Heavy-ion reactions at deep sub-barrier energies

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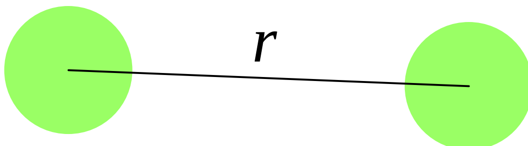
Introduction

A dream of nuclear reaction theory:
describe all the reaction processes simultaneously with a single framework

coupled-channels

Starting point:



$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V(r)$$

Woods-Saxon form:

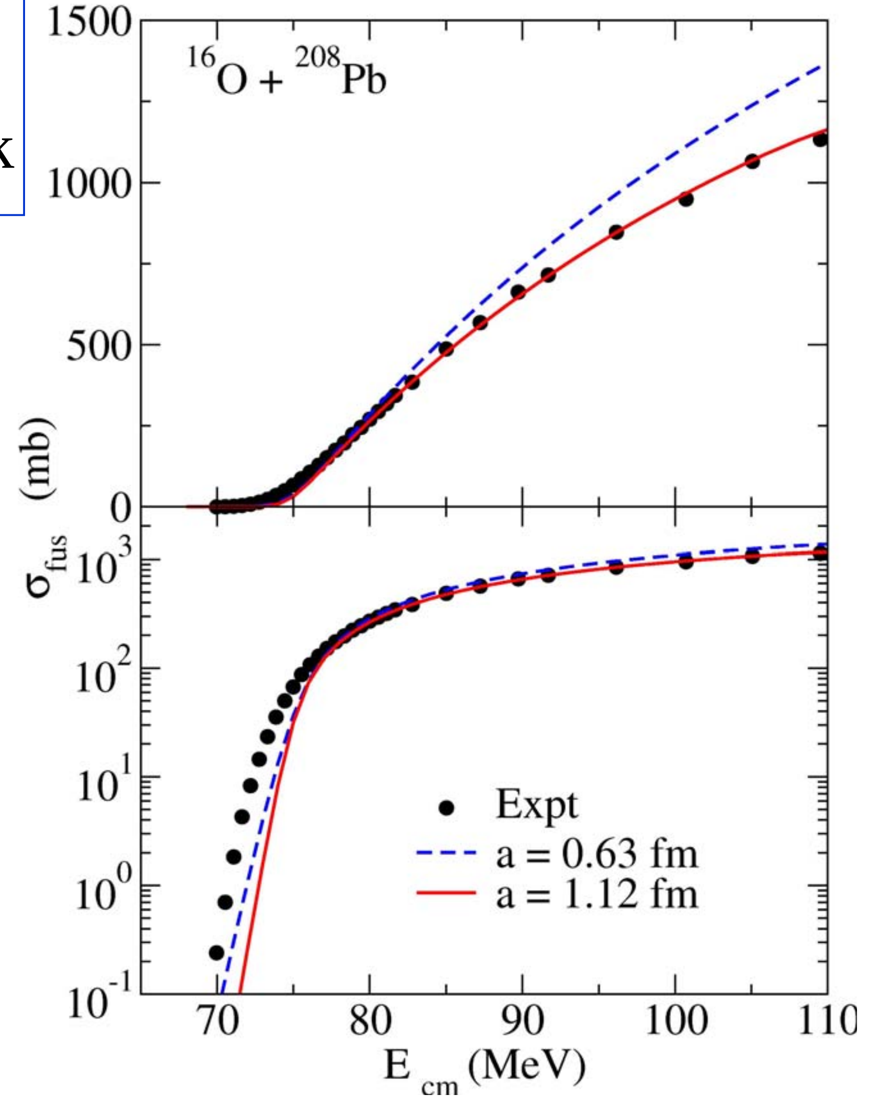
$$V_N(r) = -V_0 / [1+\exp((r-R_0)/a)]$$

Scattering processes: a ~ 0.63 fm

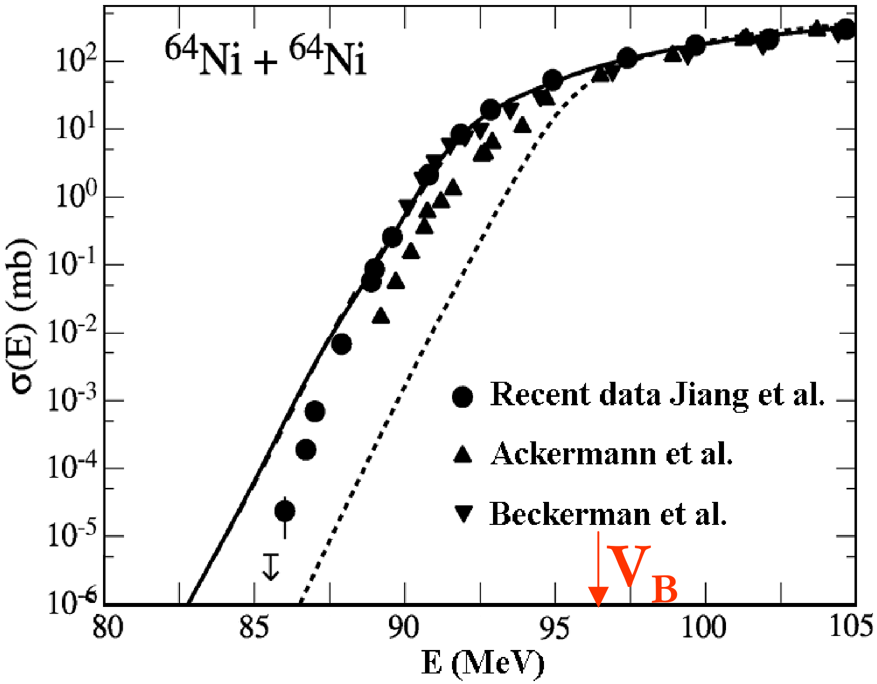
← Double folding pot.

Fusion process: not successful

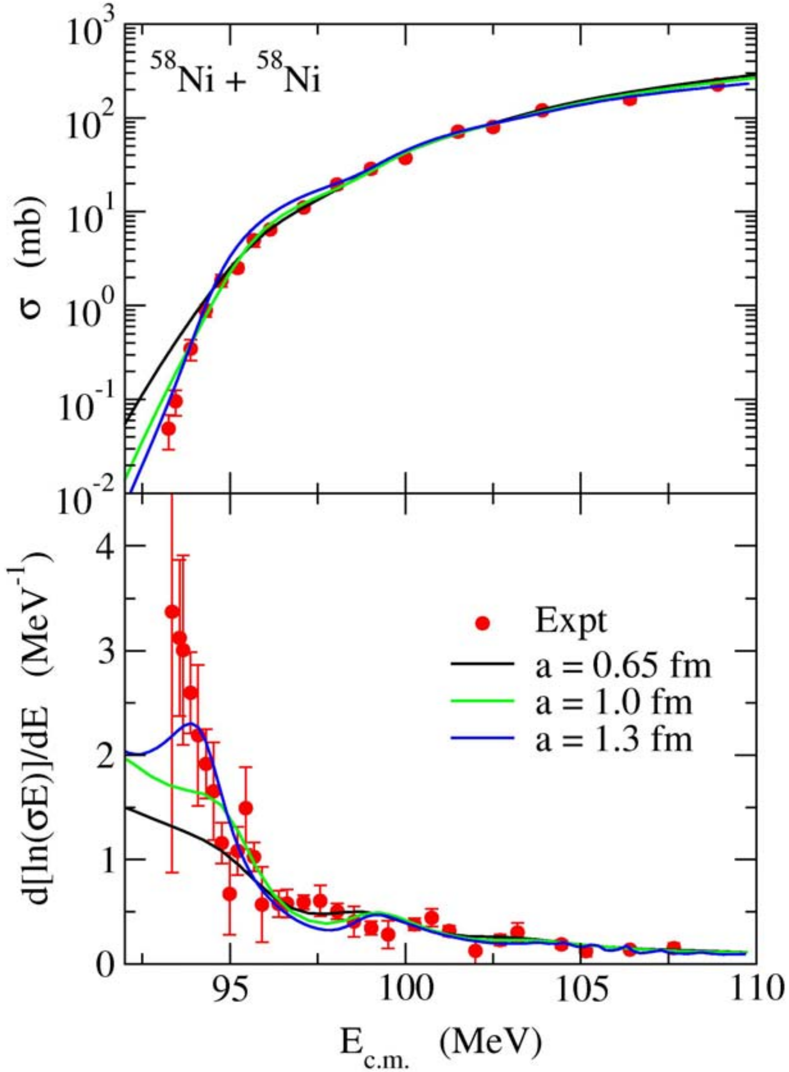
→ a ~ 1.0 fm required (if WS)



