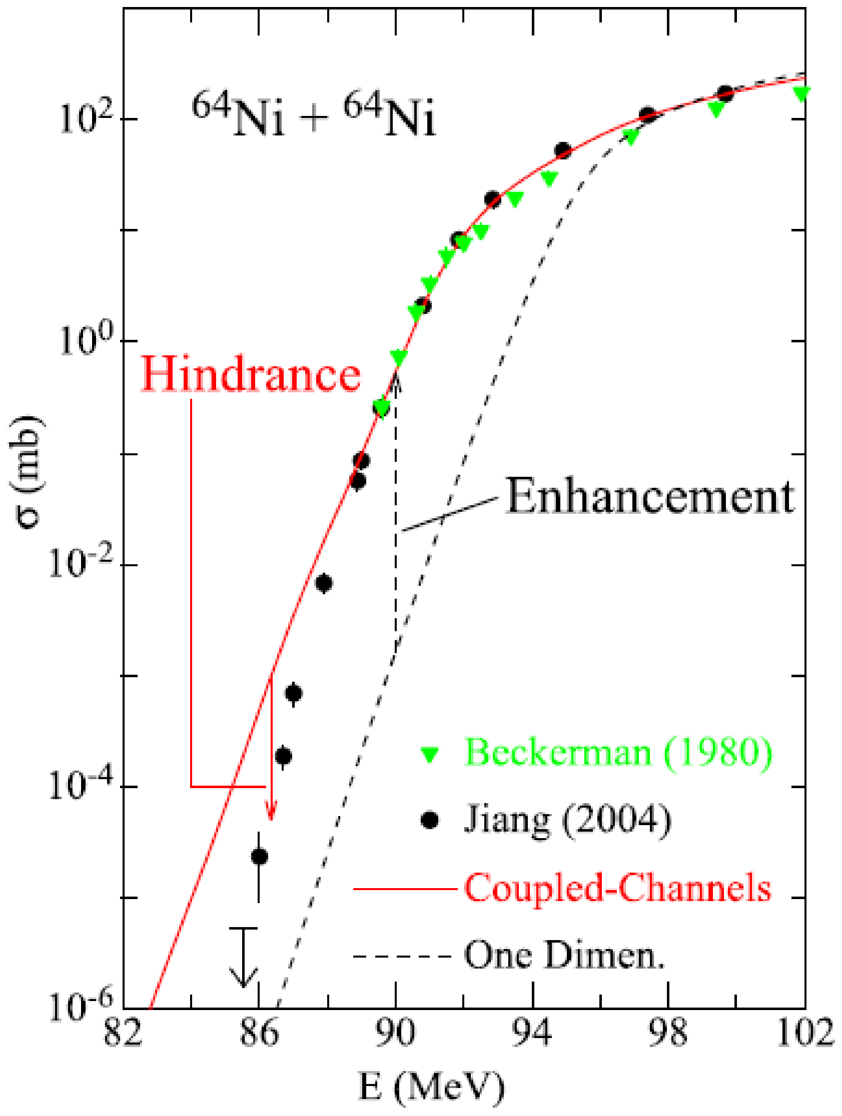
Heavy-ion fusion reactions from a view point of open quantum systems

Kouichi Hagino
Kyoto University, Kyoto, Japan

1. Deep subbarrier fusion hindrance
2. Open quantum systems: an application of the Caldeira-Leggett model to subbarrier fusion
3. Summary

"FUS++ On Heavy-ion fusion far below the barrier", University of Padova and INFN (on line), Jan. 20-21

Deep subbarrier fusion hindrance



C.L. Jiang et al., Eur. Phys. J. A57 ('21) 235

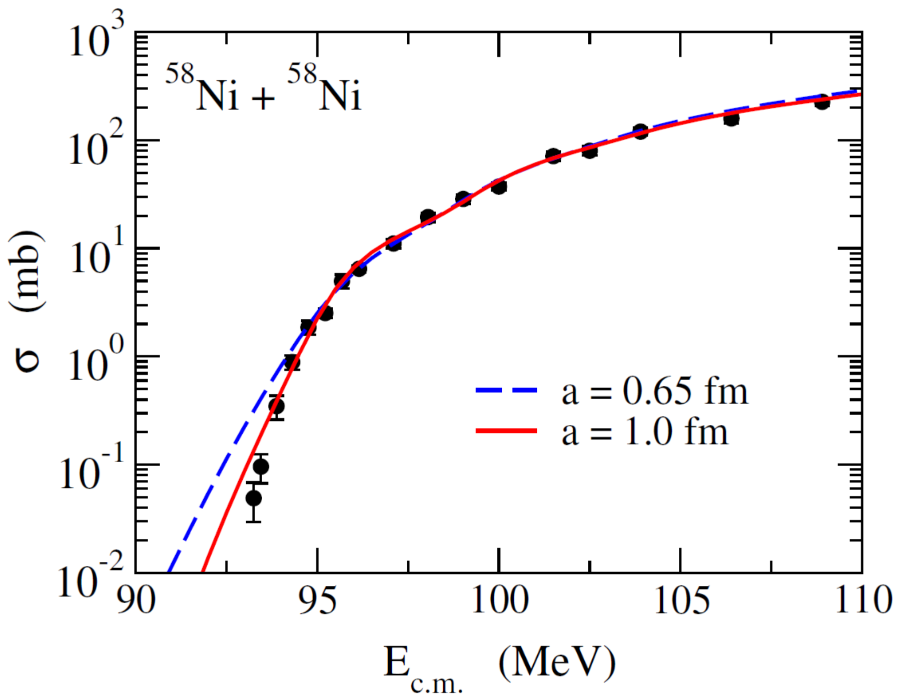
Deep subbarrier fusion hindrance

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

TABLE II. Fusion barriers and the diffuseness parameters of the nuclear potential obtained by fitting high energy fusion cross sections using a calculation with a single barrier. The values of B_0 and a are correlated; columns 3 and 5 indicate the ranges which increase the χ^2 values by 1. Higher values of B_0 correspond to lower values of a.

Reaction	B_0 (MeV)		a (fm)	
^{144}Sm + ^{16}O	61.10	0.05	0.84	0.03
^{144}Sm + ^{17}O	60.68	0.07	0.92	0.04
^{148}Sm + ^{16}O	59.85	0.08	1.05	0.04
^{154}Sm + ^{16}O	59.40	0.05	1.10	0.04
^{186}W + ^{16}O	68.90	0.06	1.11	0.04

"surface diffuness anomaly"

