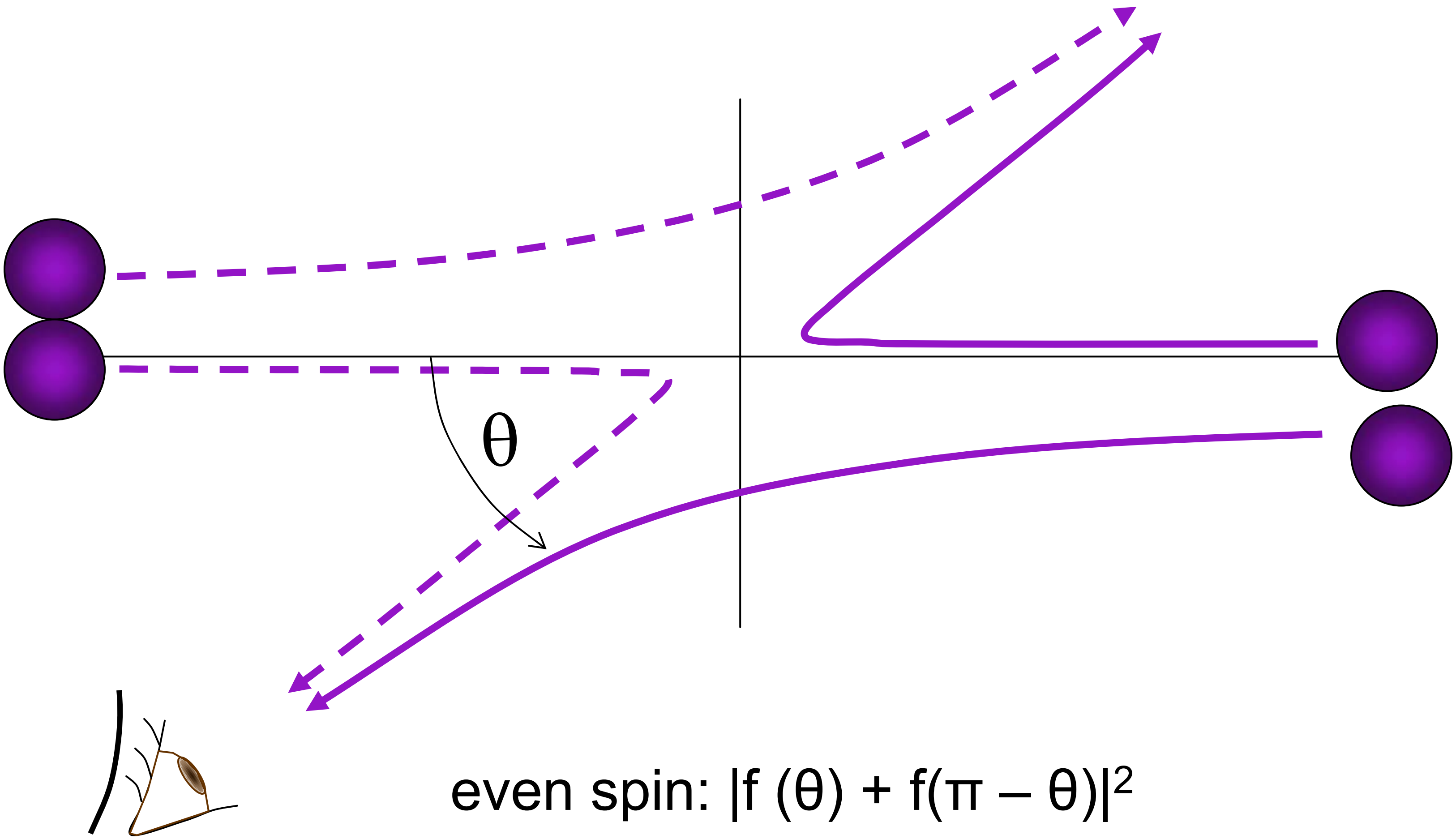
Identifying fusion in calculations



- Coupled channels - calculate tunnelling or (1-Reflected)
- Imaginary potential absorbs flux below some separation distance

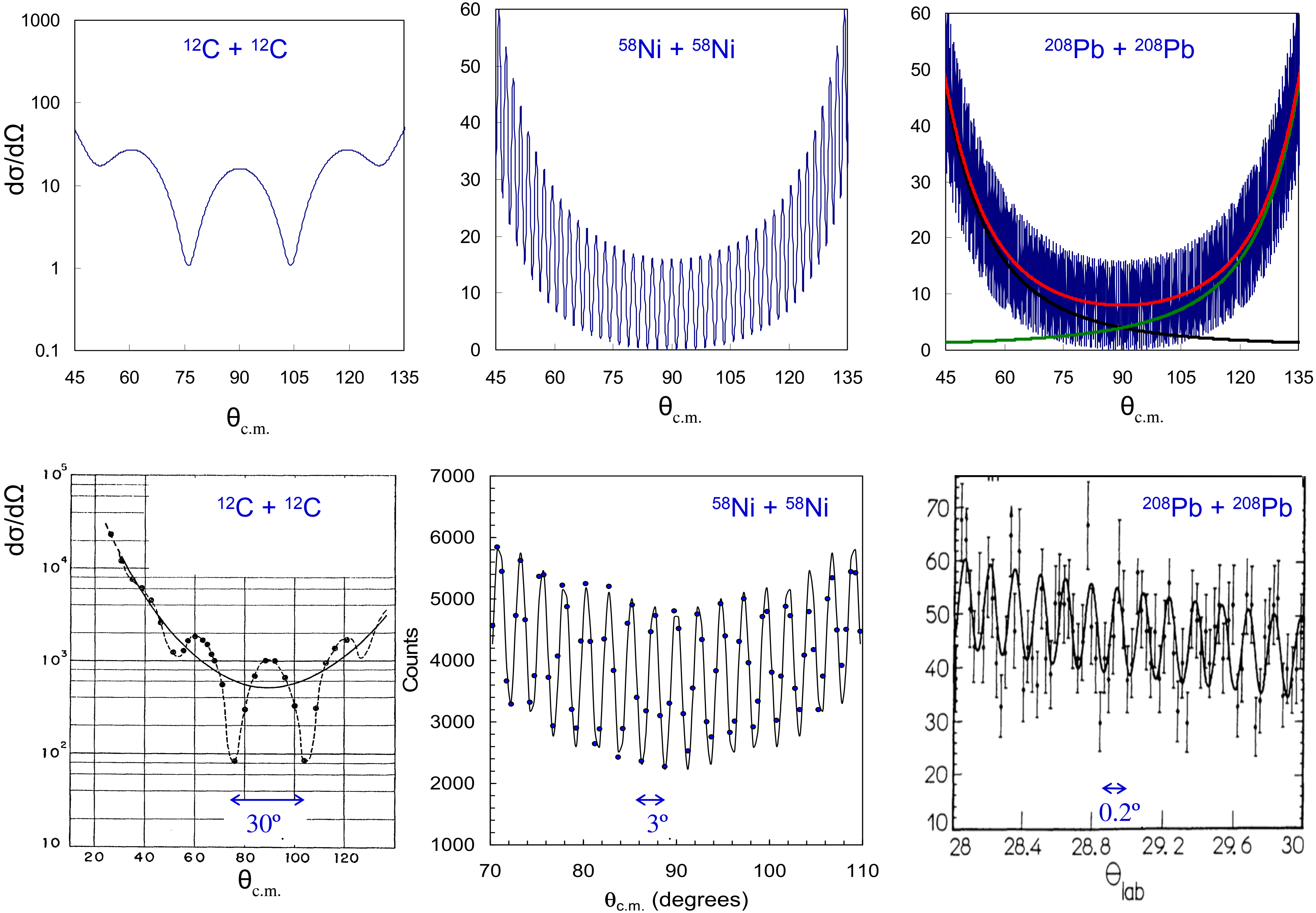
→ identified with “fusion” (loss of K.E. to heat bath not modelled)

Scattering of identical nuclei



even spin: $|f(\theta) + f(\pi - \theta)|^2$

$$|f(\theta)|^2 + |f(\pi - \theta)|^2 + \underbrace{f^*(\theta)\, f(\pi - \theta) \;\; f(\theta)\, f^*(\pi - \theta)}_{\text{Interference}}$$



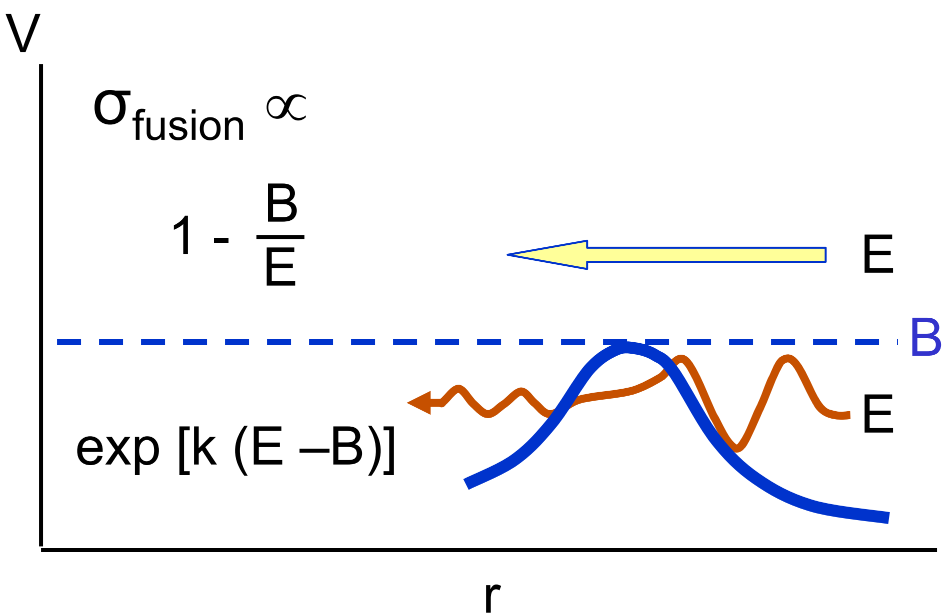
Bromley et al., Phys. Rev. 123, 878 (1961)

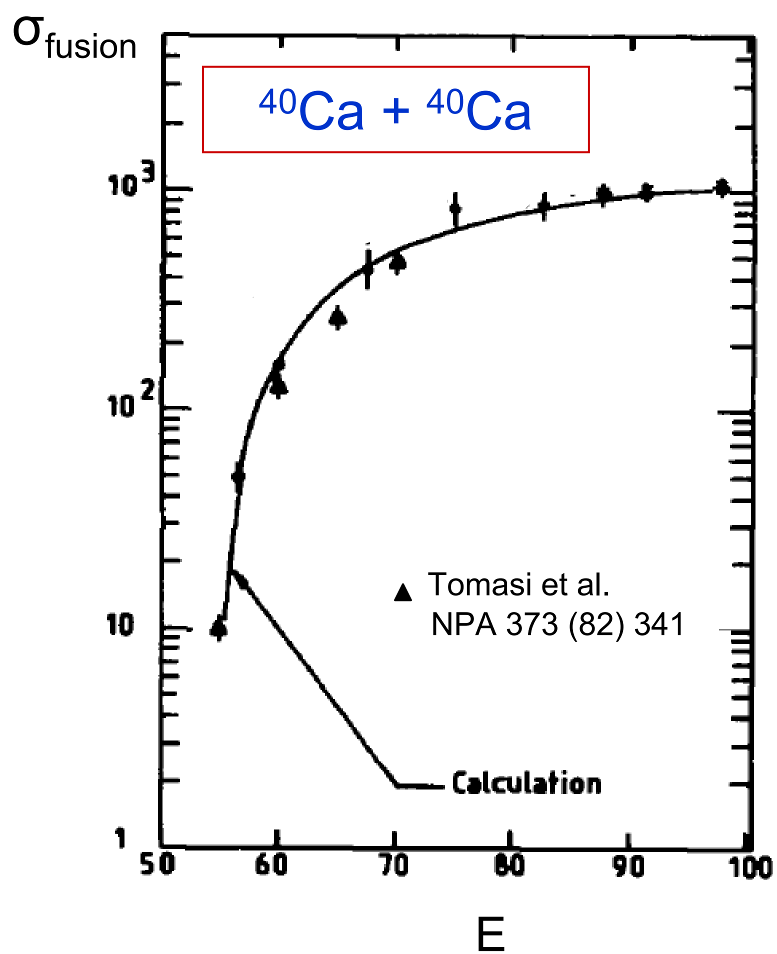
Hinde et al., PRC 76, 014617 (2007)

Villari et al., PRL 71, 2551 (1993)

Nuclear fusion – textbook treatment

Single fusion barrier



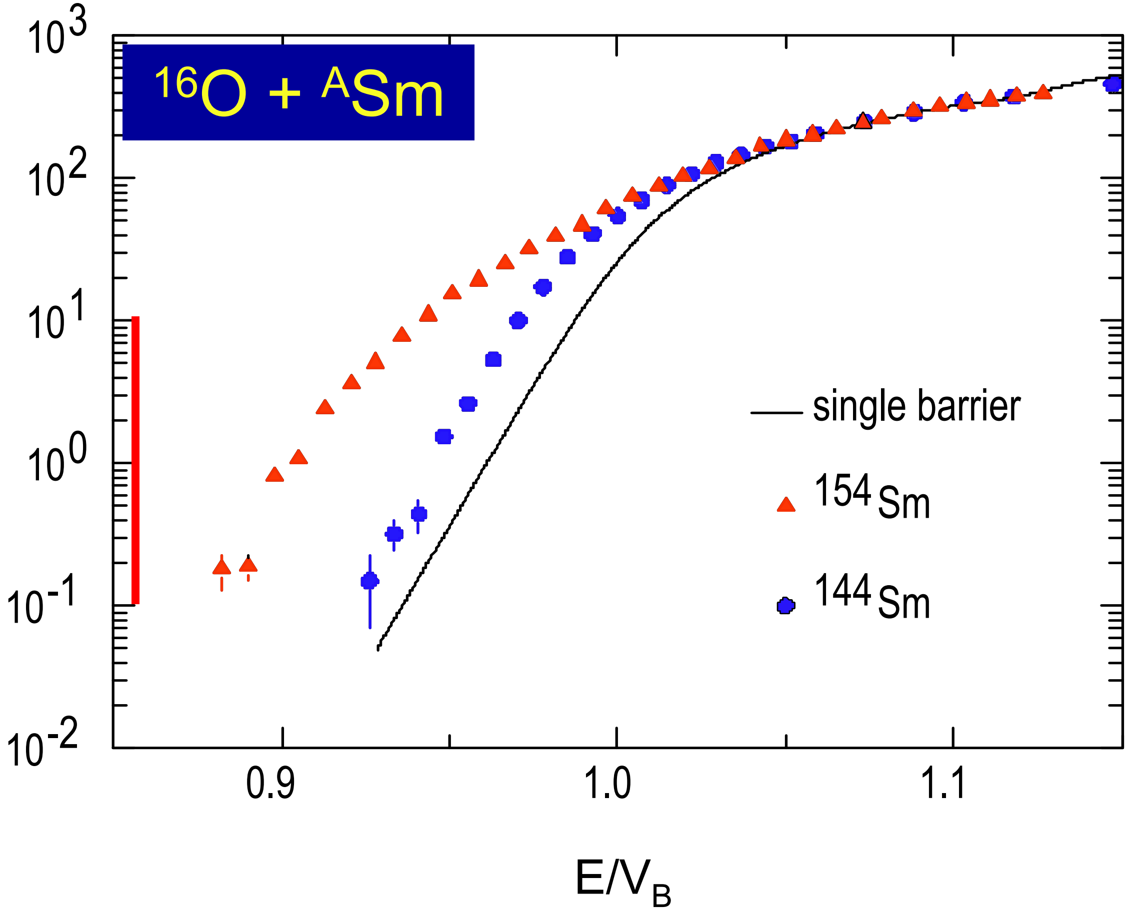


Single barrier model works well for fusion of light nuclei

Fusion of heavy nuclei: experiment vs. expectations

Fusion cross-section

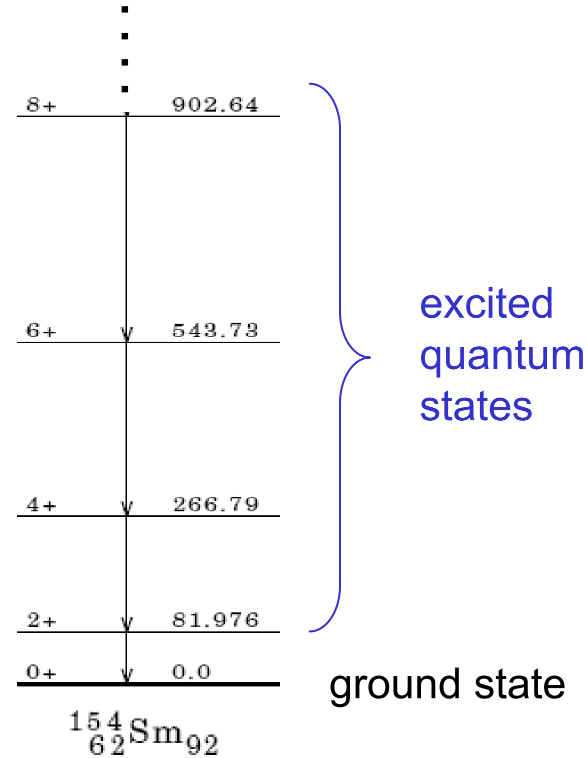
σ_{fus} (mb)



