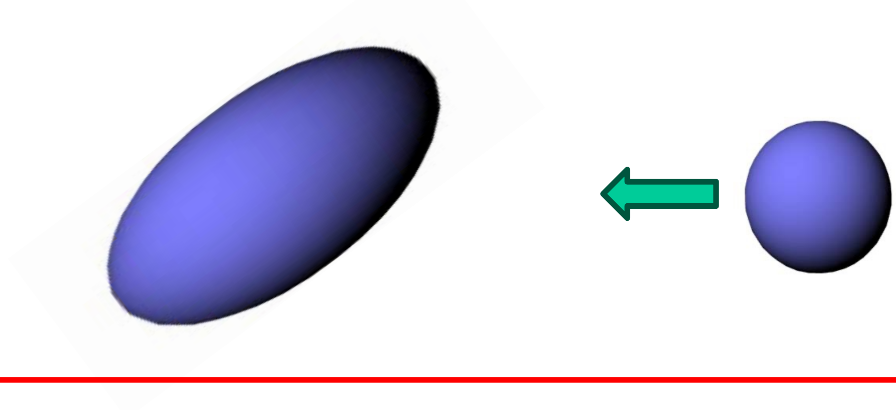
Impact of nuclear shapes in low-energy heavy-ion reactions

Kouichi Hagino
Kyoto University, Kyoto, Japan



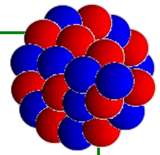
1. Low-energy Nuclear Reactions: overview
2. Role of deformation in sub-barrier fusion reactions
3. Probing nuclear shapes in quasi-elastic scattering
4. Summary

Workshop on “Exploring Nuclear Physics across Energy Scales 2024”, Beijing, China, 2024.4.23

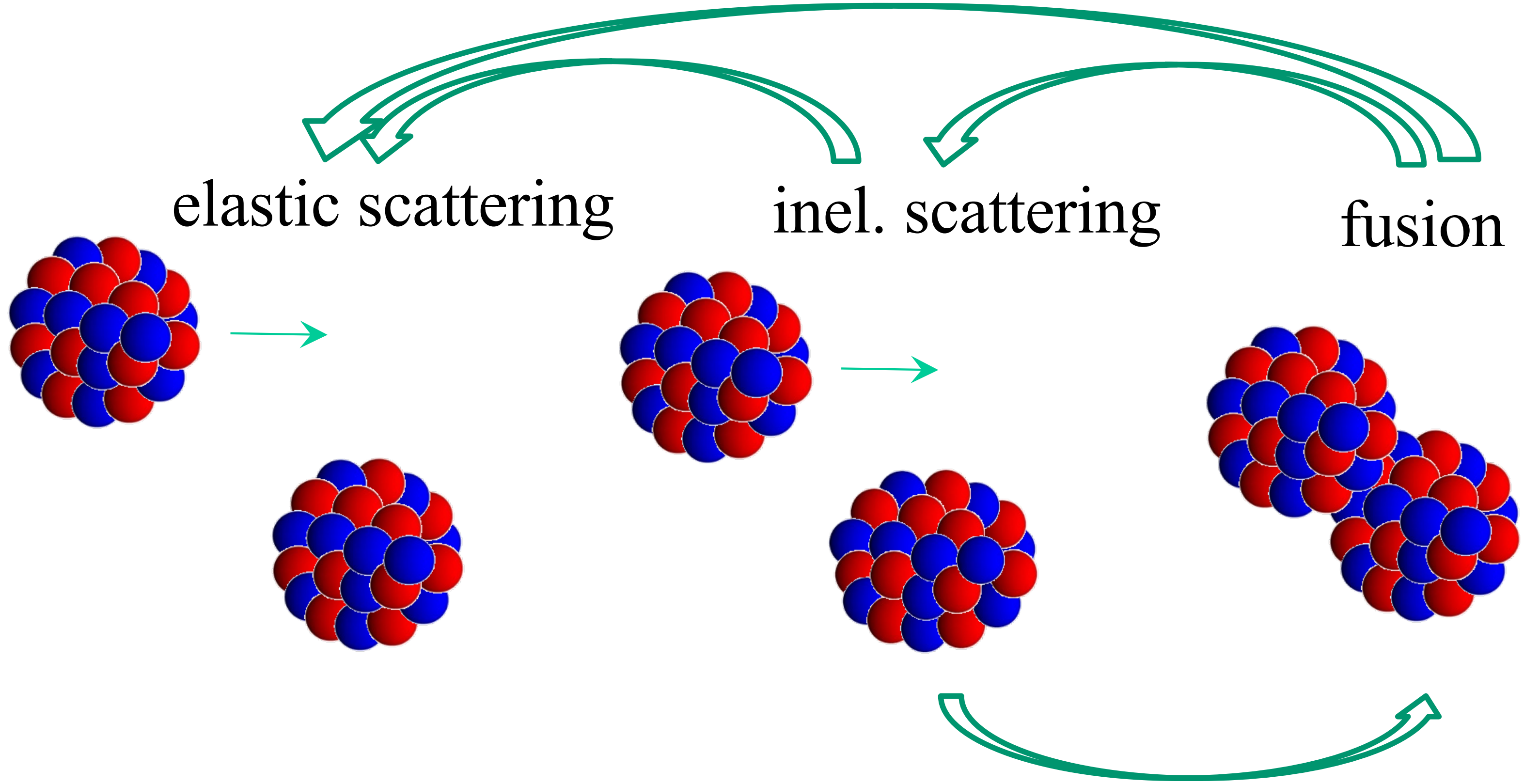
Introduction: low-energy nuclear reactions

nucleus: a composite system

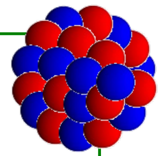
✓ various sort of reactions



- elastic scattering
- inelastic scattering
- transfer rections
- breakup reactions
- fusion reactions



Introduction: low-energy nuclear reactions



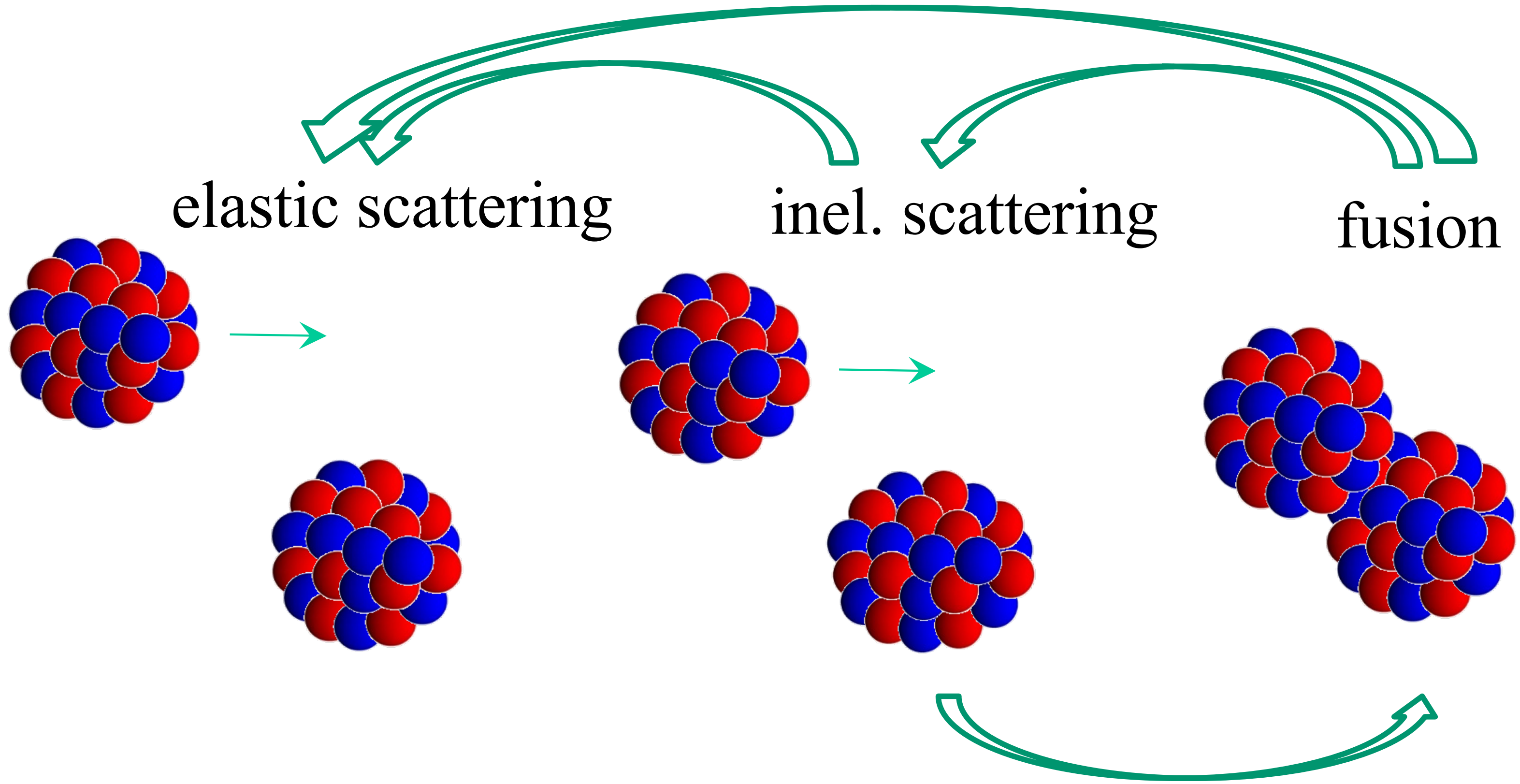
nucleus: a composite system

✓ various sort of reactions

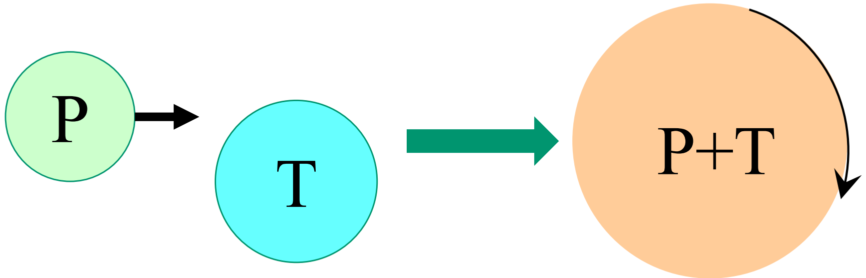
✓ an interplay between nuclear structure and reaction

shapes, excitations, …..