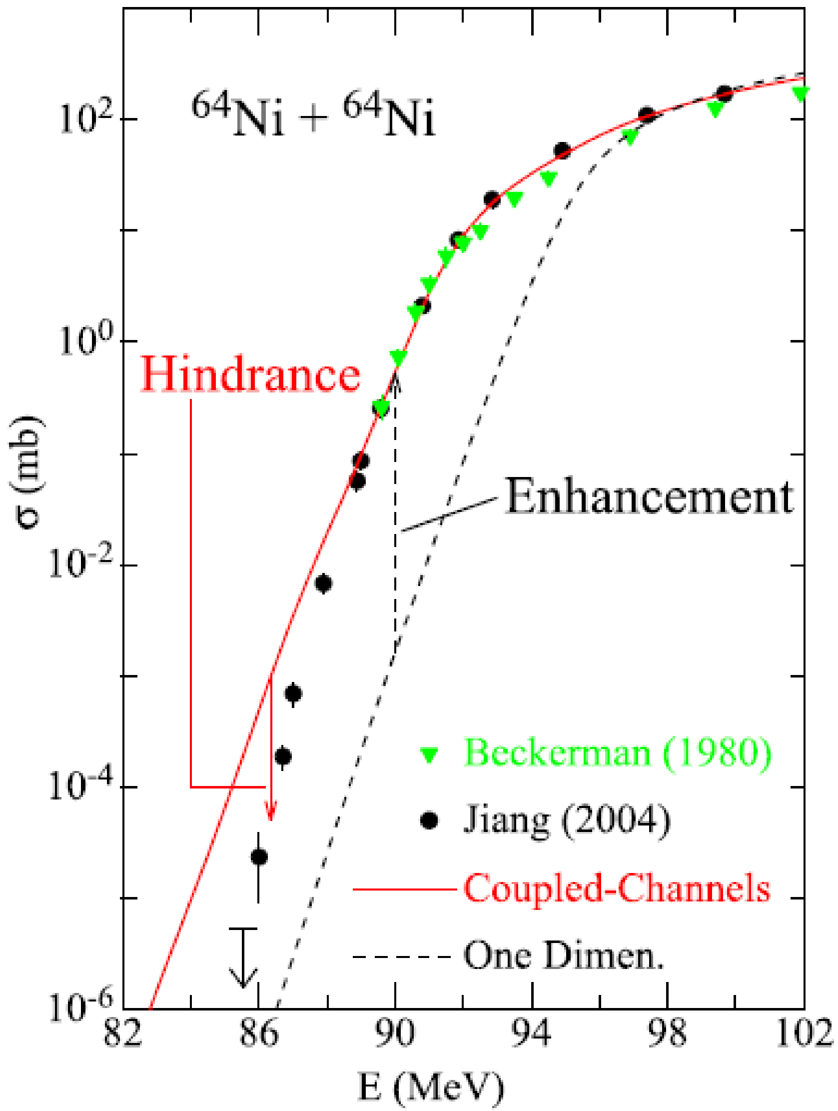


See also
J.R. Leigh et al., PRC47('93)R437,
J.O. Newton et al., PRC70 ('04)024605

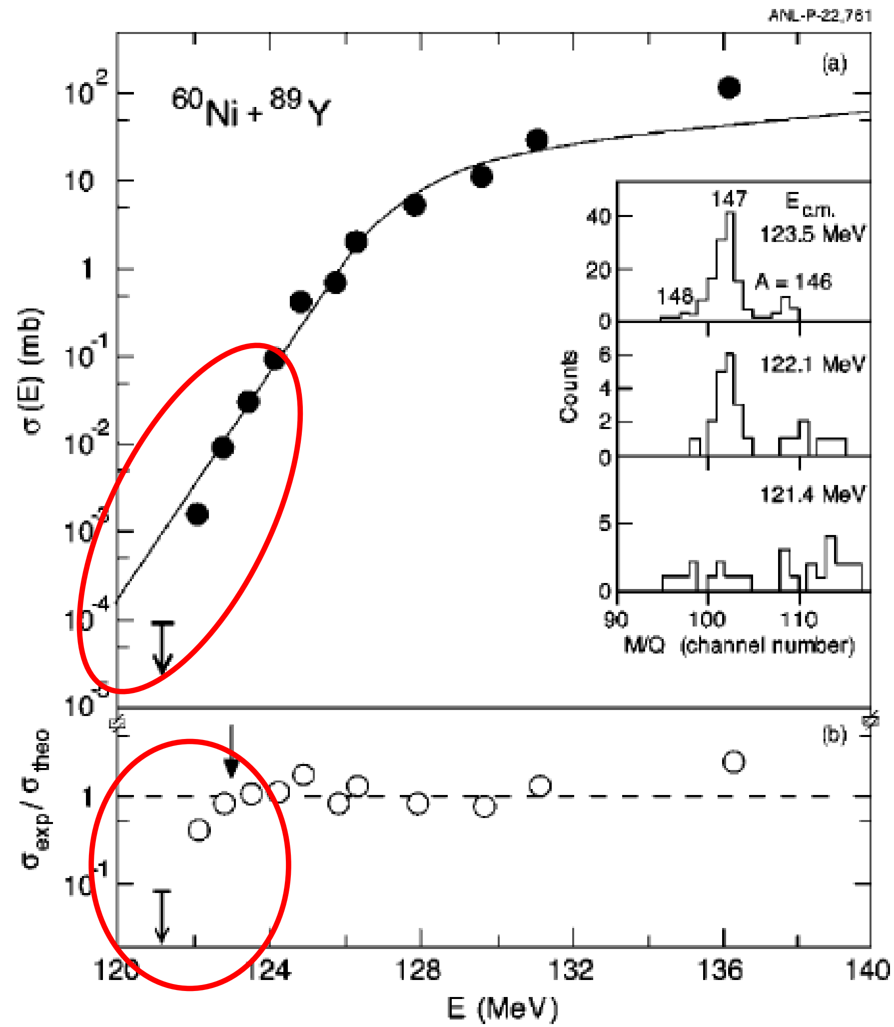
K.H., N. Rowley, M. Dasgupta,
PRC67 ('03) 054603
J.R. Leigh et al., PRC52 ('95) 3151

Deep subbarrier fusion hindrance

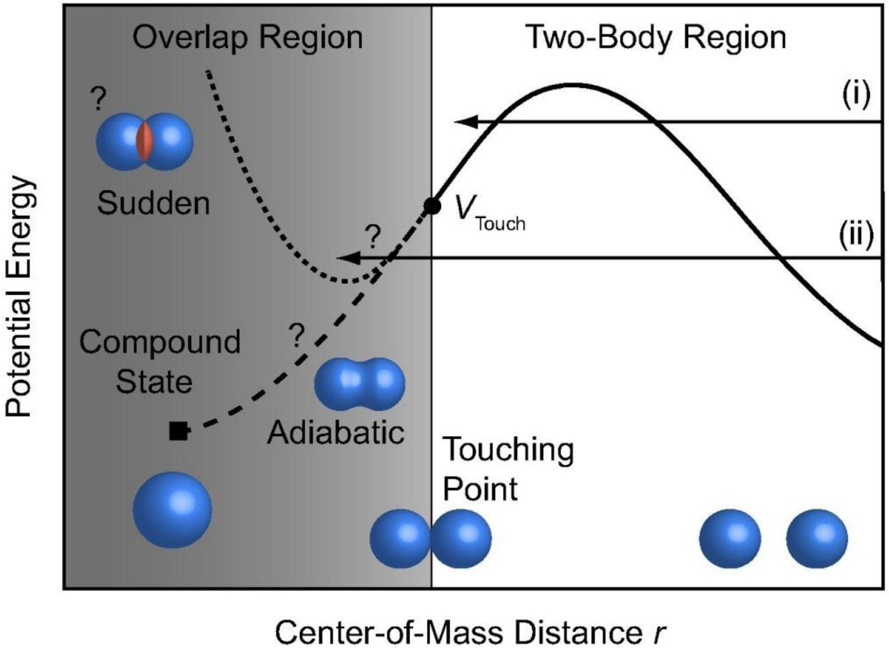
the first measurement from ANL



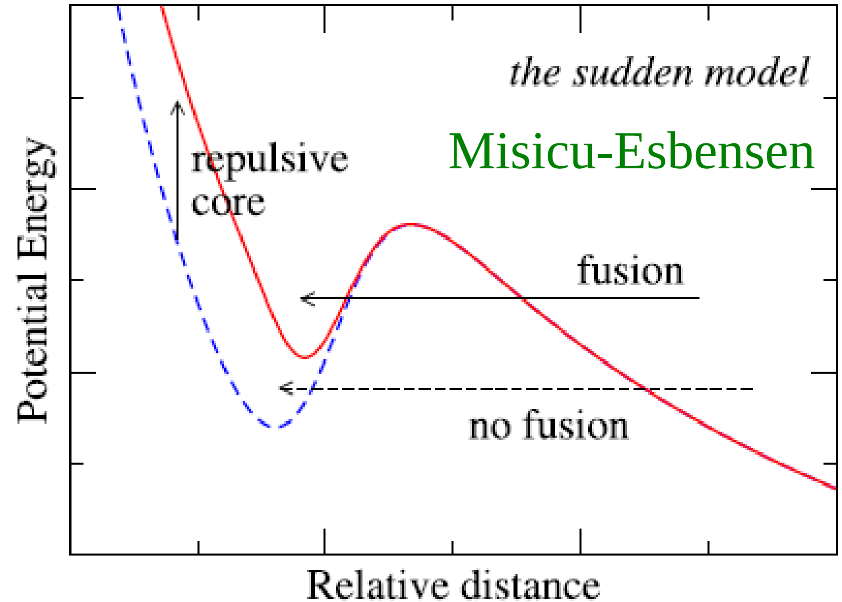
C.L. Jiang et al., Eur. Phys. J. A57 (‘21) 235

