Near Barrier Reactions – many-body quantum dynamics in action

Part II - Fusion

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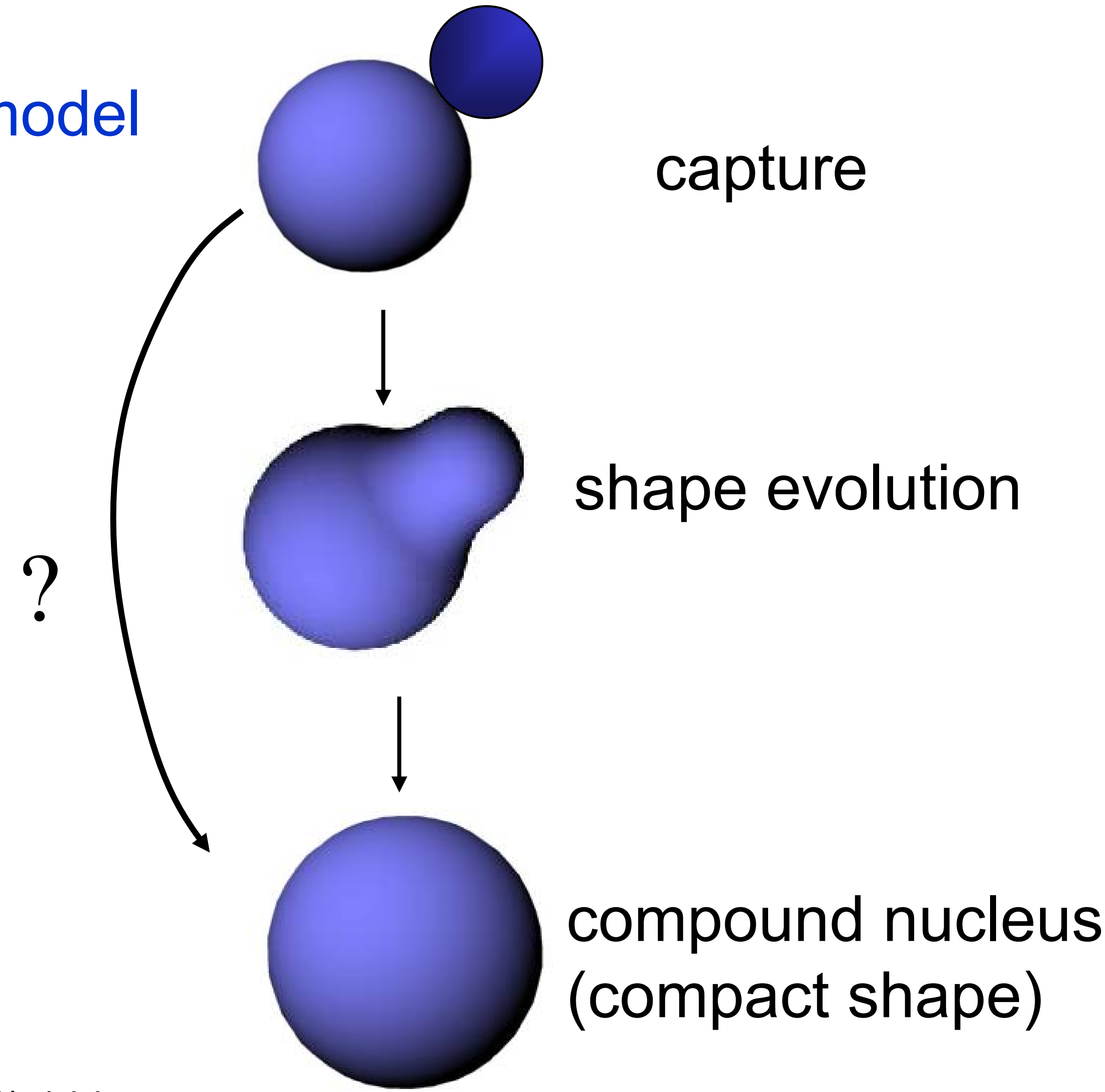
Fusion – the different stages

- Coupled channels model works well



all capture leads to compact shape?

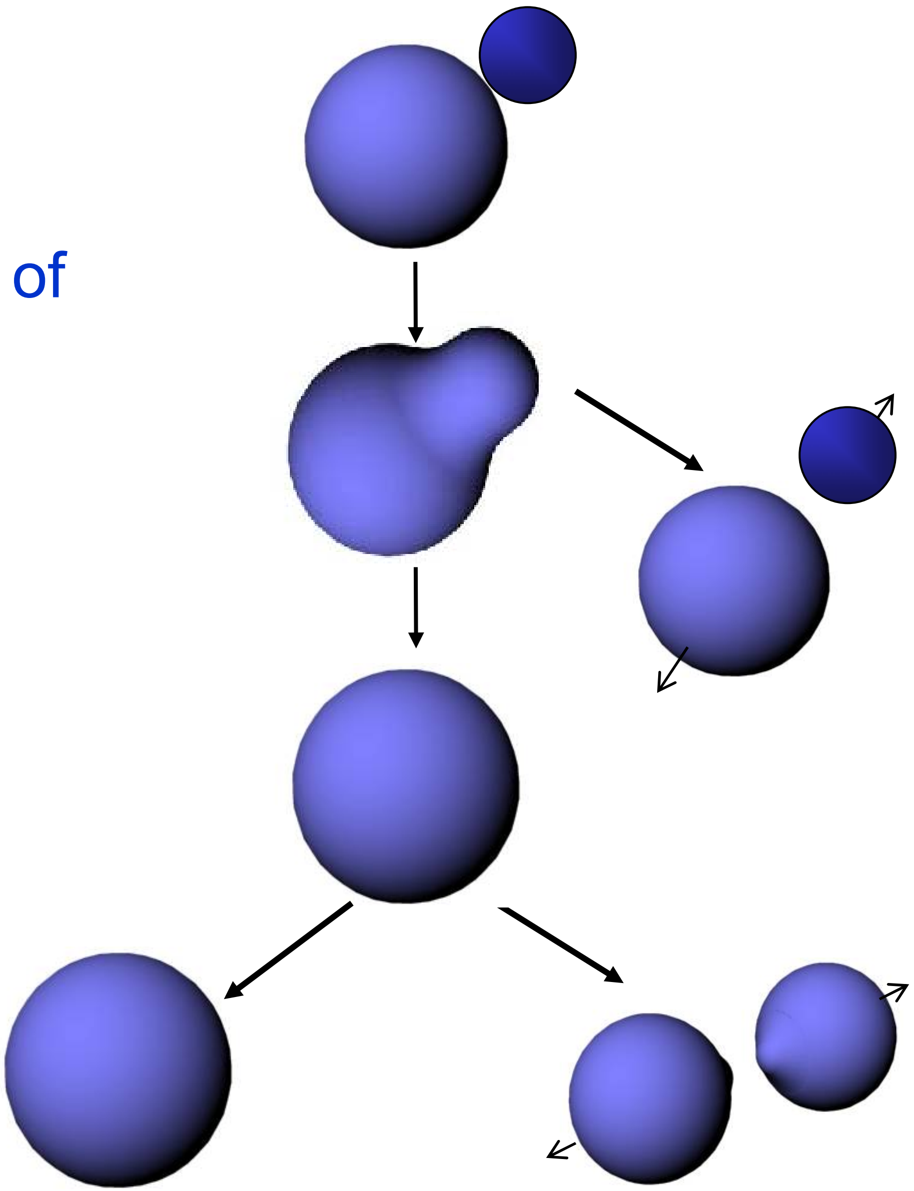
✓ Fusion of lighter nuclei

✗ Heavier nuclei

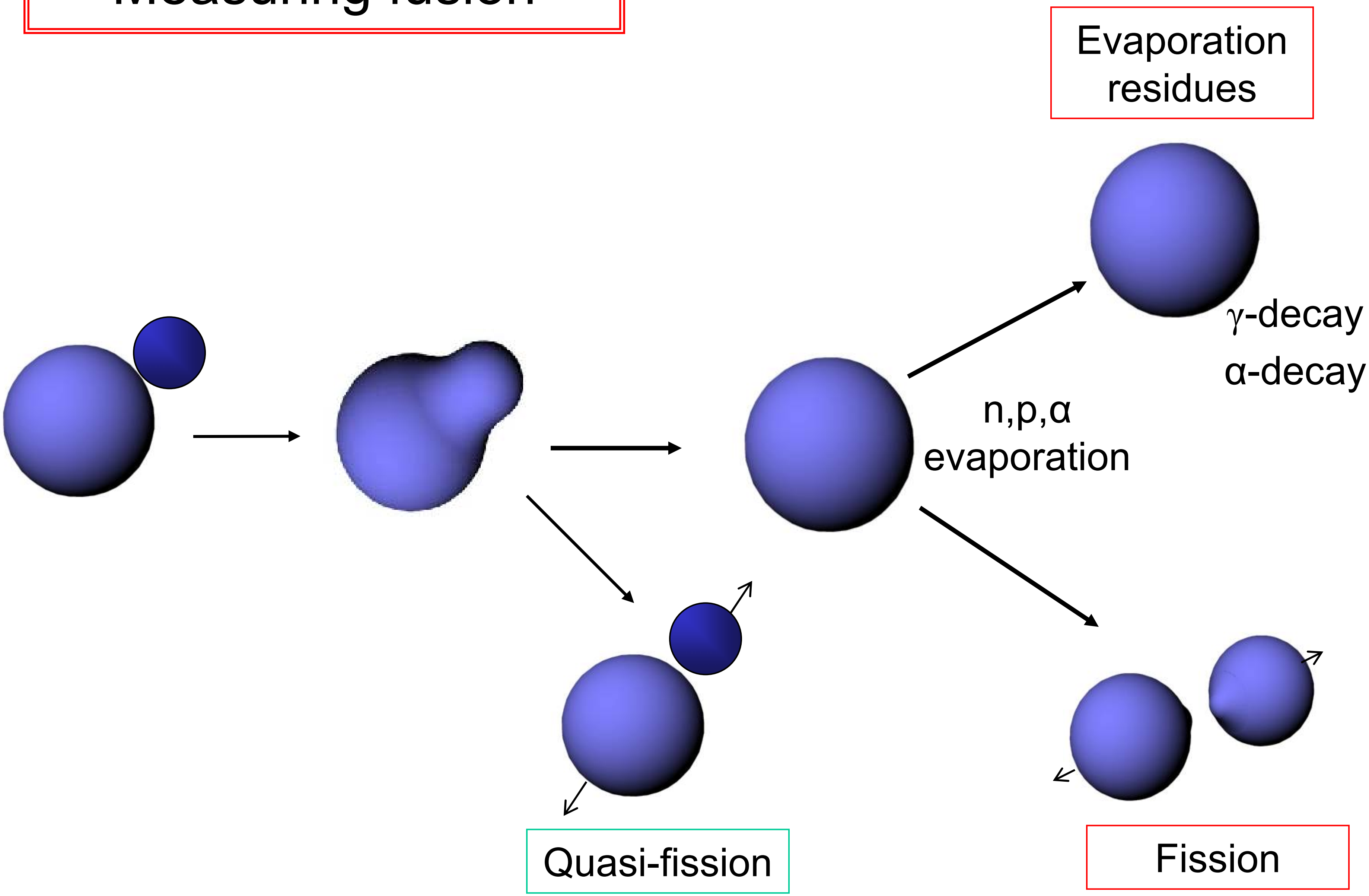
Berriman et al., Nature, 413 (2001) 144

Important questions

- What influences capture of two nuclei?
- What influences the subsequent evolution?



