Heavy-ion fusion and quasi-elastic scattering around the Coulomb barrier

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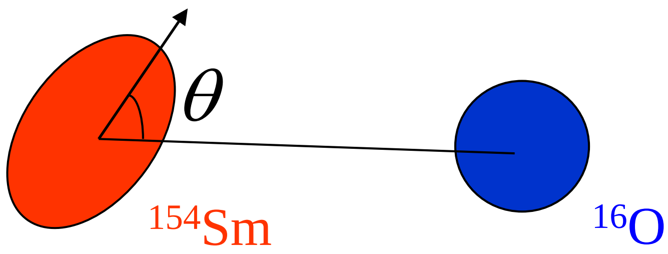
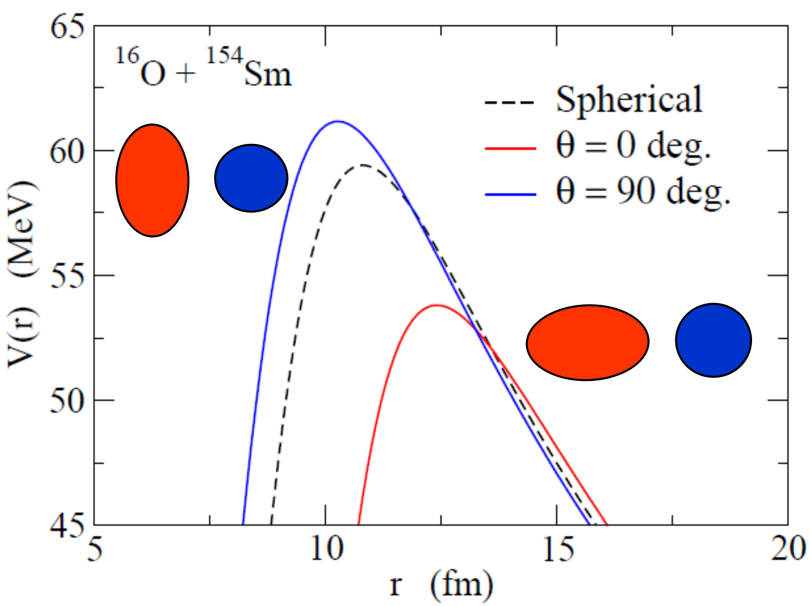
1. Introduction
: fusion and quasi-elastic barrier distributions
2. Sum-of-differences (SOD) method
- $^{16}O + ^{144}Sm$
- $^{58}Ni + ^{58}Ni$
- $^{12}C + ^{12}C$

3. Summary

Introduction

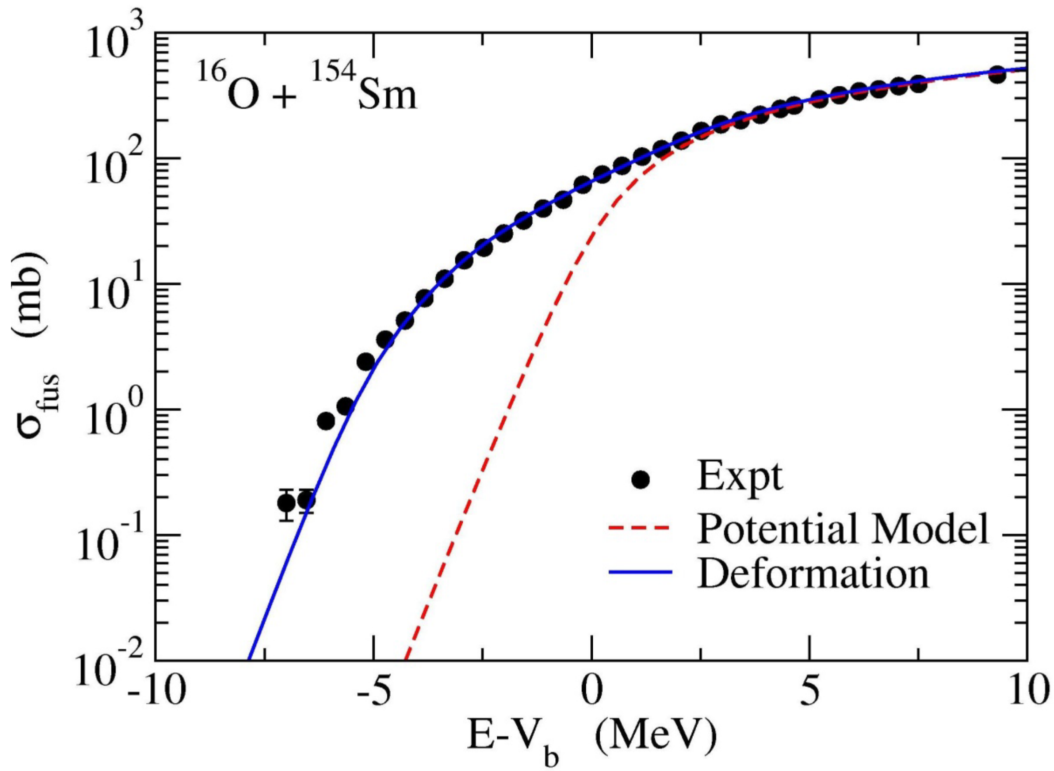
H.I. Sub-barrier fusion:
strong interplay between reaction and structure