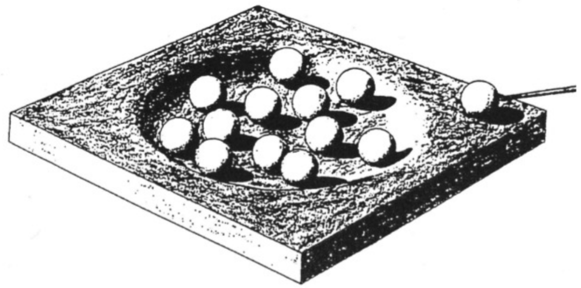
- elastic scattering
- inelastic scattering
- transfer rections
- breakup reactions
- fusion reactions



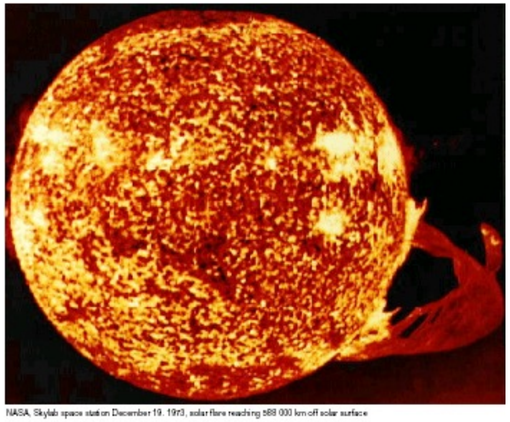
Fusion reactions: compound nucleus formation



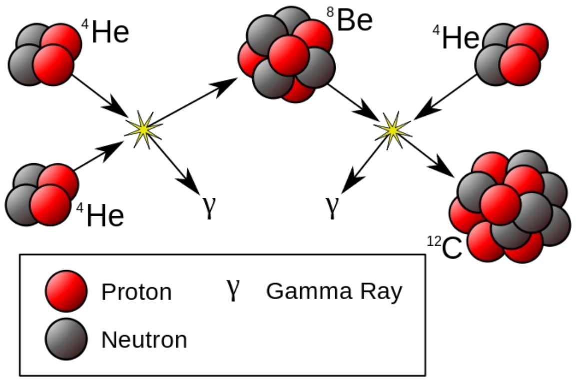
compound nucleus



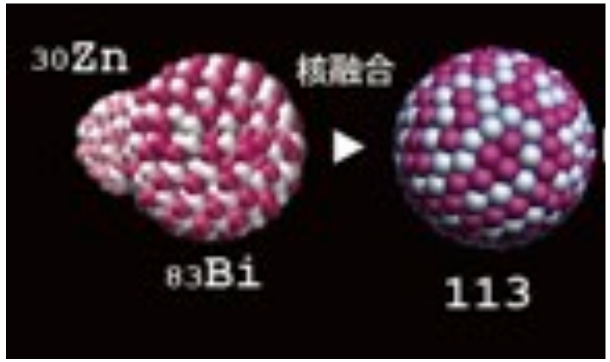
cf. Bohr '36



energy production in stars (Bethe '39)



nucleosynthesis

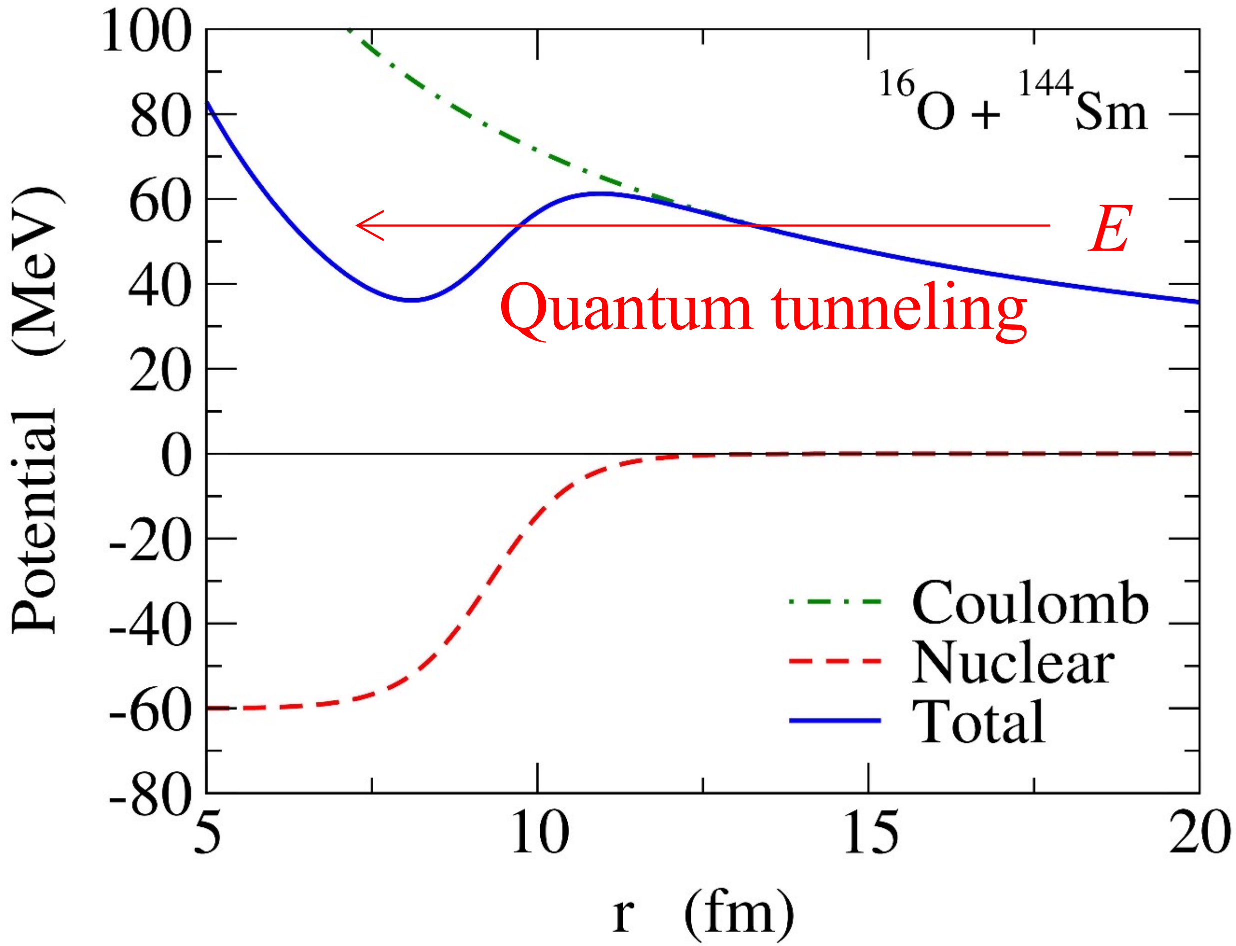


superheavy elements

Fusion and fission: large amplitude motions of quantum many-body systems with strong interaction

⟵ microscopic understanding: an ultimate goal of nuclear physics

Coulomb barrier



1. Coulomb interaction
   long range, repulsion
2. Nuclear interaction
   short range, attraction

Potential barrier
(Coulomb barrier)

Fusion: takes place by overcoming the barrier

the barrier height → defines the energy scale of a system

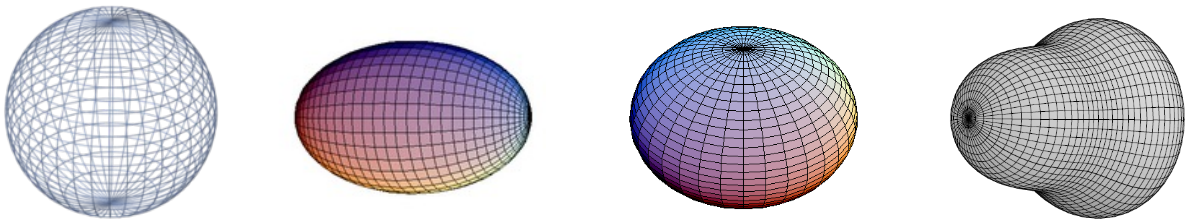
Fusion reactions at energies around the Coulomb barrier