Measuring fusion



Experimental methods

Detection of x-rays emitted by evaporation residues

identification of Z

different isotopes can be separated in favourable cases

Detection of gamma-rays from evaporation residues

identification of Z and A

need efficient detectors, background issues, efficiency

Detection of alpha decay of evaporation residues

identification of Z, A

only applicable in cases of α-active products

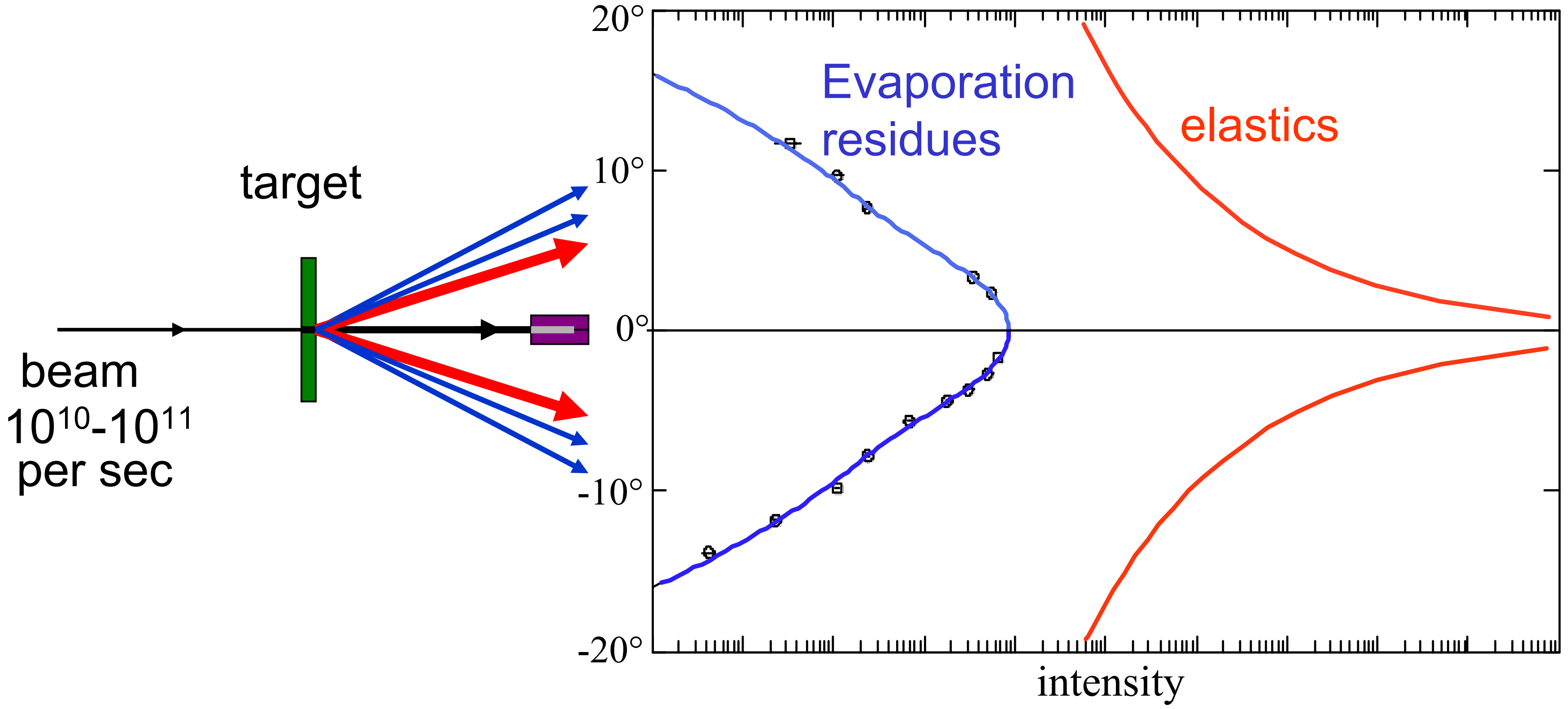
Direct detection of fusion products (evaporation residues, fission)

High precision measurements (1% uncertainty) – barrier distribution

ER measurements need care, high efficiency or known transmission

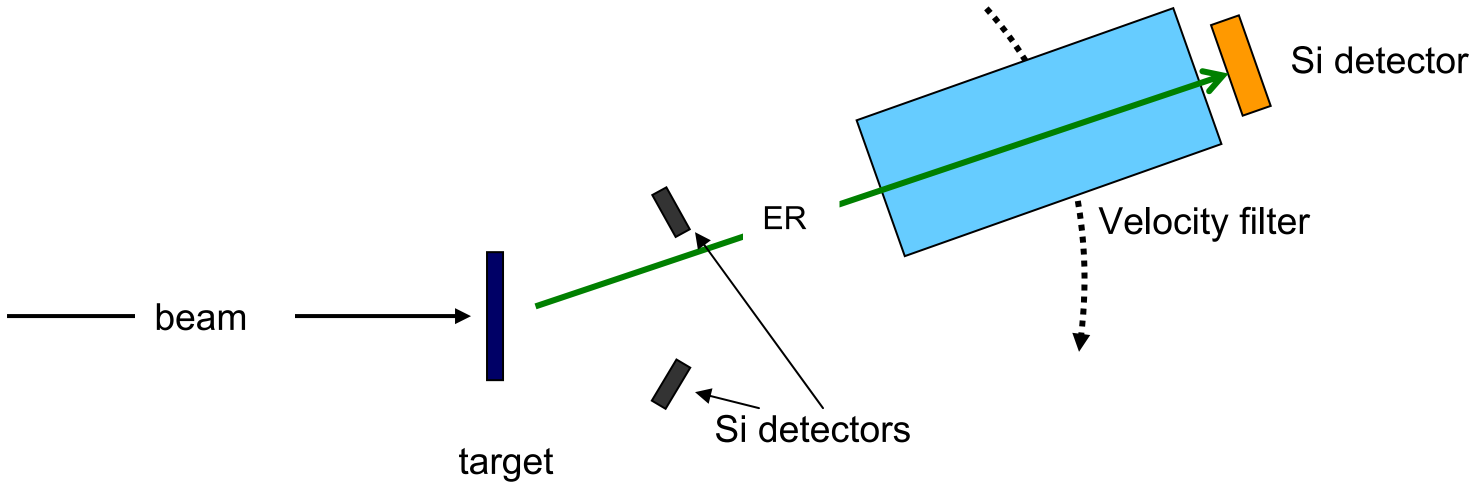
Fission measurements – large angular coverage

Fusion measurements – the challenge



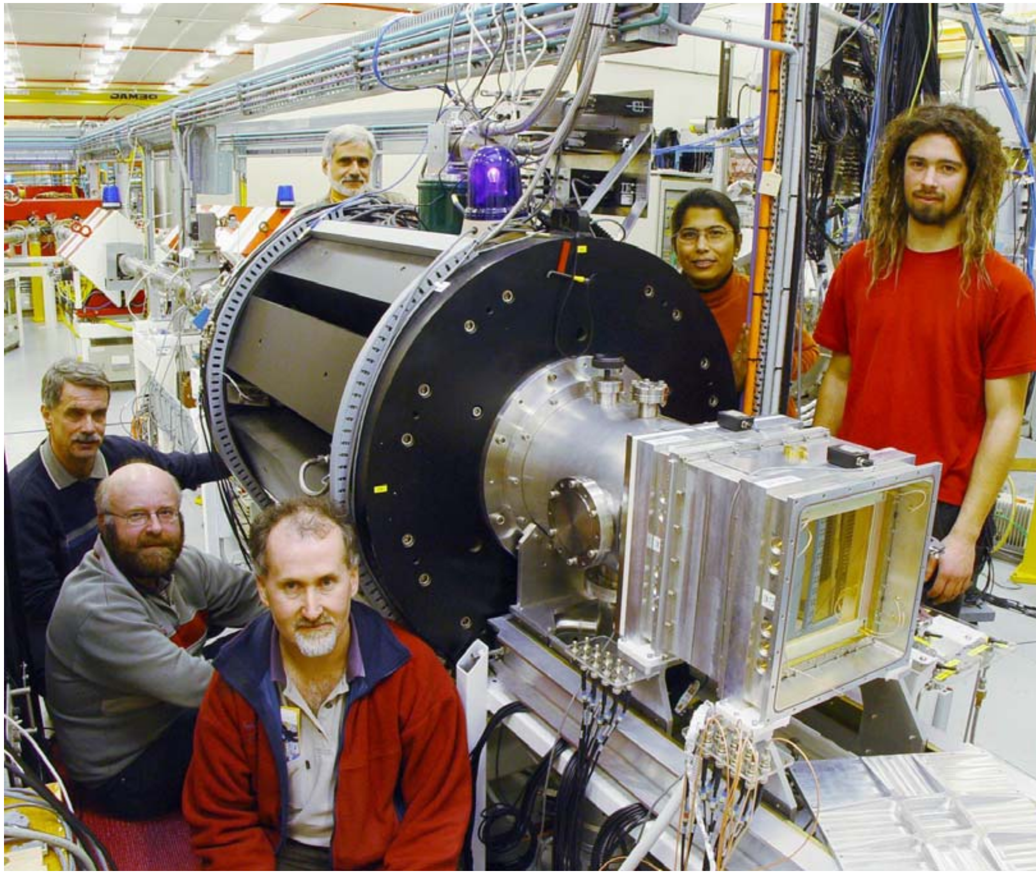
- Beam, fusion products, elastic scattering – all forward focussed
- Stop direct beam (10^{10} – 10^{11} nuclei/sec)
- 10^4 – 10^{12} elastics for every fusion product!