coupled-channels equations

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

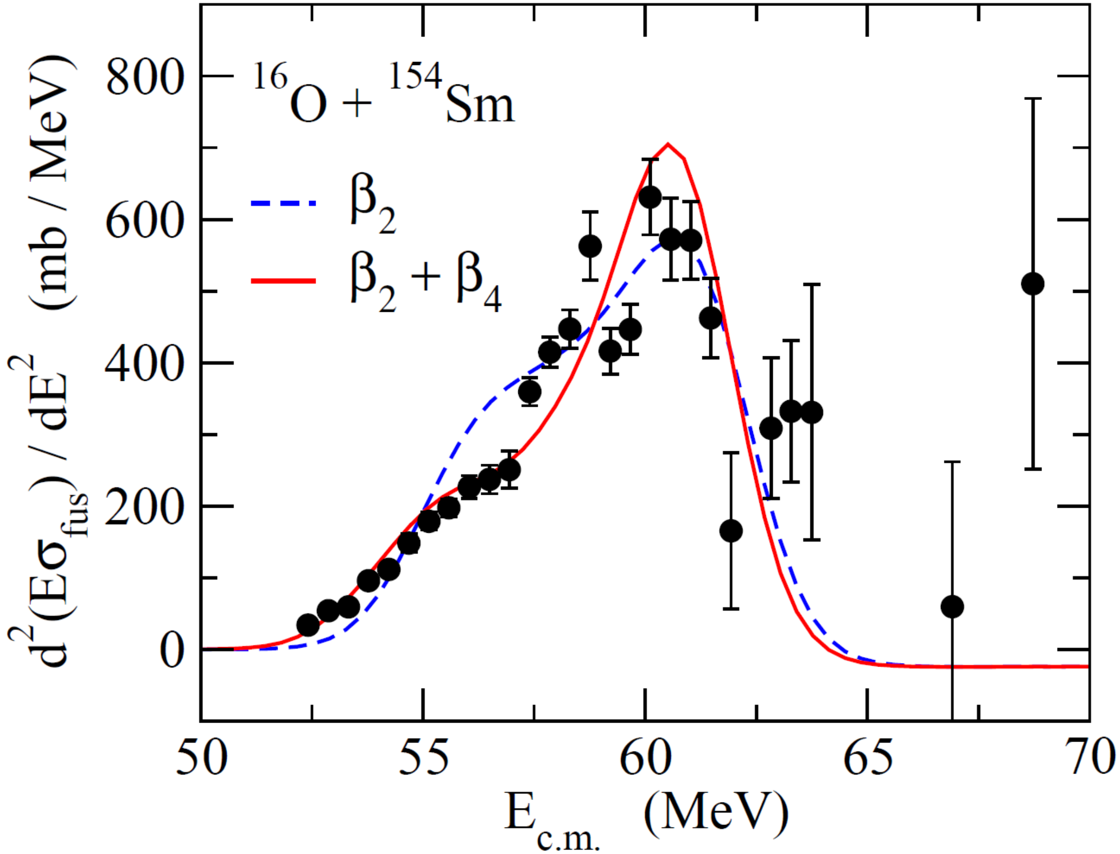


Def. Effect: enhances $\sigma_{\rm fus}$ by a factor of 10 ~ 100

Fusion barrier distribution

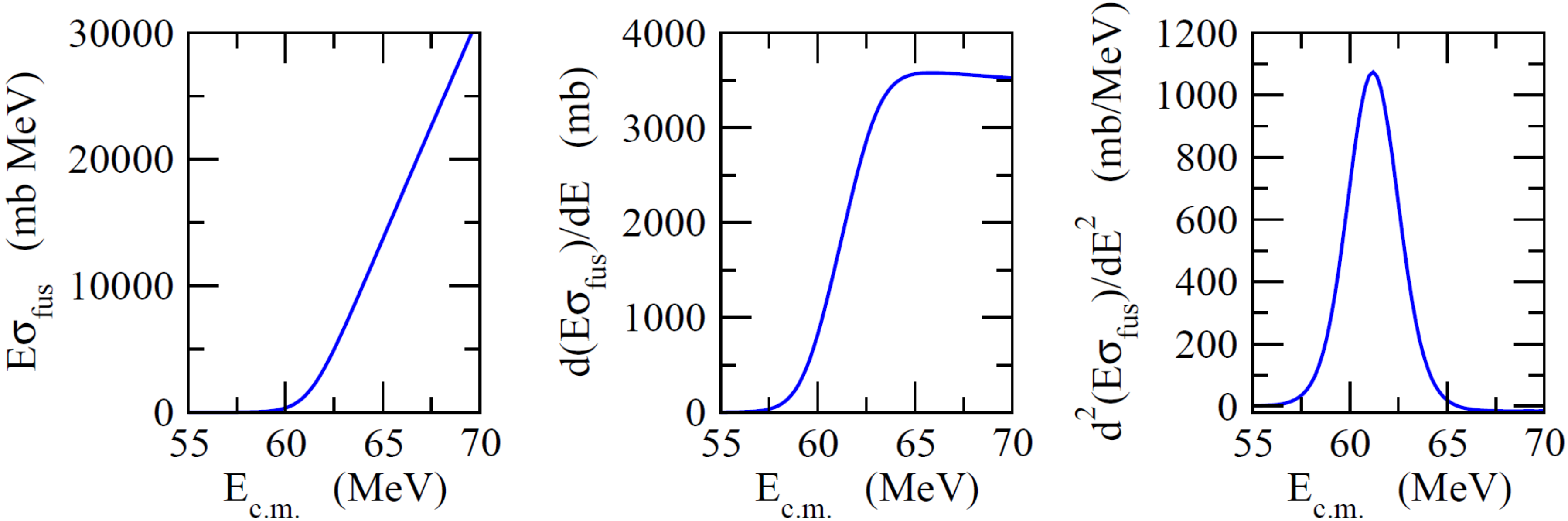
$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}$$

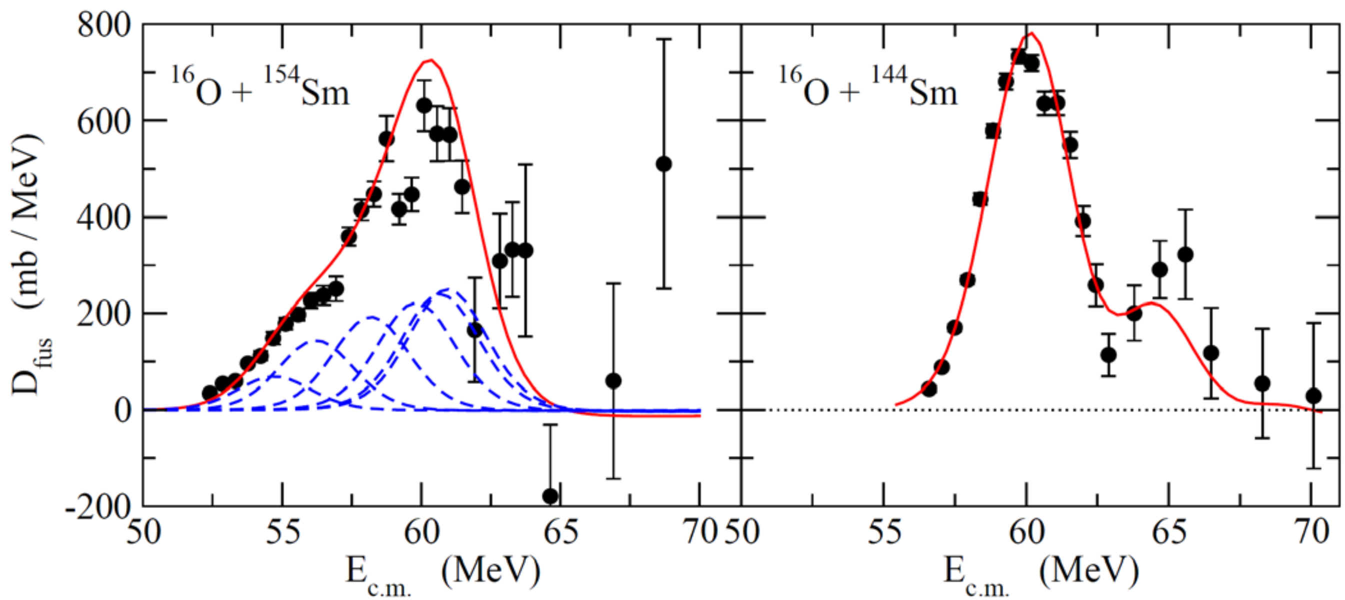
N. Rowley, G.R. Satchler, and P.H. Stelson, PLB254('91) 25
J.X. Wei, J.R. Leigh et al., PRL67('91) 3368



M. Dasgupta et al., Annu. Rev. Nucl. Part. Sci. 48('98)401

$$\sim \pi R_b^2\, P_{l=0}(E) \qquad\qquad \sim \pi R_b^2 \cdot dP_{l=0}/dE$$





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

Quasi-elastic barrier distribution

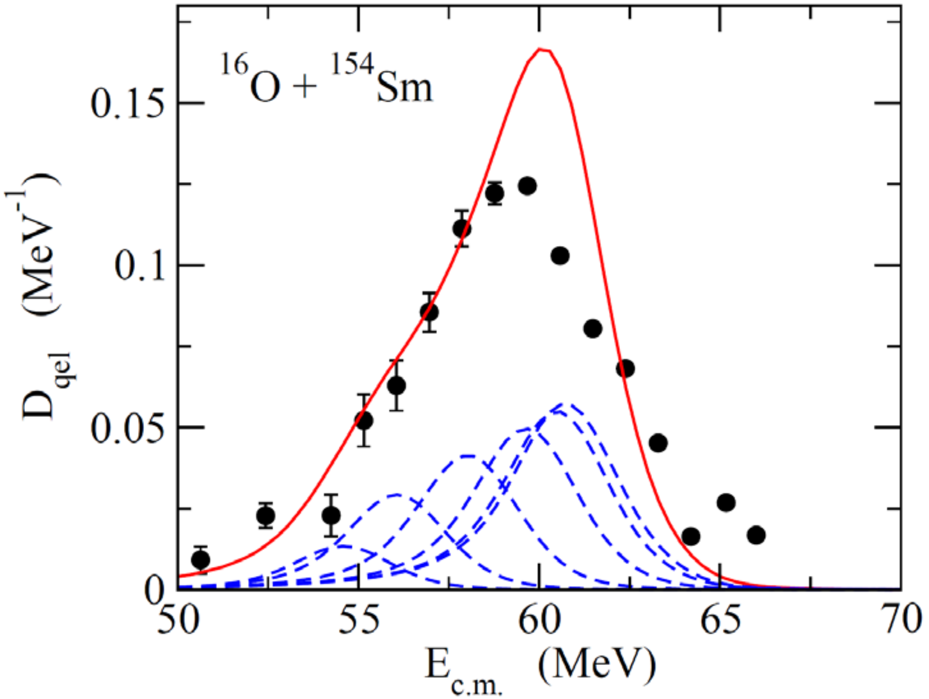
$$D_{\rm qel}(E) = -\frac{d}{dE}\left(\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_{\rm Ruth}(E,\pi)}\right)$$