Wei et al, PRL, 67 (1991) 3368

Morton et al, PRL, 72 (1994)4074

Leigh et al, PRC52 (1995) 3151



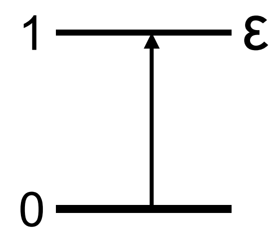
Colliding nuclei in coherent superposition of (low energy) collective states (purely quantum effect) → Coupled channels model

Not classical - excitation leads reduction in K.E. – reduced cross-sections

$$\sigma = (1-P_n)\,\boldsymbol{\sigma}(\mathbf{E}) + P_n\,\boldsymbol{\sigma}(\mathbf{E} - \boldsymbol{\varepsilon}_n)$$

Net cross-section smaller – opposite of what is seen

Two channels – approximation



F - coupling form factor

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + V(r) + \begin{pmatrix} 0 & F \\ F & \varepsilon \end{pmatrix} \right] \begin{pmatrix} u_0(r) \\ u_1(r) \end{pmatrix} = E \begin{pmatrix} u_0(r) \\ u_1(r) \end{pmatrix}$$

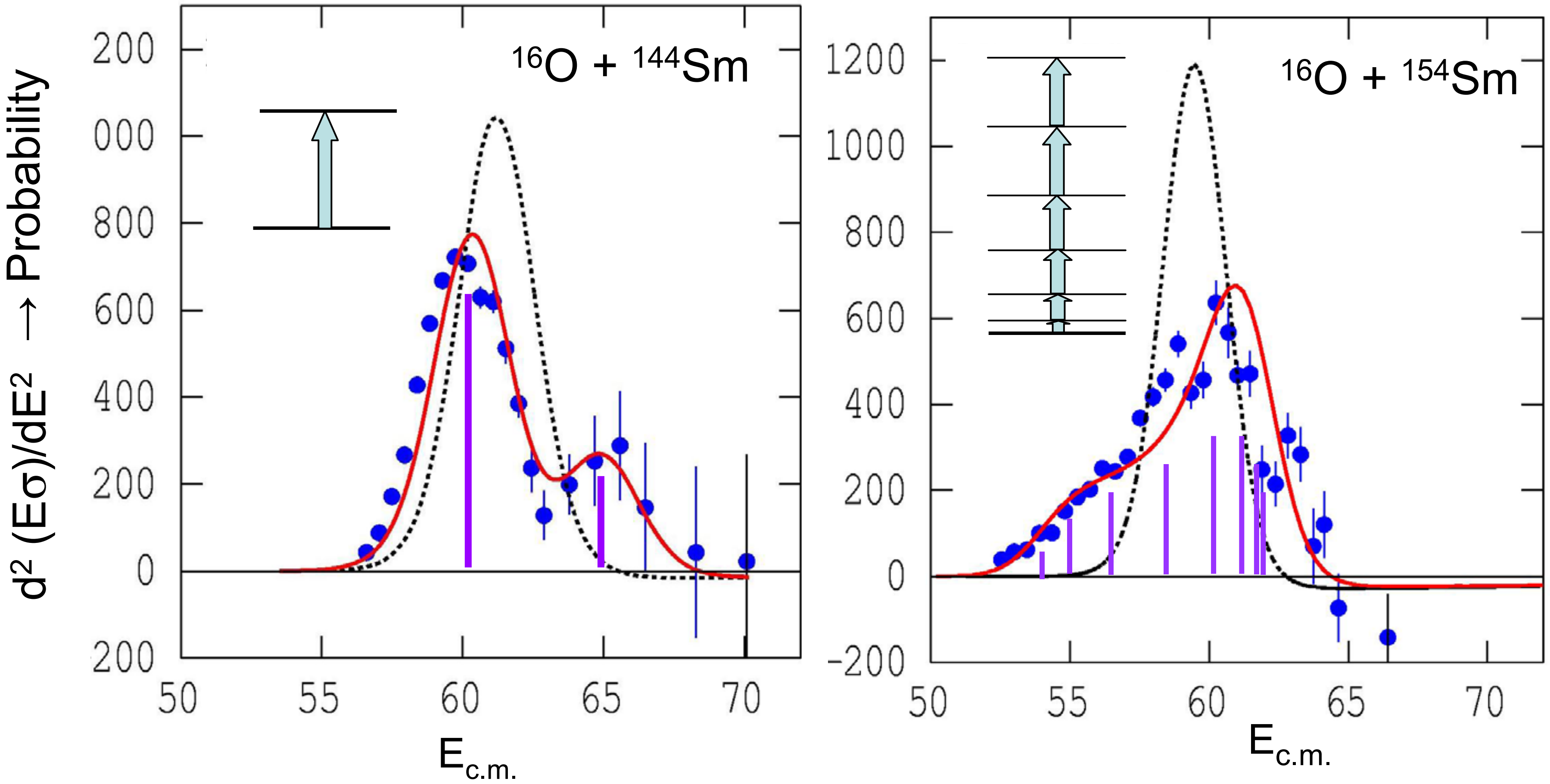
Eigenvalues of the coupling matrix: $\lambda_\pm = (\varepsilon \pm \sqrt{\varepsilon^2 + 4F^2})/2$

Coherent superposition ⇨ V splits into two eigen-barriers

$$\sigma = w_+ \sigma(E, V + \lambda_+) + w_- \sigma(E, V - \lambda_-)$$

Dasso et al, Nucl. Phys. A 405, 221

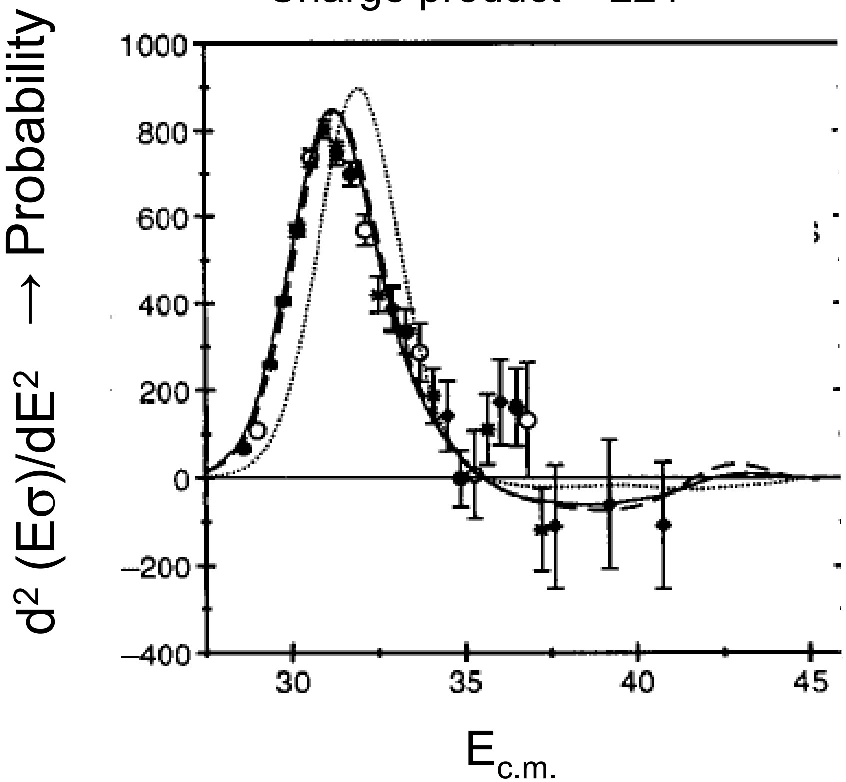
Rowley et al, Phys. Lett. B, 254,25



- Fusion as a function of energy – eigen-barriers are like filters
- Fusion - snapshot of the eigen-channels of the quantum system at contact
- Scattering – asymptotic populations of the basis states