Deep subbarrier data



C.L. Jiang et al., PRL93('04)012701
Talk at this conference



K. H., N. Rowley, and M. Dasgupta, PRC67('03)054603

What is the mechanism of deep sub-barrier hindrance?

cf. shallow inter-nucleus potential
S. Misic and H. Esbensen, PRL96('06)112701

Large-angle Quasi-elastic scattering

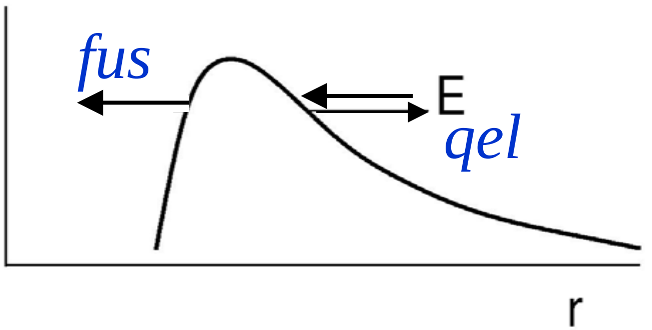
Quasi-elastic scattering:

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

→ Good counterpart of fusion

- inclusive process
- sensitive to channel couplings

cf. barrier distribution



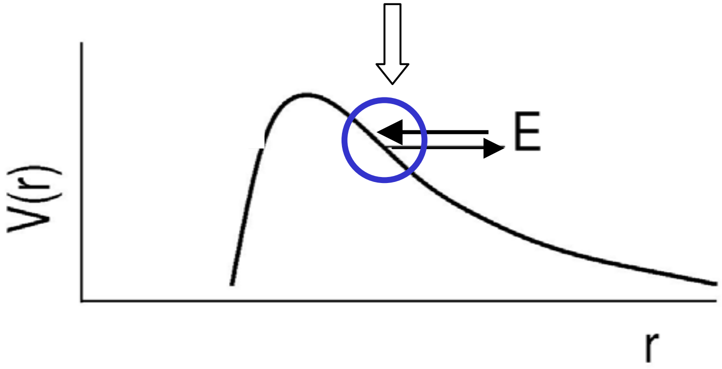
$$\sigma_{\rm fus}(E) = \frac{\pi}{k^2}\sum_l (2l+1)P_l(E)$$ ⟷ penetrability

$$\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_R(E,\pi)} \sim \left(1+\frac{V_N(r_c)}{ka}\frac{\sqrt{2a\pi k\eta}}{E}\right)\cdot R(E)$$ ⟷ reflection probability

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

Quasi-elastic scattering at deep subbarrier energies:

sensitive only to the surface region



$$\frac{\sigma_{\rm qel}(E,\pi)}{\sigma_R(E,\pi)} \sim \left(1+\frac{V_N(r_c)}{ka}\frac{\sqrt{2a\pi k\eta}}{E}\right)\cdot R(E)$$