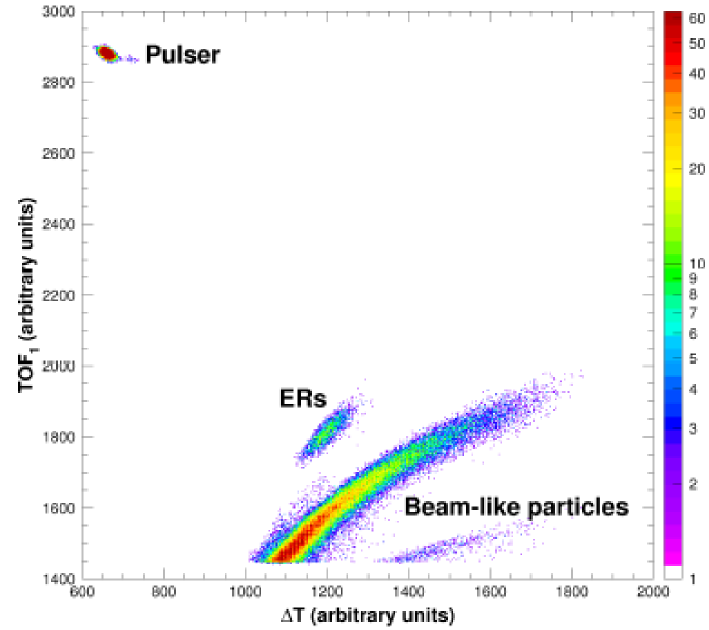
Evaporation residue measurement using compact velocity filter



- Normalization by measuring elastics at forward angles (pure Rutherford)
- Residues transported by the velocity filter
  - Detected directly or Implanted into Si detector
  - Implanted into Si detector →measurement of α-decay between beam-bursts

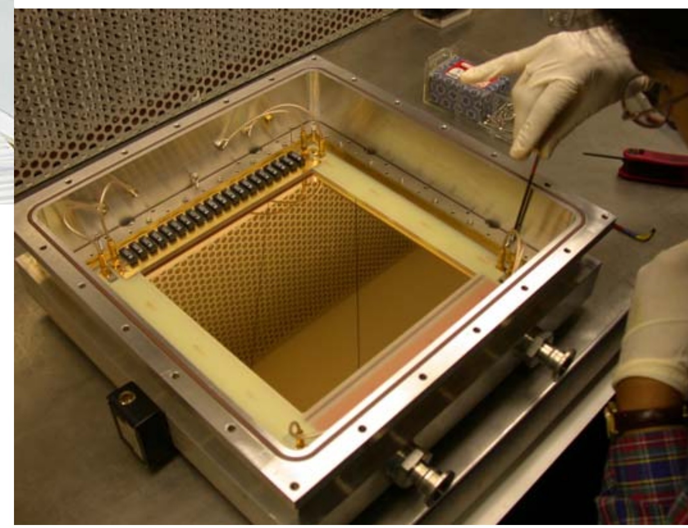
SOLITAIRE – new generation separator





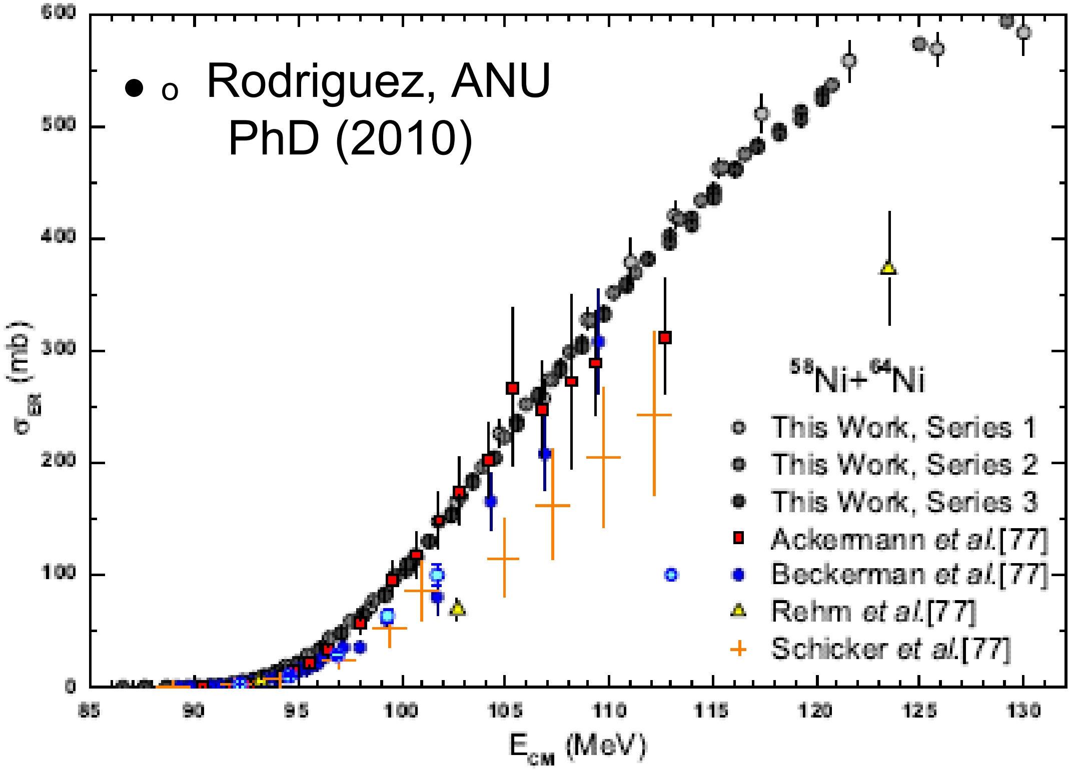
Transports ER with high efficiency

(0.45 – 9.5 degrees)



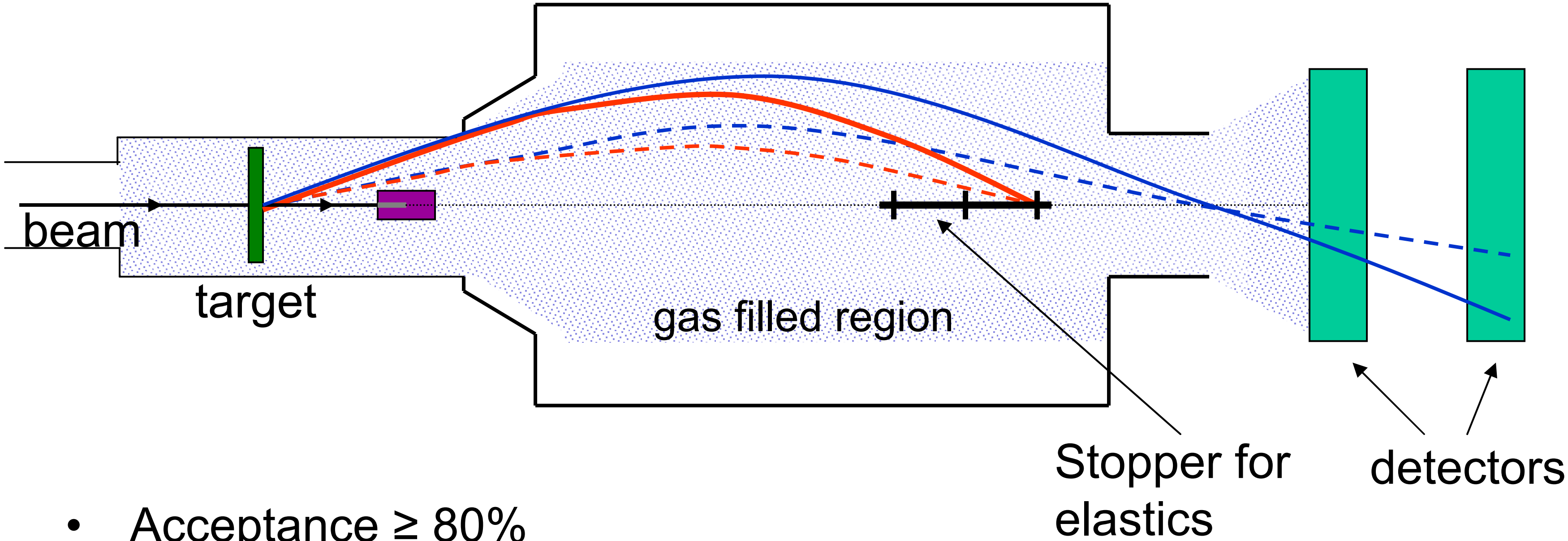
Identifies ER + track path

^{58}Ni + ^{64}Ni evaporation residue measurements using SOLITAIRE



- Absolute cross section measurements not easy
- High efficiency very advantageous

Gas filled 6.5 T Superconducting Solenoid (lens –action)



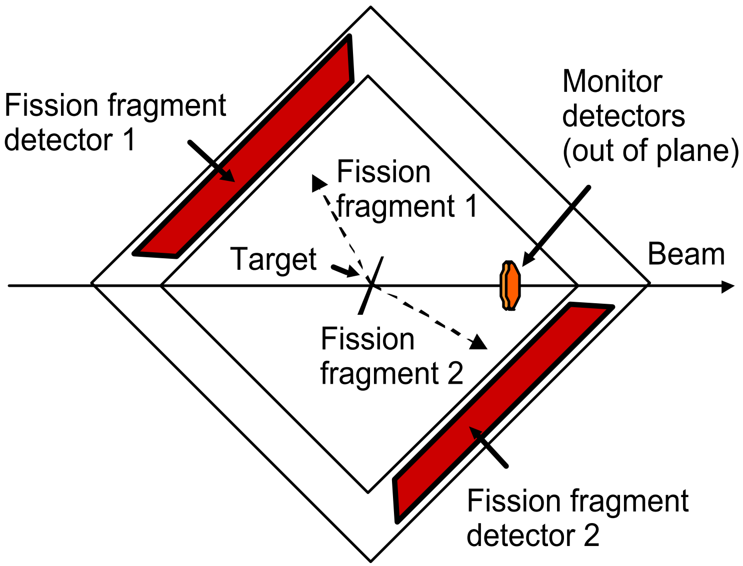
- Acceptance ≥ 80%
- $\simeq$100% detection efficiency
- Highest efficiency evaporation residue separator