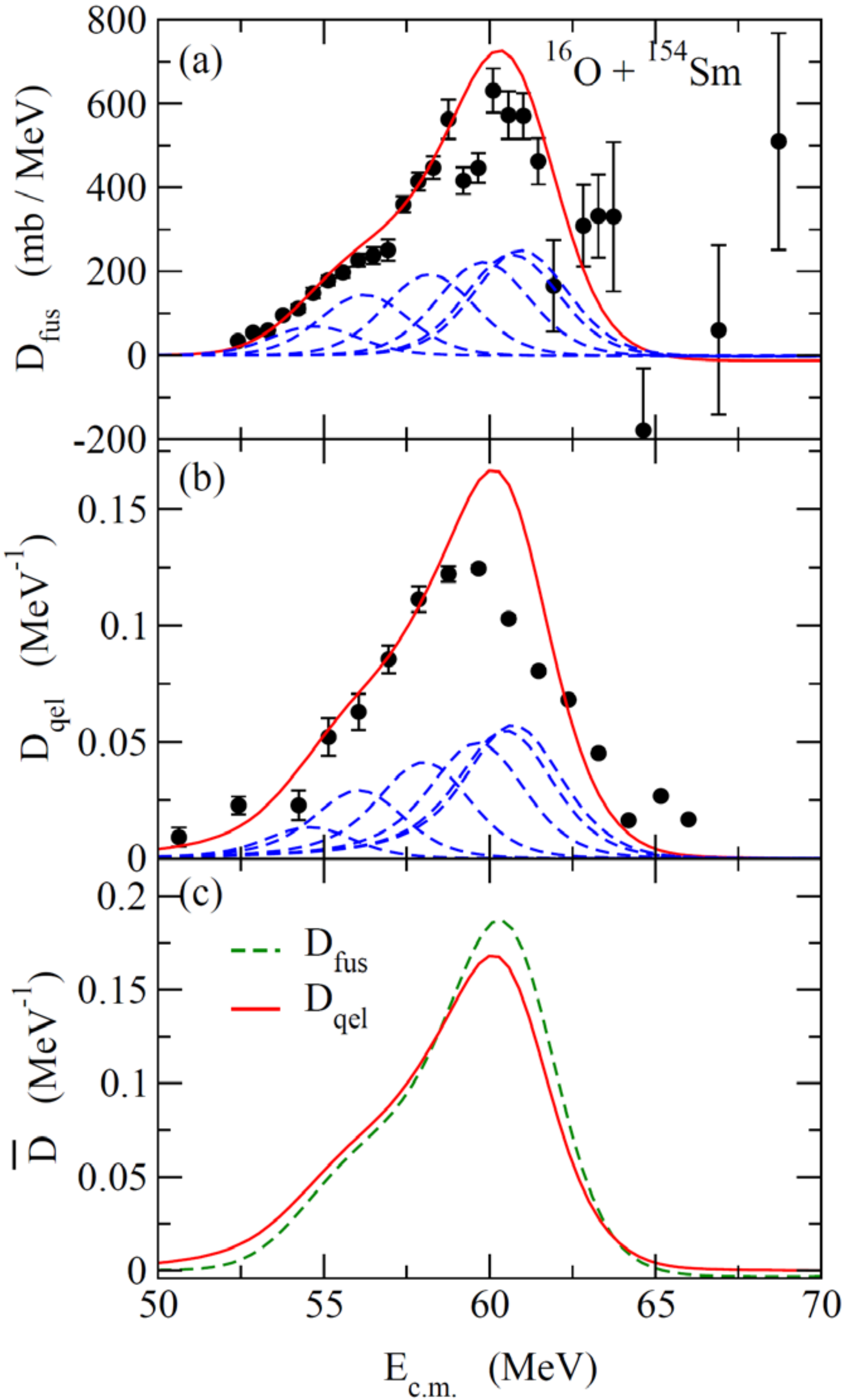
H. Timmers et al., NPA584('95)190

Quasi-elastic scattering:

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

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





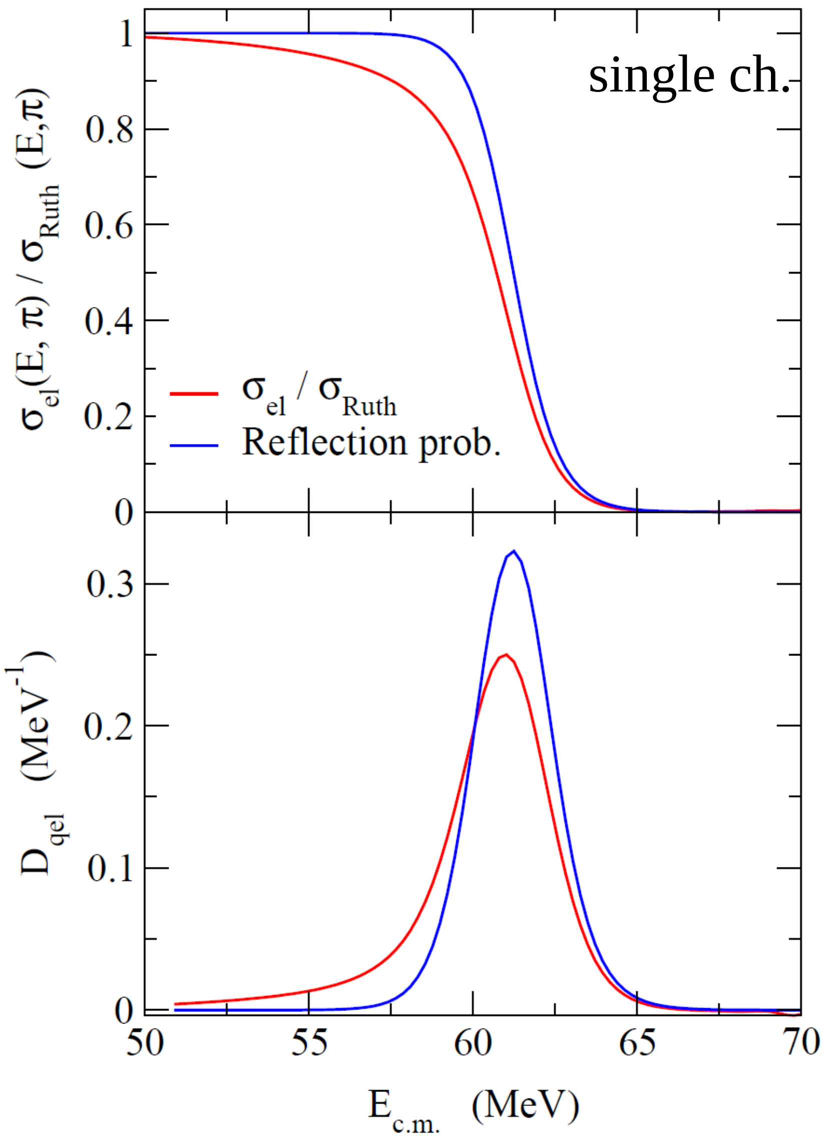
D_{fus} and D_{qel}: behave similarly to each other

cf. Eryk Piasecki's talk on Friday

cf. Application to reactions relevant to SHE [S. Mitsuoka et al., PRL99('07)182701]