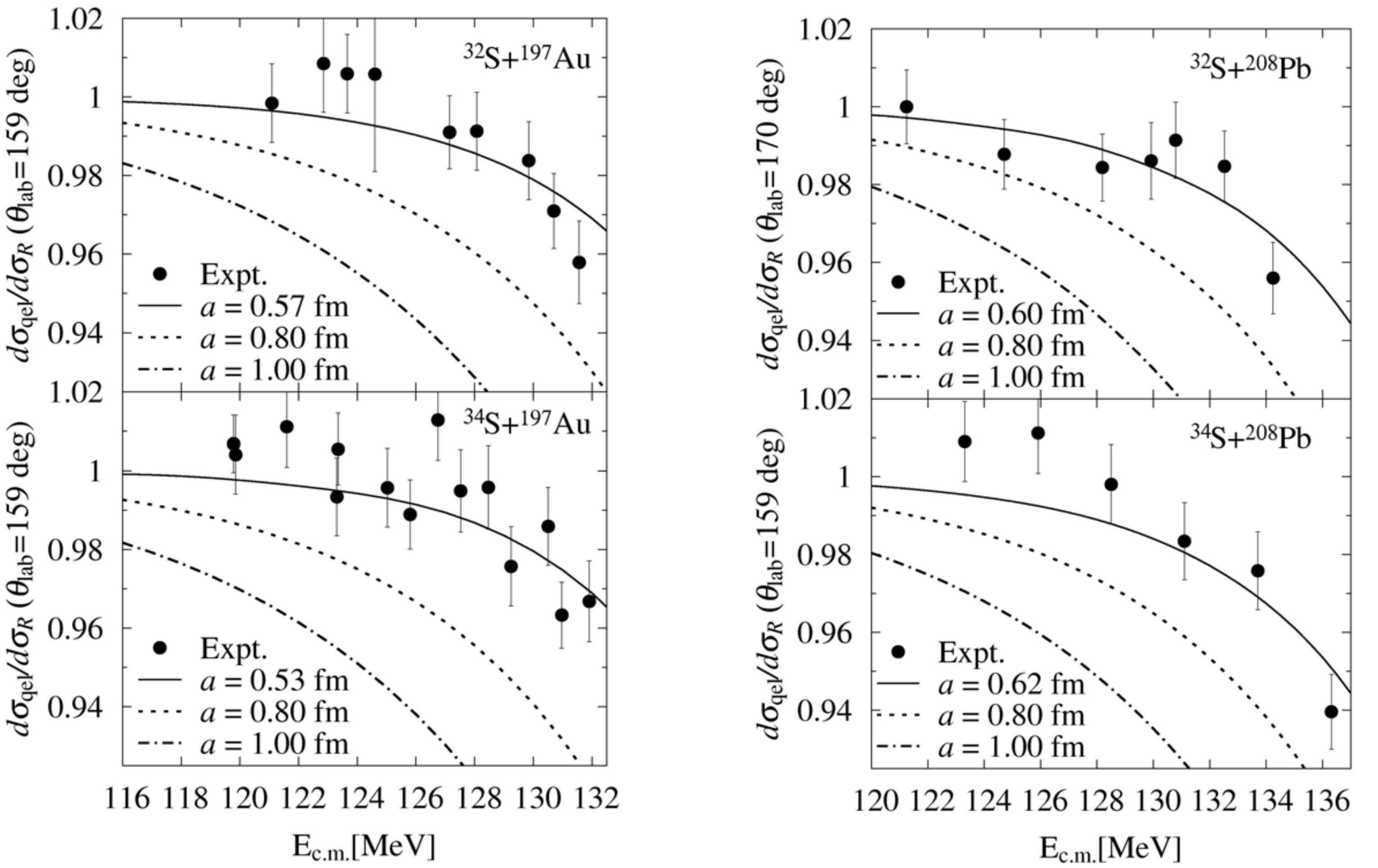
$$\sim 1+\frac{V_N(r_c)}{ka}\frac{\sqrt{2a\pi k\eta}}{E}$$