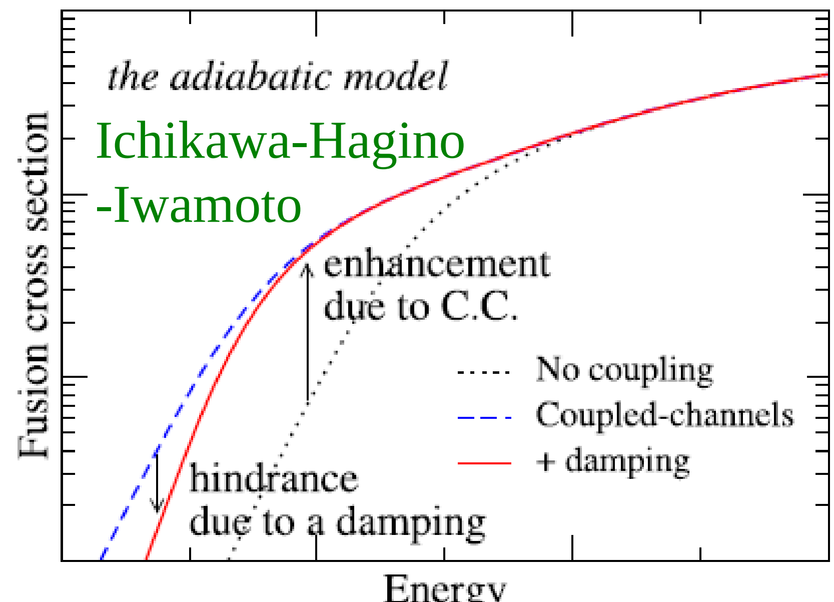


C.L. Jiang et al., PRL89 (‘02) 052701



T. Ichikawa, K.H., A. Iwamoto,
PRC75('07) 064612 & 057603

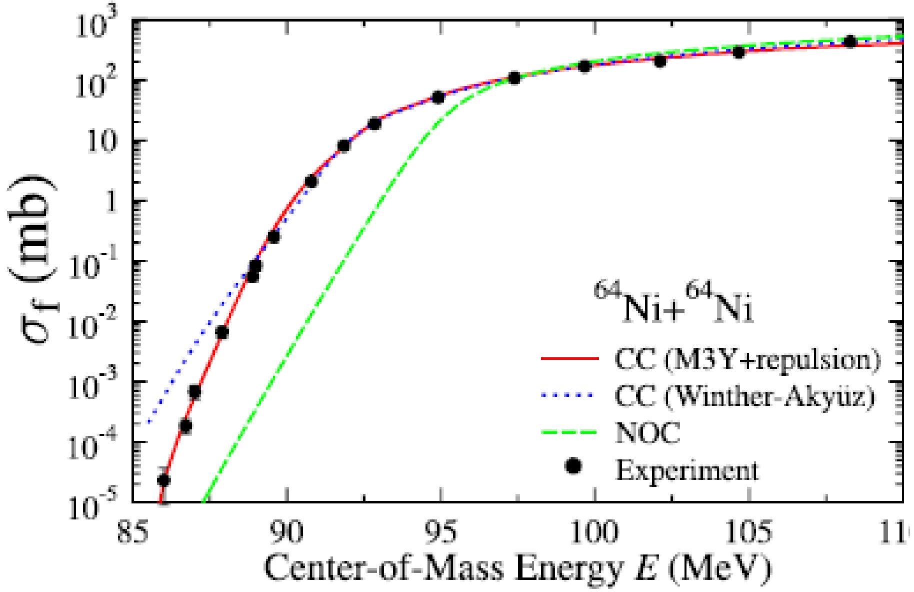




C.L. Jiang et al., Eur. Phys. J. A57 ('21) 235

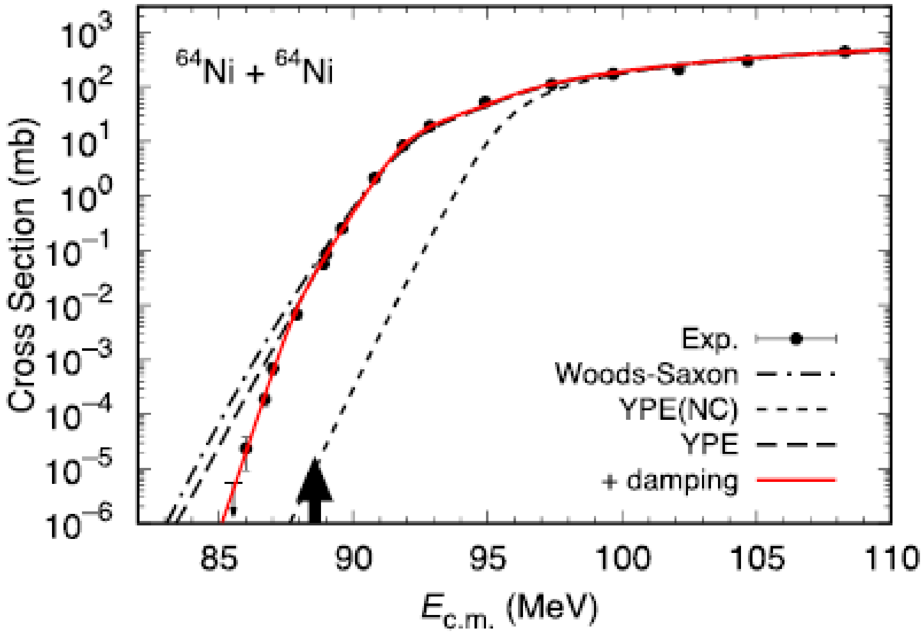
the sudden versus the adiabatic models: $^{64}Ni+^{64}Ni$