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

Problems with quasi-elastic barrier distributions



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

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

D_{qel} and D_{fus}: behave similarly,
but not identically

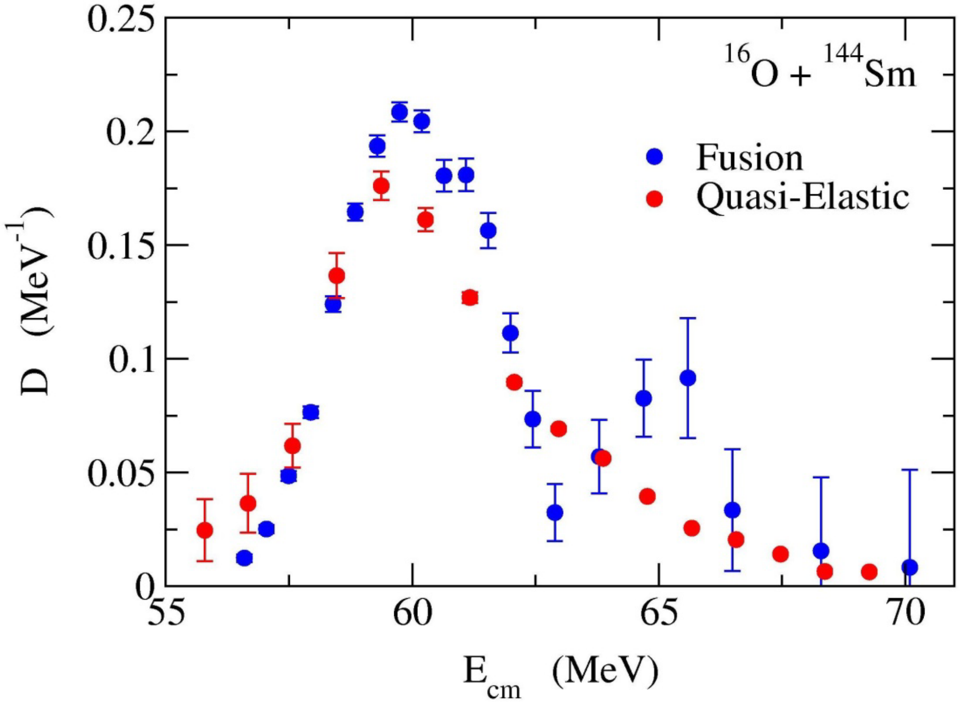
↑

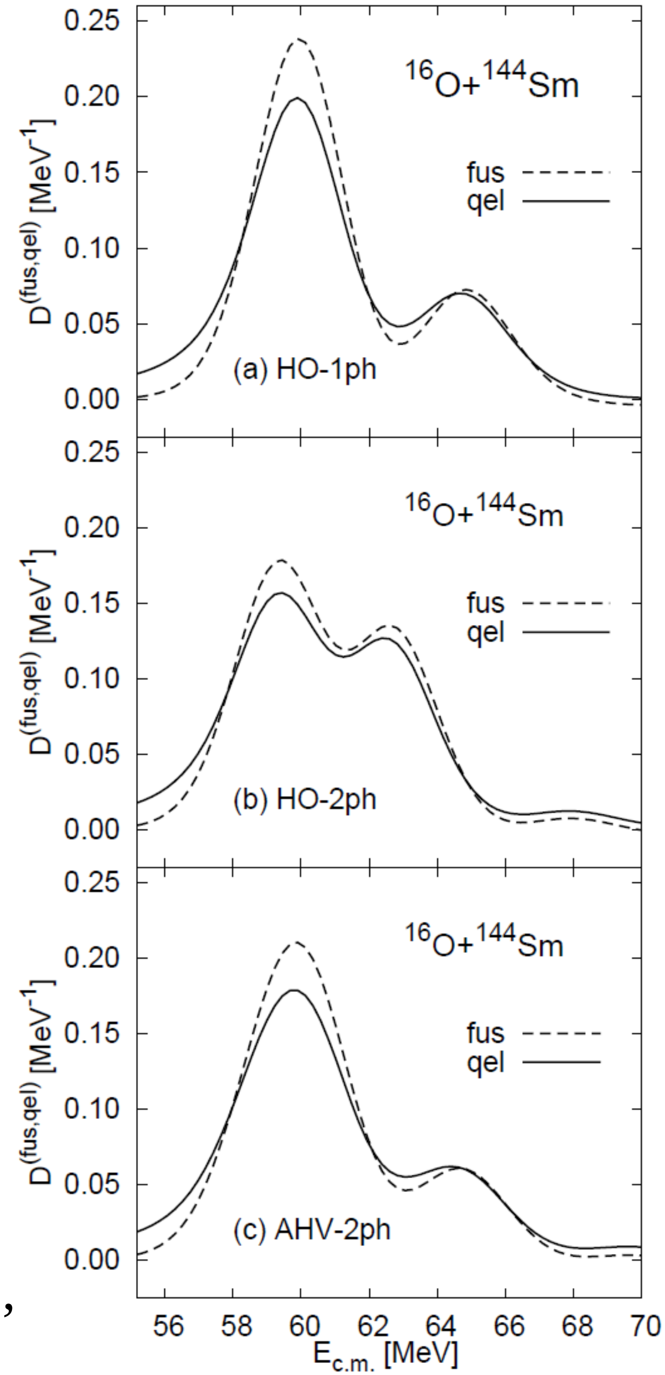
the effect of nuclear distortion of the classical trajectory

$$R_{l=0} \neq \frac{\sigma_{qel}(E,\pi)}{\sigma_{Ruth}(E,\pi)} = \alpha \cdot R_{l=0}$$

$$\alpha \sim 1 + \frac{V_N(r_c)}{ka}\frac{\sqrt{2a\pi k\eta}}{E}$$

S. Landowne and H.H. Wolter, NPA351('81)171





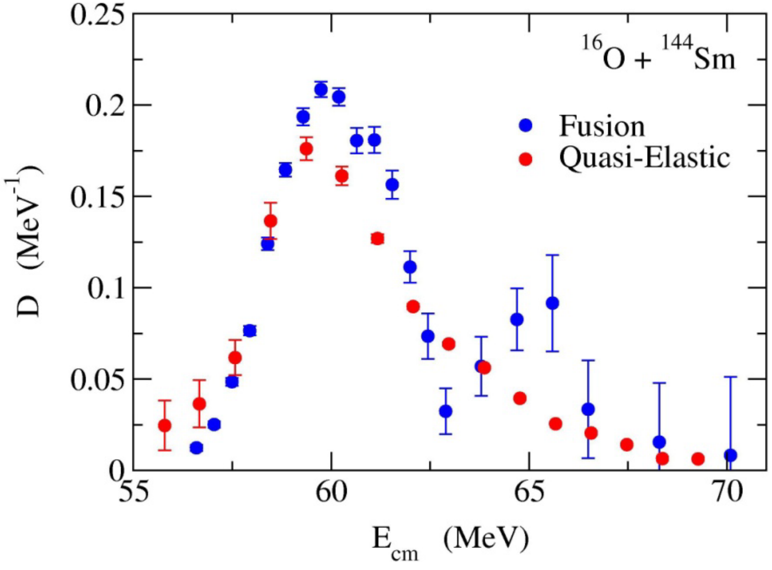
discrepancy: open problem

M. Zamrun F. and K.H.,
PRC77('08)014606

Problems with quasi-elastic barrier distributions

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

- D_{qel} and D_{fus}: behave similarly, but not identically



- D_{qel} : not applicable to symmetric systems

$$\sigma(\theta) = |f(\theta) \pm f(\pi - \theta)|^2$$

$\longrightarrow$ diverges at $\theta = \pi$

Sum-of-differences (SOD) method

J.T. Holdeman and R.M. Thaler, PRL14('65)81, PR139('65)B1186
C. Marty, Z. Phys. A309('83)261, A322('85)499

$$\sigma_R \sim 2\pi \int_{\theta_{\rm min}}^{\pi} \sin\theta \, d\theta \, (\sigma_{\rm Ruth}(\theta) - \sigma_{\rm el}(\theta))$$

expt.: H. Wojciechowski et al., PRC16('77)1767
T. Yamaya et al., PLB417('98)7 etc.

generalization (K.H. and N. Rowley, in preparation)

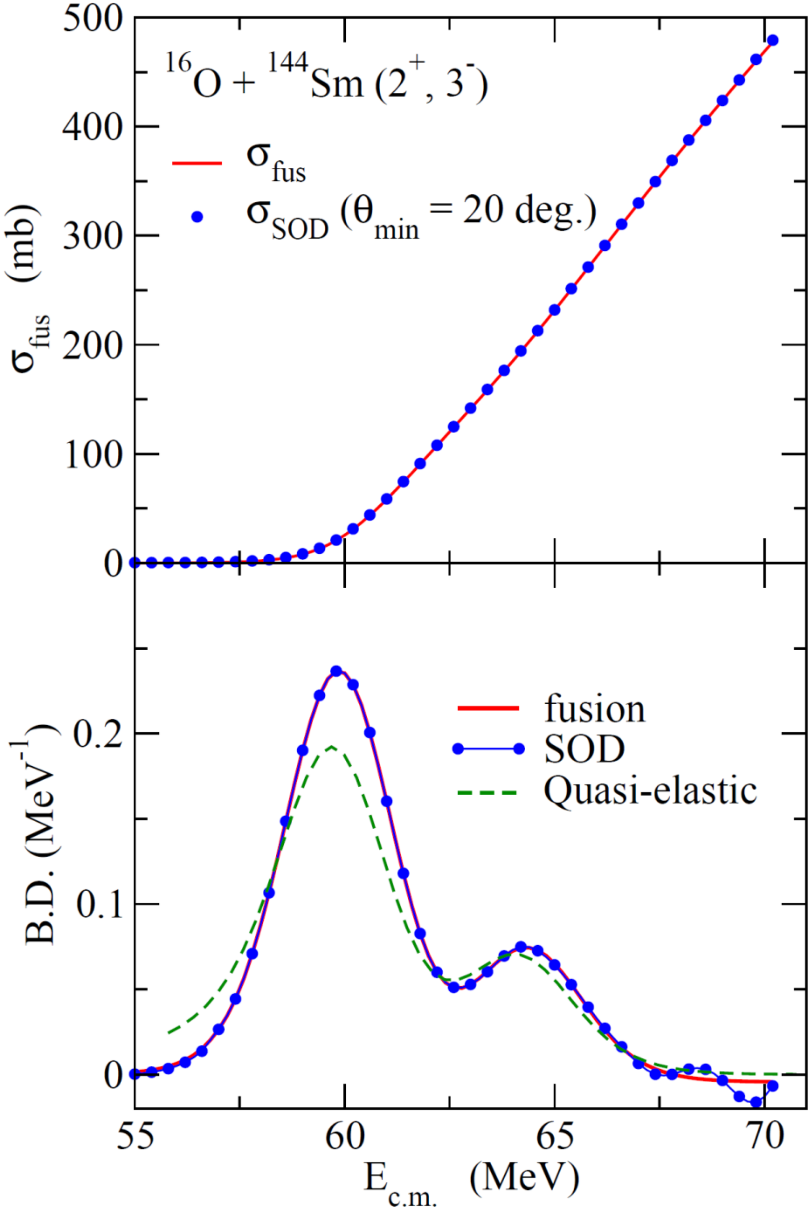
$$\sigma_R = \sigma_{\rm fus} + \sigma_{\rm inel} + \sigma_{\rm tr}$$