Low-energy heavy-ion fusion reactions and quantum tunneling

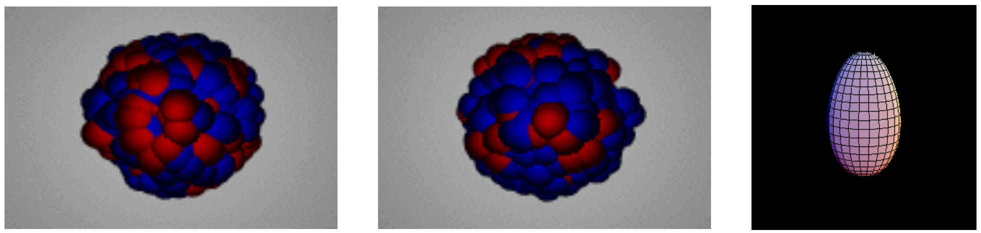
Fusion with quantum tunneling

with many degrees of freedom

- several nuclear shapes



- several surface vibrations



several modes and adiabaticities

- several types of nucleon transfers

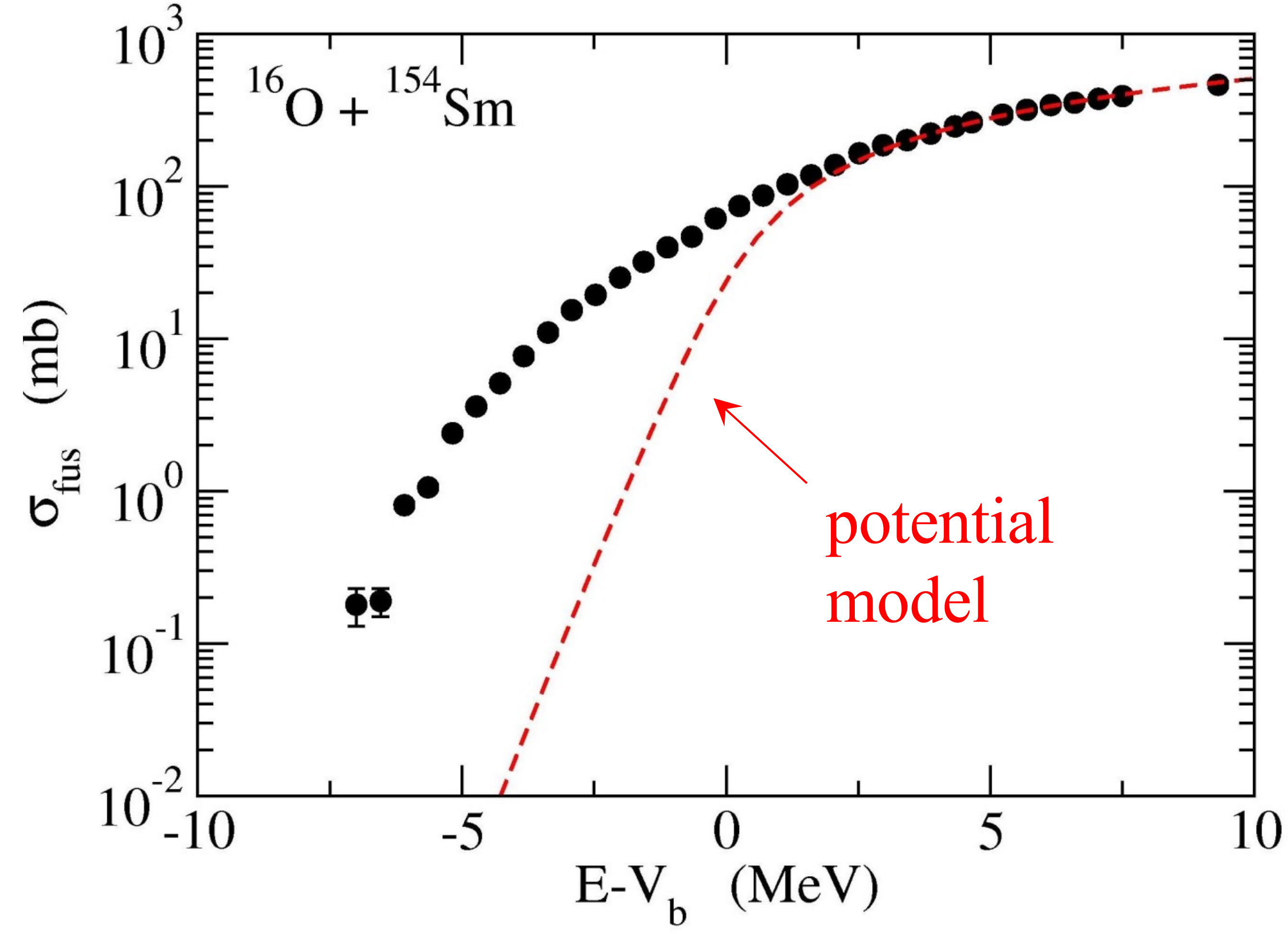
Tunneling probabilities: the exponential E dependence

$\rightarrow$ nuclear structure effects are amplified

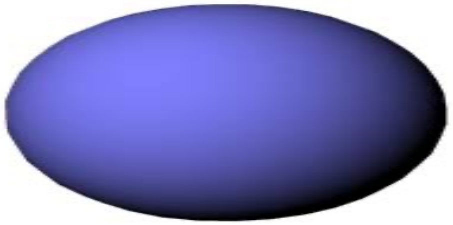
Discovery of large sub-barrier enhancement of σ_{fus} (~80's)

the potential model: inert nuclei (no structure)

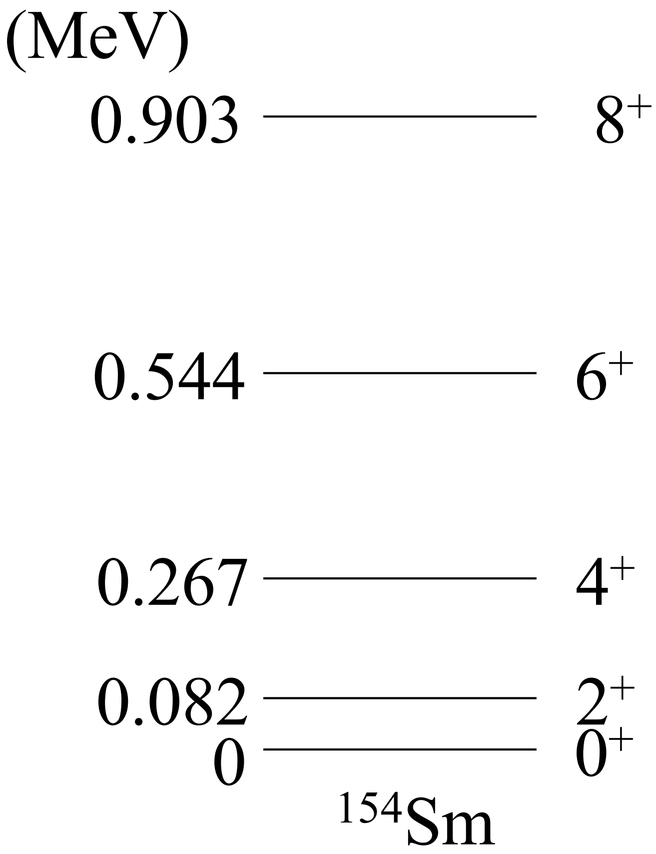
$$\sigma_{\rm fus} = \frac{\pi}{k^2} \sum_l (2l+1)(1-|S_l|^2)$$