- C.C. effects: negligible at deep subbarrier energies ⟵ $R(E) \sim 1$
- Inclusive process ⟶ Almost no ambiguity for Im. potential

⟹ a clean way to extract the *a* parameter

Surface diffuseness parameter for deep sub-barrier QEL

K. Washiyama, K.H., M. Dasgupta, PRC73('06)034607



→ $a \sim 0.6$ fm

→ Double folding pot.: seems reasonable at least in the tail region

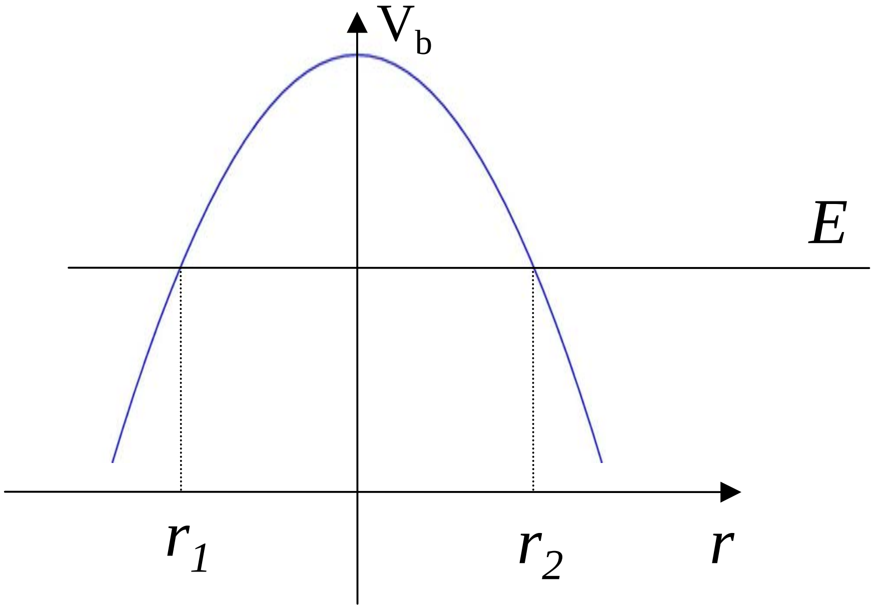
Potential inversion with sub-barrier fusion data

K.H. and Y. Watanabe, to be submitted

Potential inversion

$$P_0(E) = 1/[1+S_0(E)], \quad S_0(E) = \int_{r_1}^{r_2} dr \sqrt{\frac{2\mu}{\hbar^2}(V(r)-E)}$$

$$t(E) \equiv r_2 - r_1 = -\frac{2}{\pi}\sqrt{\frac{\hbar^2}{2\mu}} \int_E^{V_b} \frac{\left(\frac{dS_0(E')}{dE'}\right)}{\sqrt{E'-E}} dE'$$