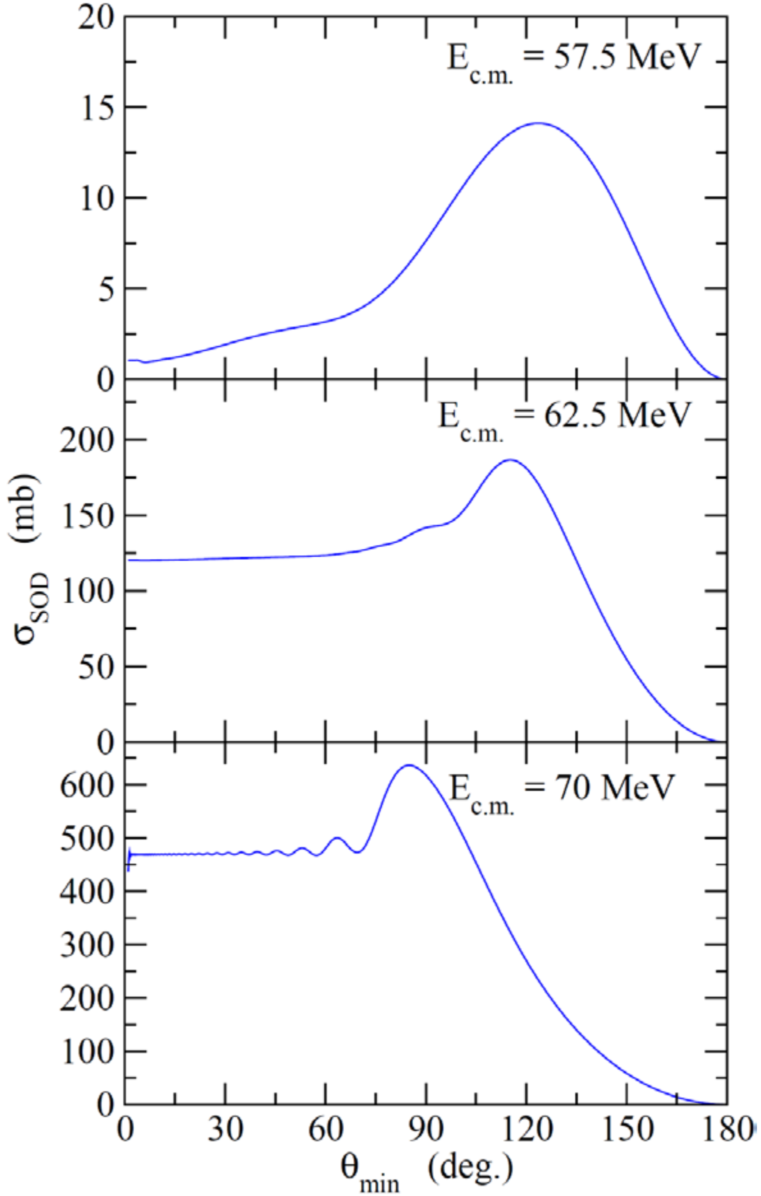
$$\begin{aligned}\sigma_{\rm fus} &\sim 2\pi \int_{\theta_{\rm min}}^{\pi} \sin\theta \, d\theta \, (\sigma_{\rm Ruth}(\theta) - \sigma_{\rm qel}(\theta)) \\ &= 2\pi \int_{\theta_{\rm min}}^{\pi} \sin\theta \, d\theta \, \sigma_{\rm Ruth}(\theta) \left(1 - \frac{\sigma_{\rm qel}(\theta)}{\sigma_{\rm Ruth}(\theta)}\right)\end{aligned}$$

$\longrightarrow$ $D_{\rm fus}$ from $\sigma_{\rm qel}$?

Does SOD work for fusion barrier distributions?

$$\sigma_{SOD} = 2\pi \int_{\theta_{min}}^{\pi} \sin\theta \, d\theta \, (\sigma_{Ruth}(\theta) - \sigma_{qel}(\theta))$$



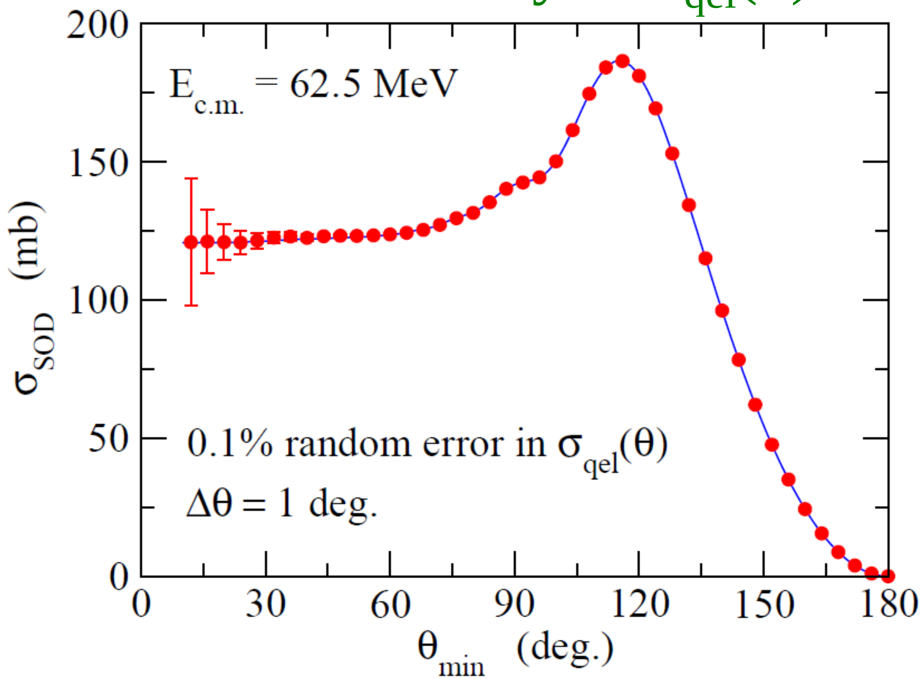


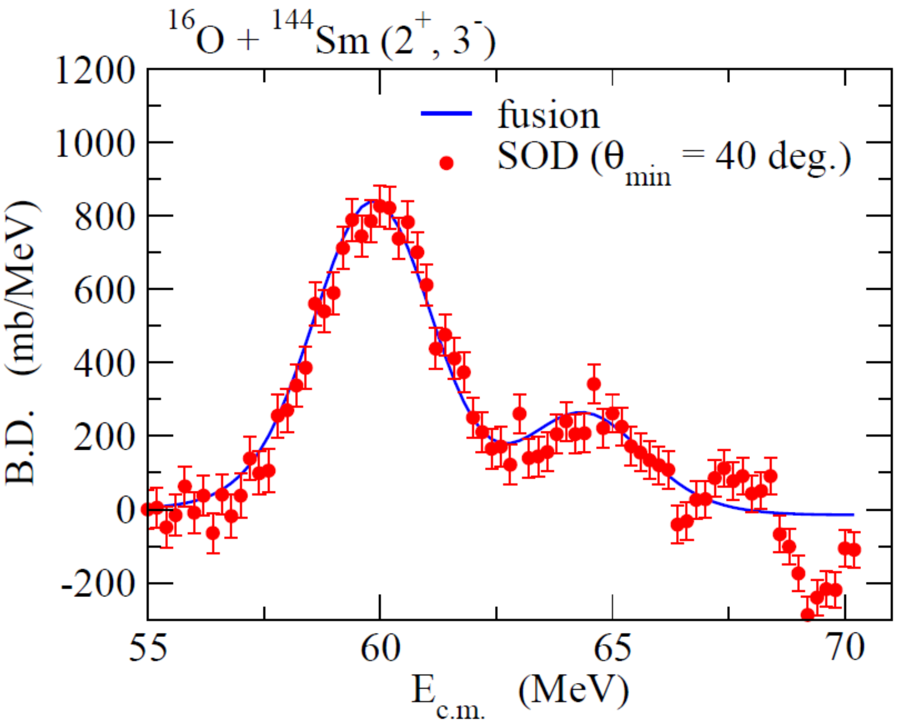
SOD with "experimental" quasi-elastic cross sections

$$\sigma^{(\mathrm{exp})}_{\mathrm{qel}}(E,\theta) \sim \sigma^{(\mathrm{th})}_{\mathrm{qel}}(E,\theta) + \Delta\sigma^{(\mathrm{th})}_{\mathrm{qel}}(E,\theta)$$