the sudden model



S. Misicu and H. Esbensen,
PRL96 ('06) 112701
PRC75 ('07) 034606

the adiabatic model

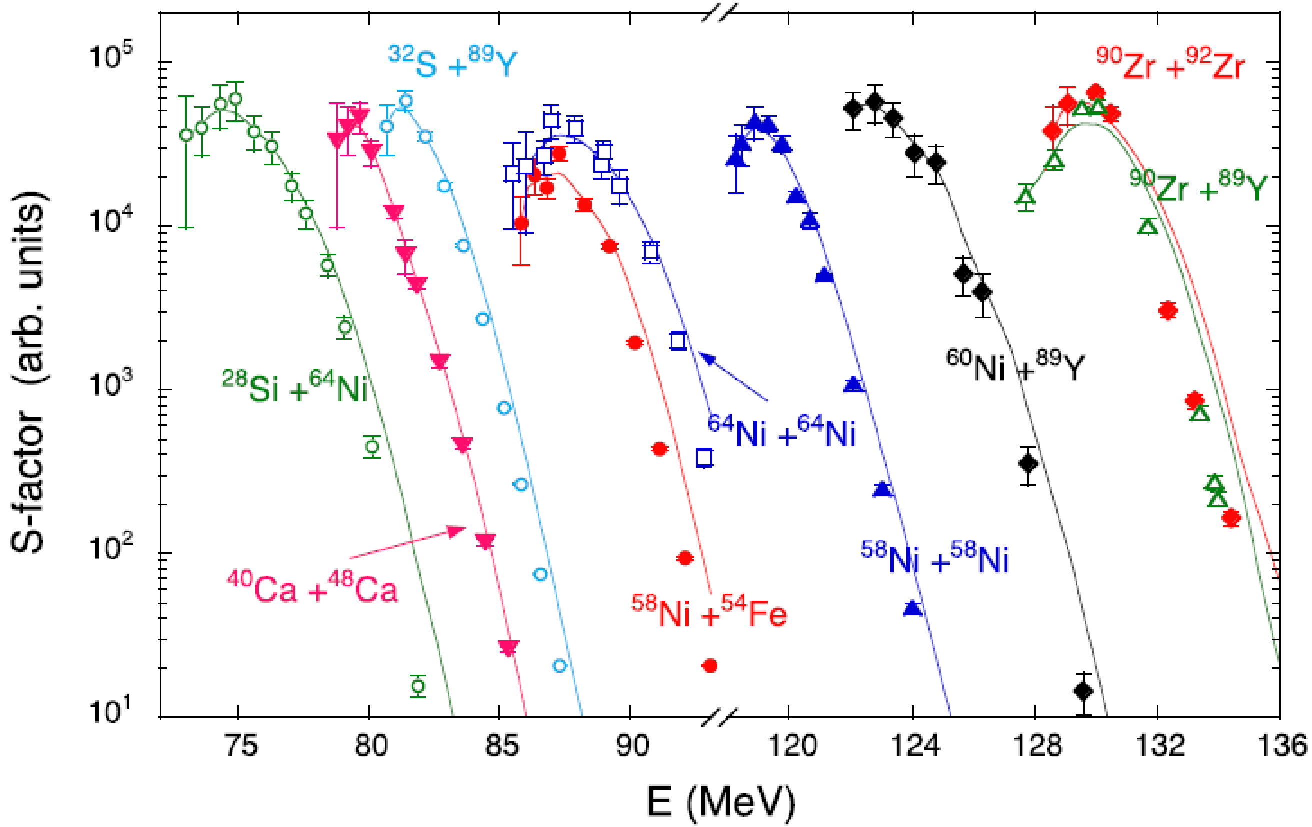


T. Ichikawa,
PRC92 ('15) 064606

Both models reproduce the data equally well.

S-factor maximum

$$\tilde{S}(E) = E\sigma e^{2\pi(\eta-\eta_0)}$$

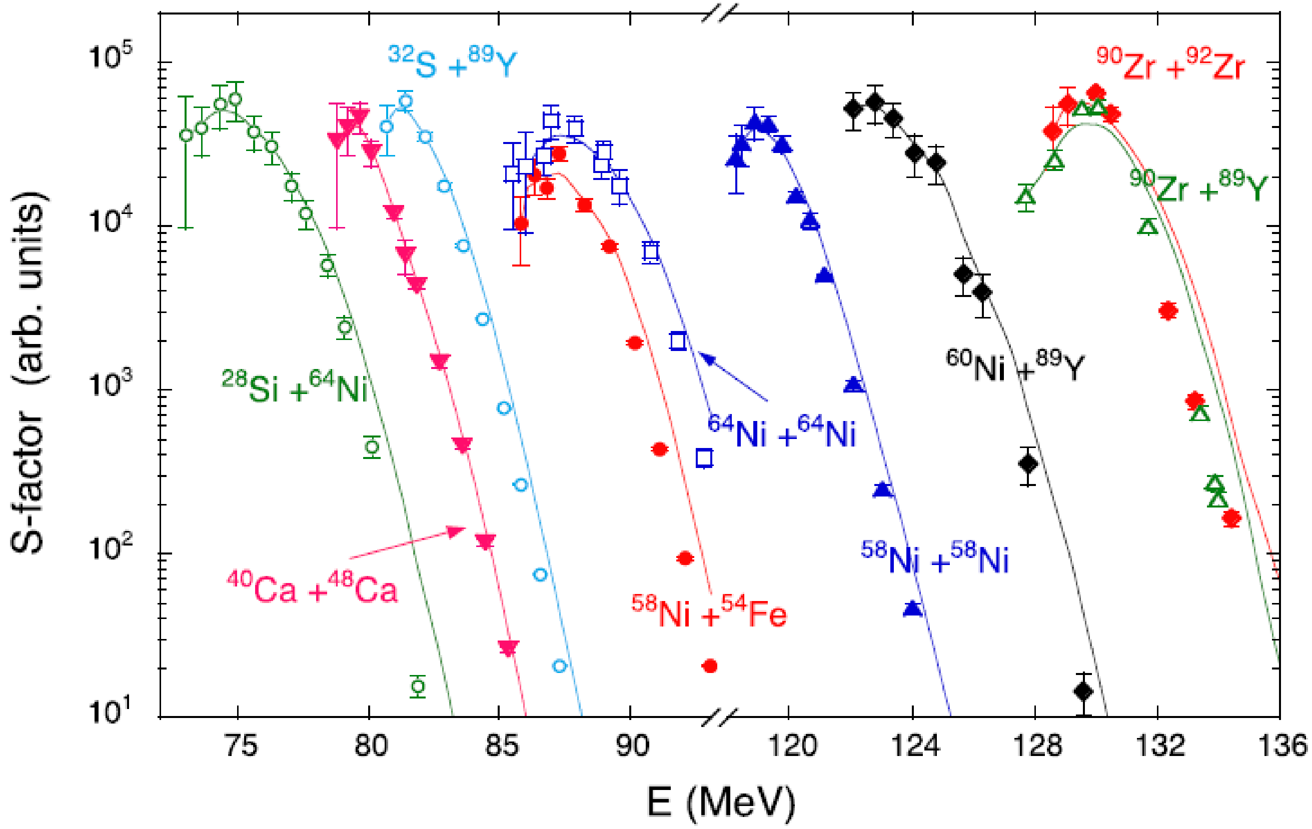


C.L. Jiang et al., Eur. Phys. J. A57 (‘21) 235

C.L. Jiang et al.: $E_{\mathrm{max}} \sim E_{\mathrm{threshold}}$

S-factor maximum

$$\tilde{S}(E) = E\sigma e^{2\pi(\eta-\eta_0)}$$



C.L. Jiang et al., Eur. Phys. J. A57 ('21) 235

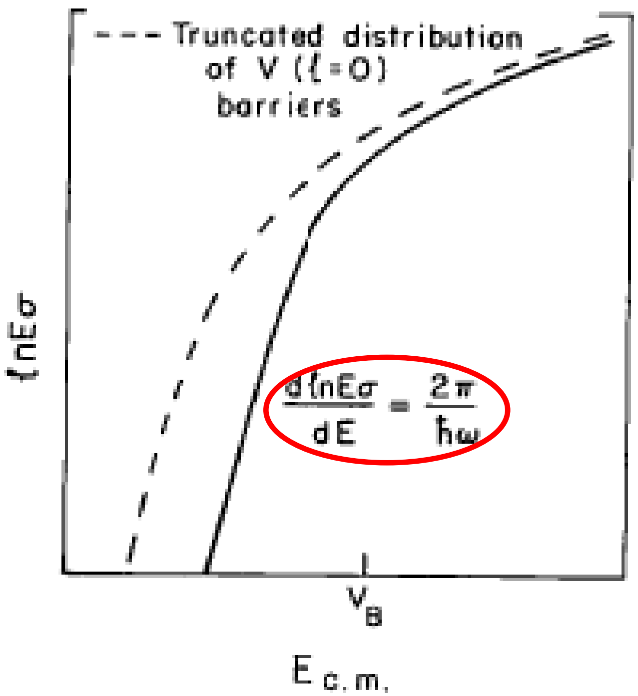
C.L. Jiang et al.: $E_{max} \sim E_{threshold} \rightarrow$ justifiable?

S-factor maximum

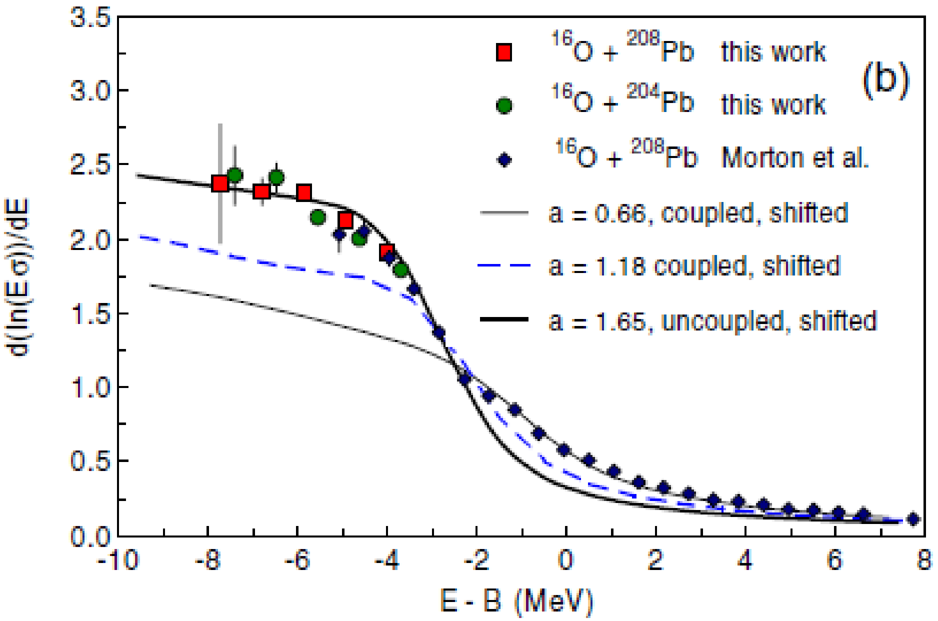
$$\tilde{S}(E) = [E\sigma]e^{2\pi(\eta-\eta_0)}$$

$$\frac{1}{\tilde{S}}\frac{d\tilde{S}}{dE} = L(E) - \frac{\pi\eta}{E}; \qquad L(E) = \frac{d}{dE}\ln(E\sigma)$$