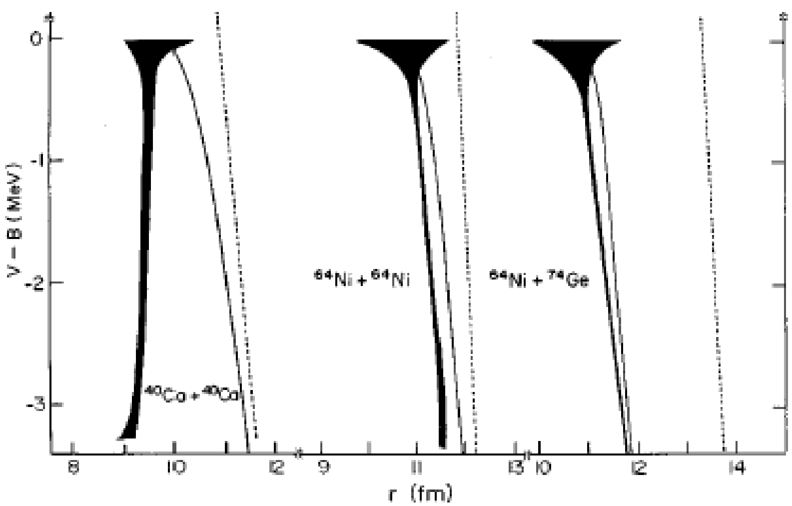


the radial shape of pot. barrier

can be extracted in a model independent way

Balantekin et al. ('83):
assumed an E-indep, local,
single-ch. potential

Unphysical potentials



A.B. Balantekin, S.E. Koonin, and
J.W. Negele, PRC28('83)1565

Our new approach:

Takes into account the C.C. effect

$$P(E) = \sum_n w_n P_n(E)$$

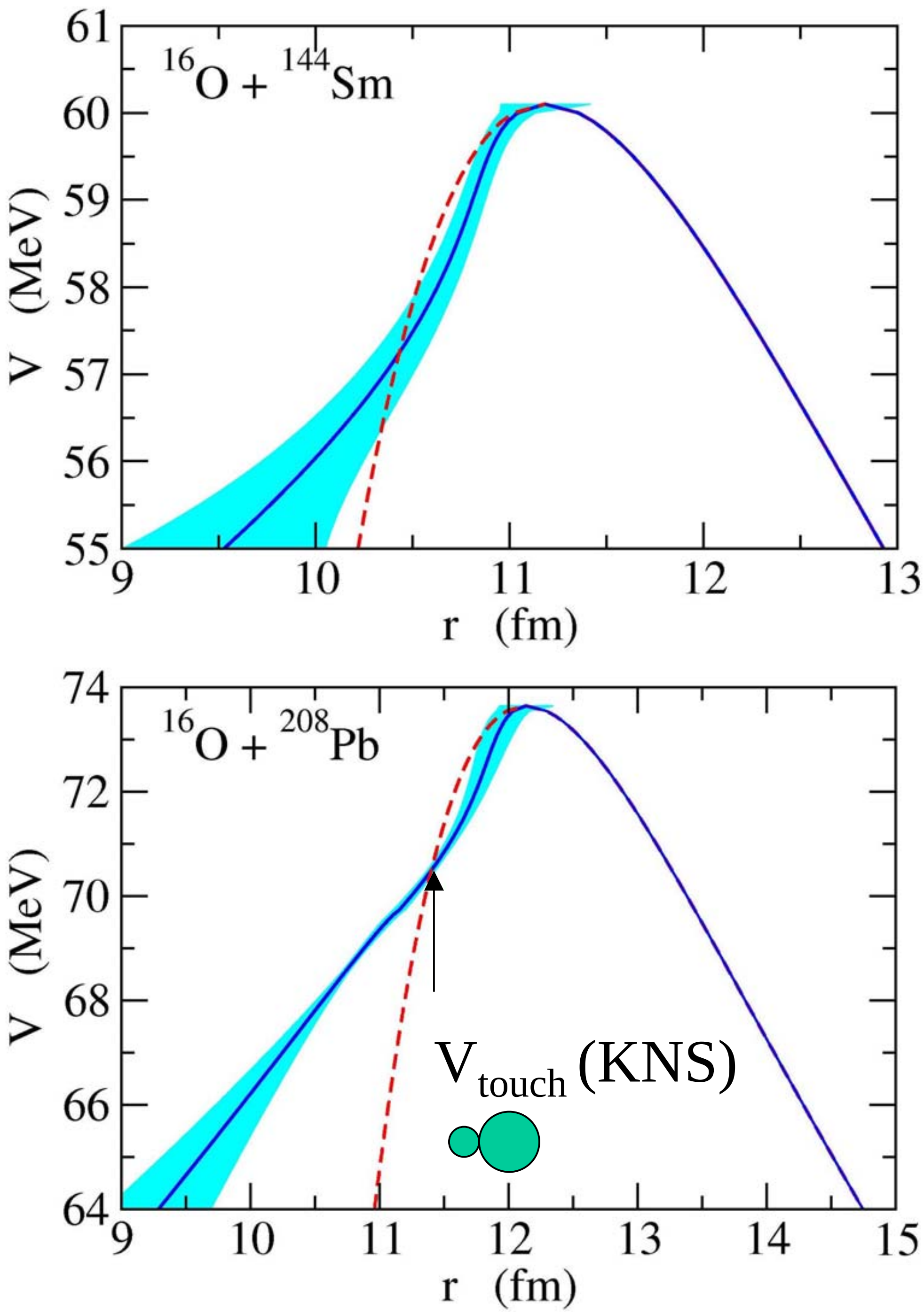
Apply the inversion method
only to the lowest (adiabatic) pot.