$^{16}O + ^{58}Ni$

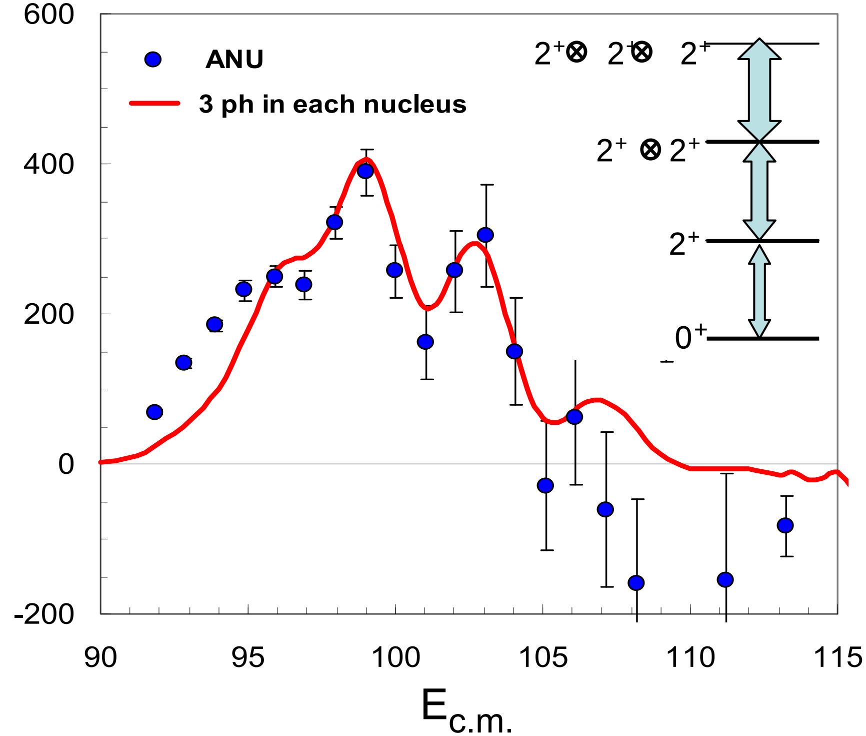
Charge product = 224



N. Keeley et al., Nucl. Phys. A628, 1 (1998)

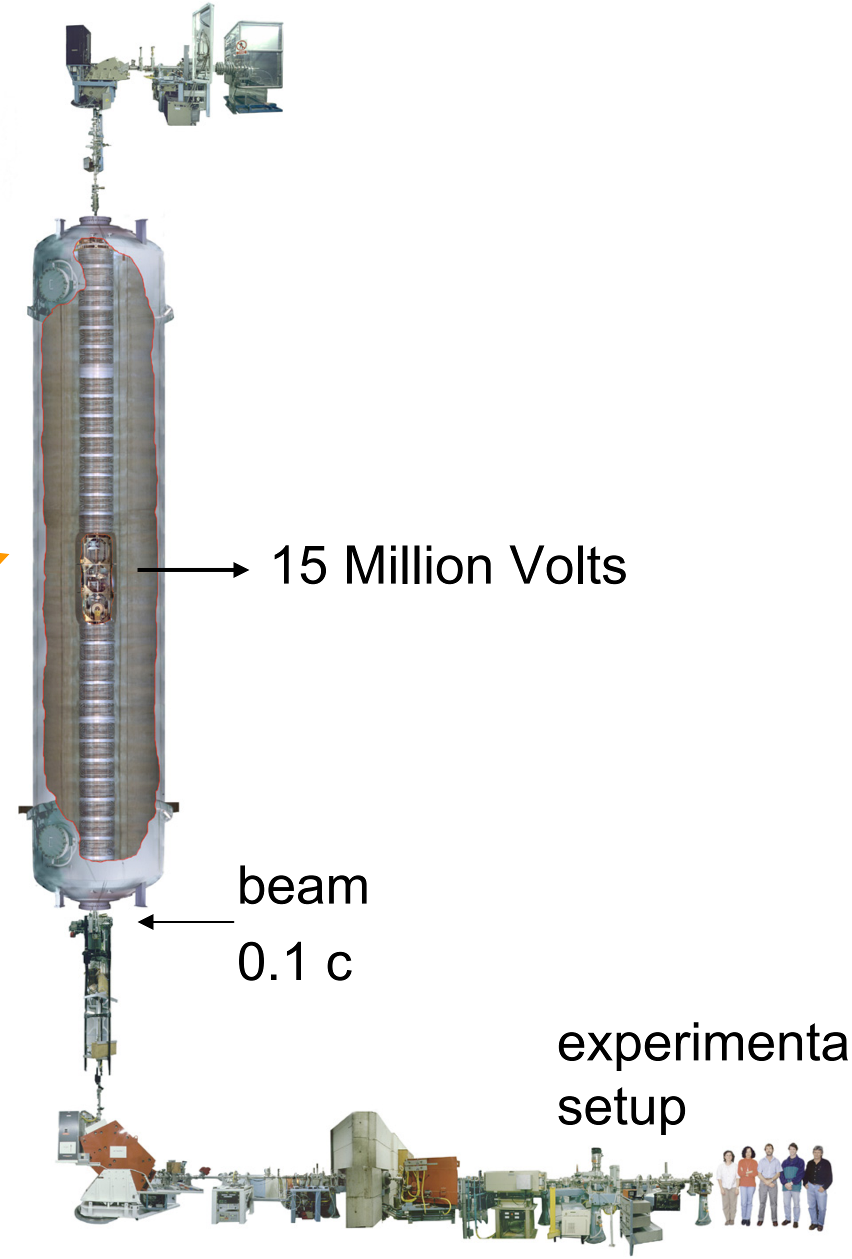
$^{58}Ni + ^{60}Ni$

Charge product 784



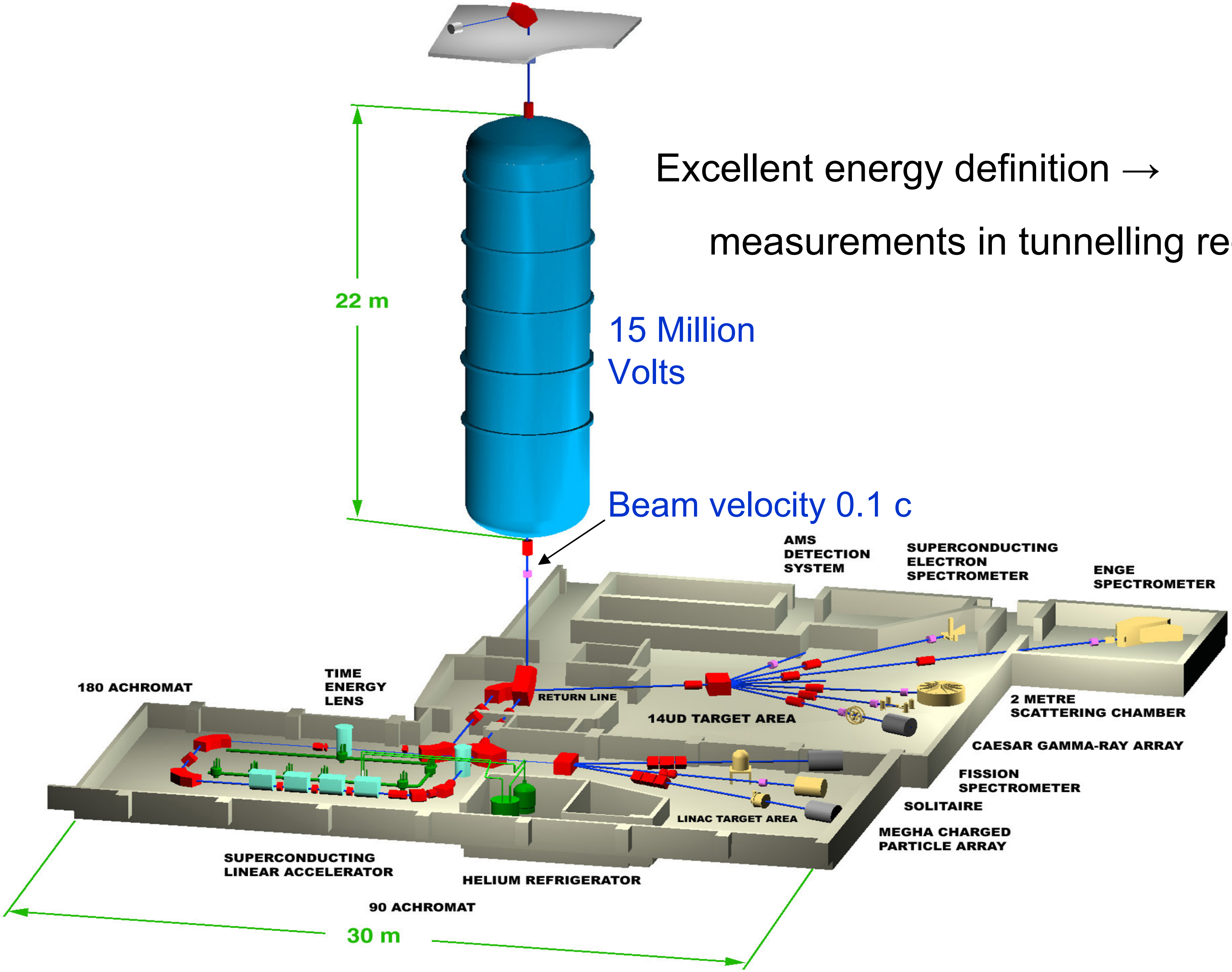
M. Rodriguez, ANU PhD work (2009)

Heavy Ion Accelerator facility at the ANU

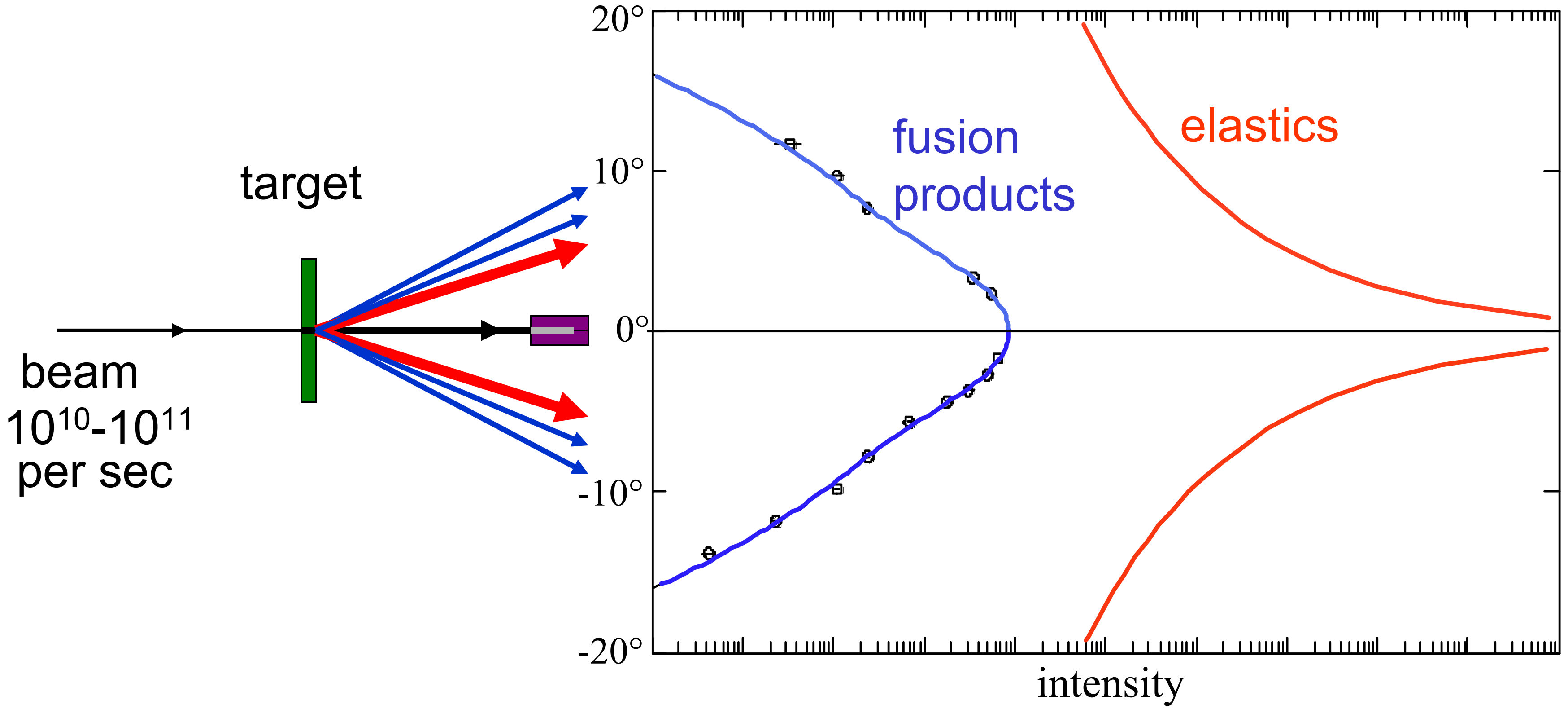


Excellent energy definition →

measurements in tunnelling regime

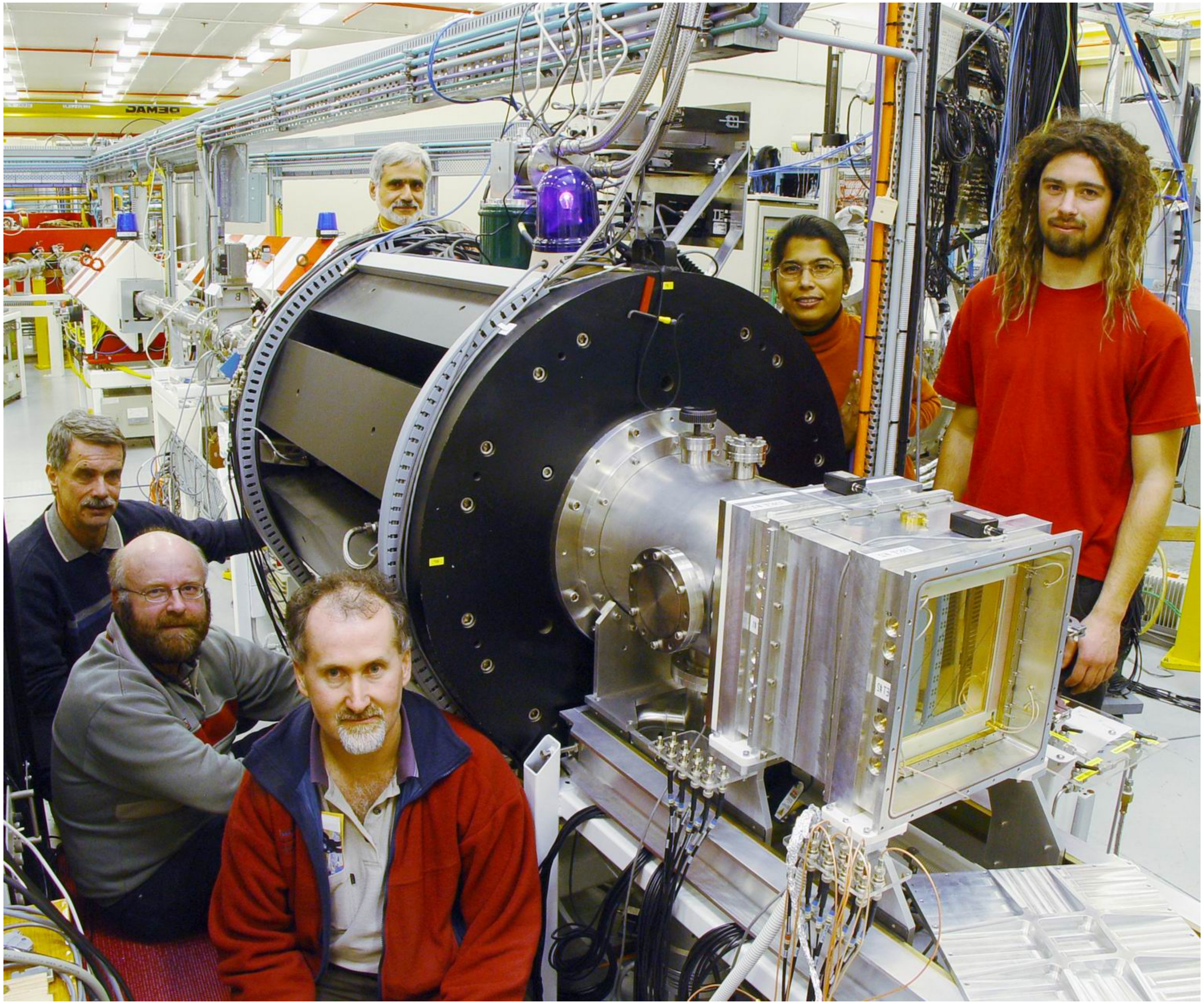


Fusion measurements – the challenge



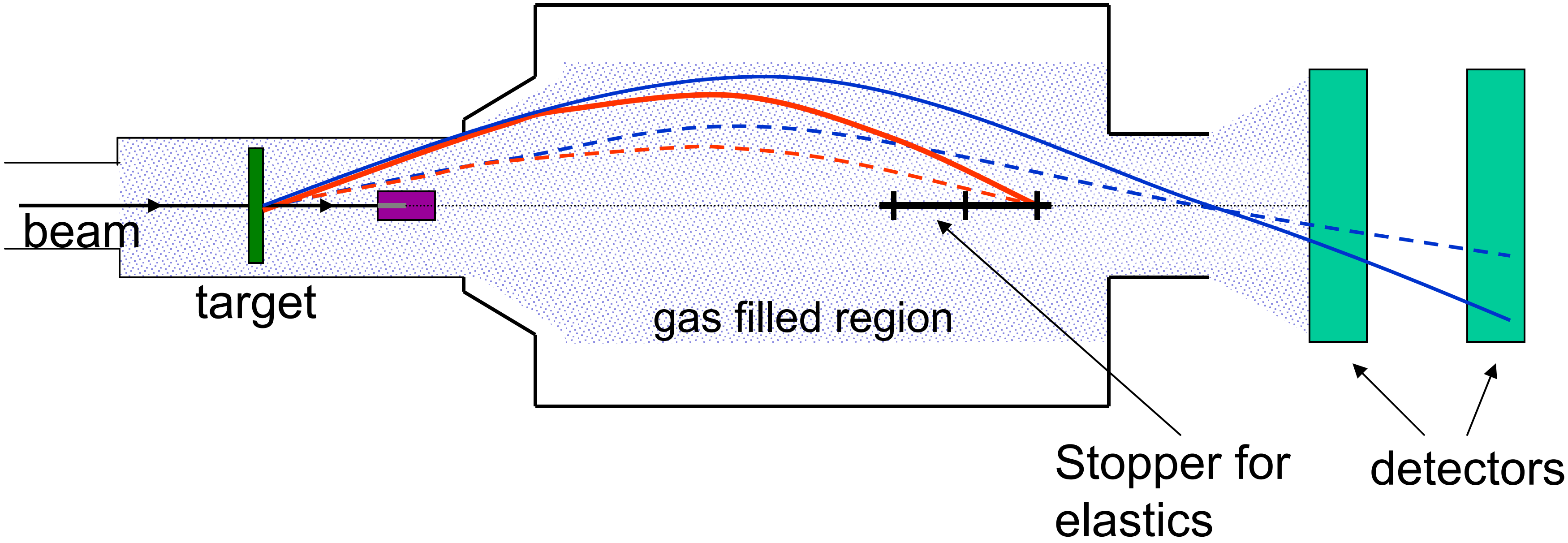
- Beam, fusion products, elastic scattering – all forward focussed
- Stop direct beam (10^{10} –10^{11} nuclei/sec)
- 10^4 – 10^{12} elastics for every fusion product!