+



R. Vandenbosch,
Ann. Rev. Nucl. Part. Sci. 42('92)447



M. Dasgupta et al., PRL99('07) 192701

S-factor maximum

$$\tilde{S}(E) = [E\sigma]e^{2\pi(\eta-\eta_0)}$$

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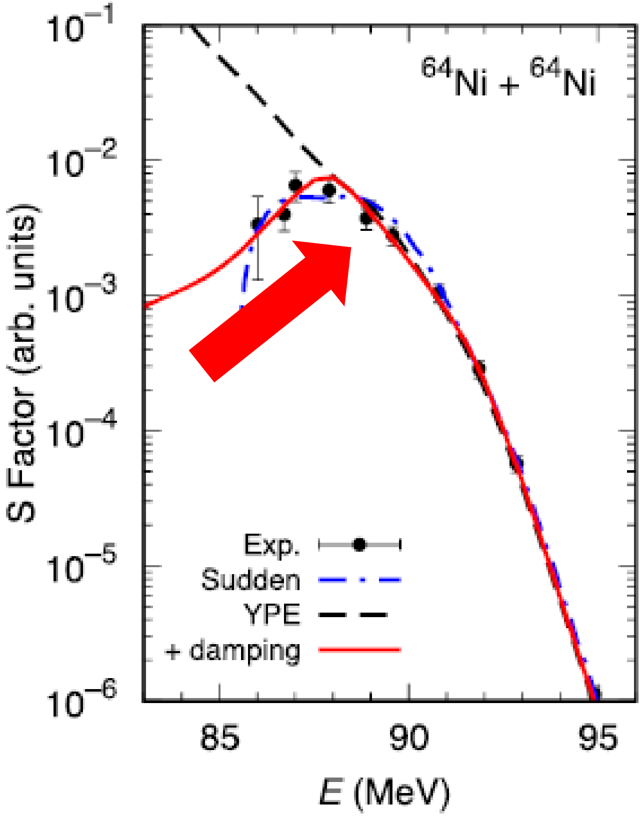
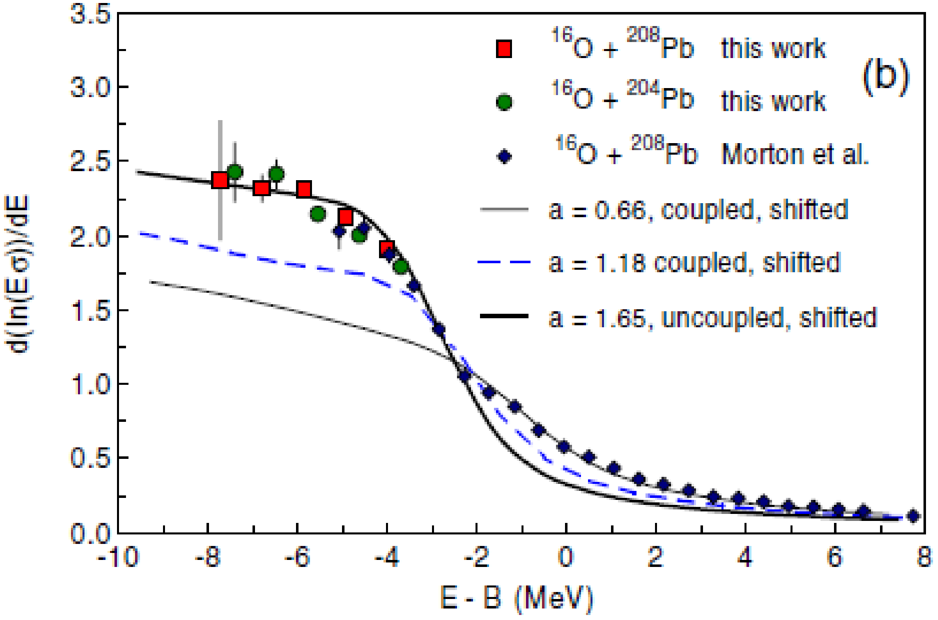