$$P(E) = \sum_n w_n P_n(E)$$
$$\sim w_0 P_0(E)$$

deep sub-barrier E

$$P(E) \sim \frac{1}{\pi R_b^2} \frac{d(E\sigma_{\rm fus})}{dE}$$

$$P_0(E) \propto \frac{d(E\sigma_{\rm fus})}{dE}$$



- Similar to WS around the Coulomb barrier
- Much thicker than WS at deep sub-barrier

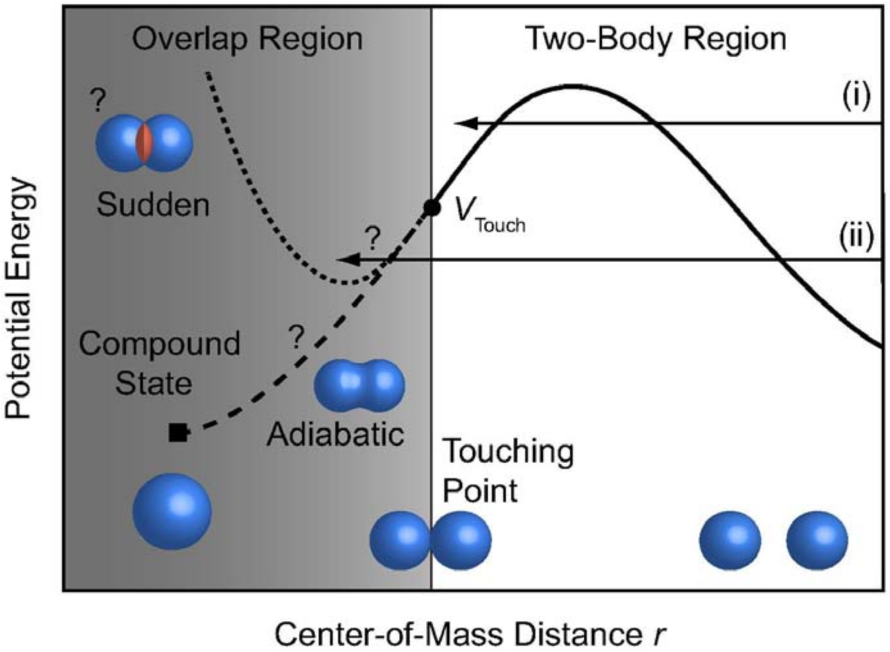
↓

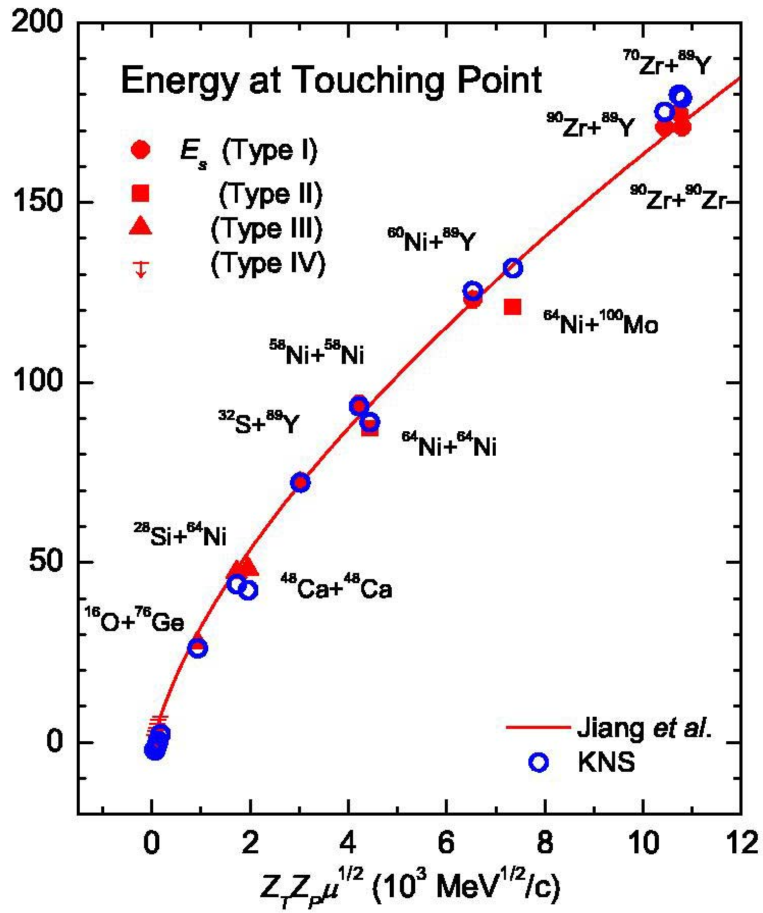
dynamics after touching

cf. T. Ichikawa
a talk at this conf.

K.H. and Y. Watanabe,
to be submitted

Systematics for pot. energy at the touching config.





T. Ichikawa, K.H., A. Iwamoto, PRC, in press.