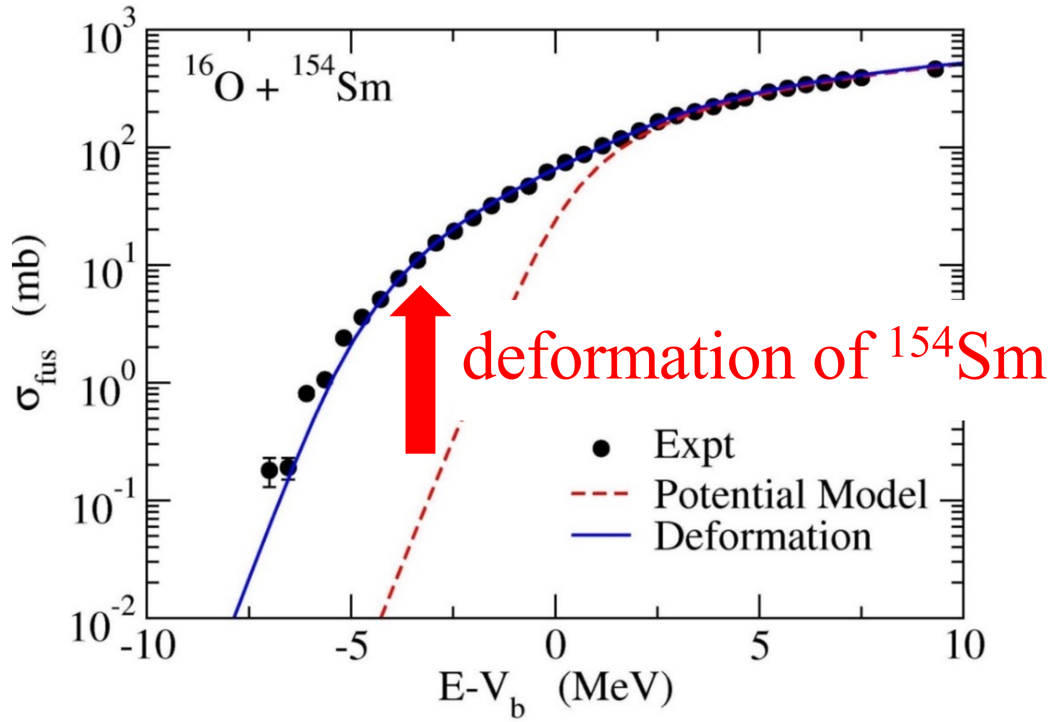
^{154}Sm : a typical deformed nucleus



^{154}Sm



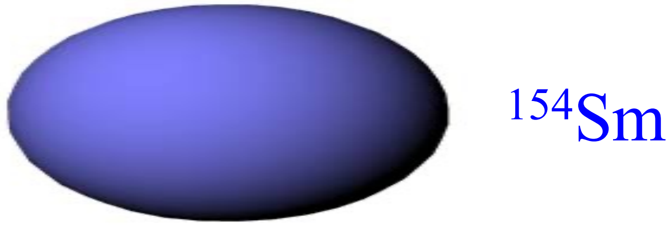
rotational spectrum

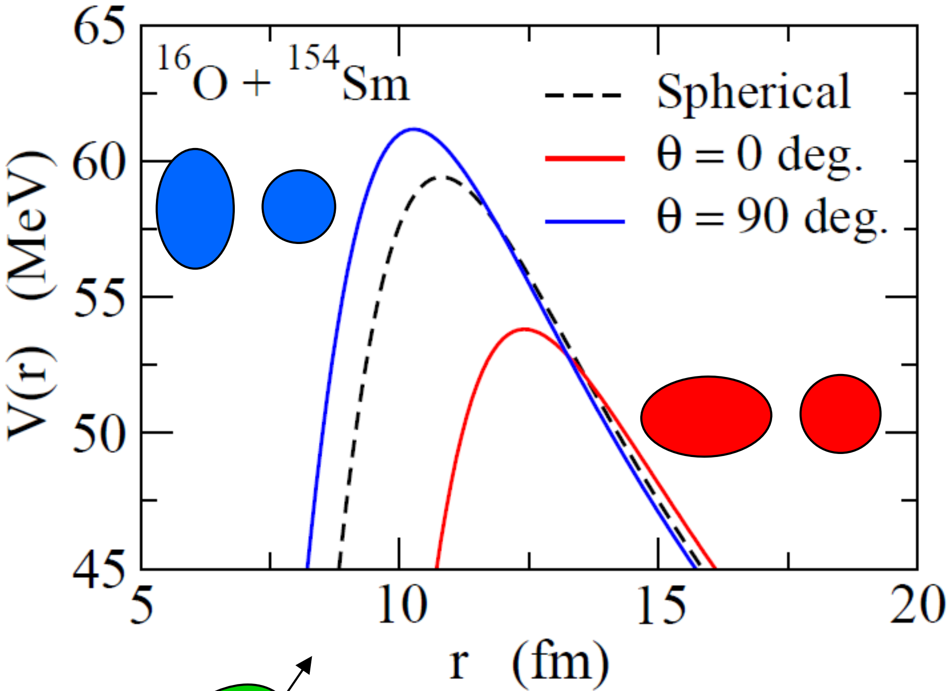


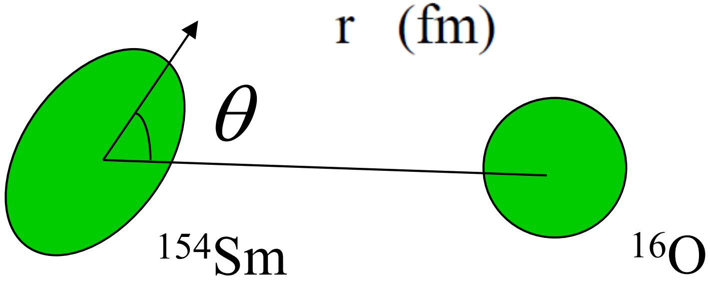
K. H. and N. Takigawa,
Prog. Theo. Phys.128 ('12)1061.