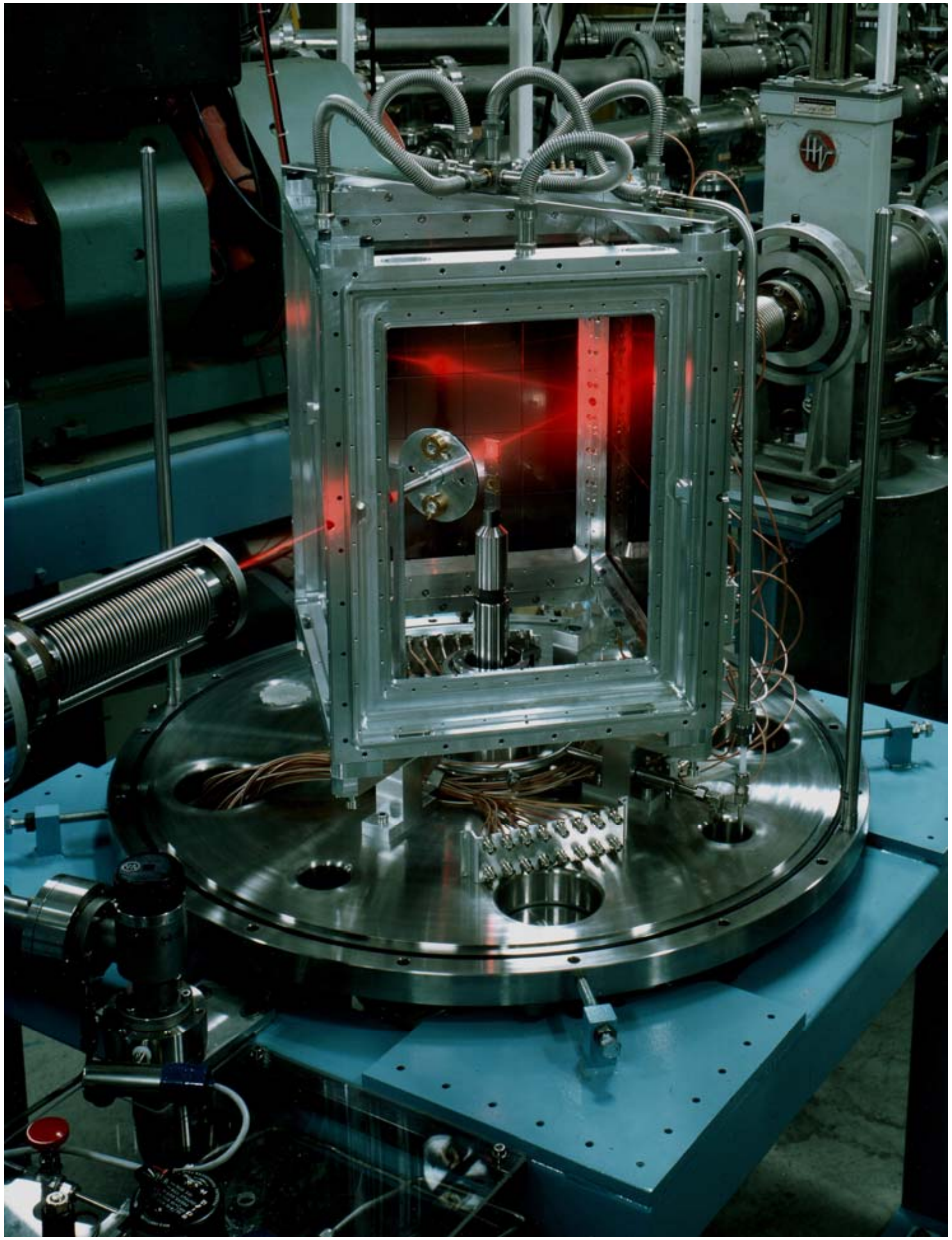
Rodriguez et al, NIM A614 (2010) 119

- Fusion measurement, coincidence and implantation studies (materials, medical)
- production of ^{6}He for experiments

Rafiei et al,NIM A631 (2011) 12
Horsley et al, NIM A646 (2011) 174

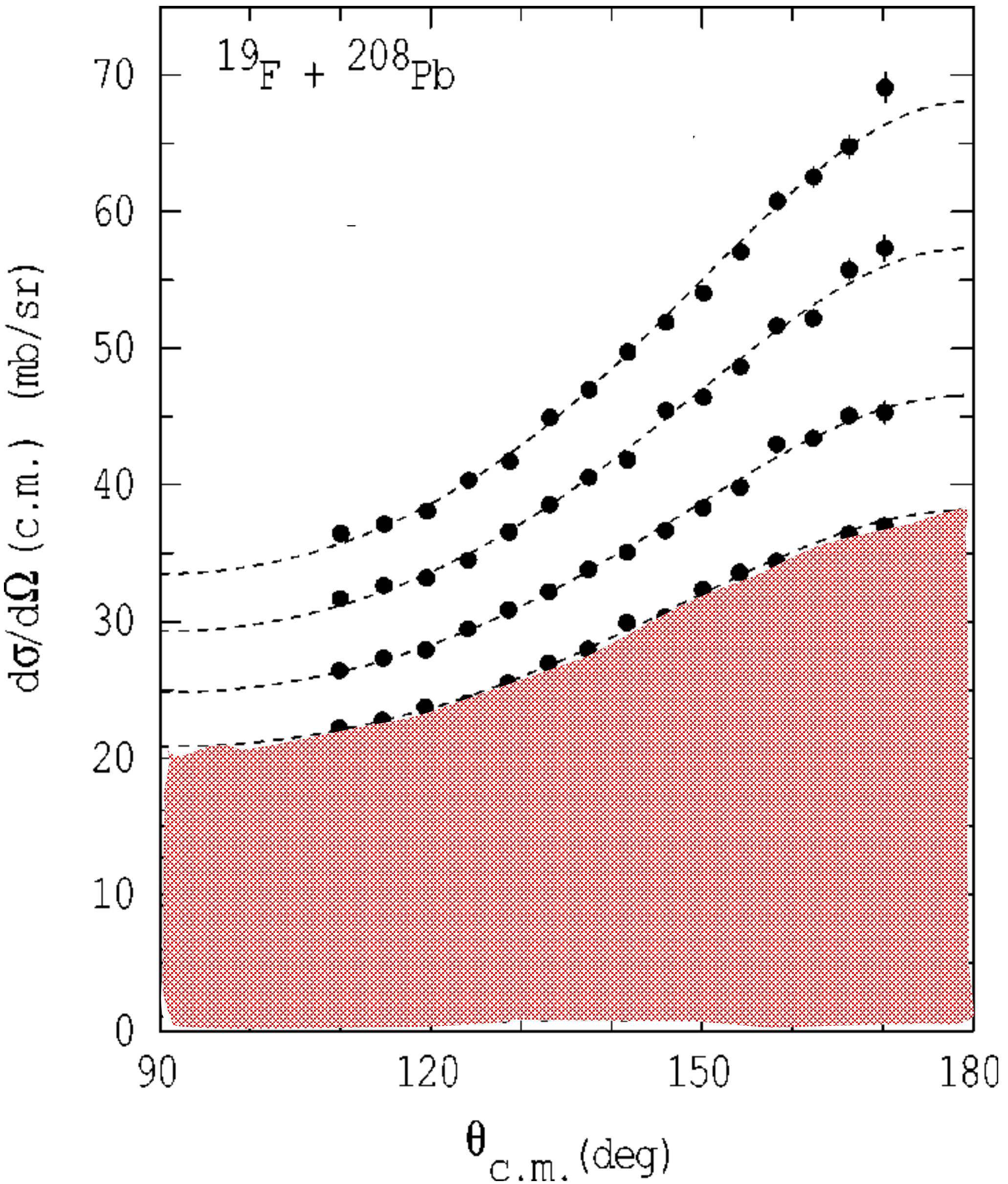
Fission Measurements





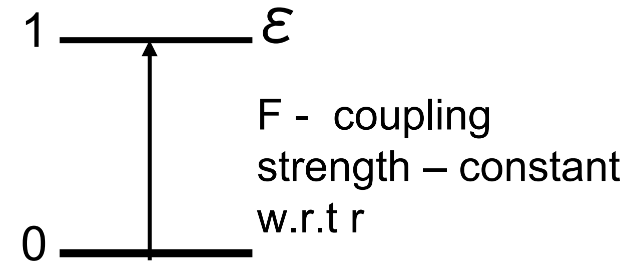
- Measure fission fragment positions
- Measure flight times
- Deduce velocity vectors

Measured fission-fragment angular distributions



Constant coupling approximation – two channel

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+V+\begin{pmatrix}0 & F\\ F & \varepsilon_T\end{pmatrix}\right]\begin{pmatrix}\chi_1\\ \chi_2\end{pmatrix}=E\begin{pmatrix}\chi_1\\ \chi_2\end{pmatrix}$$



Eigenvalues of the coupling matrix: $$\lambda_{\pm}=\frac{1}{2}(\varepsilon\pm\sqrt{\varepsilon^2+4F^2})$$

$$w_{\pm}=\frac{F^2}{F^2+\lambda_{\pm}^2}$$

Coherent superposition ⇒ V splits into two eigen-barriers

$$\sigma_{fusion}(E_{cm})=w_{+}\sigma_{fusion}(E_{cm},V_B+\lambda_{+})+w_{-}\sigma_{fusion}(E_{cm},V_B+\lambda_{-})$$

Home work problem

The sum of the Coulomb and nuclear potentials between ^{16}O and ^{144}Sm nuclei gives: barrier energy = 61.00 MeV;
inter-nuclear separation at the barrier = 10.86 fm,
barrier curvature (assuming parabolic) = 4.25 MeV.