← randomly generated

0.1% accuracy in $\sigma_{qel}(\theta)$



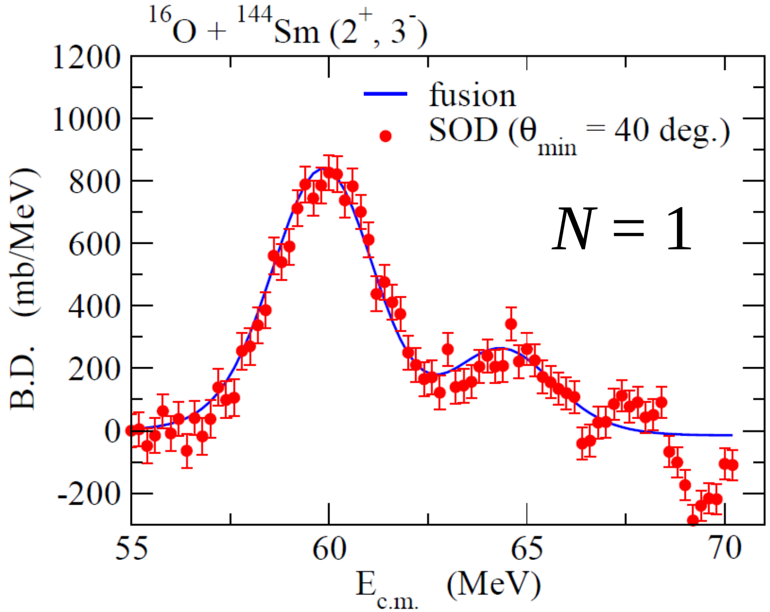


uncertainty in σ_{SOD}

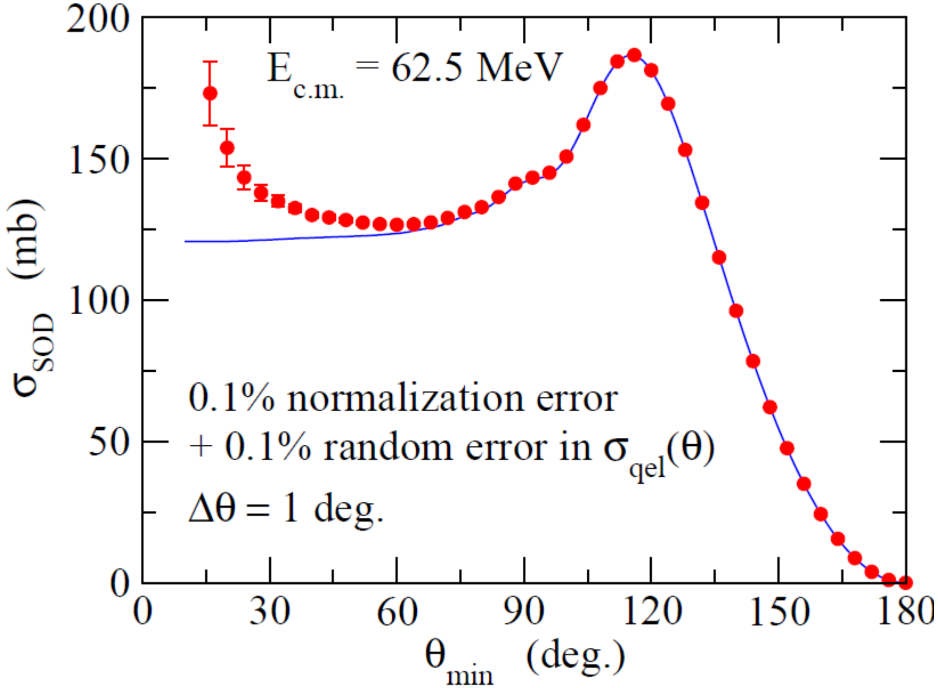
θ_{min} = 40 deg.	0.95%
30 deg.	1.96%
20 deg.	5.41%

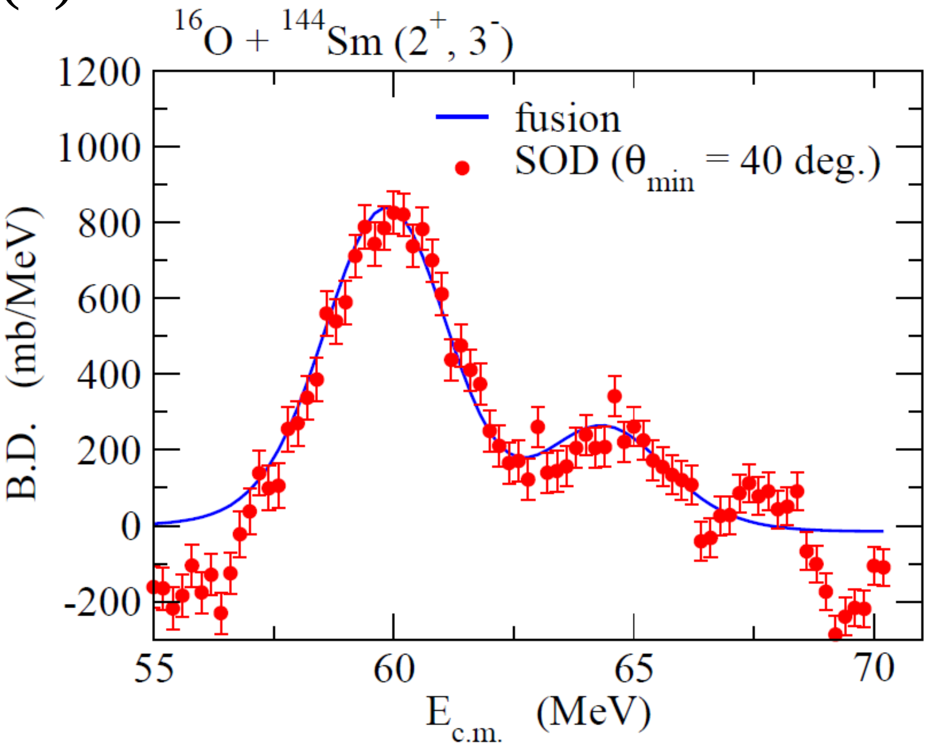
Effect of normalization error

$$\sigma_{\rm qel}^{\rm (exp)}(E,\theta) \sim N\sigma_{\rm qel}^{\rm (th)}(E,\theta) + \Delta\sigma_{\rm qel}^{\rm (th)}(E,\theta)$$