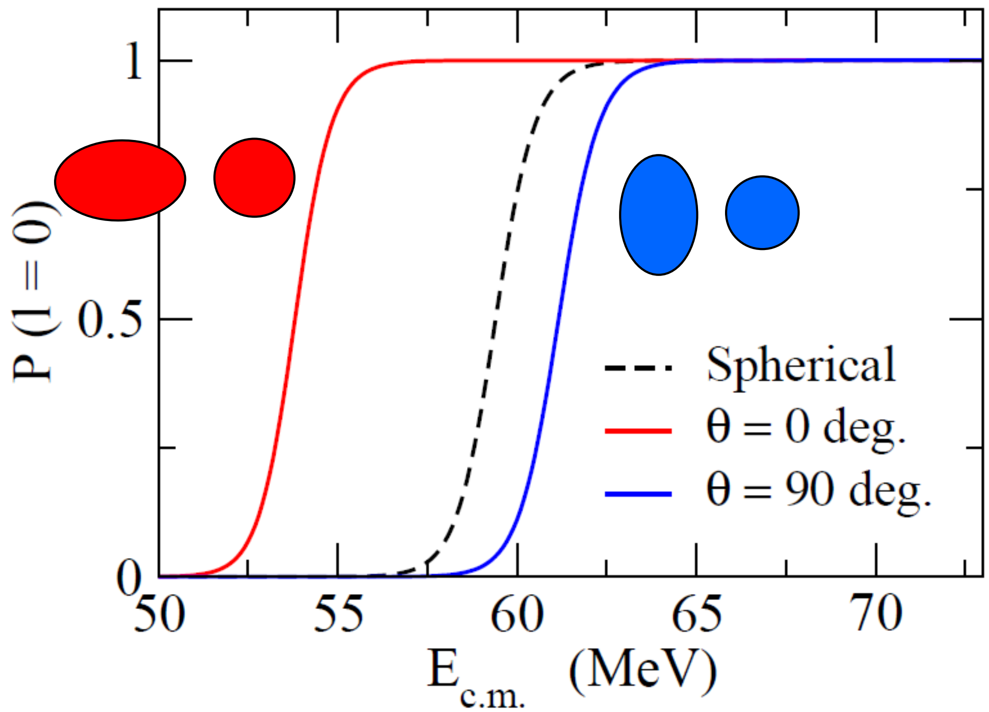
Effects of nuclear deformation

^{154}Sm : a typical deformed nucleus



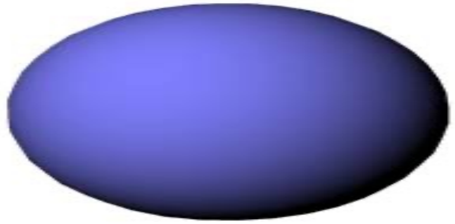




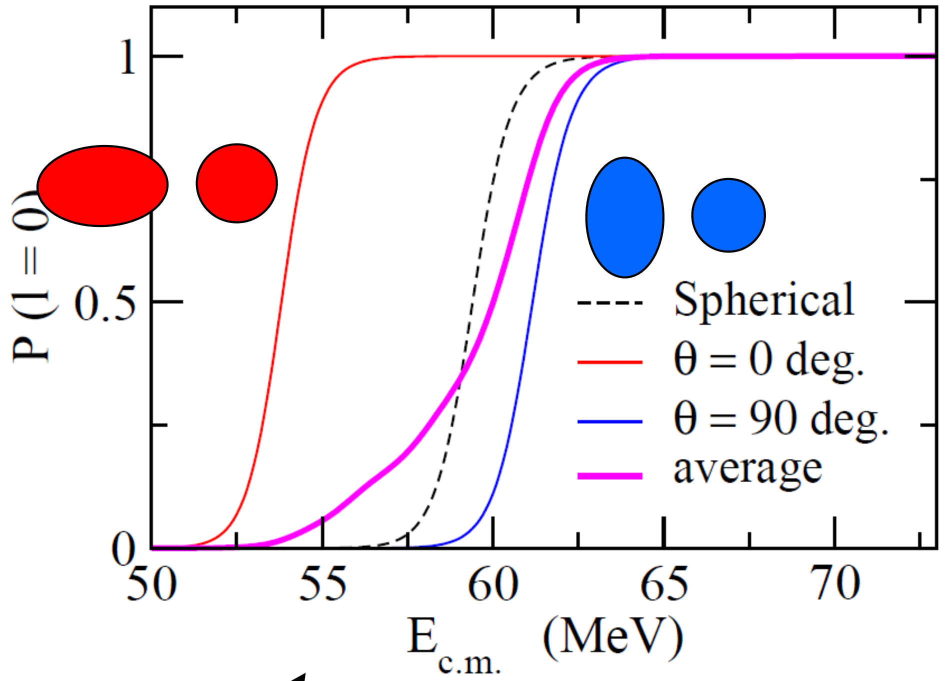


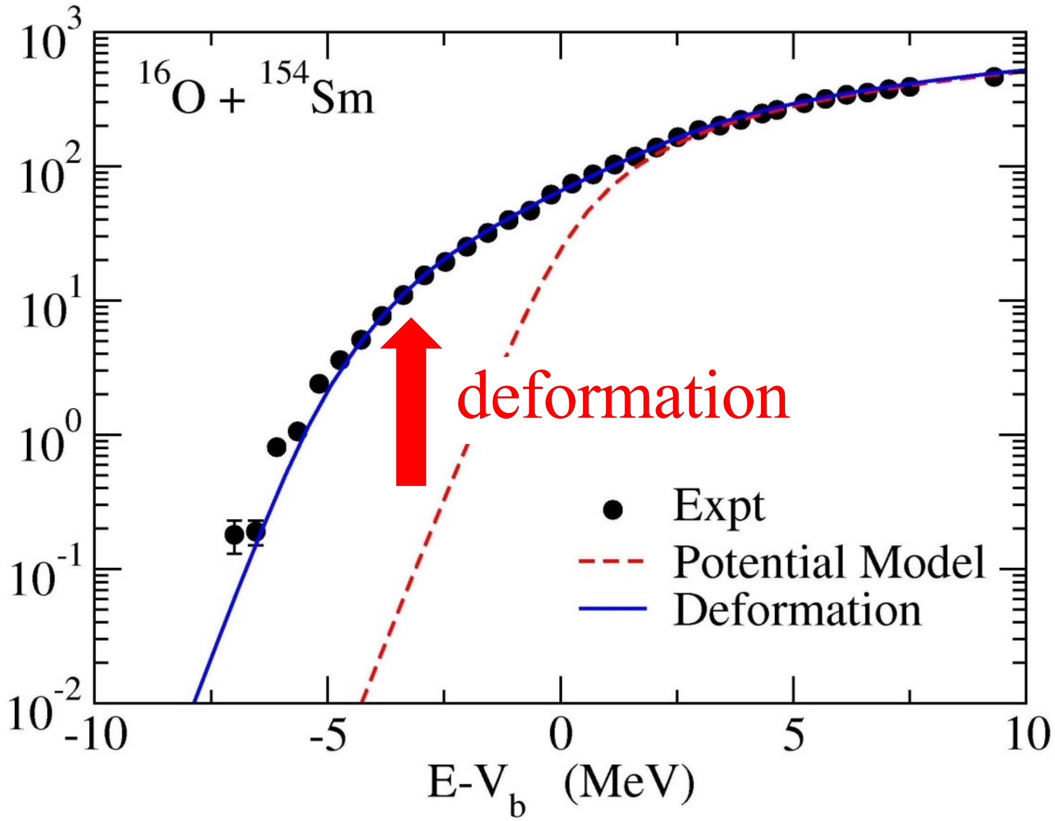
Effects of nuclear deformation

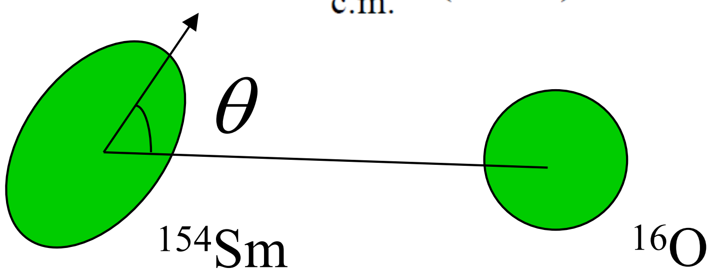
^{154}Sm : a typical deformed nucleus



^{154}Sm

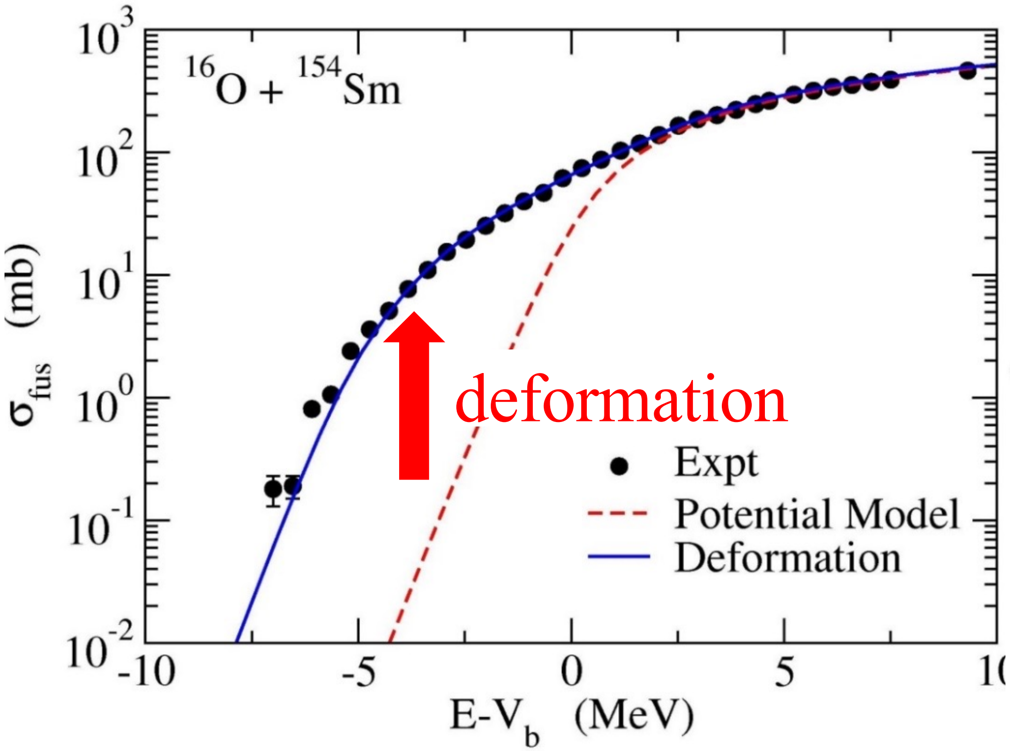




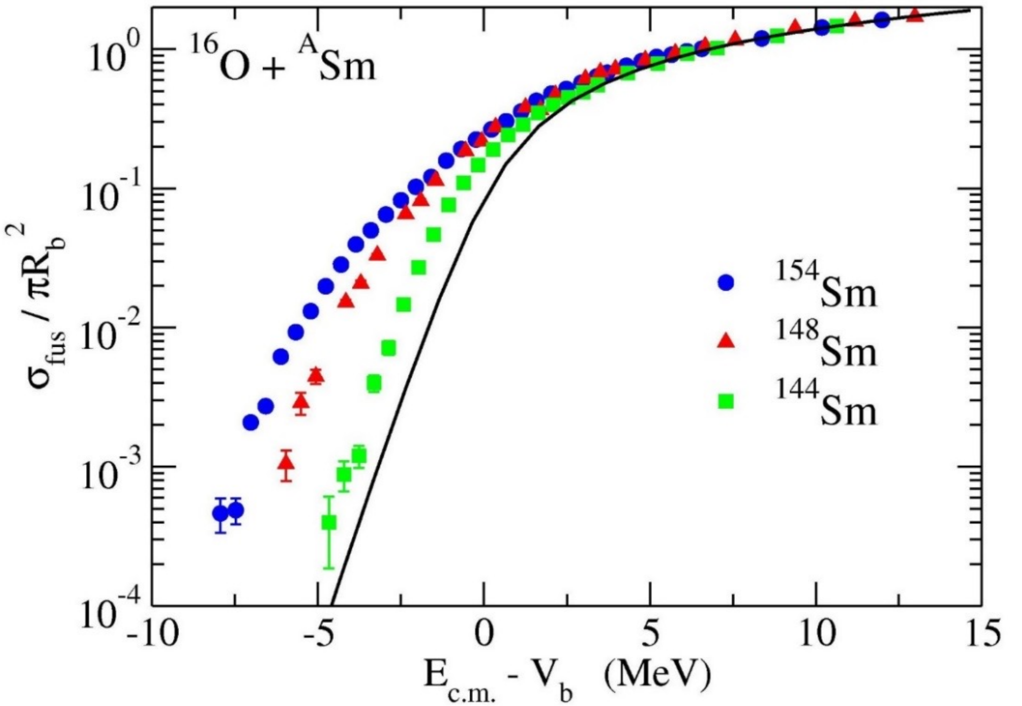


$$\sigma_{\text{fus}}(E) = \int_0^1 d(\cos\theta)\sigma_{\text{fus}}(E;\theta)$$

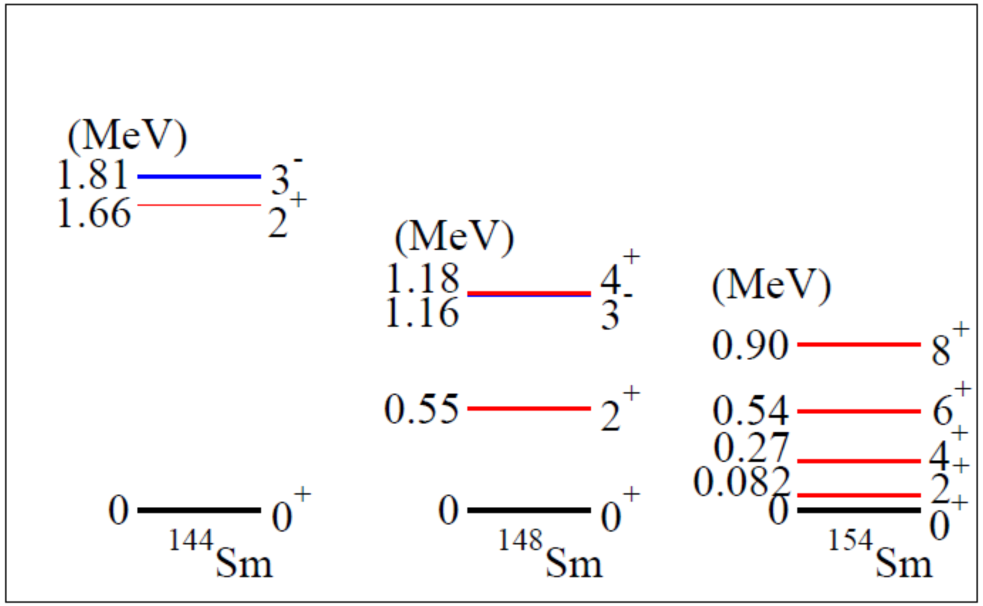
Fusion: strong interplay between nuclear structure and reaction



similar enhancement
for non-deformed nuclei



strong correlation
with nuclear spectrum
→ coupling assisted
tunneling phenomena



Fusion barrier distribution

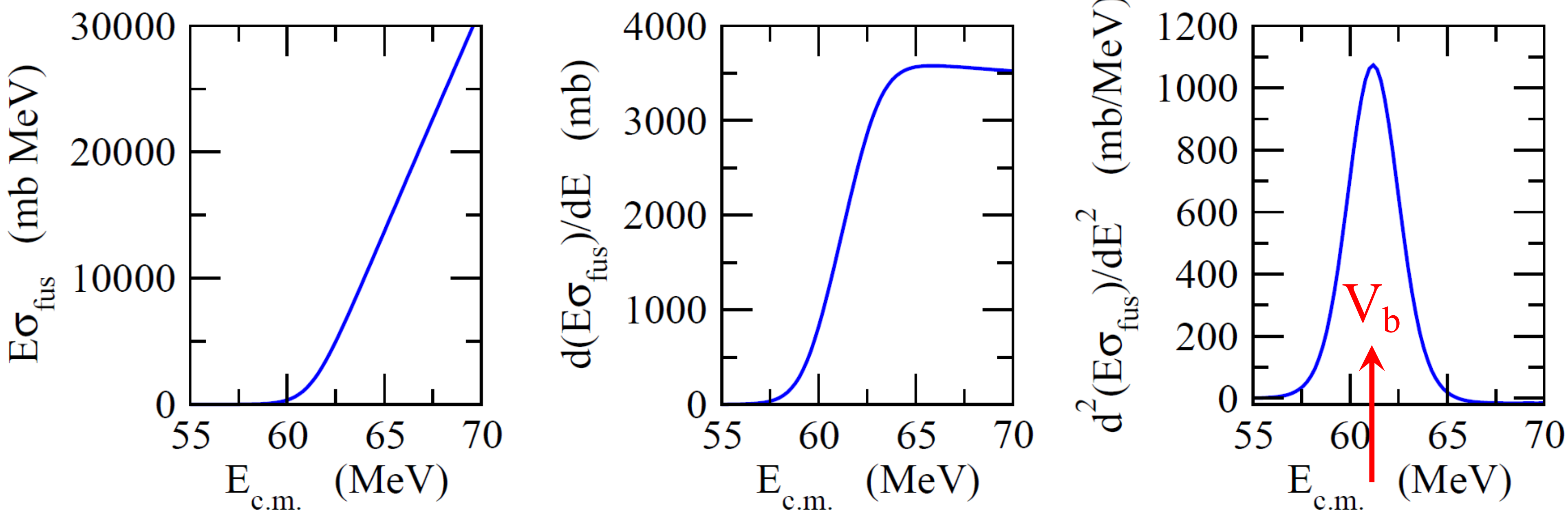
$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$