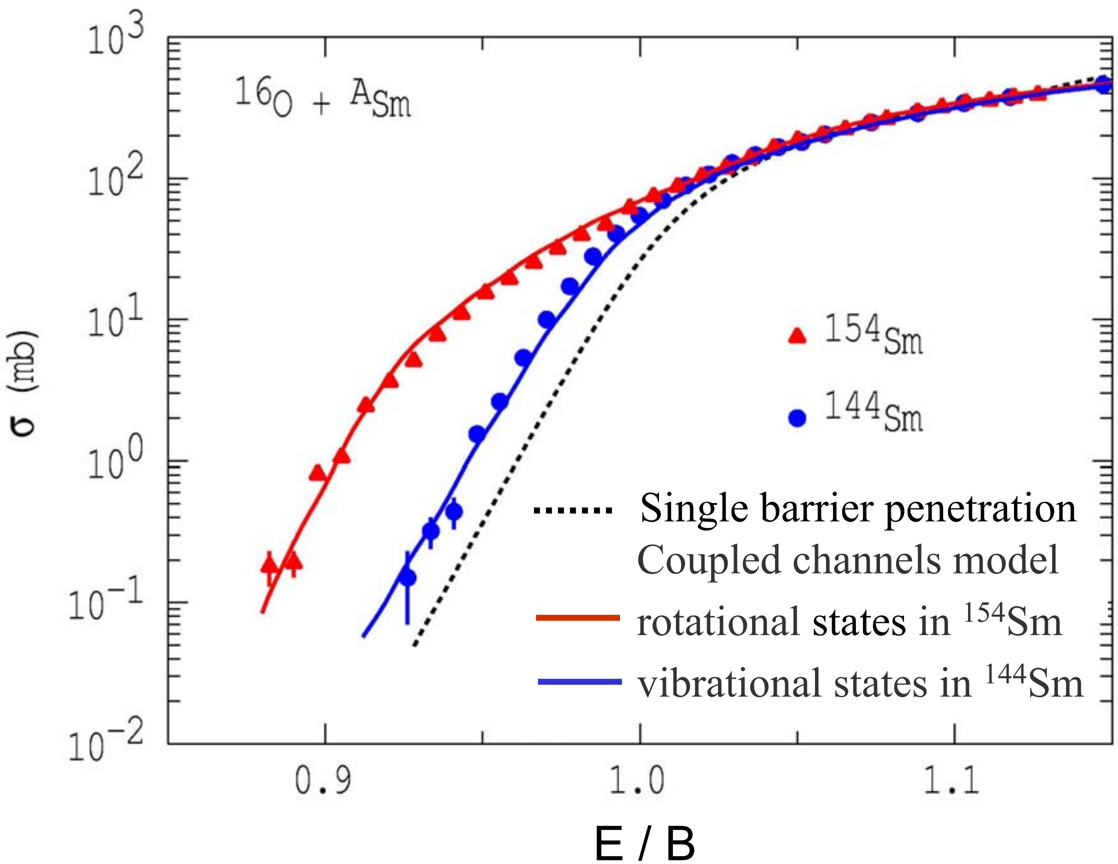
(1) Using parabolic approx. calculate the expected fusion cross-section (in mb) at $E_{c.m}$=60.00 MeV and 75 MeV.

(2) The target ^{144}Sm has an excited state at 1.8 MeV. Assume a coupling strength of 3 MeV to this state, independent of inter-nuclear separation.

Calculate the fusion cross-section at $E_{c.m.}$ = 60, 75 MeV when coupling to this state is included. Assume that the barrier curvature does not change with couplings.

What is the factor by which the cross section is enhanced/suppressed compared with that obtained in (1), i.e., when single barrier, no coupling was assumed

Effect of nuclear structure on fusion – included in coupled channels model



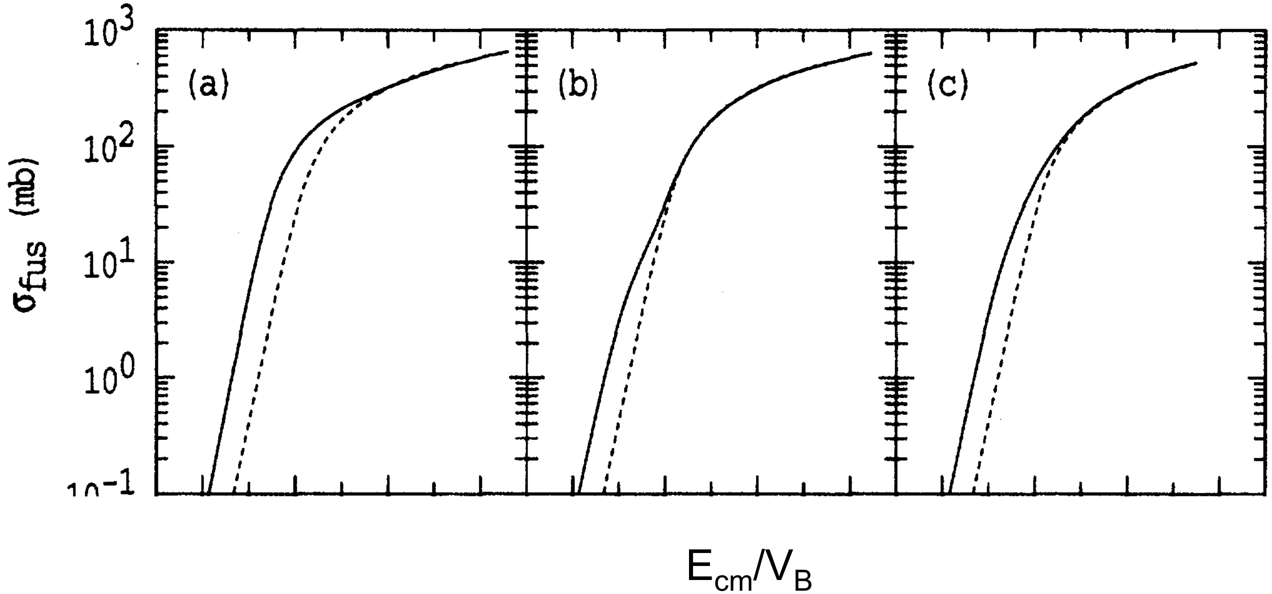
How do we know that we have got the mechanism right?