SOLITAIRE – new generation fusion detection system



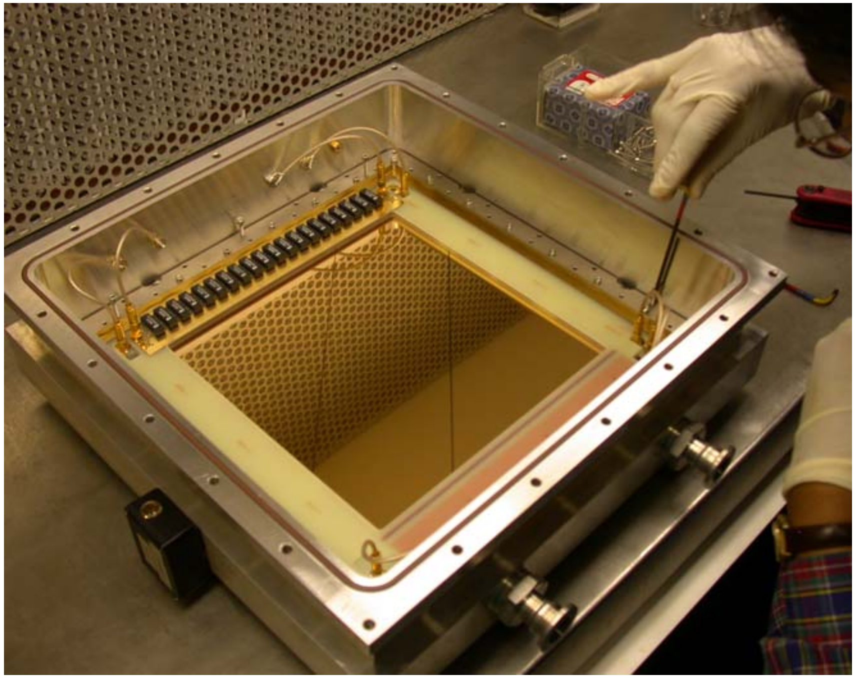
M.Rodriguez et al, NIM A614 (2010) 119

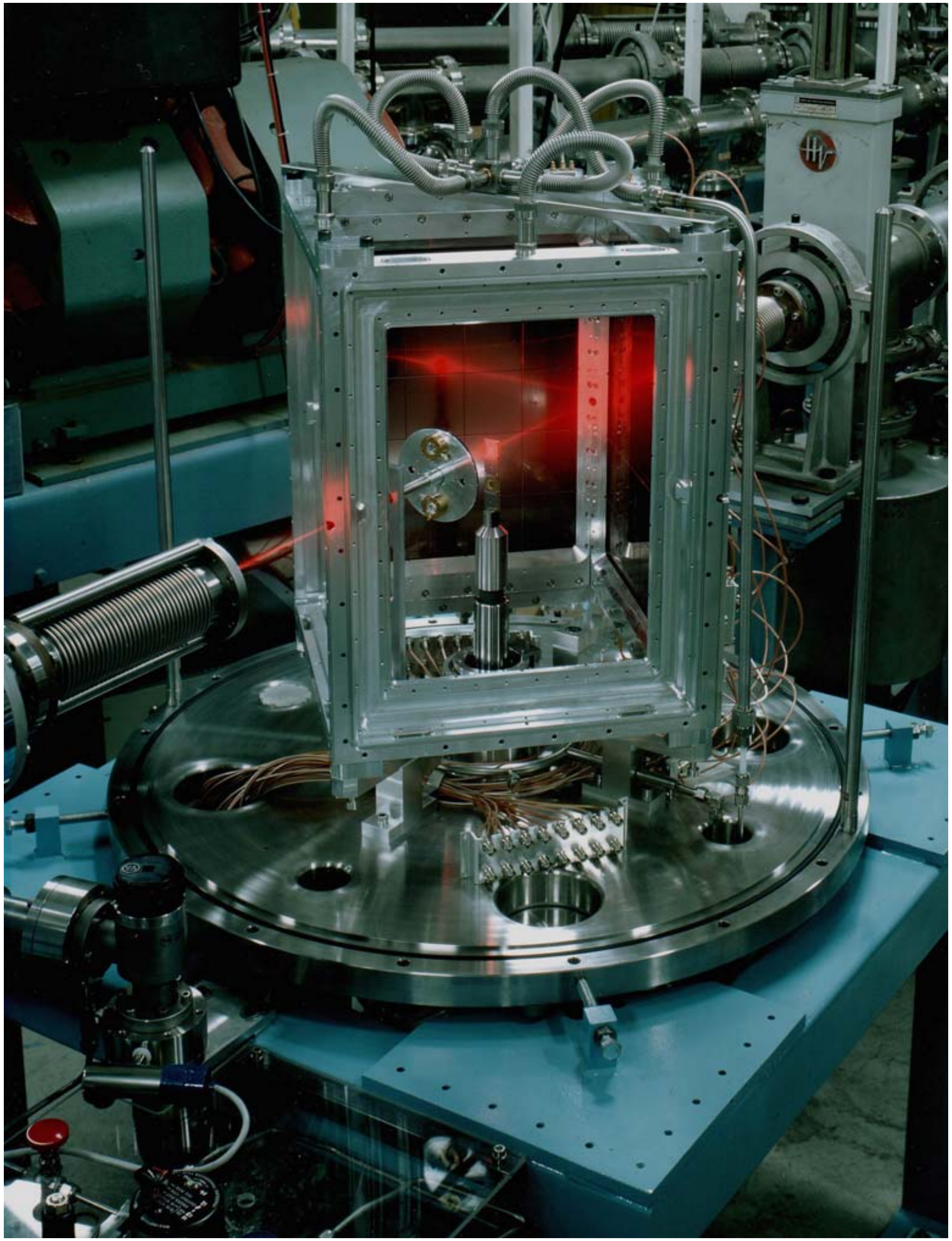
Gas filled 6.5 T Superconducting Solenoid (lens –action)



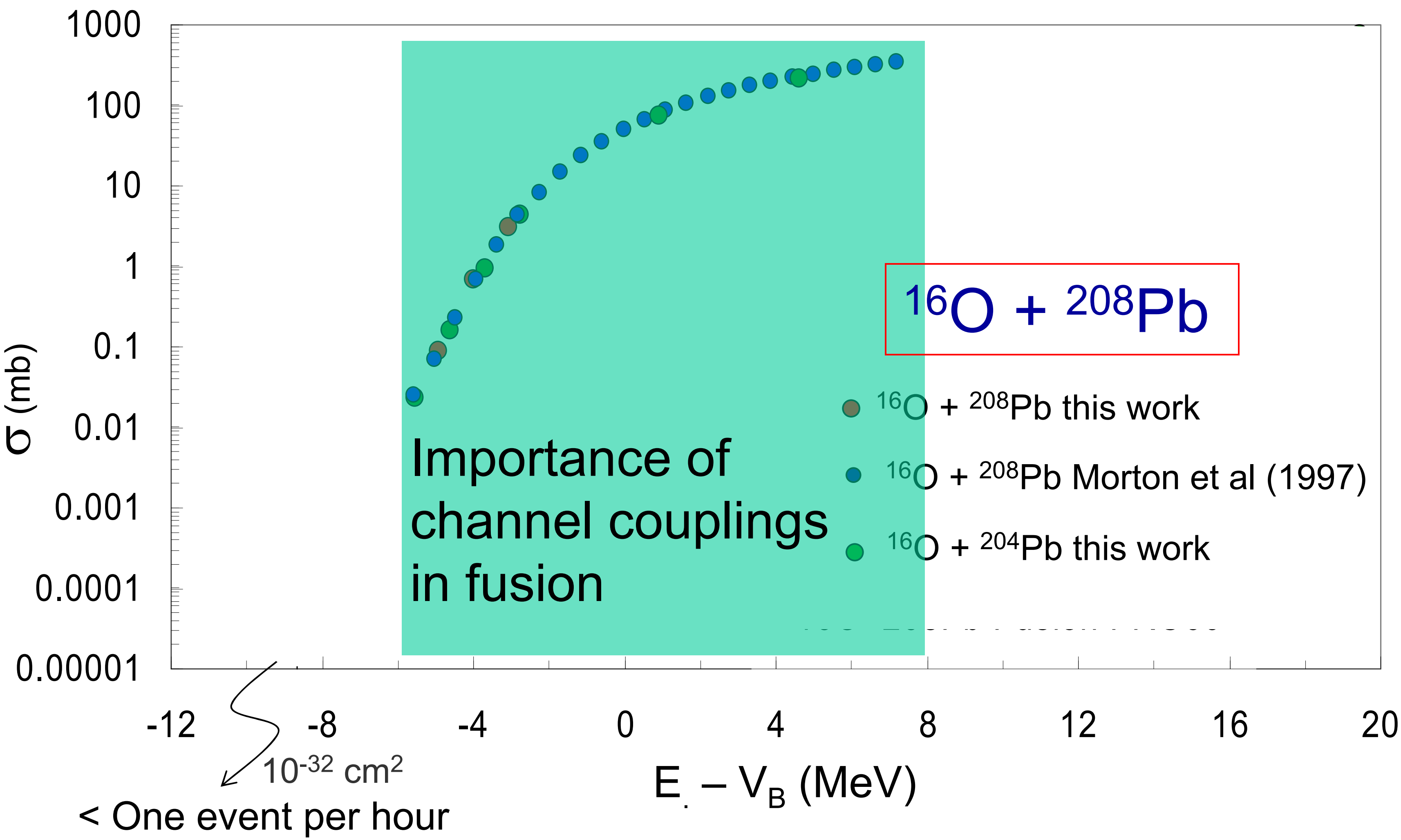
- Acceptance ≥ 80%
- $\simeq$100% detection efficiency
- Highest efficiency separator for fusion studies
- Fusion measurement, coincidence and implantation studies

Highly efficient fission detector array developed in-house





So where is the problem now?



Dasgupta et al, PRL 99 (2007) 192701

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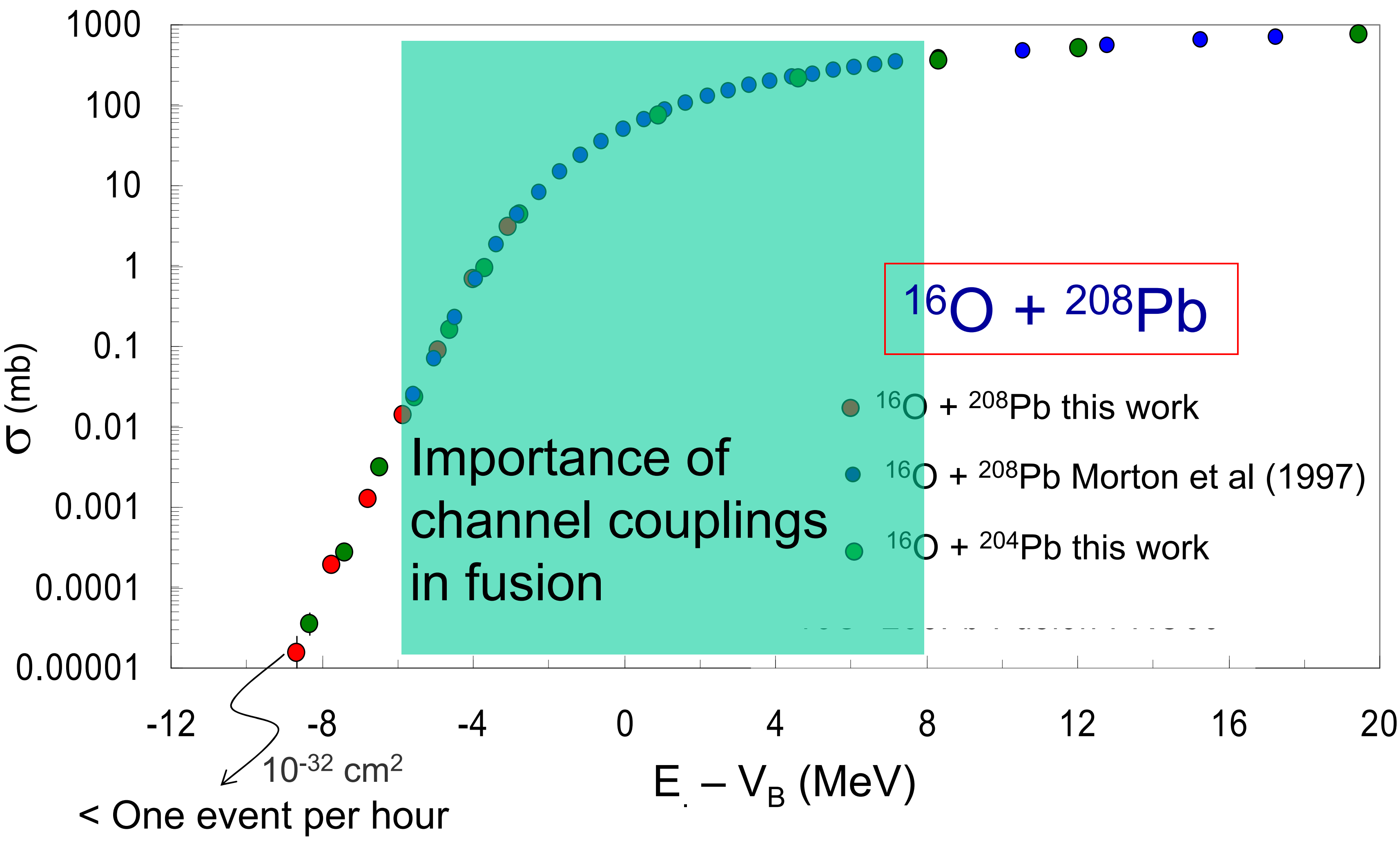
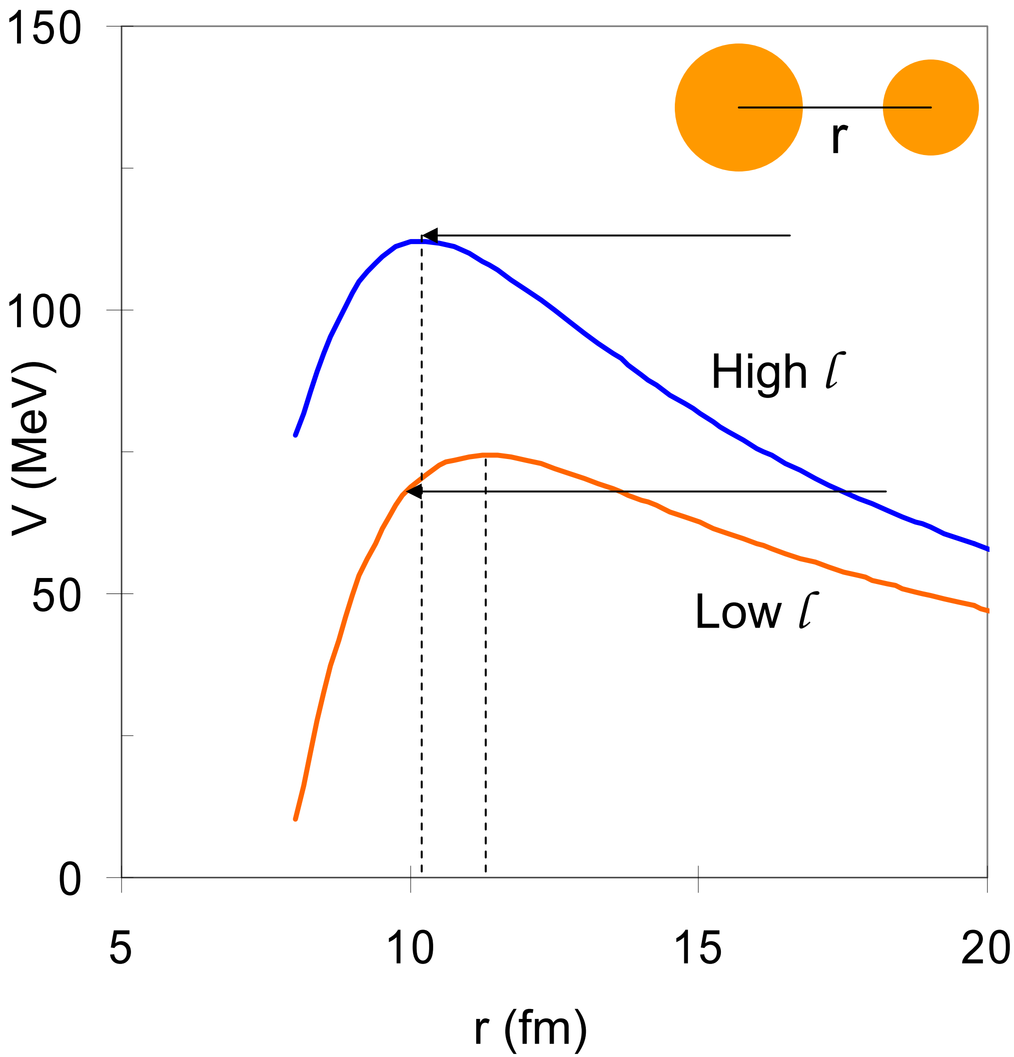