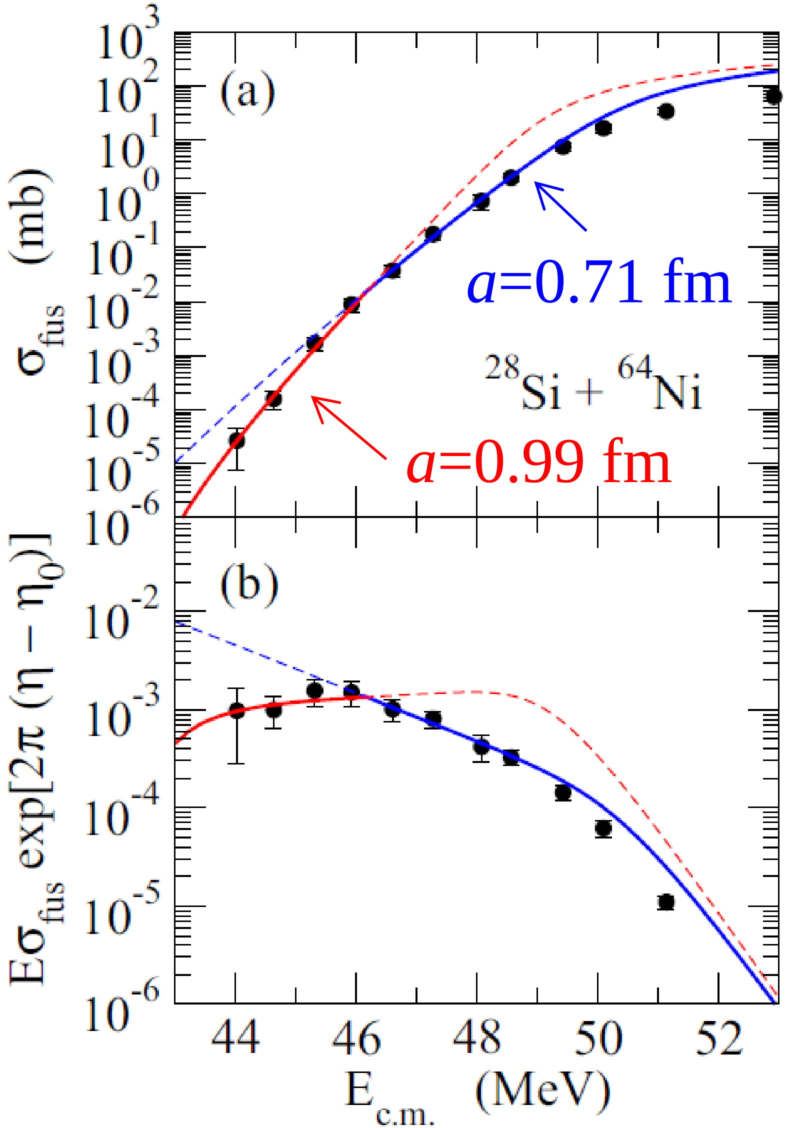
T. Ichikawa, PRC92 (‘15) 064606



M. Dasgupta et al., PRL99(‘07) 192701

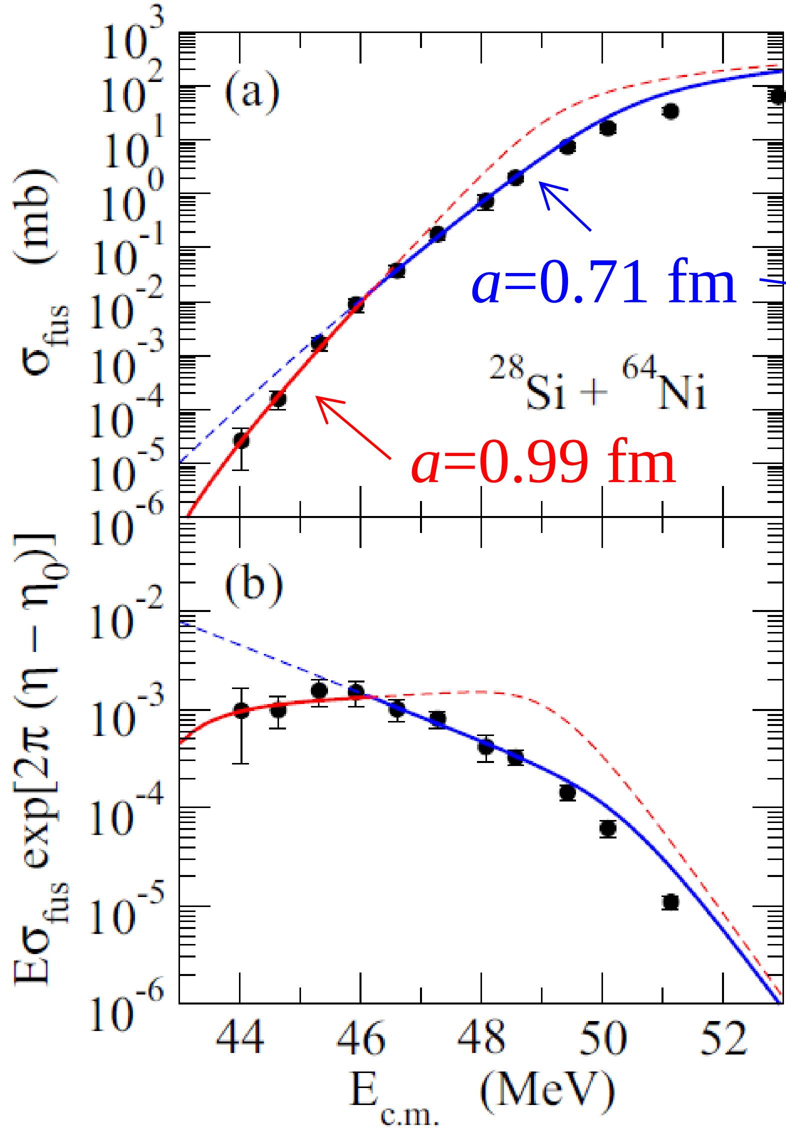
large $L(E)$ → a positive slope of $S(E)$

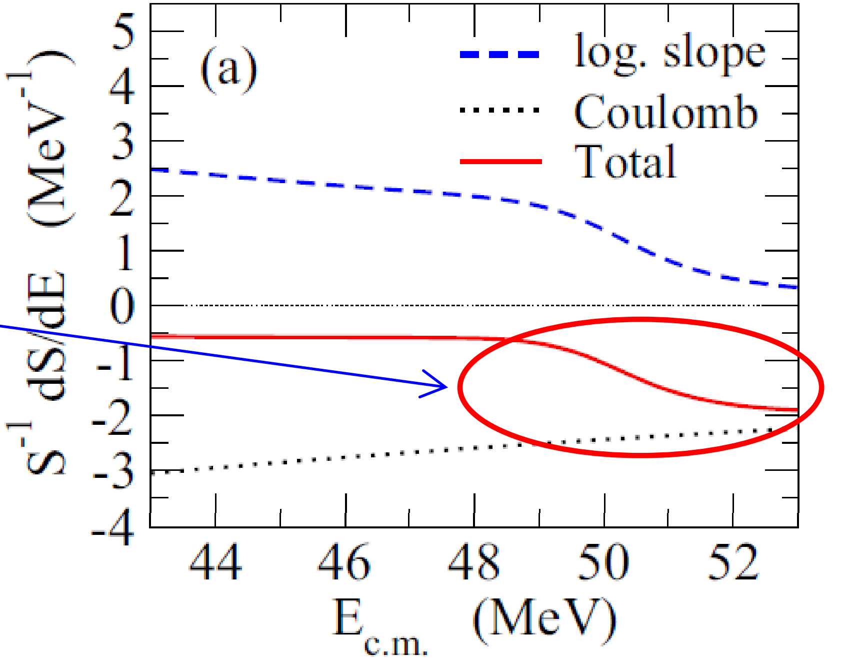
[two-potential fit]