Wei et al, PRL, 67 (1991) 3368

Morton et al, PRL, 72 (1994)4074

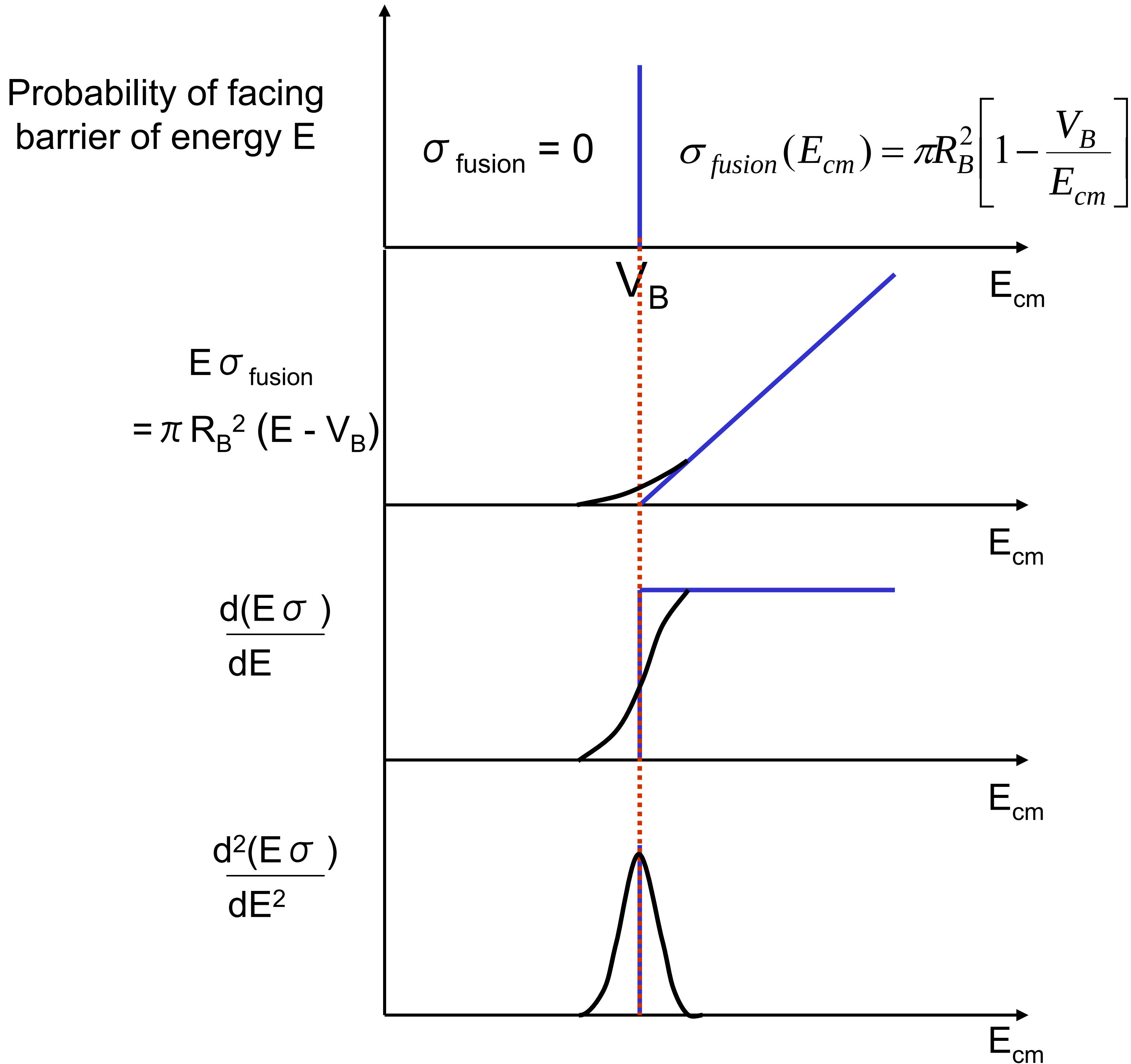
Leigh et al, PRC52 (1995) 3151

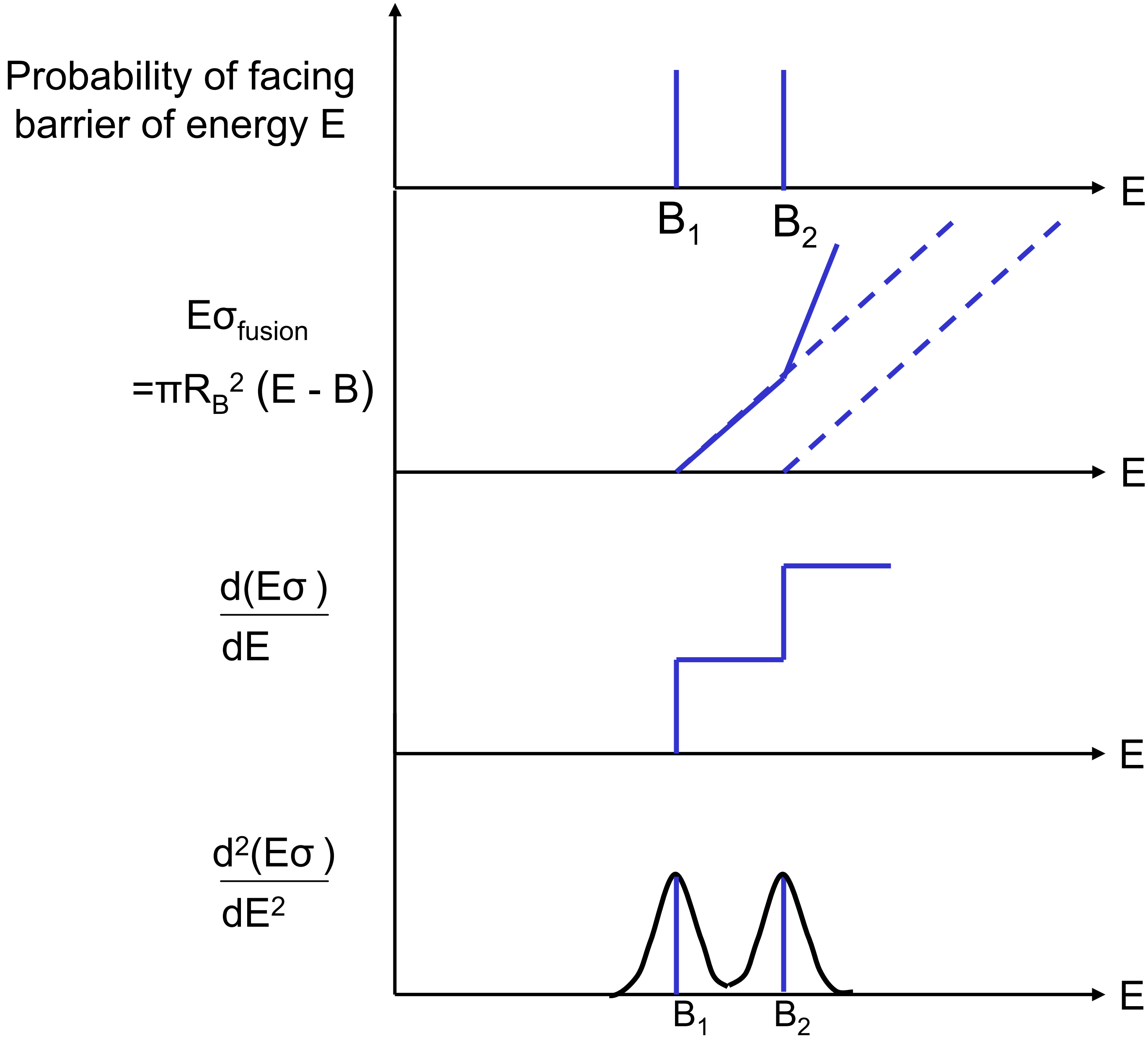
- Presence of quantum levels ⟹ enhancement by factors of 10 –100 of below-barrier fusion cross-sections
- Coupling assisted quantum tunnelling



Similar cross-section enhancement w.r.t.

single barrier

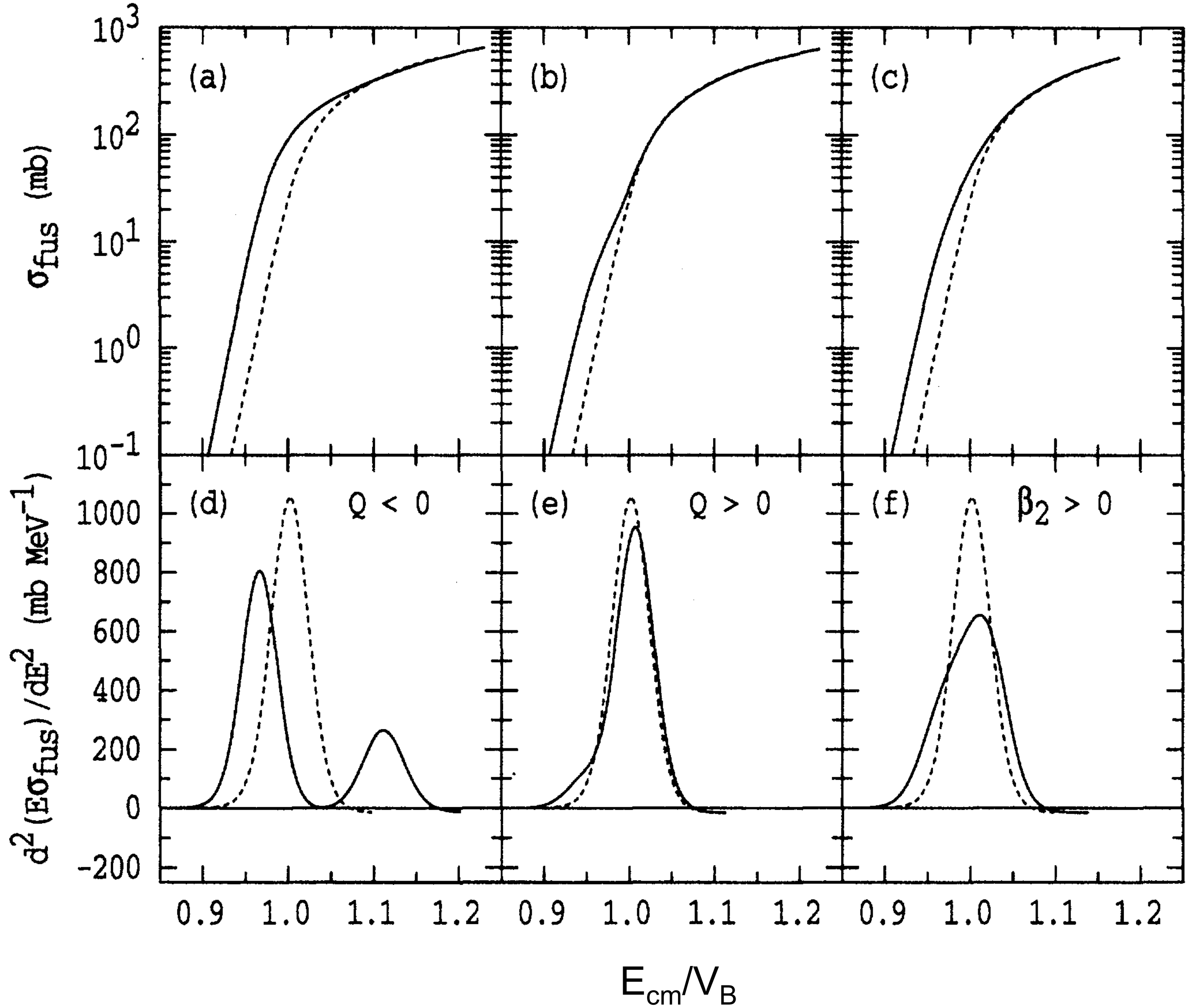

Probability of facing barrier of energy E
$\sigma_{fusion} = 0$
$\sigma_{fusion}(E_{cm}) = \pi R_B^2 \left[1 - \frac{V_B}{E_{cm}}\right]$
V_B
E_{cm}
$E\sigma_{fusion}$
$= \pi R_B^2 (E - V_B)$
E_{cm}
$\frac{d(E\sigma)}{dE}$
E_{cm}
$\frac{d^2(E\sigma)}{dE^2}$
E_{cm}



- second derivative of data required

Rowley et al., Phys. Lett. B, 254, 25 (1991)

Advantages of taking derivatives



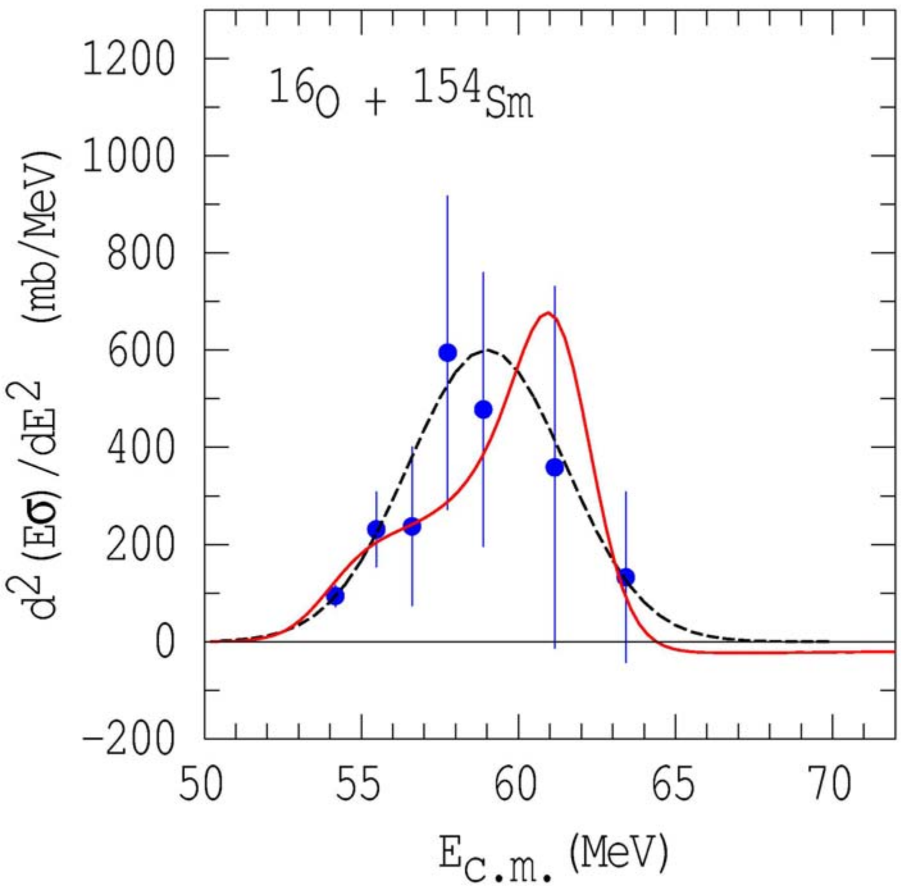
Similar cross-section enhancement w.r.t.