Dasgupta et al, PRL 99 (2007) 192701

Fusion well-below and well-above the barrier

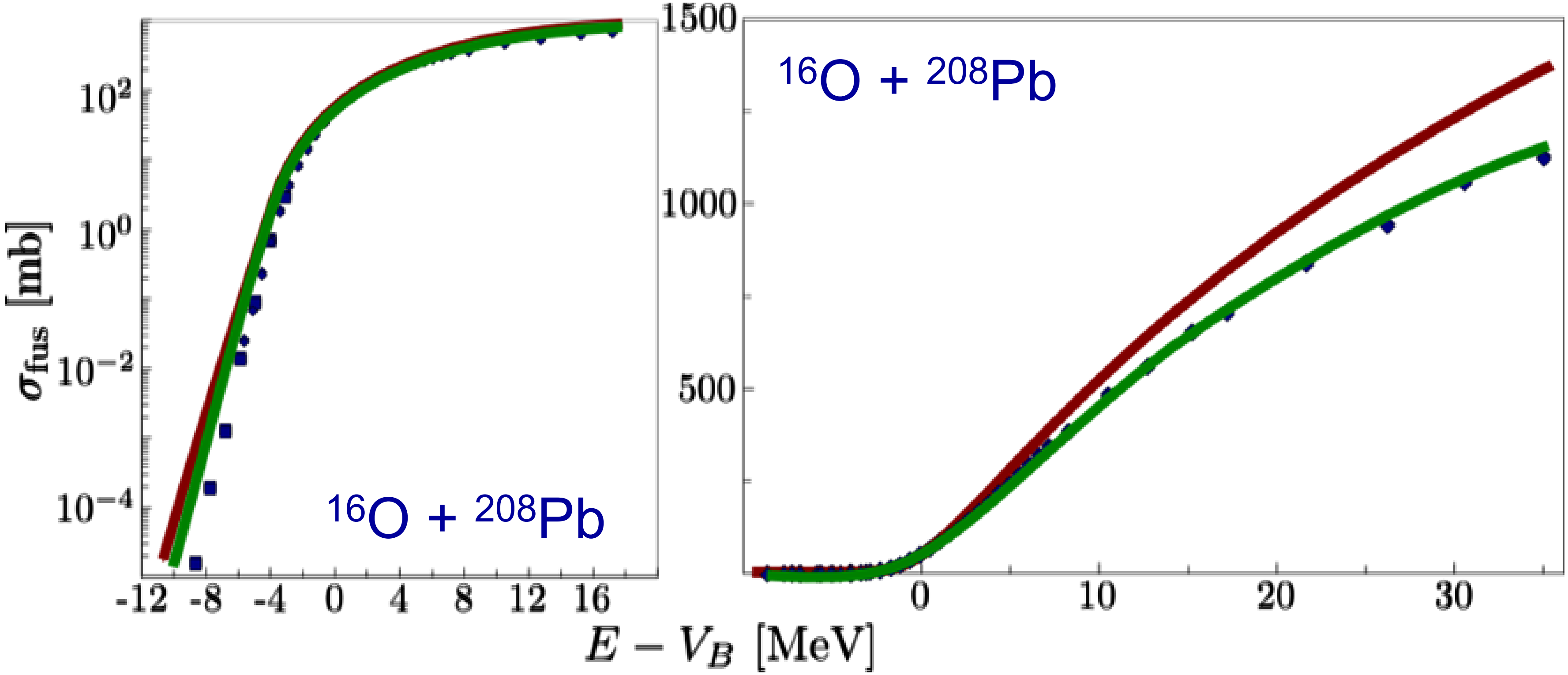


For a given above barrier E – cross-section determined by the limiting l → determined by high-ℓ barrier, R

R_l at smaller separations than R_0

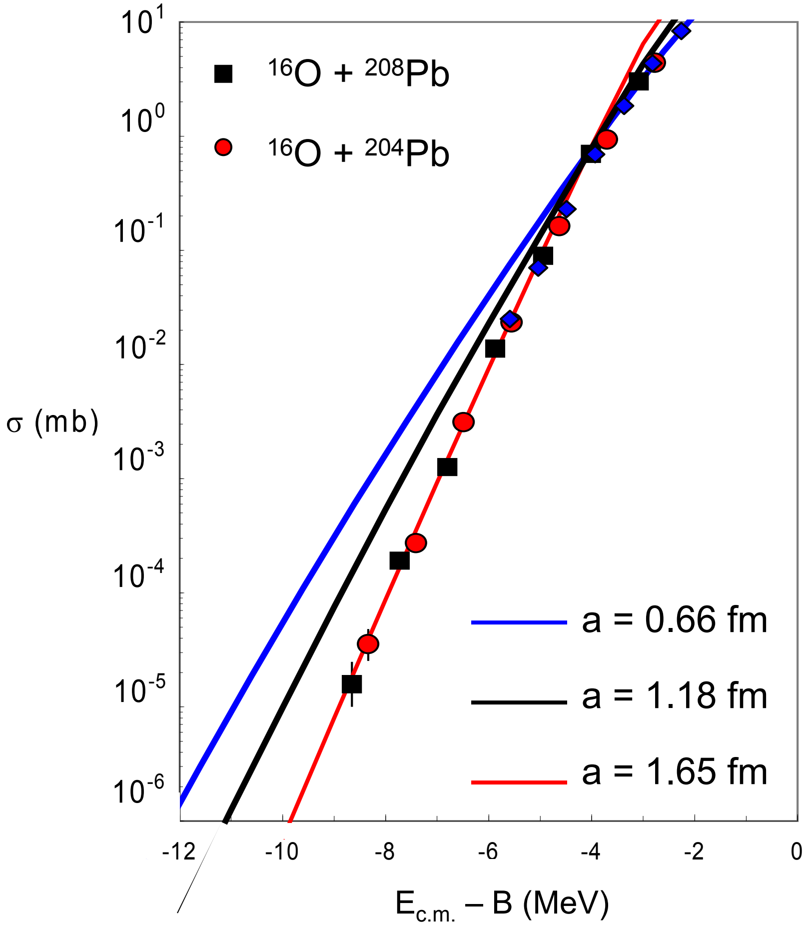
Inner turning point for a below barrier E appears at same separation distance as the top of the high ℓ–barrier

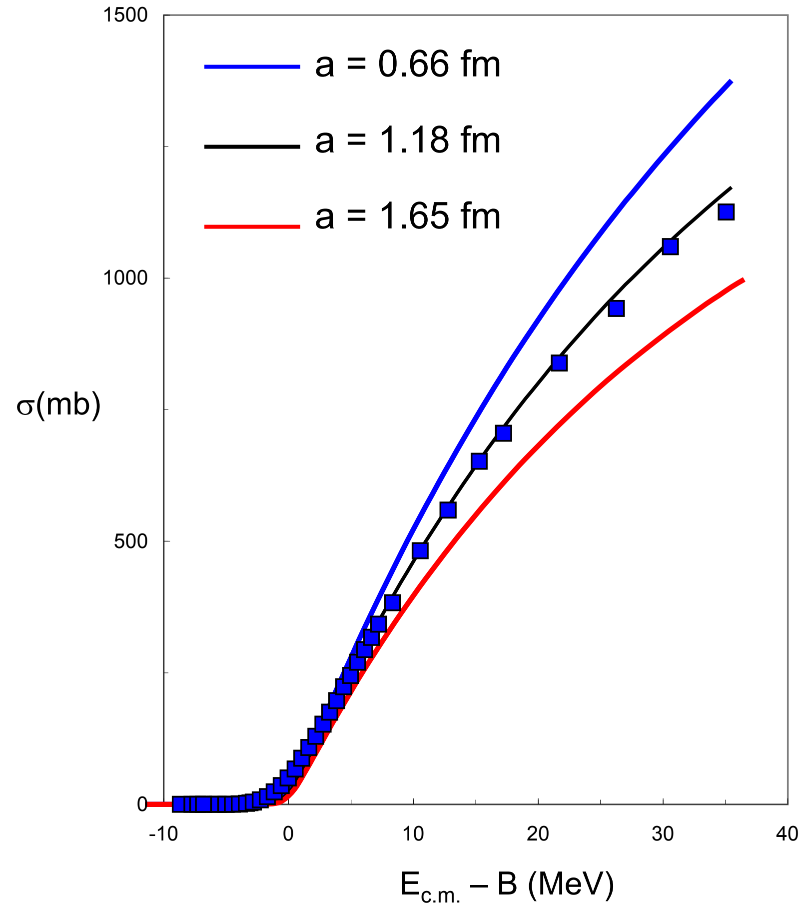
Two parts of fusion excitation function both probe smaller separations



- Coupled channels calculations
- Real Woods-saxon nuclear potential (diffuseness 0.65 fm)
- Incoming wave boundary condition/imaginary W (mimic fusion)

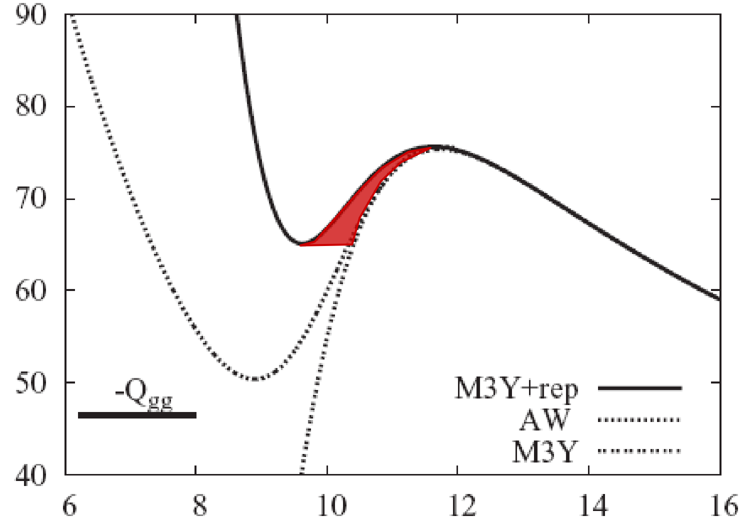
simultaneous description of fusion well-above and well-below the barrier is not obtained





Some physical effect not being included → affects fusion in both energy regimes

Dasgupta et al, PRL 99 (2007) 192701



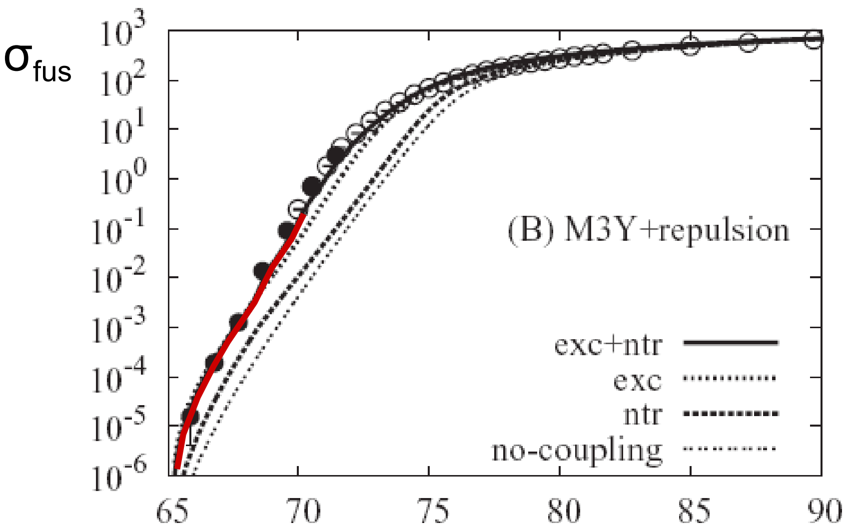
Nuclear incompressibility – shallower potential pocket (sudden potential)

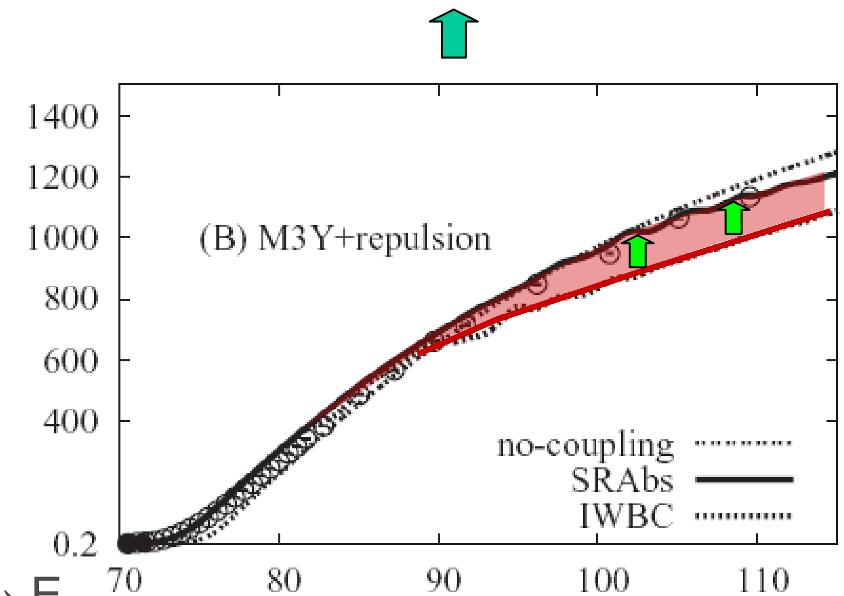
Mişicu and Esbensen PRL96 (2006) 112701

Jiang et al, PRL 93 (2004) 012701

Esbensen and Mişicu PRC76 (2007) 054609

Importance of energy and angular momentum dissipation above barrier



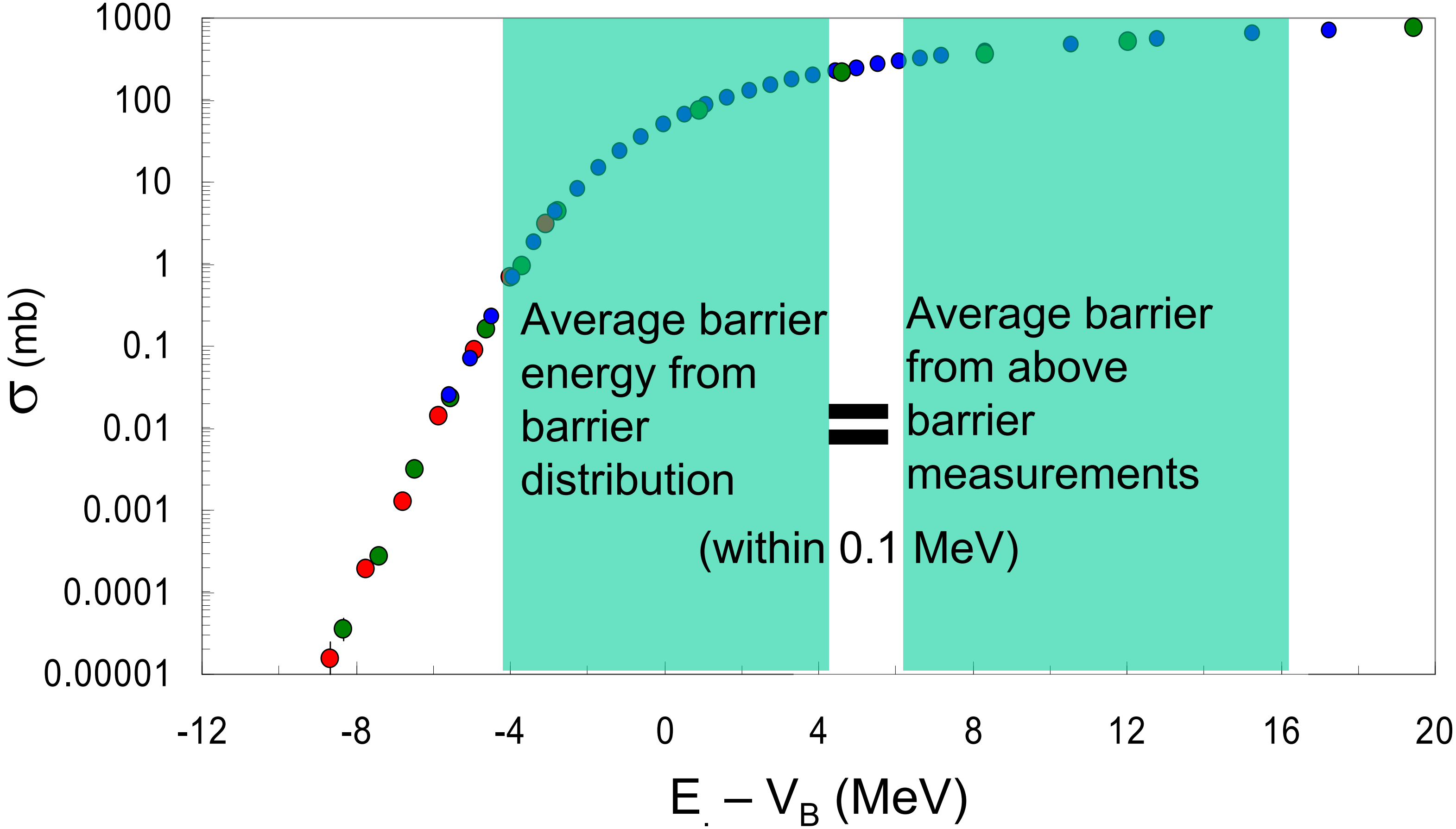


→ E

- Deep sub-barrier – cross-sections with IWBC (σ not hindered for imaginary pot.)
- Well-above barrier – no pot. pocket - need short range imaginary potential

Energy dependence of bare potential ?