N. Rowley, G.R. Satchler, and P.H. Stelson, PLB254 ('91) 25

$E\sigma_{\text{fus}}$

$\frac{d(E\sigma_{\text{fus}})}{dE} \sim \pi R_b^2 \, P_{l=0}(E)$

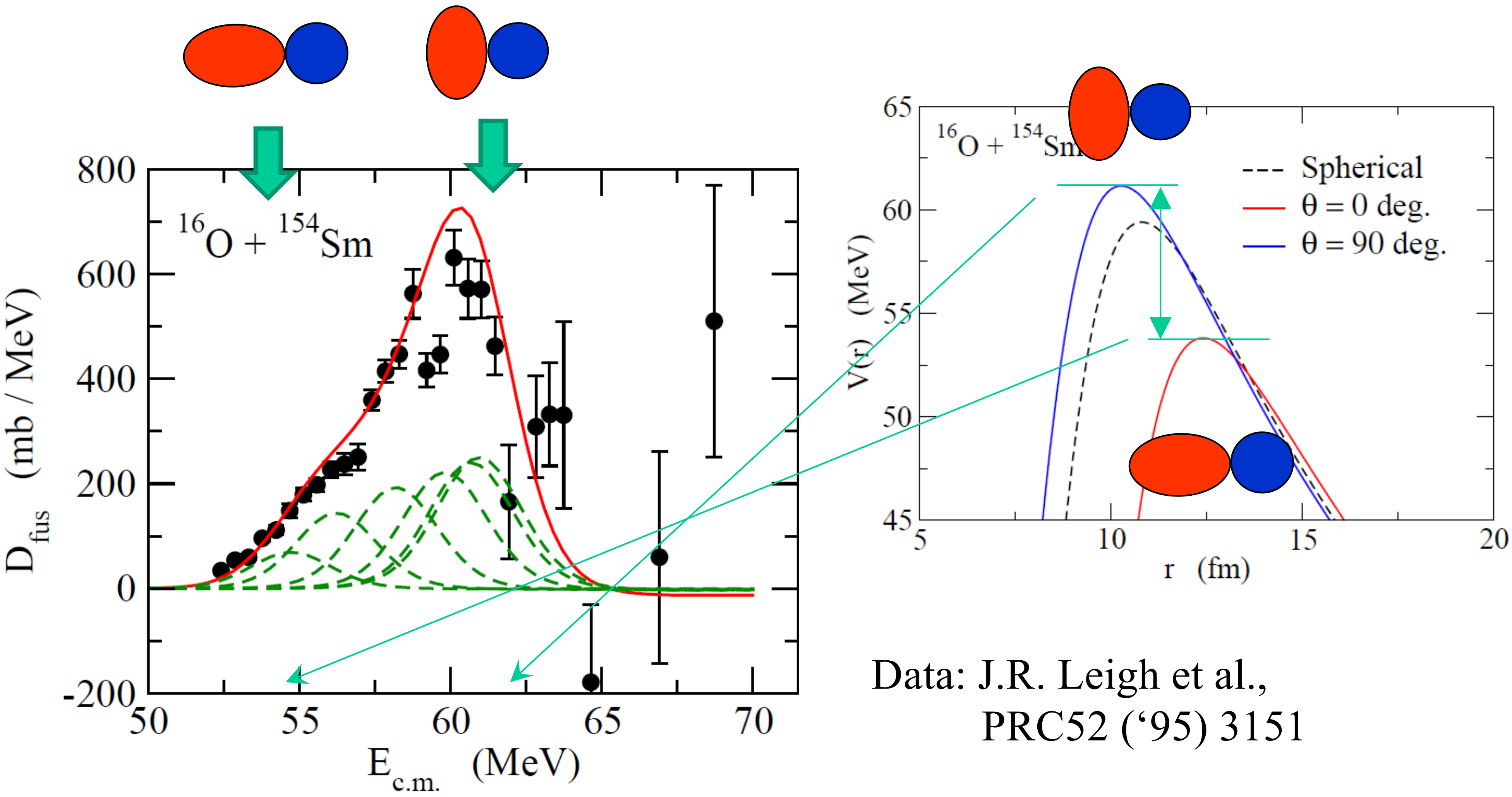
$\frac{d^2(E\sigma_{\text{fus}})}{dE^2} \sim \pi R_b^2 \cdot dP_{l=0}/dE$



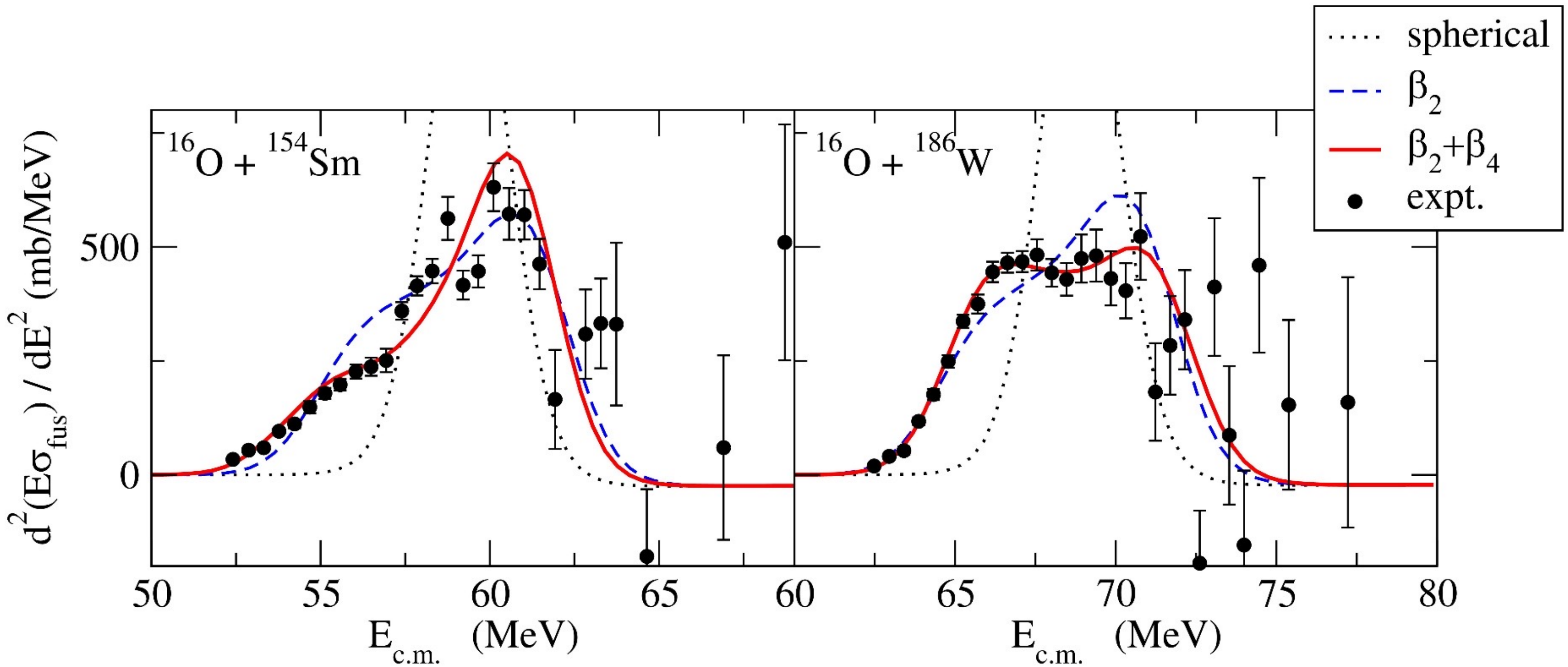
K.H. and N. Takigawa, PTP128 ('12) 1061

✓ Fusion barrier distribution (Rowley, Satchler, Stelson, PLB254('91))

$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2} \sim \pi R_b^2 \frac{dP_{l=0}}{dE}$$



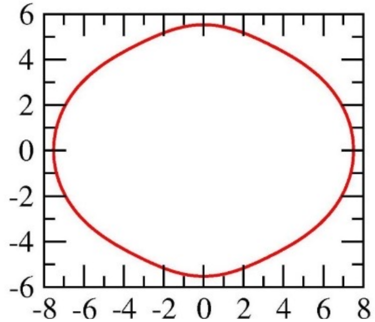
Data: J.R. Leigh et al.,
PRC52 ('95) 3151

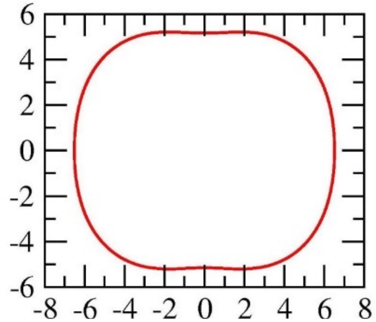


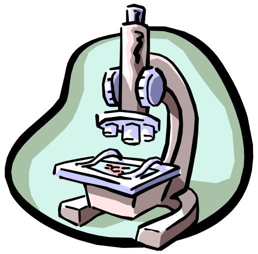
$$R(\theta) = R_0(1 + \beta_2 Y_{20}(\theta) + \beta_4 Y_{40}(\theta) + \cdots)$$

$$\beta_2 = 0.33 \qquad \beta_2 = 0.29$$

$$\beta_4 = +0.05 \qquad \beta_4 = -0.03$$







sensitive to the sign of β_4!