...... single barrier

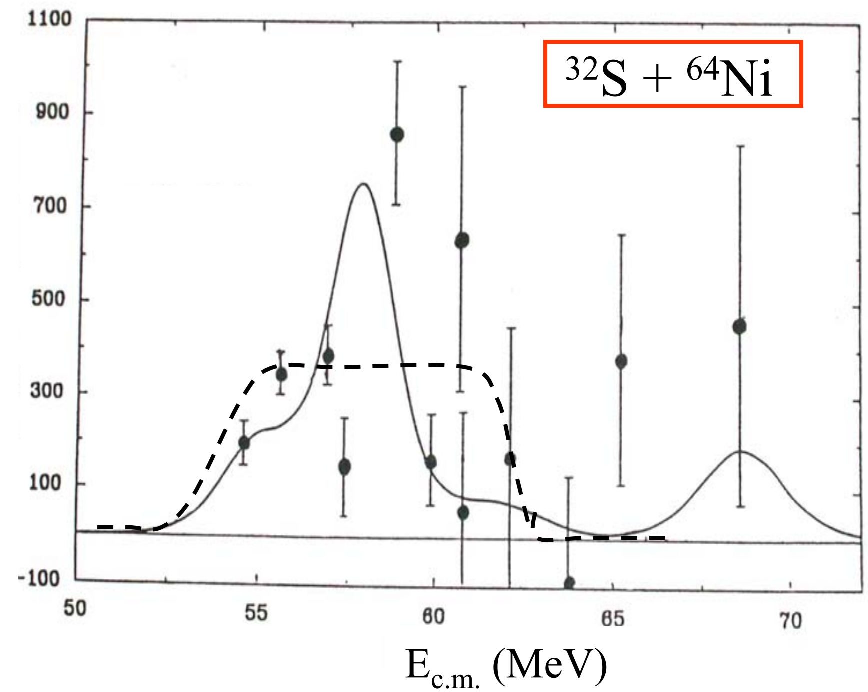
2nd derivative brings out the physics

Barrier distributions for data with 5-10% uncertainty

Stockstad et al. (1980)



Tighe et al. (1990)
Dasgupta PhD thesis (1991)



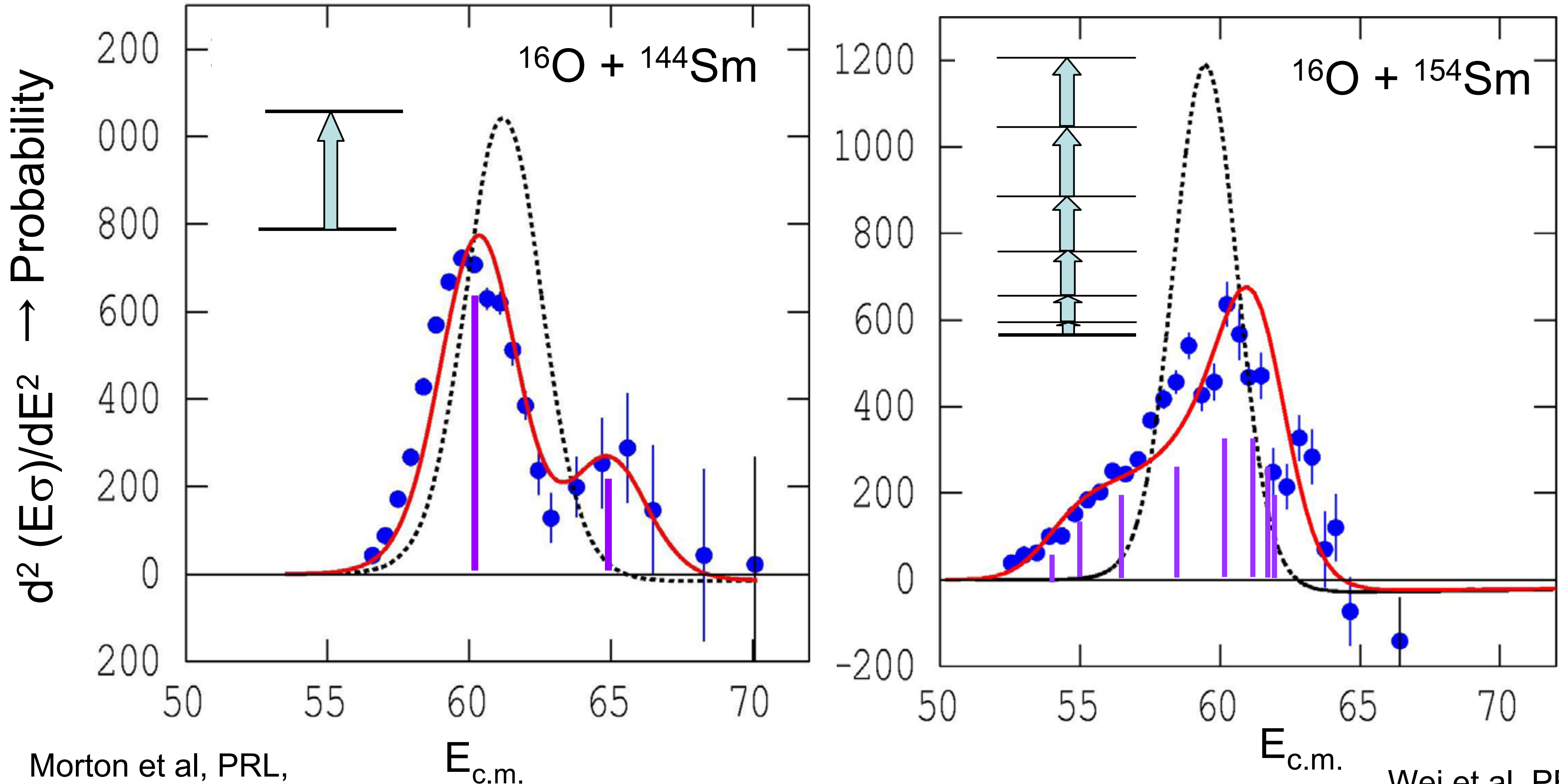
much higher precision required!