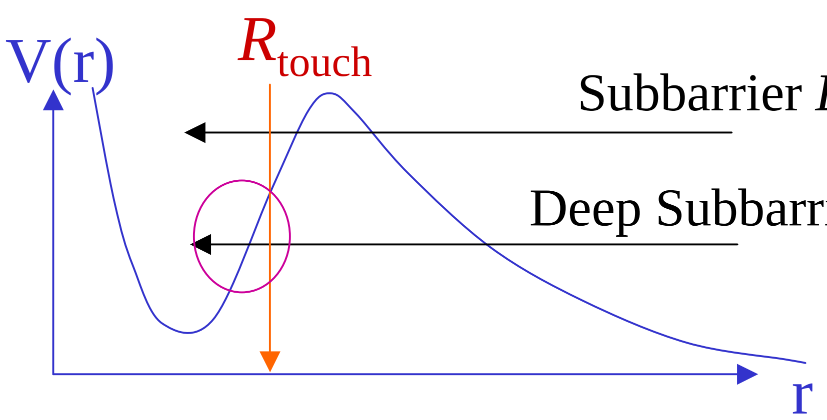
Summary

Surface diffuseness parameter ⟵ Quasi-elastic scattering at deep subbarrier energies

$a \sim 0.6$ fm

⟹ consistent with DF in the tail region

Origin of surface diffuseness anomaly in fusion?



Large overlap region

- Sudden approach:
  Pauli principle
- Adiabatic approach:
  Coordinate dep. mom. inertia

- Potential inversion ⟹ much thicker barrier than WS
- V_{KNS} (R_{touch}) ⟹ closely follows the threshold E for fus. hindrance

deep subbarrier fus. hindrance ⟺ dynamics after touching