→ Fusion as a quantum tunneling microscope for nuclei

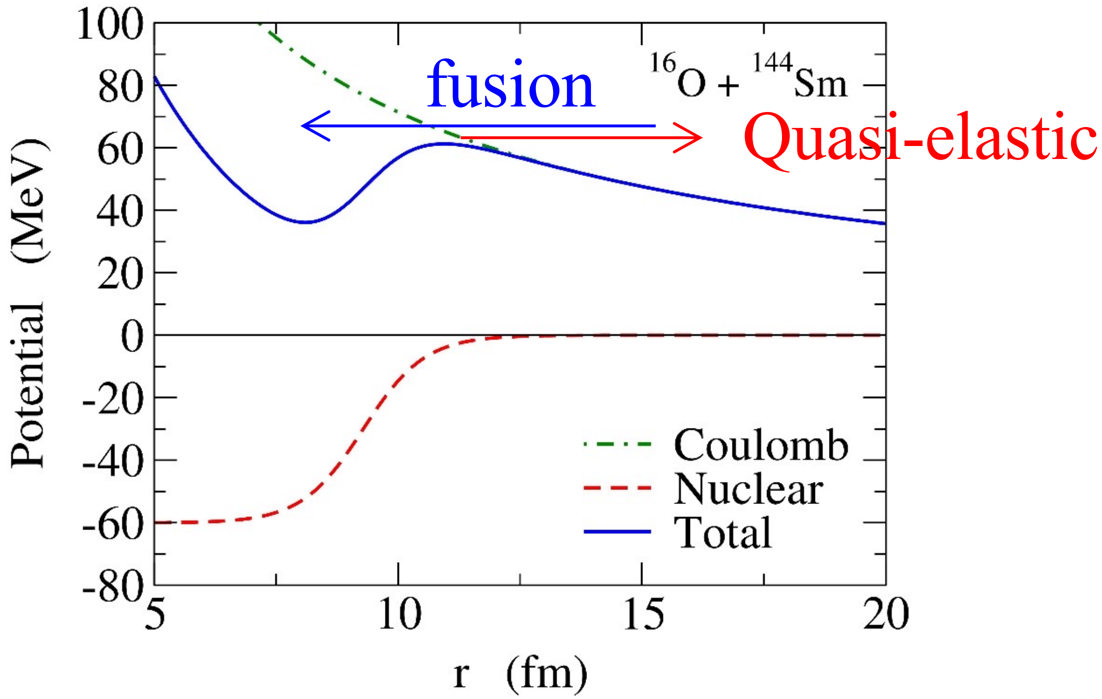
Quasi-elastic barrier distribution

$$D_{\text{qel}}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\text{qel}}(E,\pi)}{\sigma_{\text{Ruth}}(E,\pi)}\right)$$

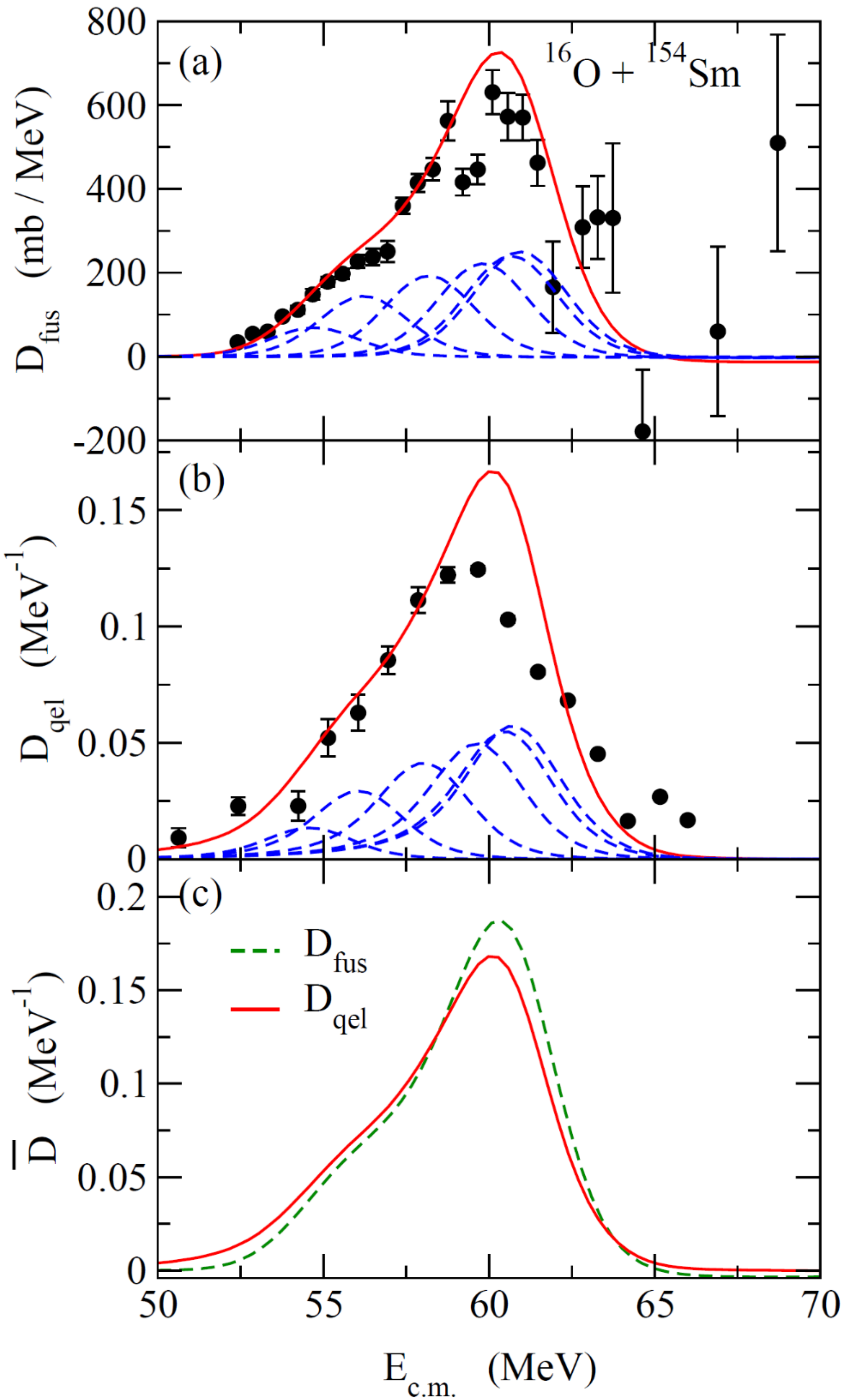
H. Timmers et al., NPA584('95)190

Quasi-elastic scattering:

A sum of all the reaction processes other than fusion
(elastic + inelastic + transfer + ……)



$$P_{l=0}(E) = 1 - R_{l=0}(E) \sim 1 - \frac{\sigma_{\text{qel}}(E,\pi)}{\sigma_{\text{Ruth}}(E,\pi)}$$