K.H., A.B. Balantekin, N.W. Lwin, and E.S.Z. Thein,
PRC97 (‘18) 034623

two-potential fit

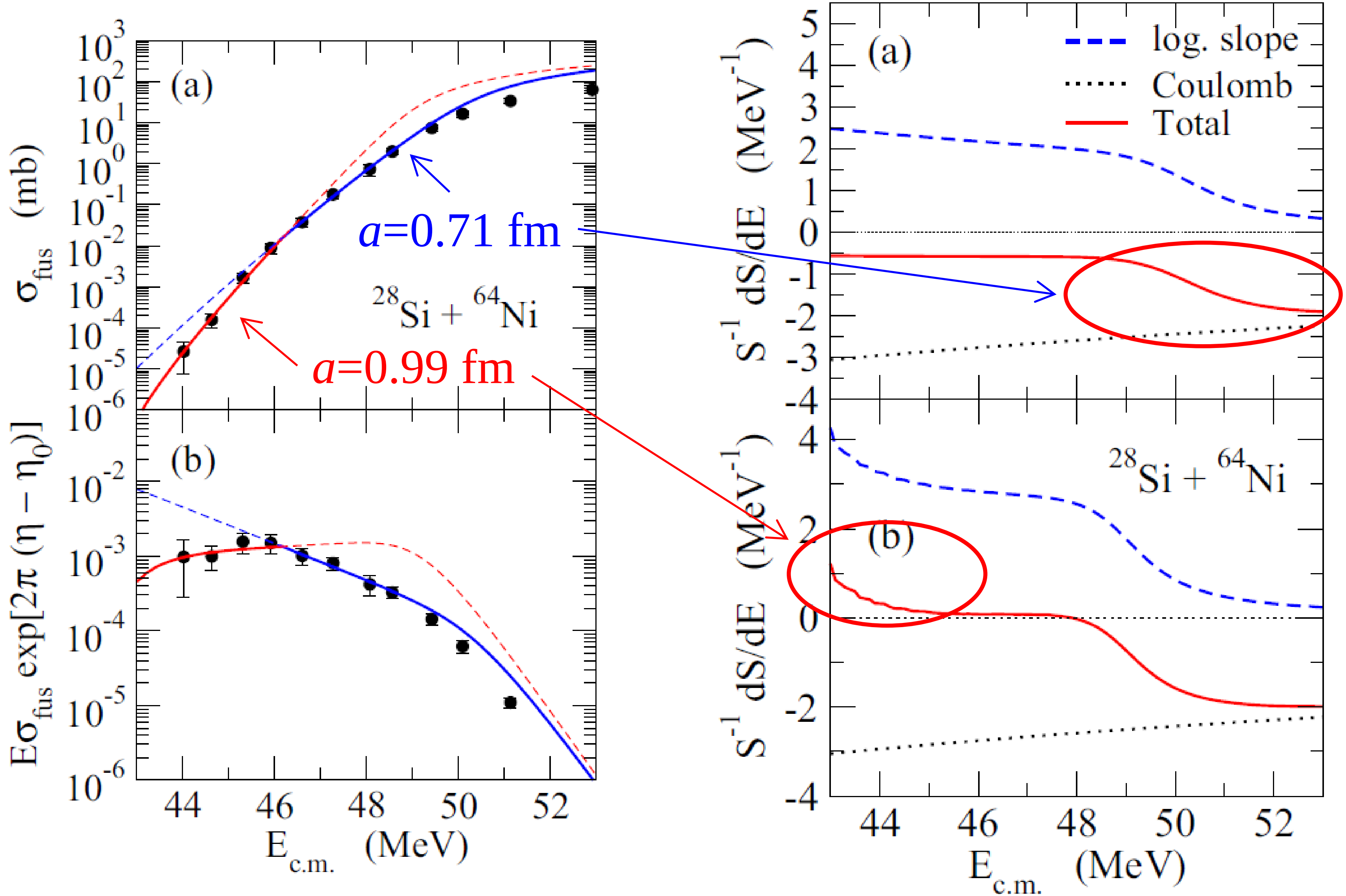




K.H., A.B. Balantekin, N.W. Lwin, and E.S.Z. Thein, PRC97 ('18) 034623

$$\frac{1}{\tilde{S}}\frac{d\tilde{S}}{dE} = L(E) - \frac{\pi\eta}{E}$$

two-potential fit



K.H., A.B. Balantekin, N.W. Lwin, and E.S.Z. Thein,
PRC97 (‘18) 034623

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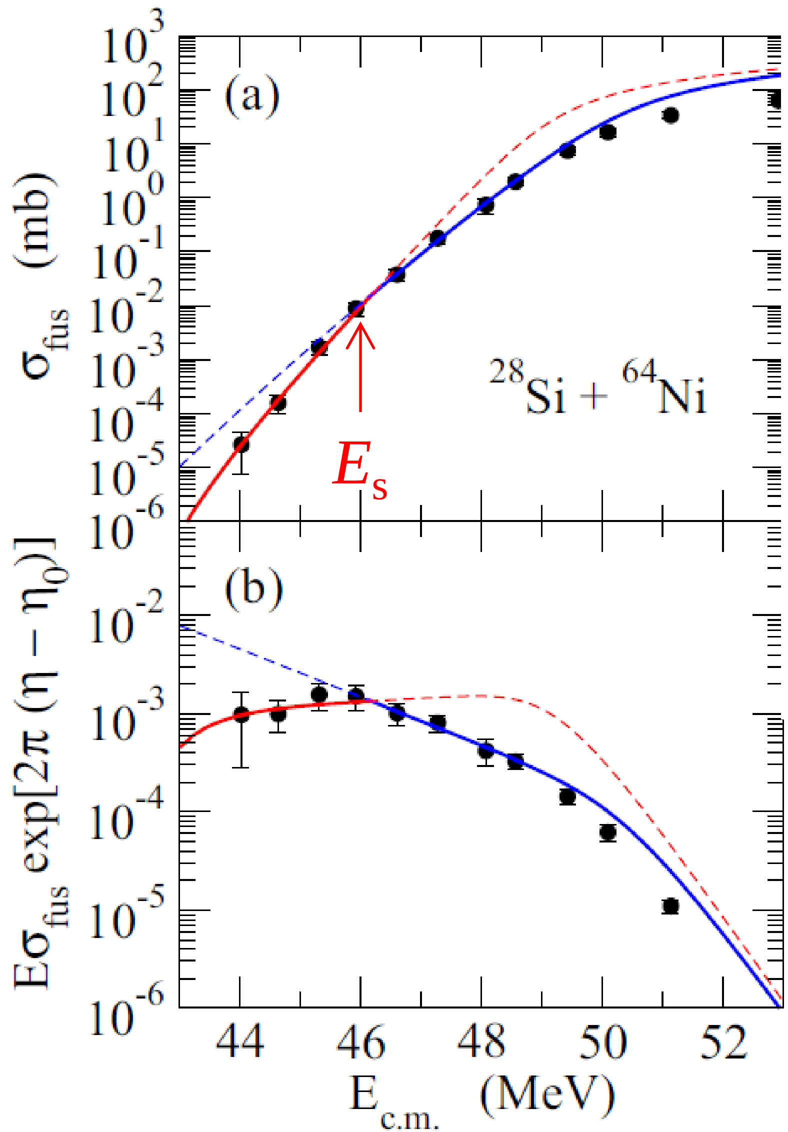
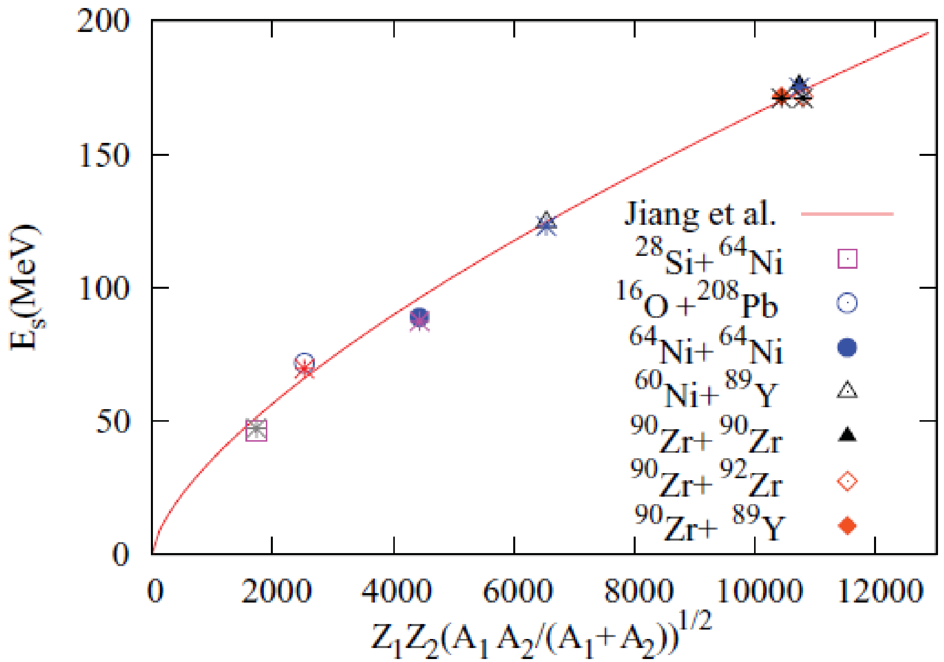
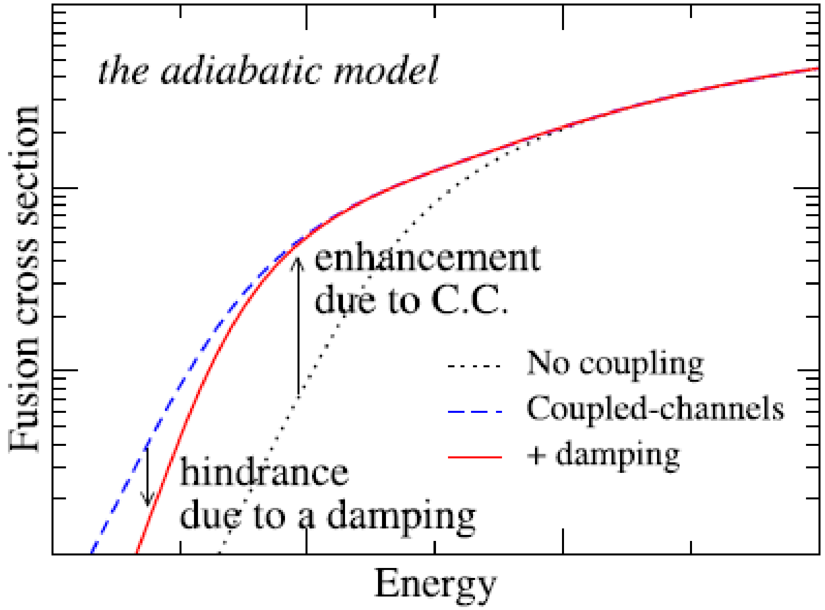