From experimental data (within the potential model)

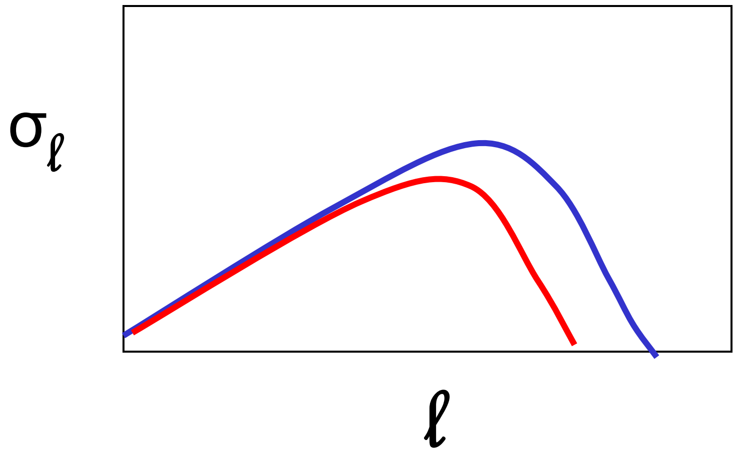


Measurements for the $^{16}O + {}^{208}Pb$ reaction

Transmitted flux:

- Fusion cross-sections
- Fusion mean square angular momentum

  - sensitive to angular momentum dependence of the barrier



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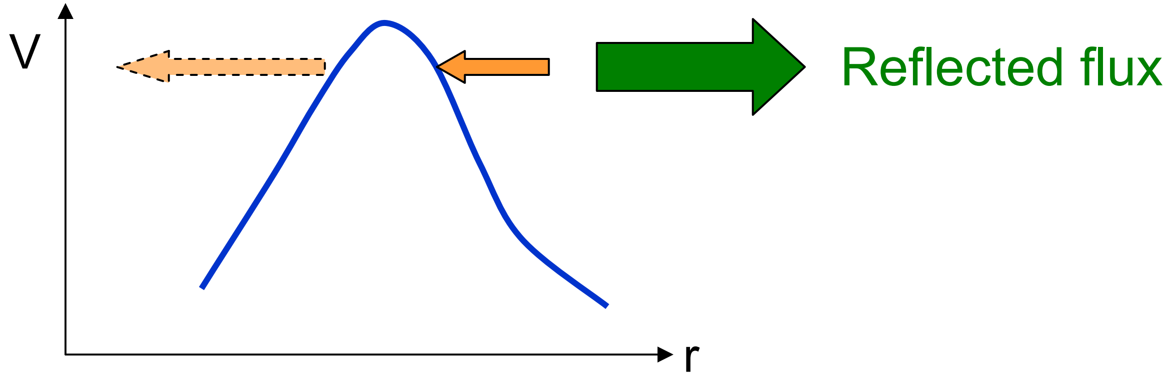


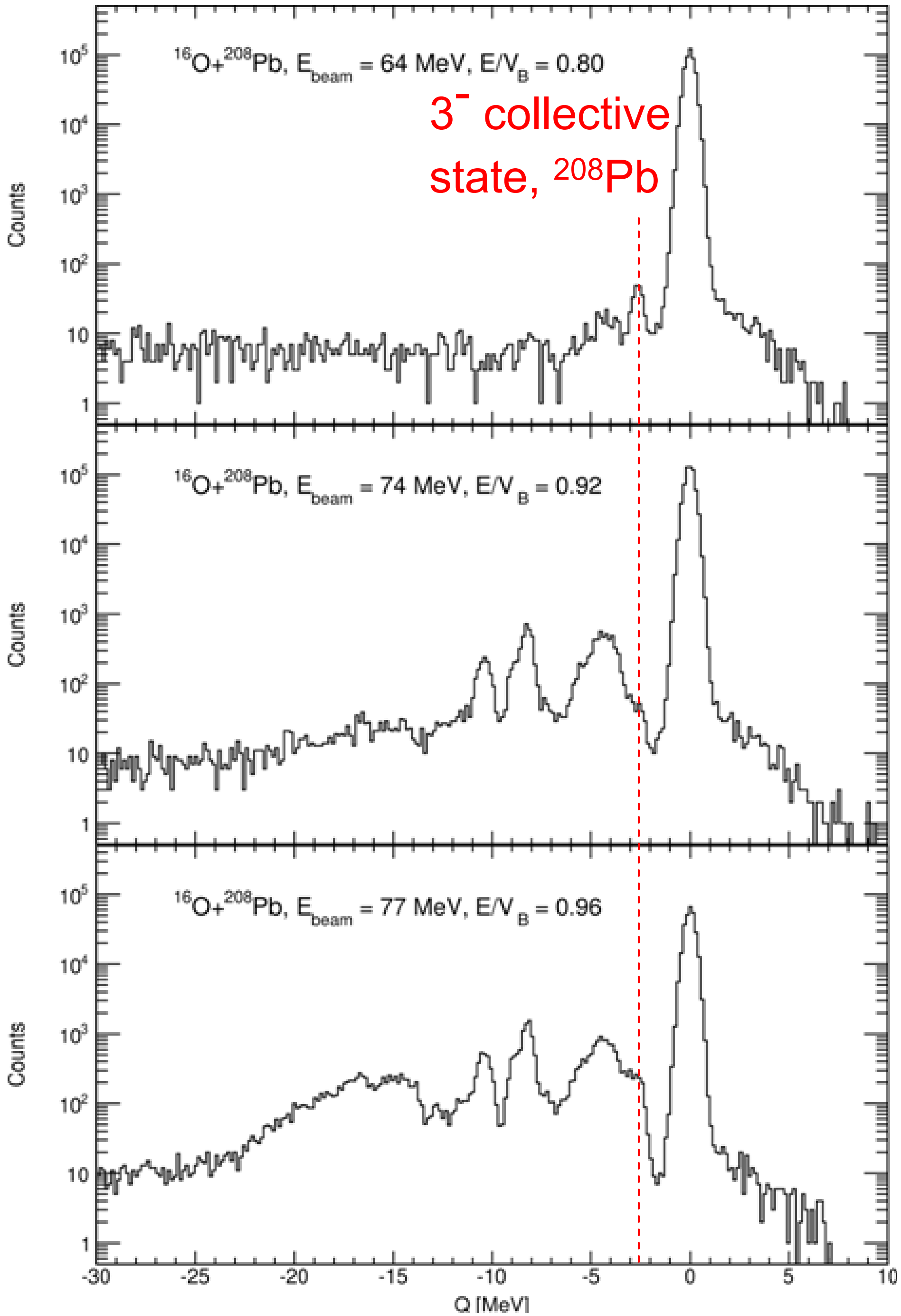
The ^{16}O + ^{208}Pb reaction

Transmitted flux:

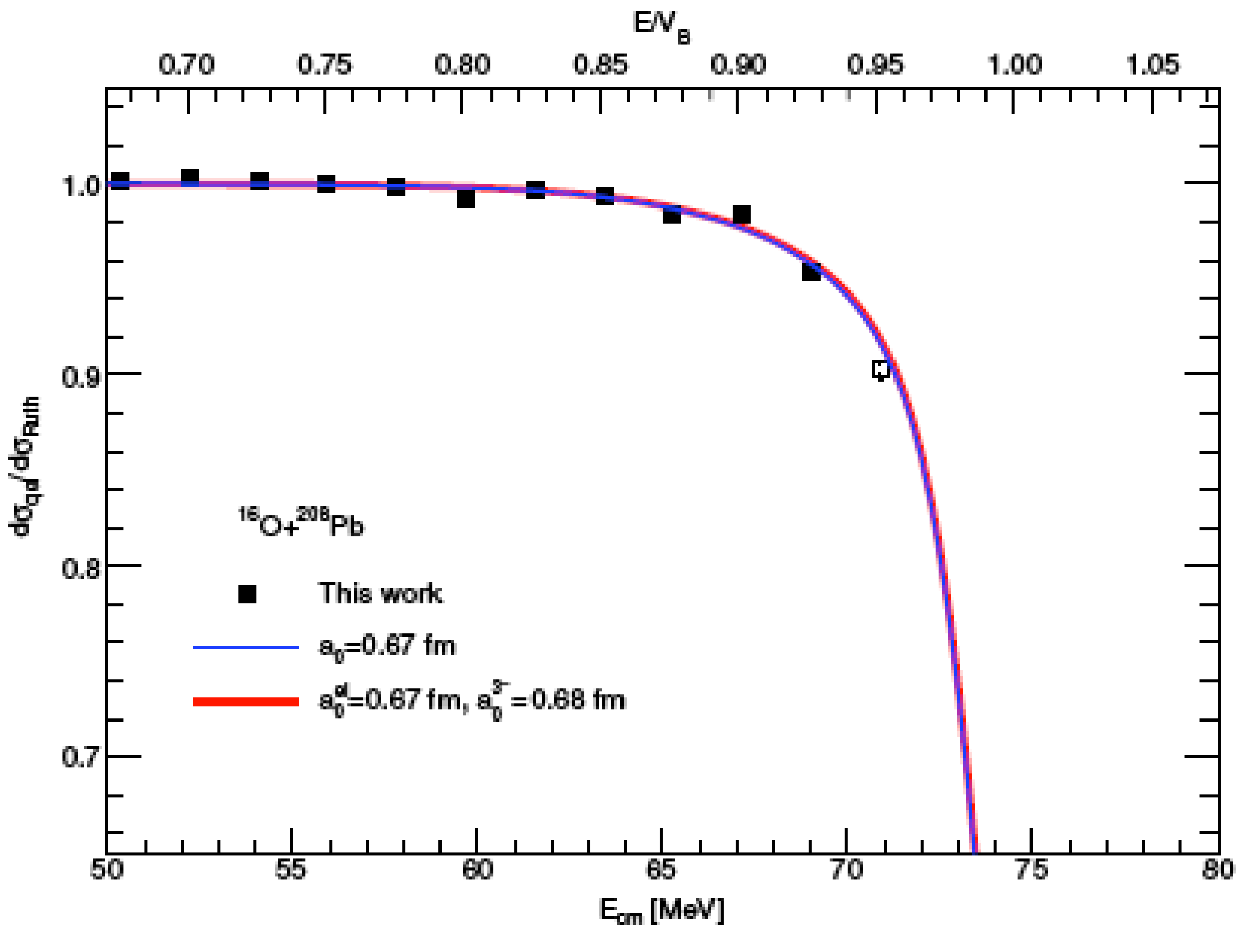
- Fusion cross-sections
- Fusion mean square angular momentum
  - sensitive to angular momentum dependence of the barrier

Reflected flux:

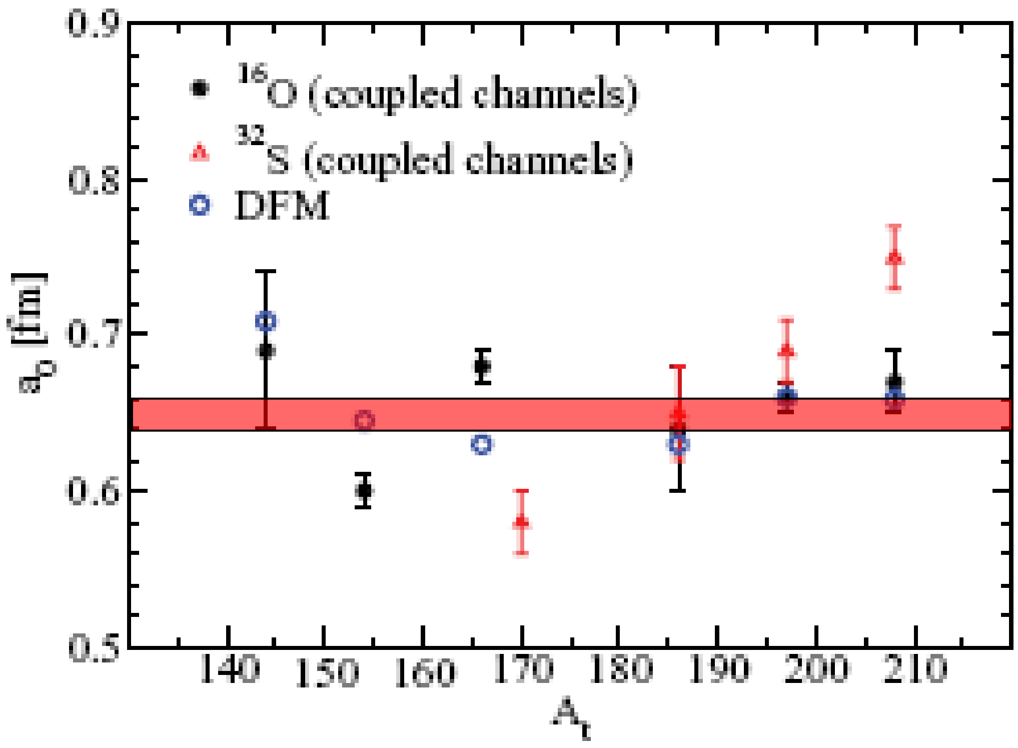
- High precision measurements of elastic scattering – near barrier
- Measurements of all quasi-elastic channels (inelastic, transfer)
- Inelastic scattering – octupole vibrational – coulomb nuclear interference
- neutron transfer, p, 2p transfer


$^{16}O+^{208}Pb$, E_{beam} = 64 MeV, E/V_B = 0.80
3^- collective state, ^{208}Pb
$^{16}O+^{208}Pb$, E_{beam} = 74 MeV, E/V_B = 0.92
$^{16}O+^{208}Pb$, E_{beam} = 77 MeV, E/V_B = 0.96
Counts
Q [MeV]

Total quasi-elastic excitation function



Evers et al., PRC 81, 014602 (2010)