$N = 0.999$ + 0.1% accuracy in $\sigma_{\rm qel}(\theta)$

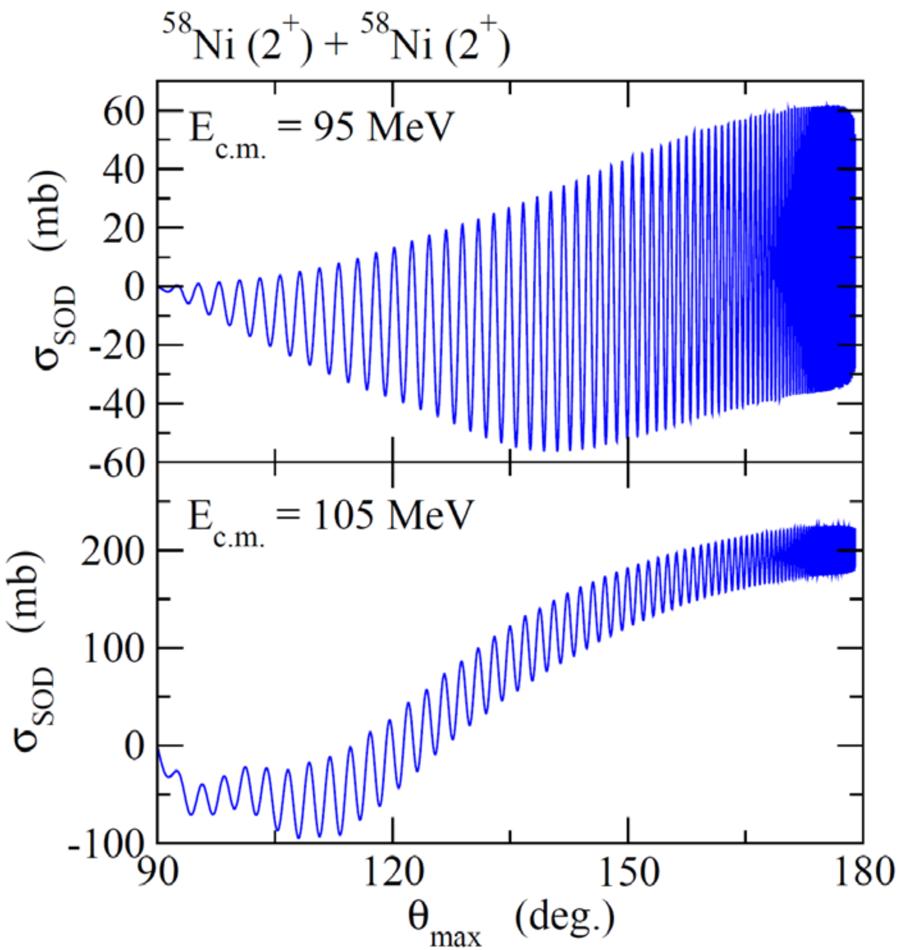


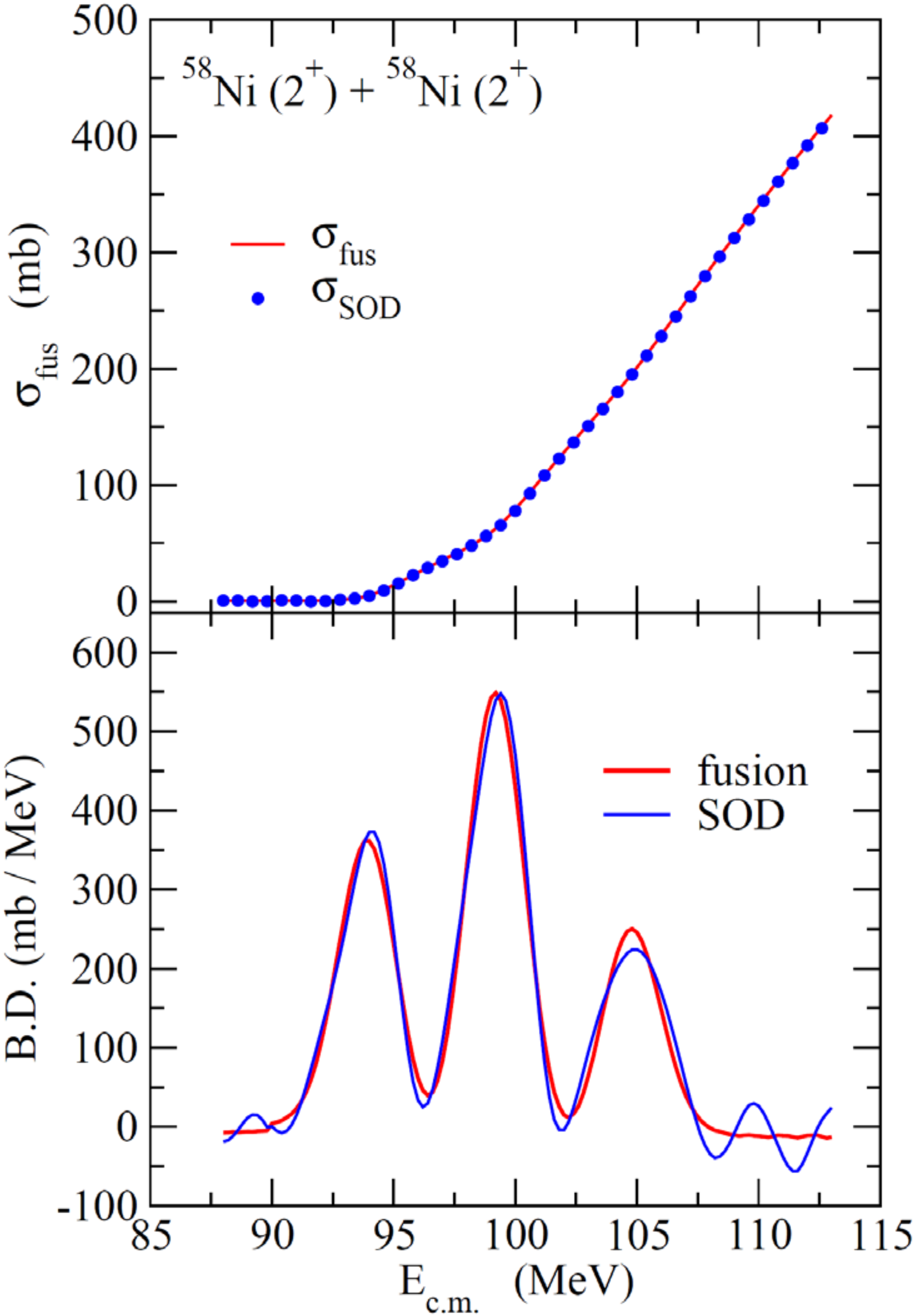


Symmetric sysmtes

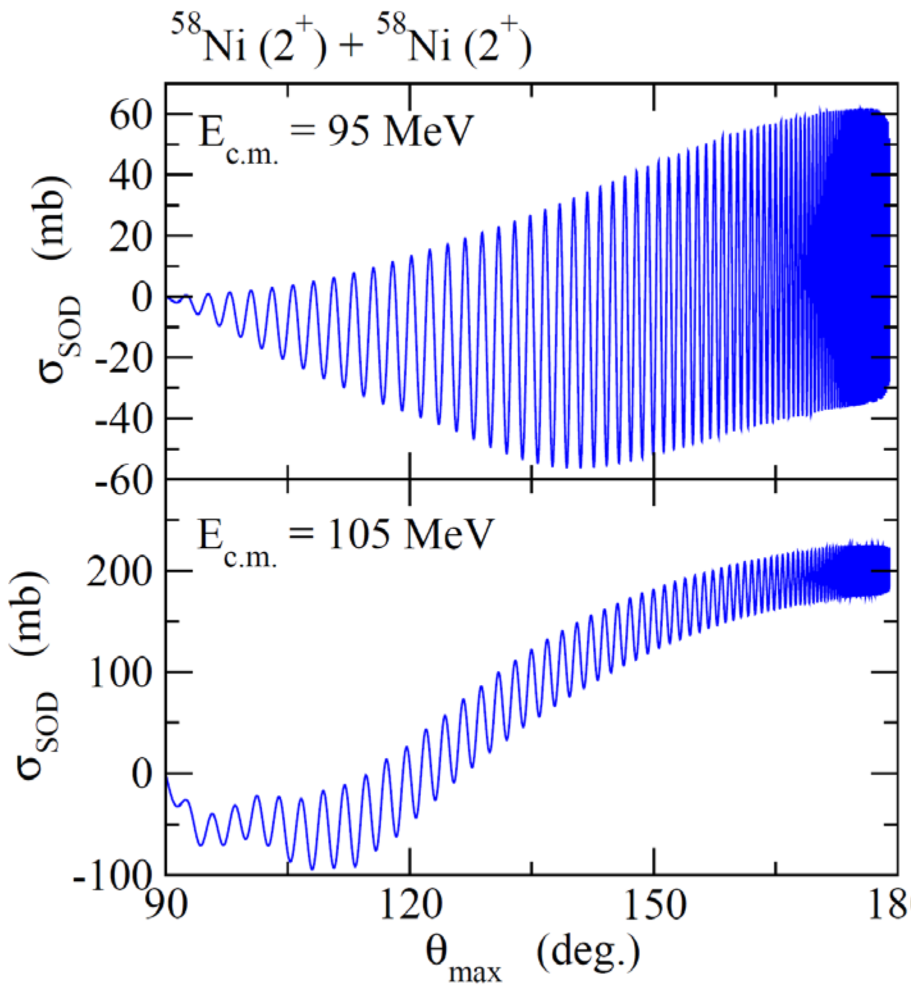
$$\sigma_{\rm fus} \sim 2\pi \int_{\theta_{\rm min}}^{\pi} \sin\theta\, d\theta \left(\sigma_{\rm Ruth}(\theta) - \sigma_{\rm qel}(\theta)\right)$$

$$\longrightarrow \boxed{\sigma_{\rm fus} \sim 2\pi \int_{\pi/2}^{\theta_{\rm max}} \sin\theta\, d\theta \left(\sigma_{\rm Mott}(\theta) - \sigma_{\rm qel}(\theta)\right)}$$