- novel instrumentation and measurement procedures required

→ precision measurements (1% uncertainty) – pioneered by our ANU group

First measurement: Wei et al, PRL, 67 (1991) 3368

Leigh et al, PRC52 (1995) 3151

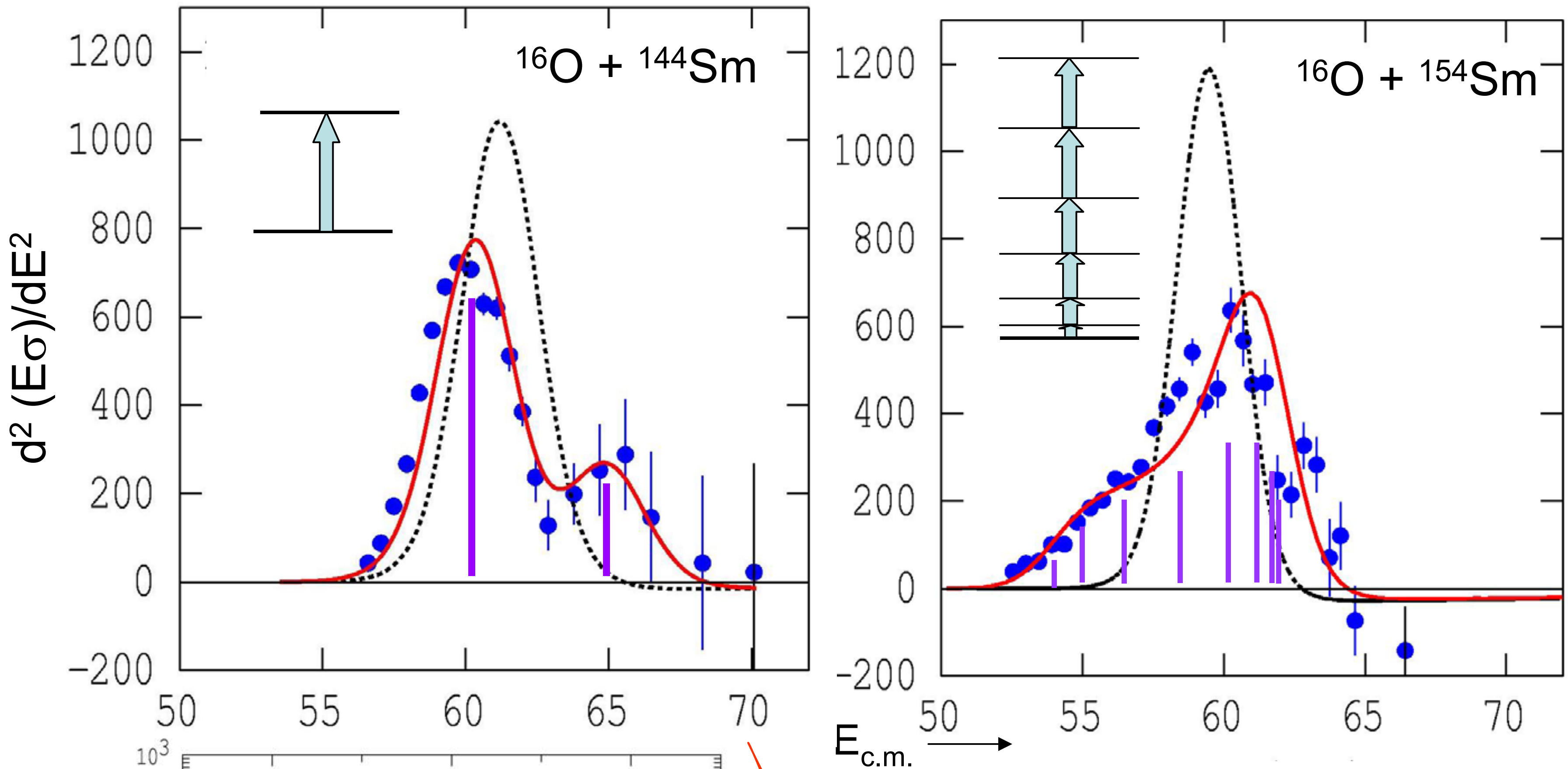


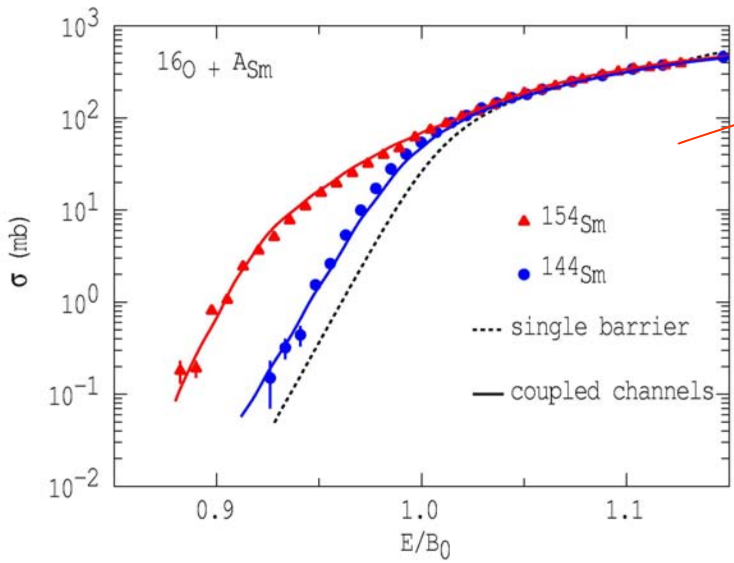
Morton et al, PRL, 72 (1994)4074

Wei et al, PRL, 67 (1991) 3368

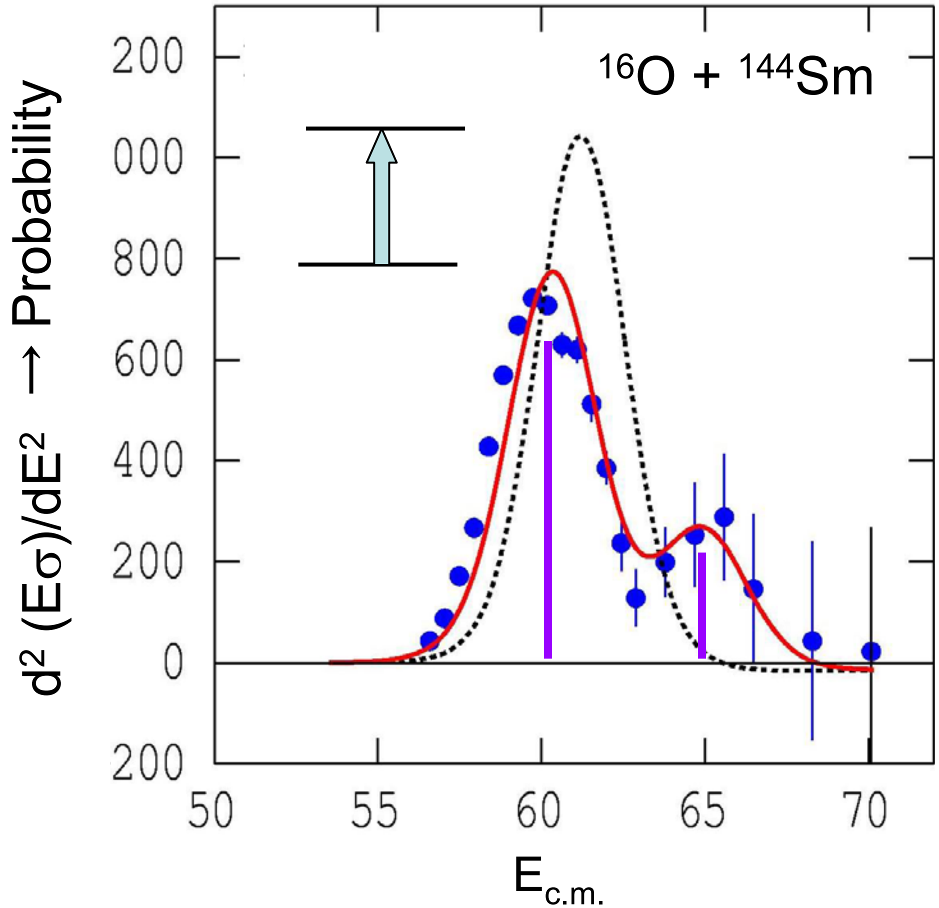
- Fusion as a function of energy – barriers are like filters
- Fusion - snapshot of the eigen-channels of the quantum system at contact

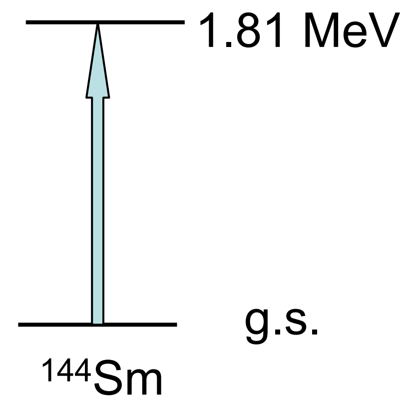
Dasgupta et al., Annual Rev. of Nuclear & Particle Science 48 (1998) 401



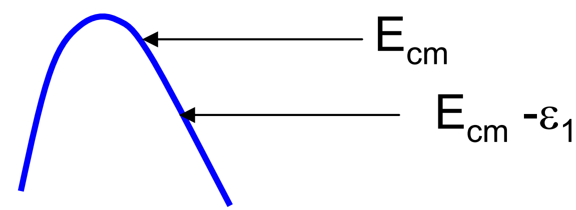


can not be explained by excitation followed by fusion, but is an effect of superposition





^{16}O – effectively no excitations



excitation leads reduction in K.E. →reduced cross-sections

$$\sigma = (1-P_1)\,\sigma(\mathbf{E}_{cm}) + \underline{P_1\,\sigma(\mathbf{E}_{cm} - \varepsilon_{\mathbf{1}})}$$

Net cross-section smaller – opposite of what is seen

Cross section enhancement due to superposition of quantum states

Main messages

- Development of unique detection systems – an important role
  - Data of unmatched precision
  - Reveal new aspects of interacting many-body quantum systems

- Colliding nuclei in a superposition of states – quantum effects
  - Single barrier → effectively "distribution of barrier energies"
  - this effect clear from high precision measurements

Additional material follows

$$\sigma_{fusion}(E_{cm}) = \sum_l \sigma_l = \int \sigma_l \; dl$$

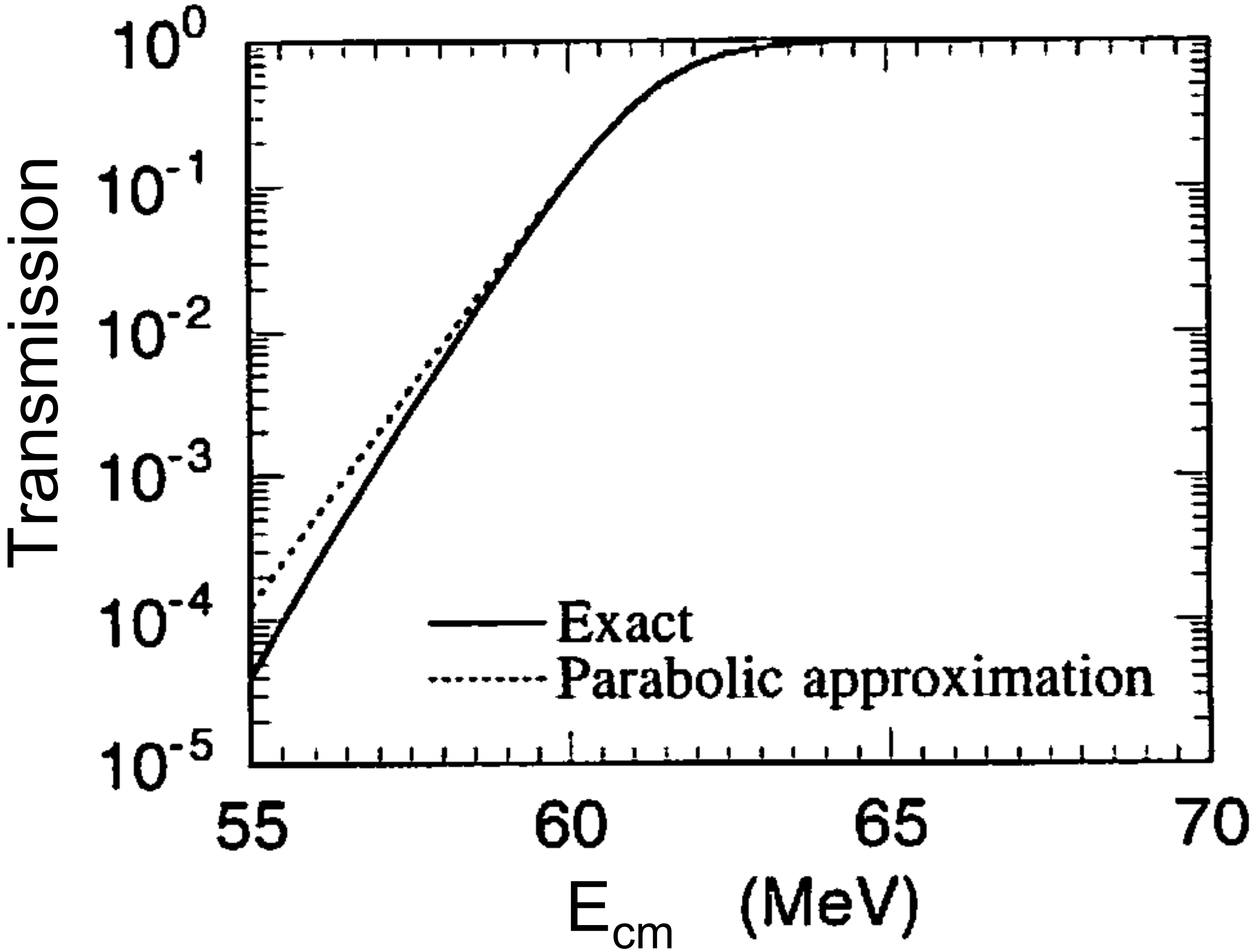
$$= \frac{\pi}{k^2} \int \frac{(2l+1)}{1 + \exp\left\{ \frac{2\pi}{\hbar\omega}(V_{Bl} - E_{cm}) \right\}} dl$$

Use: $V_{Bl} = V_B + \frac{l(l+1)\hbar^2}{2\mu R_B^2}$

$$\sigma_{fusion}(E_{cm}) = \frac{\hbar\omega}{2E_{cm}} R_B^2 \ln\left[1 + \exp\left\{ \frac{2\pi}{\hbar\omega}(E_{cm} - V_B) \right\} \right]$$

Not too bad – good insights

- exact - solve Schrödinger Eqn.



Insights to fusion cross-sections – take limits of

$$\sigma_{fusion}(E_{cm}) = \frac{\hbar\omega}{2E_{cm}} R_B^2 \ln\left[1 + \exp\left\{\frac{2\pi}{\hbar\omega}(E_{cm} - V_B)\right\}\right]$$

$E_{cm} >> V_B$

$$\sigma_{fusion}(E_{cm}) \approx \pi R_B^2 \left[1 - \frac{V_B}{E_{cm}}\right]$$

Goes up with E_{cm}: $\sigma_{fusion} E_{cm}$ goes up linearly with E_{cm}-V_B

Same as that obtained classically

$E_{cm} << V_B$

$$\sigma_{fusion}(E_{cm}) \approx \frac{\hbar\omega}{2E_{cm}} R_B^2 \exp\left\{\frac{2\pi}{\hbar\omega}(E_{cm} - V_B)\right\}$$

Fusion cross-sections falls exponentially as E_{cm} falls below V_B