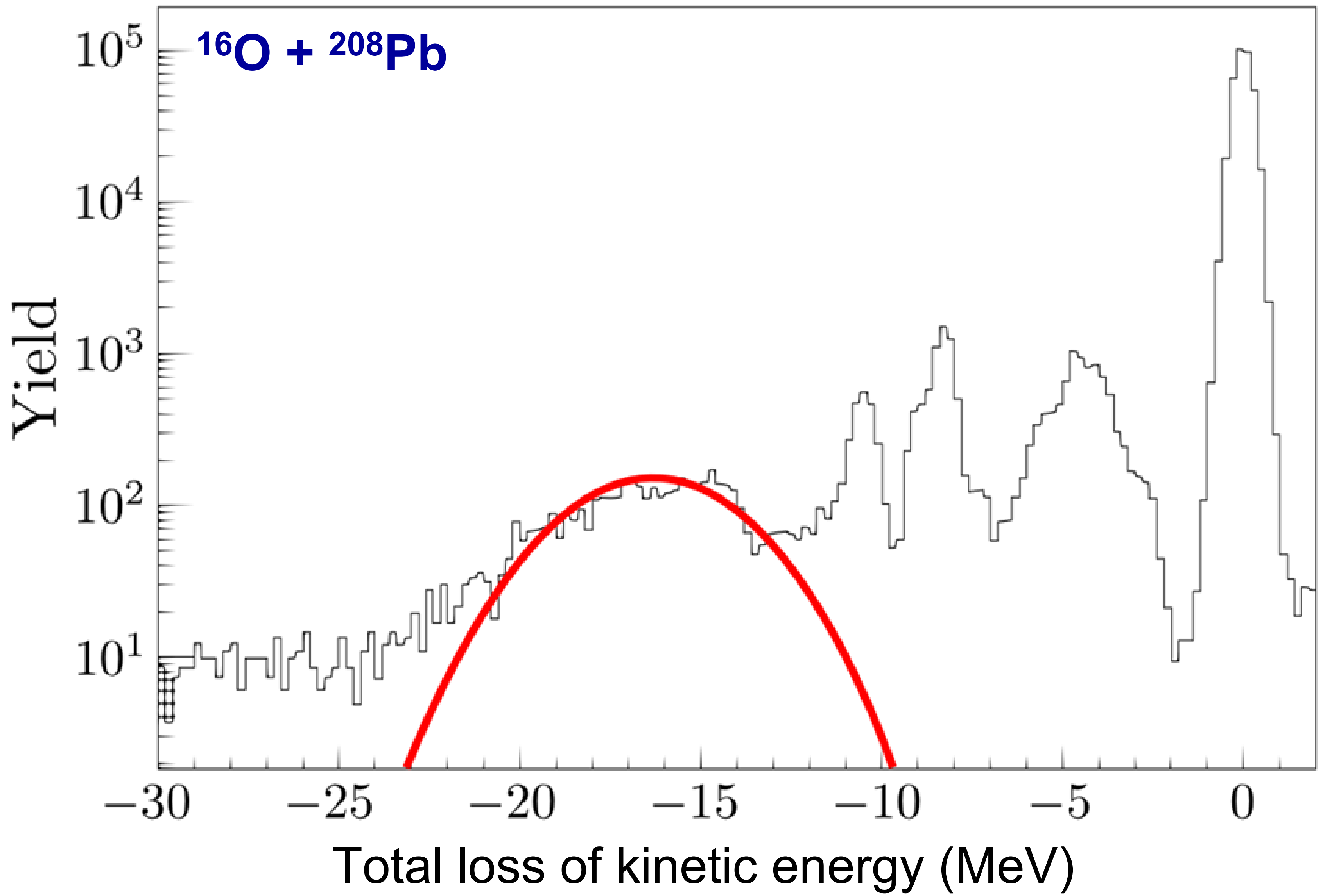


Evers et al, PRC 78 (2008) 034614

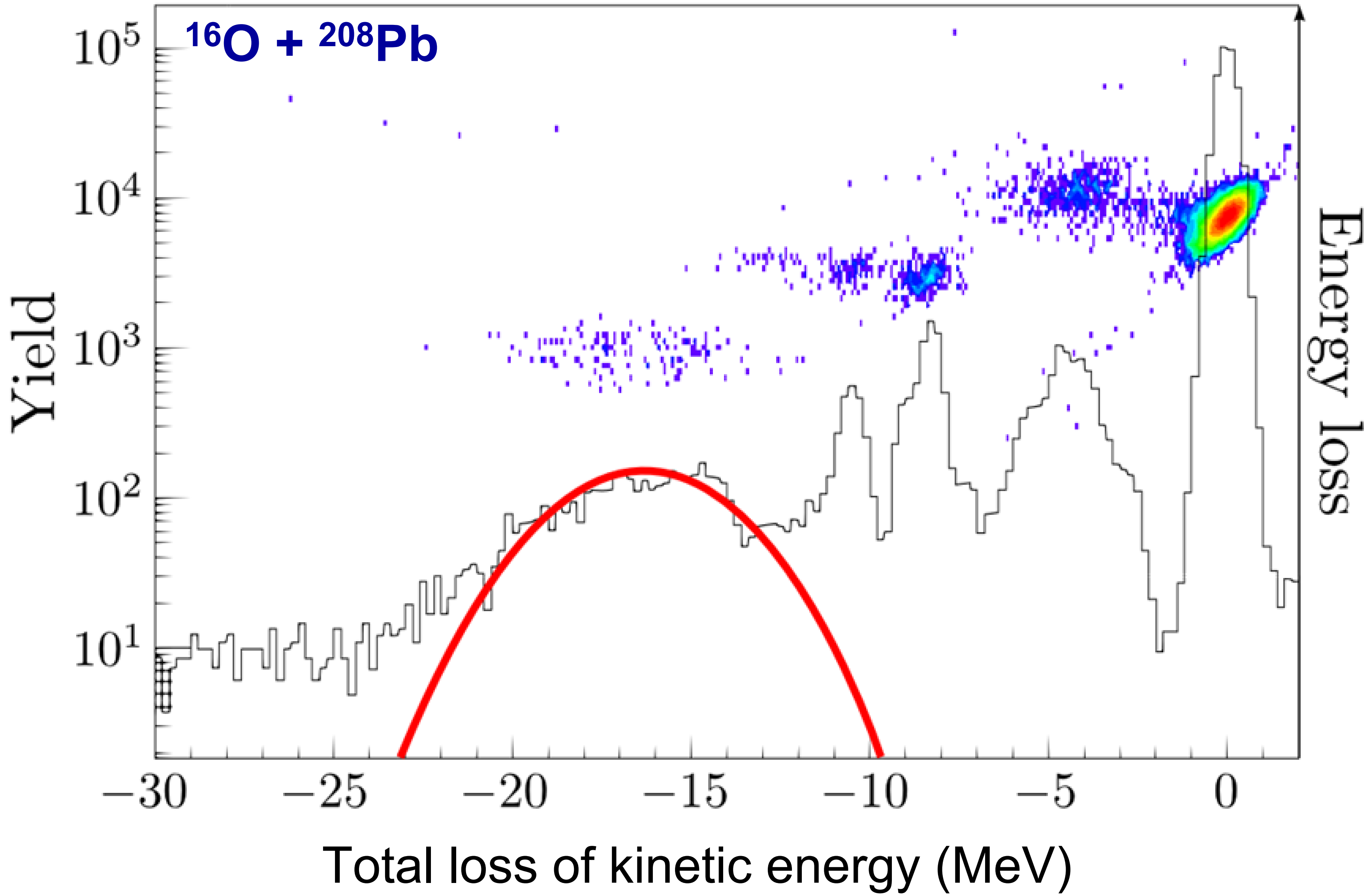
- Mean diffuseness for ^{16}O induced reactions: 0.65 fm

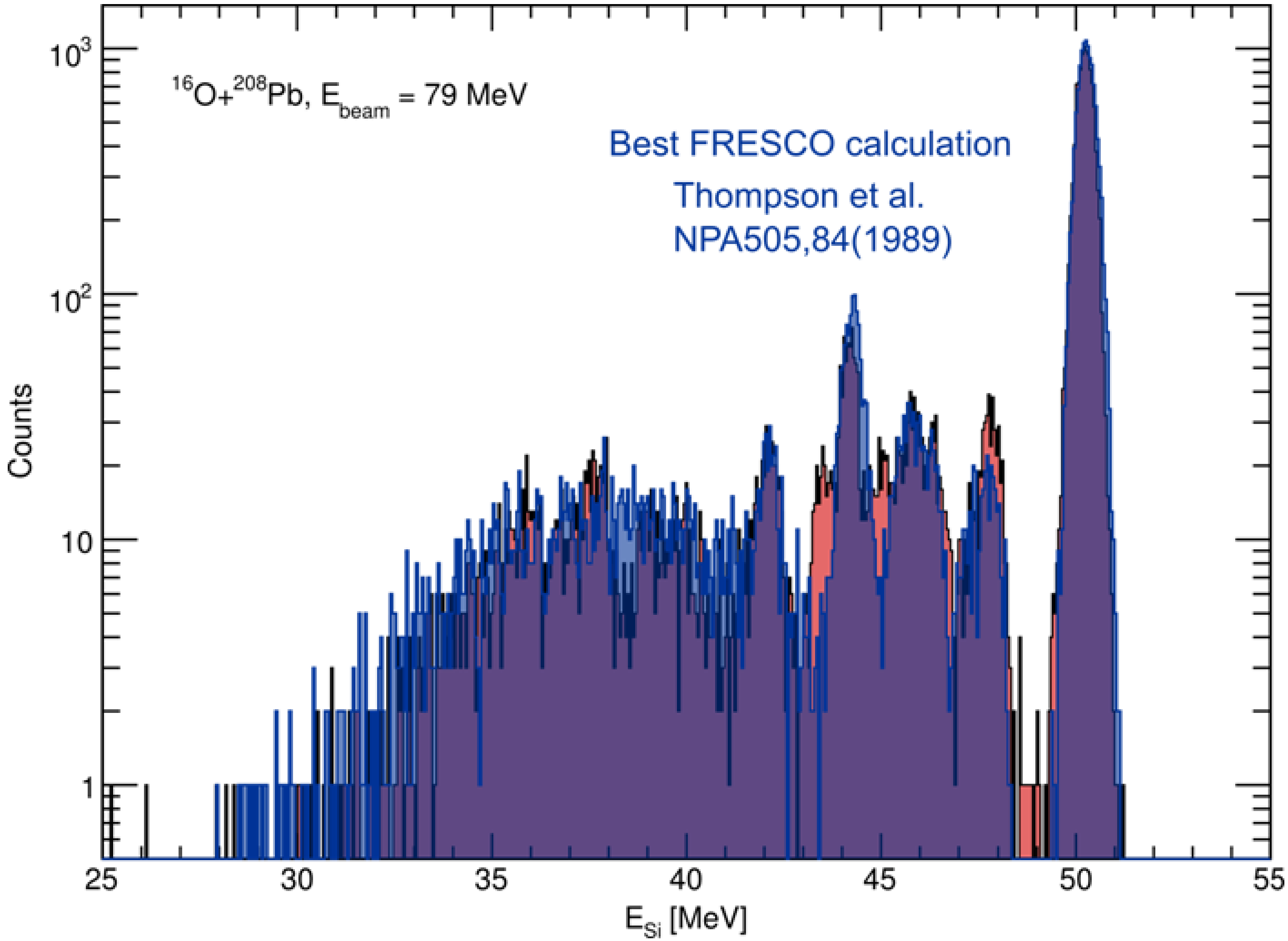
confirms – shape of nuclear potential in the tail region