D_{fus} and D_{qel}: behave similarly to each other

cf. Application to reactions relevant to SHE

$^{48}Ca + ^{248}Cm \rightarrow {}^{296}{}_{116}Lv^{*}$

T. Tanaka et al., JPSJ 87 ('18) 014201
PRL124 ('20) 052502

$^{51}V + ^{248}Cm \rightarrow {}^{299}119^{*}$

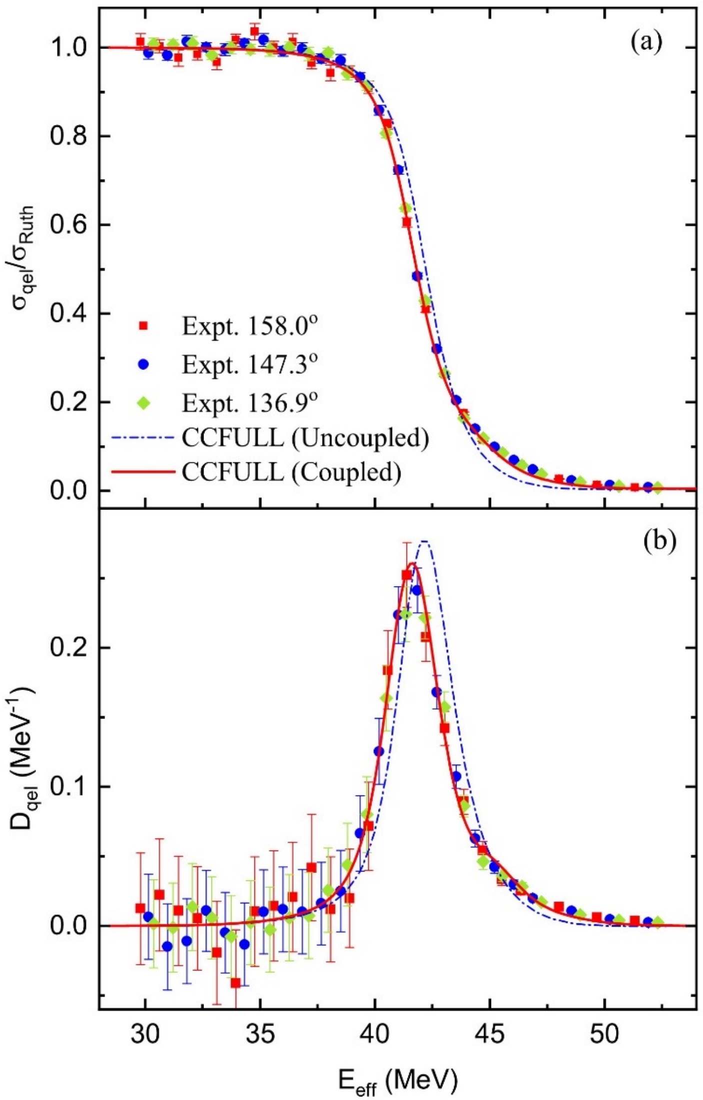
M. Tanaka et al., JPSJ 91 ('22) 084201

K.H. and N. Rowley, PRC69('04)054610

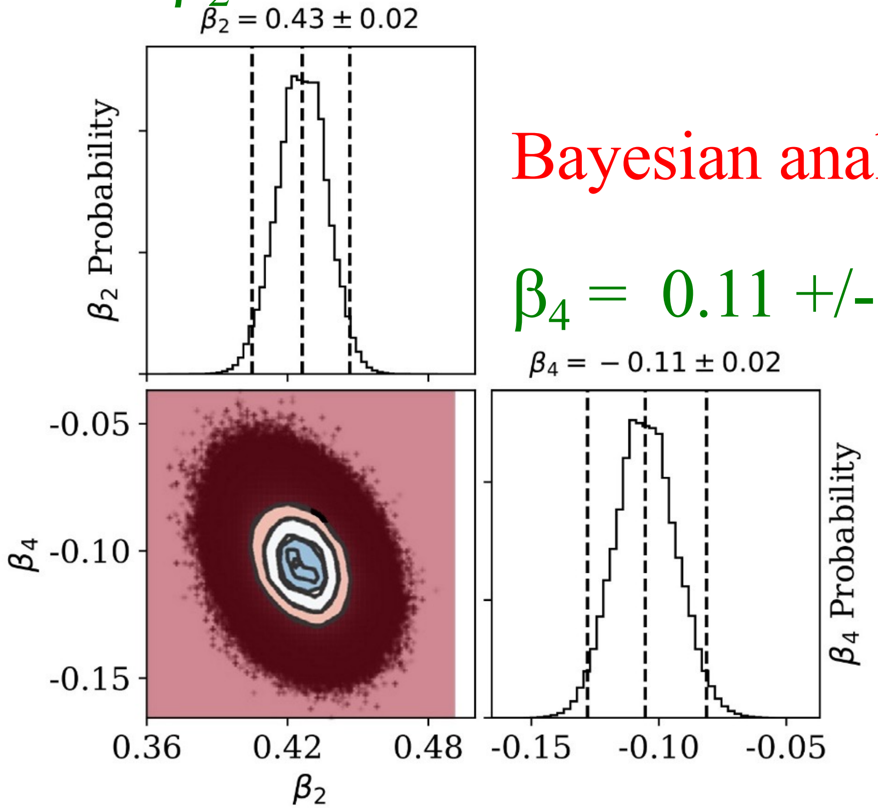
Determination of β_4 of ^{24}Mg with quasi-elastic scattering

Y.K. Gupta, B.K. Nayak, U. Garg, K.H., et al., PLB806, 135473 (2020).

^{24}Mg + ^{90}Zr



β_2 = 0.43 +/- 0.02



Bayesian analysis

β_4 = 0.11 +/- 0.02

high precision determination of β_4
→ for the first time

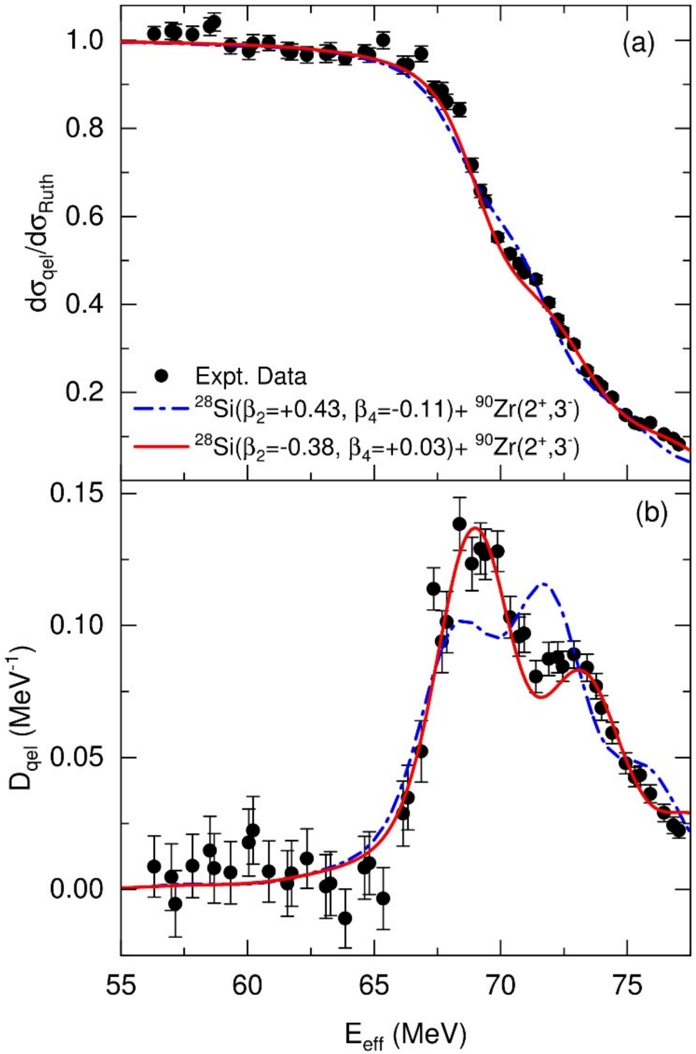
cf. (p,p'): β_4 = -0.05 +/- 0.08

R. De Swiniarski et al., PRL23, 317 (1969)

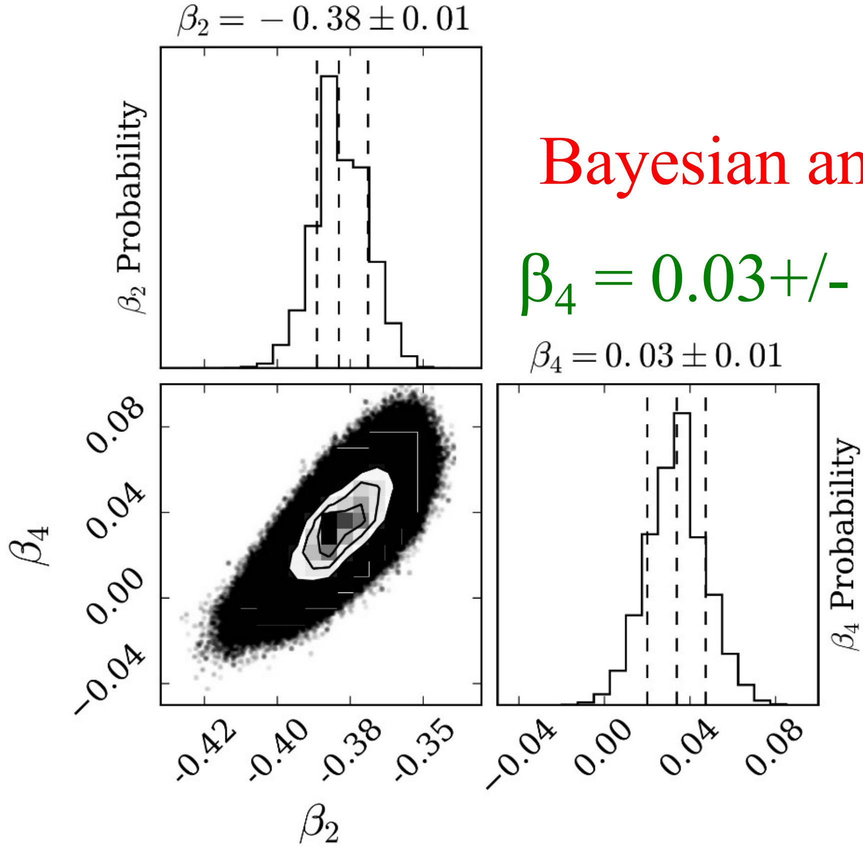
Determination of β_4 of ^{28}Si with quasi-elastic scattering

Y.K. Gupta, V.B. Katariya, G.K. Prajapati, K.H., et al., PLB845, 138120 (2023).

$^{28}Si + ^{90}Zr$



β_2 = -0.38 +/- 0.01



Bayesian analysis

β_4 = 0.03+/- 0.01

cf. (n,n'): β_4 = 0.20 +/- 0.05

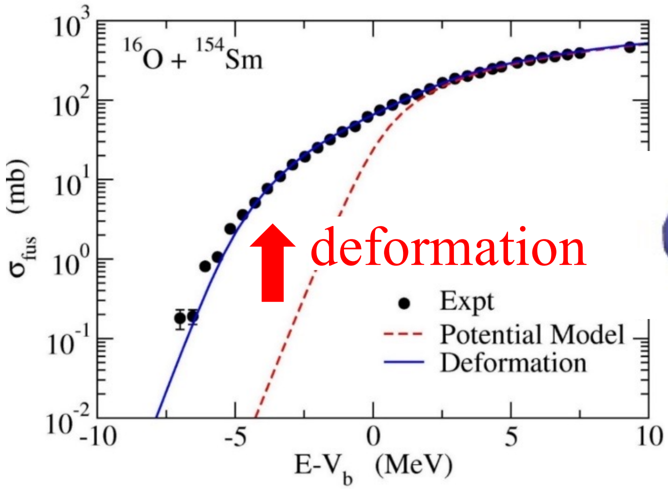
G. Haouat et al., PRC30, 1795 (1984)

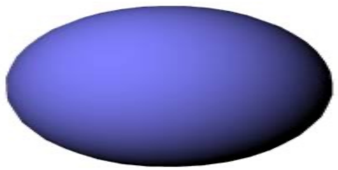
Summary

Heavy-ion fusion reactions around the Coulomb barrier

✓Strong interplay between nuclear structure and reaction
✓Quantum tunneling with various intrinsic degrees of freedom
✓Role of deformation in sub-barrier enhancement

amplified





✓ Fusion barrier distribution $$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$

✓ Quasi-elastic barrier distribution $$D_{\text{qel}}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\text{qel}}(E,\pi)}{\sigma_{\text{Ruth}}(E,\pi)}\right)$$

sensitive to the nuclear structure

recent applications to ^{24}Mg, ^{28}Si + ^{90}Zr → determination of β_4