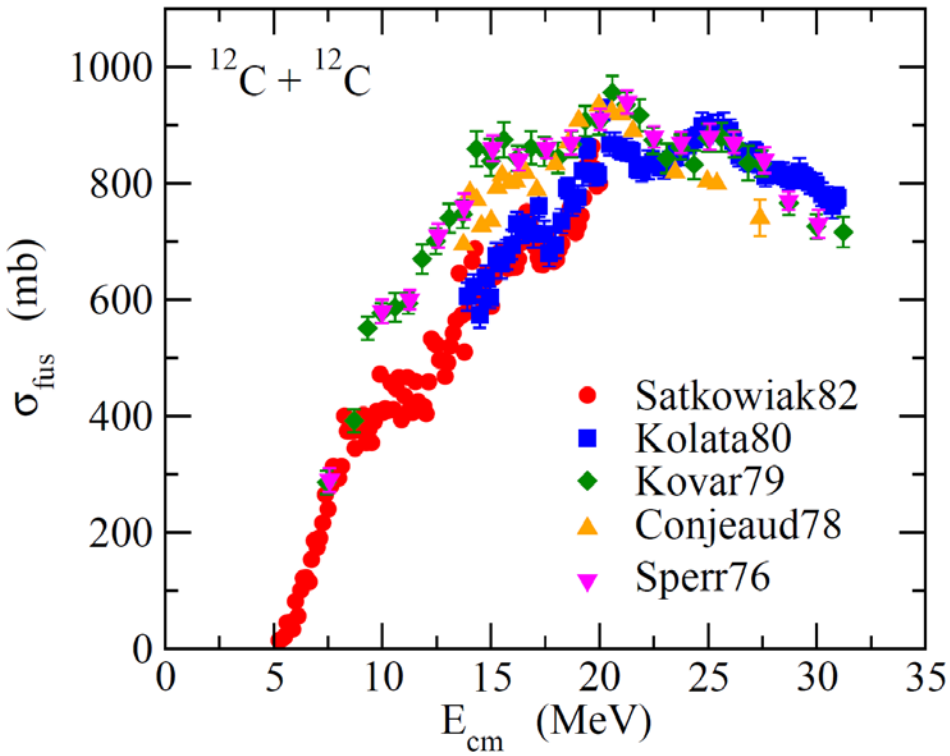


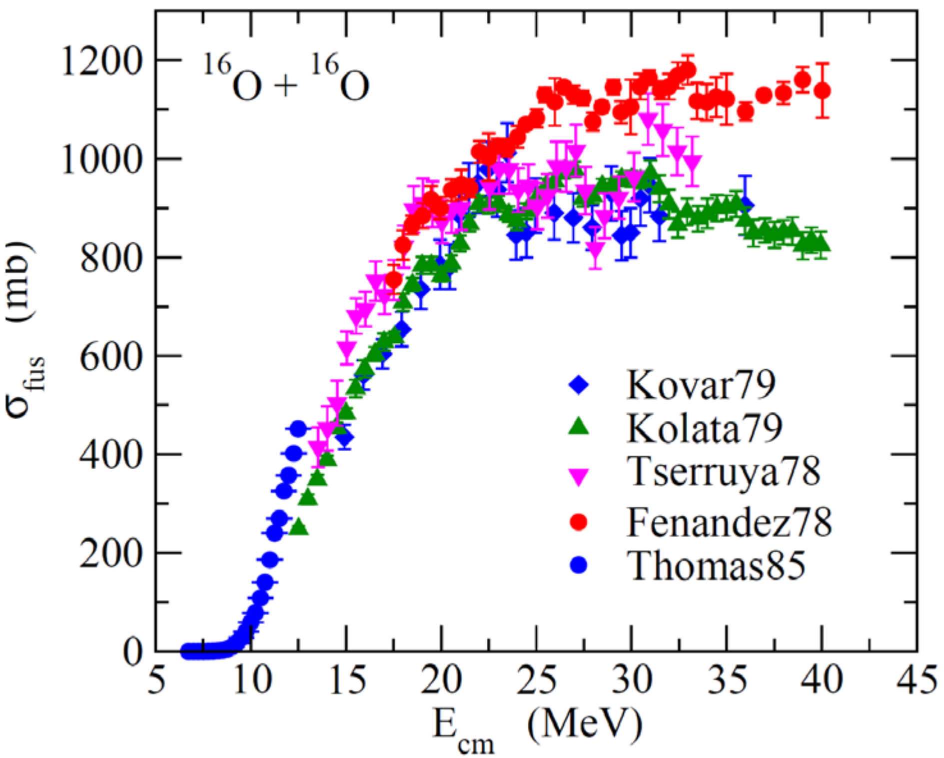


average in the range of θ_{max} = (176.5, 179.5) deg.



Fusion of light symmetric systems: fusion oscillations



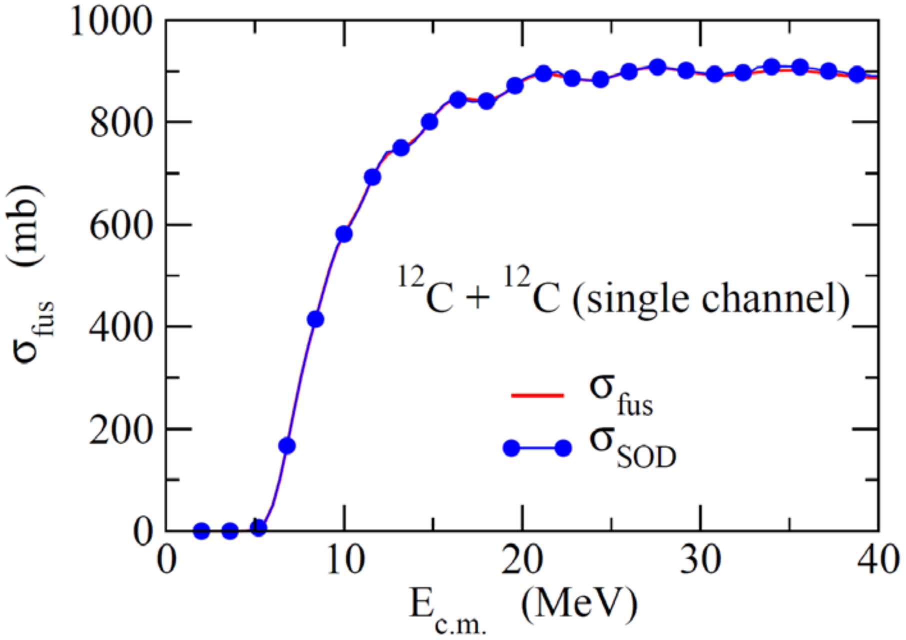


The expt. data: rather scattered

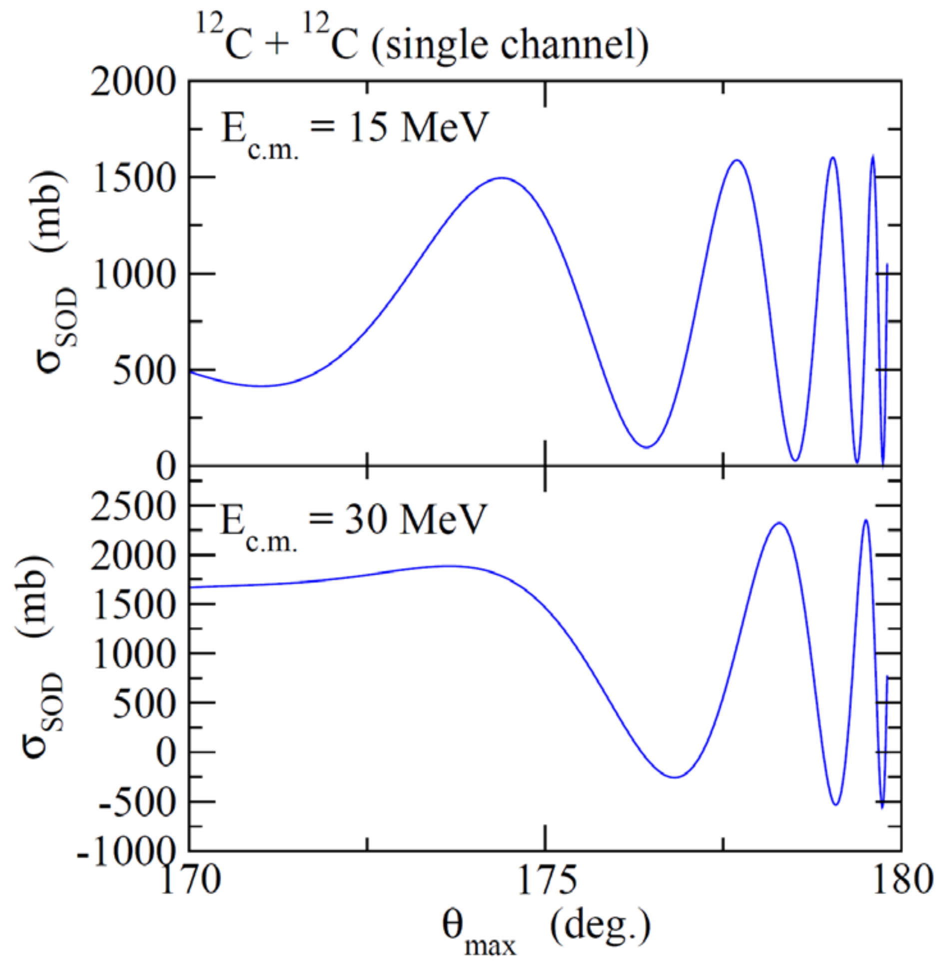
✓systematic errors

✓missing evaporation channels

⟶ σ_{fus} from SOD?



average of a maximum and a minimum in σ_{SOD}



Summary

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

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

✓ Sum-of-differenecs (SOD) method

$$\sigma_{\rm fus} \sim 2\pi \int_{\theta_{\rm min}}^{\pi} \sin\theta\, d\theta\, (\sigma_{\rm Ruth}(\theta) - \sigma_{\rm qel}(\theta))$$

D_{SOD}:

- closer correspondence to D_{fus} compared to D_{qel}
- need an accuracy of $\Delta\sigma_{qel}$ ~ 0.1%
- applicable also to symmetric systems

➢ application to light symmetric systems? (fusion oscillations)