Identifying the components in the reflected flux

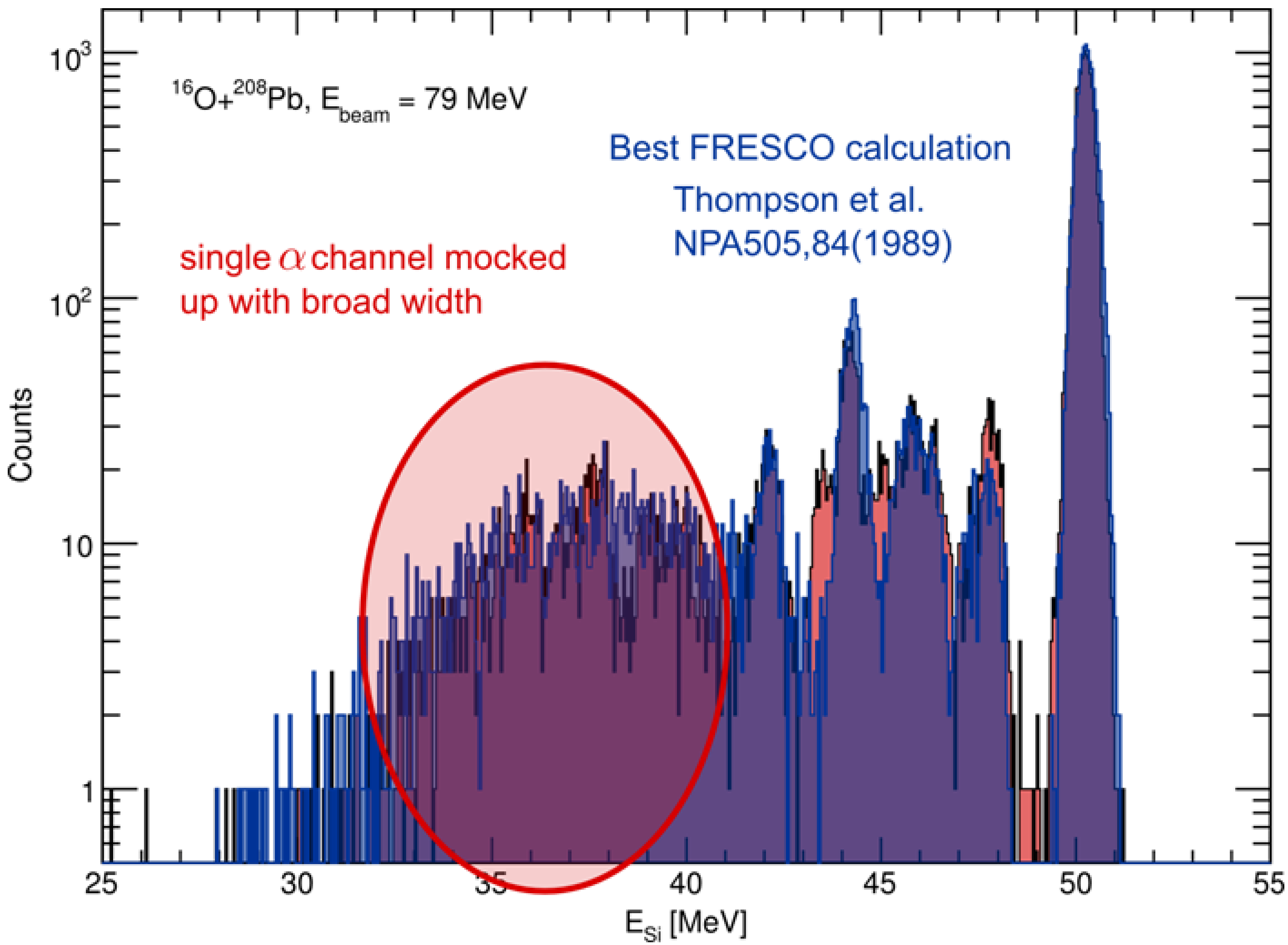


Identifying the components in the reflected flux

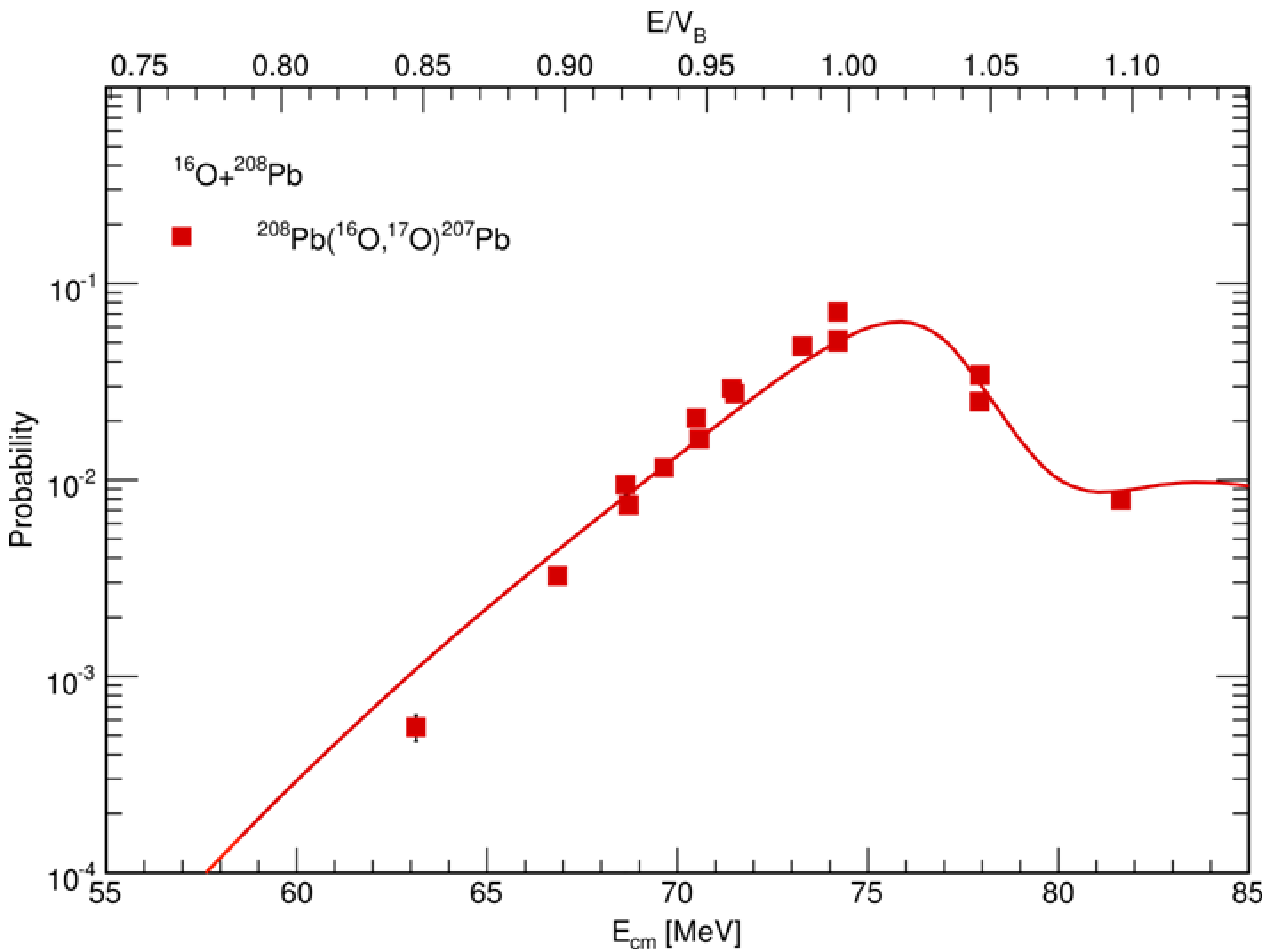




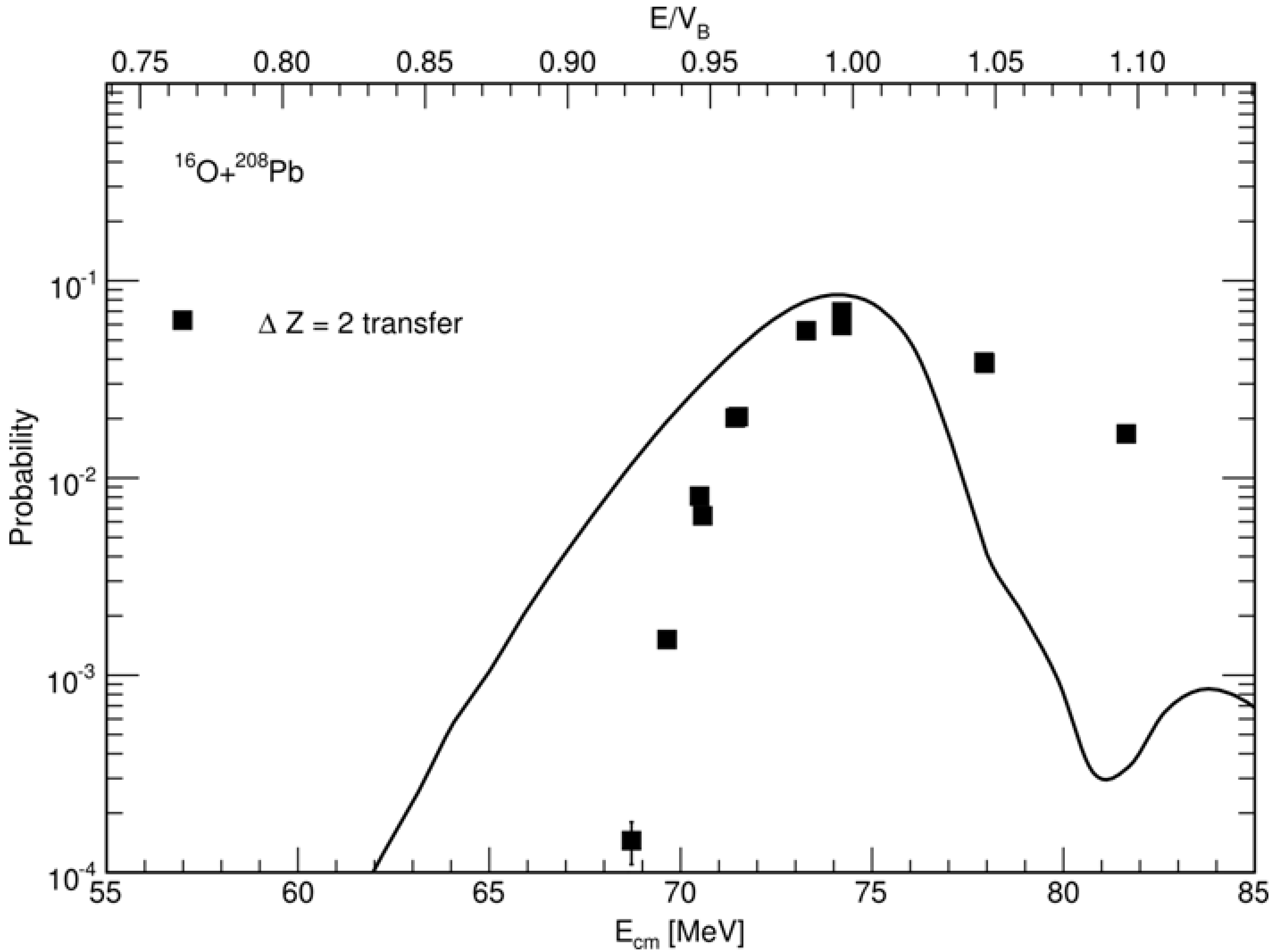
$^{16}O+^{208}Pb$, E_{beam} = 79 MeV
Best FRESCO calculation
Thompson et al.
NPA505,84(1989)
Counts
10^3
10^2
10
1
25
30
35
40
45
50
55
E_{Si} [MeV]



$^{16}O+^{208}Pb$, E_{beam} = 79 MeV
Best FRESCO calculation
Thompson et al.
NPA505,84(1989)
single α channel mocked
up with broad width
Counts
E_{Si} [MeV]



Evers et al. (2010), to be published



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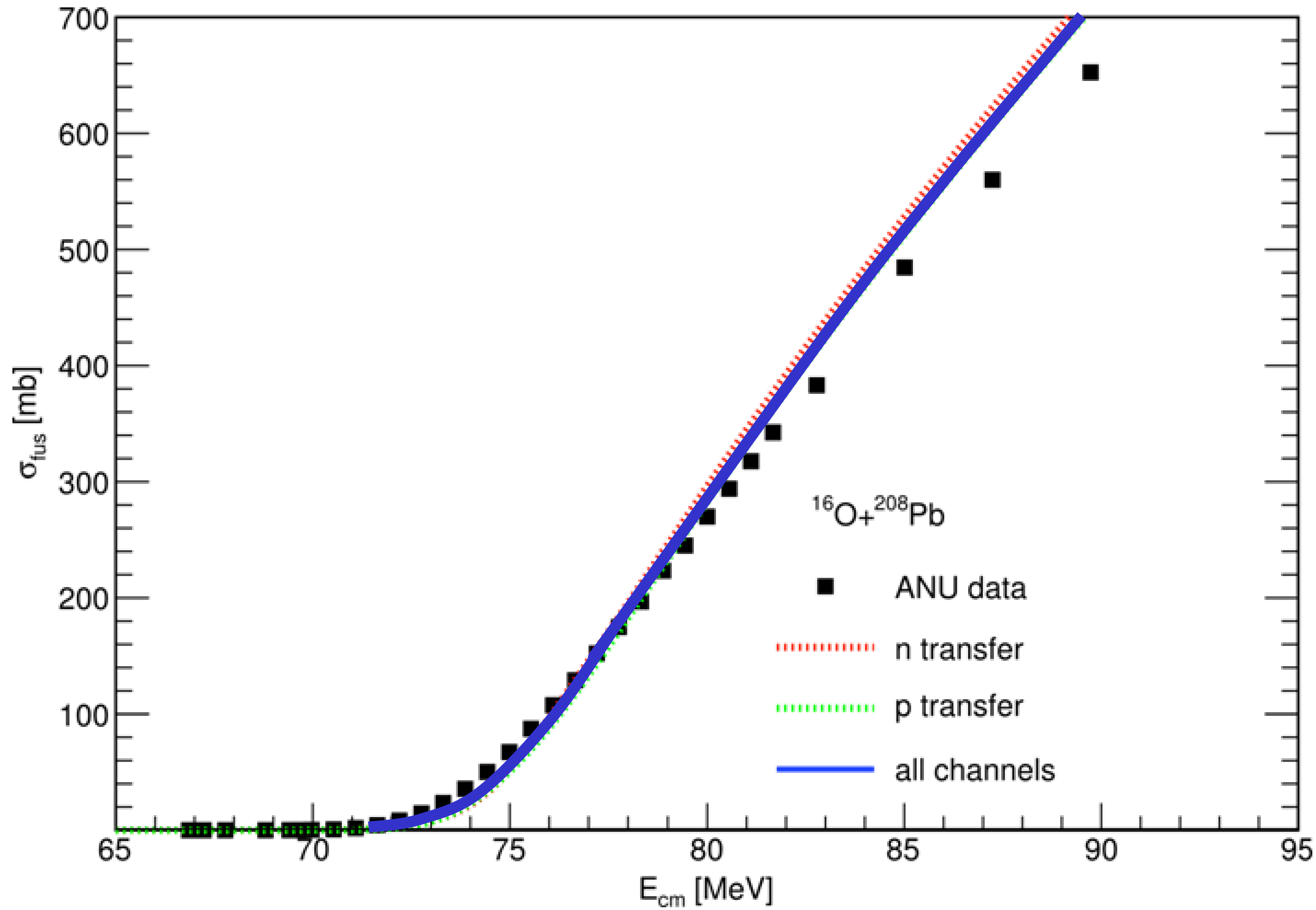
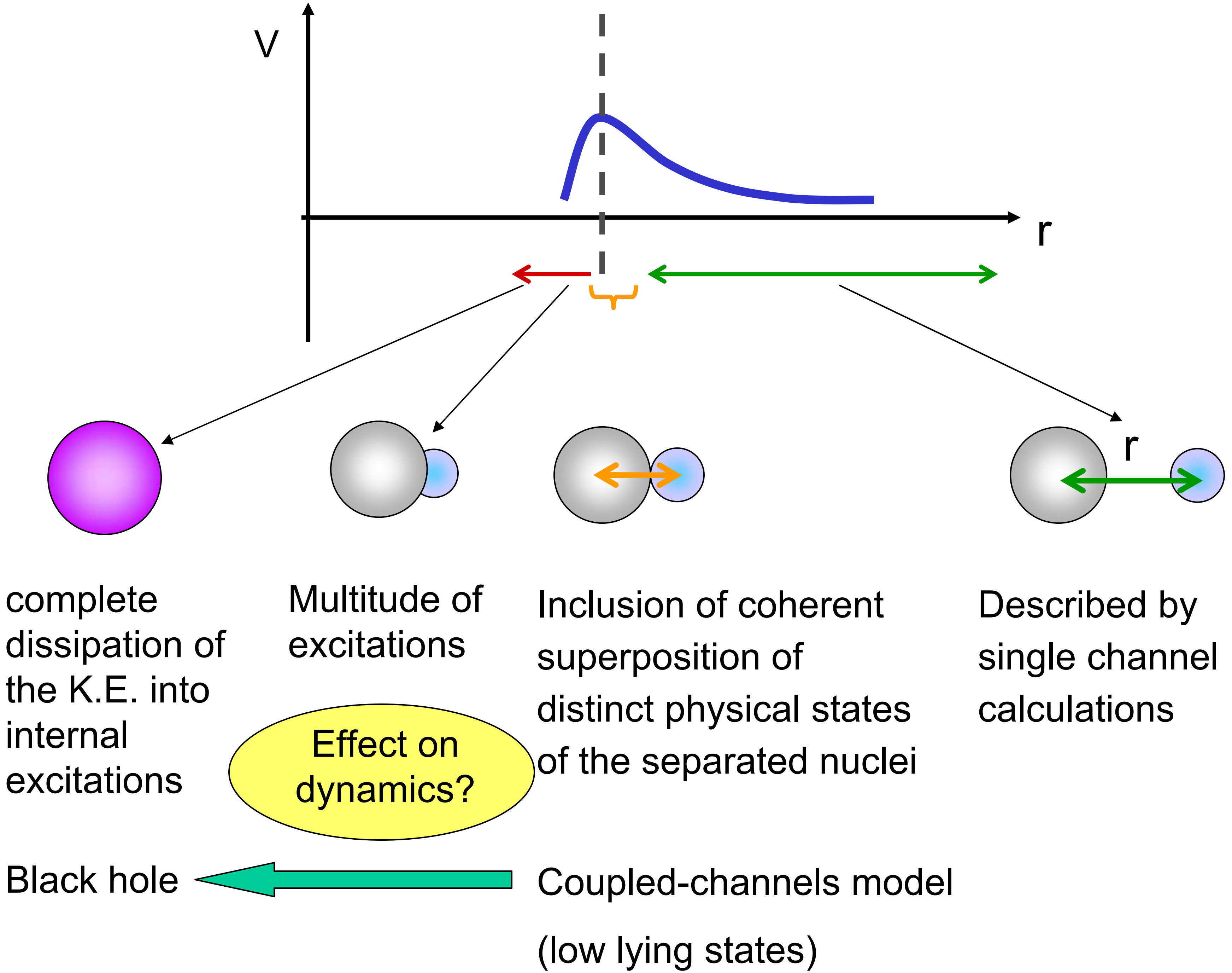


700
600
500
400
300
200
100
σ_{fus} [mb]
65
70
75
80
85
90
95
E_{cm} [MeV]
$^{16}O+^{208}Pb$
ANU data
n transfer
p transfer
all channels


V
r
r
complete dissipation of the K.E. into internal excitations
Multitude of excitations
Inclusion of coherent superposition of distinct physical states of the separated nuclei
Described by single channel calculations
Effect on dynamics?
Black hole
Coupled-channels model
(low lying states)