E.S.Z. Thein, N.W. Lwin, and K.H., PRC85 ('12) 057602

K.H., A.B. Balantekin, N.W. Lwin, and E.S.Z. Thein, PRC97 ('18) 034623

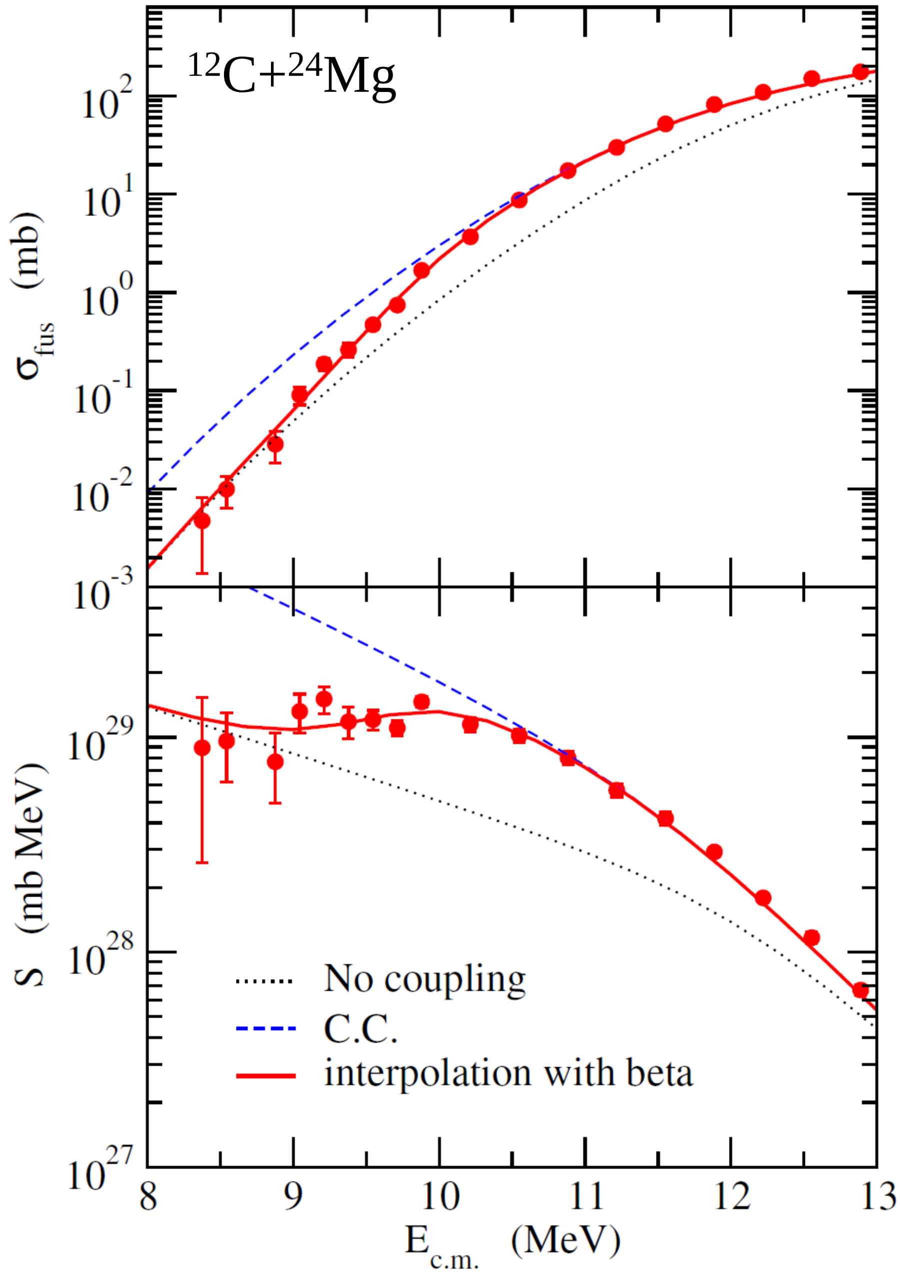
A simplified adiabatic model



a simple interpolation:

$$\ln(\sigma(E)) \sim \beta(E)\ln(\sigma_{\rm cc}(E)) + (1-\beta(E))\ln(\sigma_{\rm noc}(E))$$

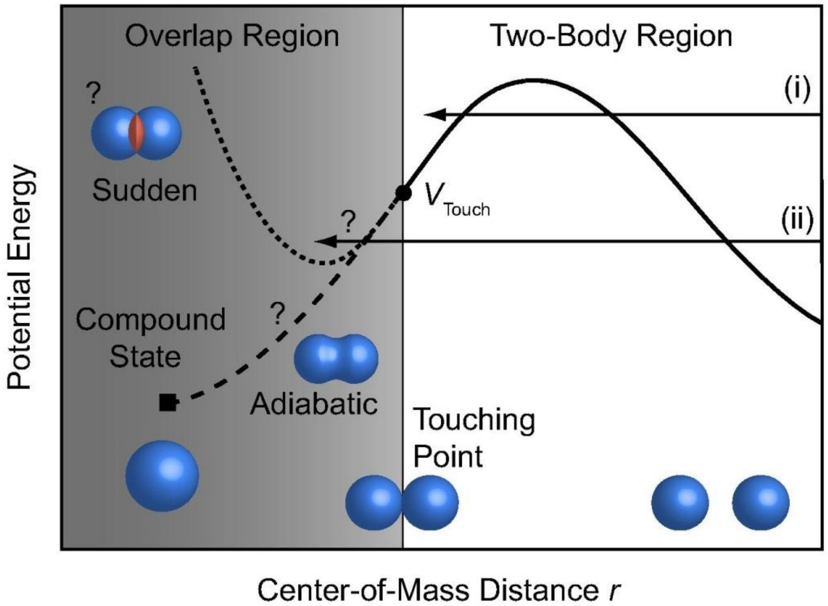
$$\beta(E) = \frac{1}{1+e^{\alpha_0(E-E_0)}}$$



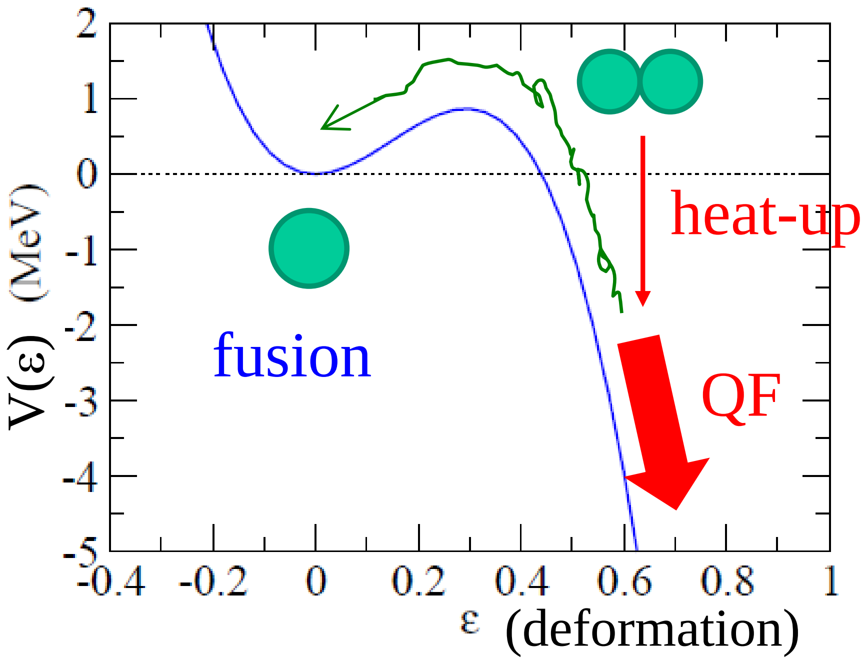
G. Montagnoli et al. (2021)

Fusion from a viewpoint of open quantum systems

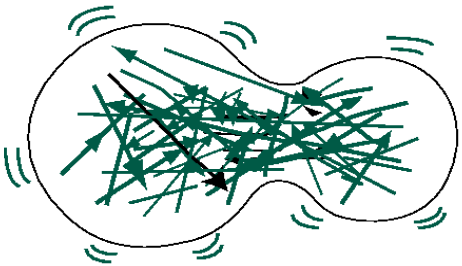
deep subbarrier fusion

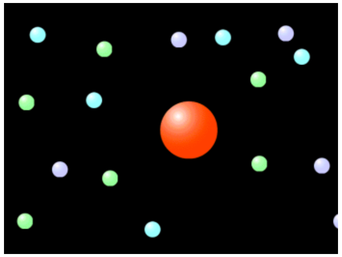


fusion for SHE



many-body dynamics after contact
→ open quantum systems

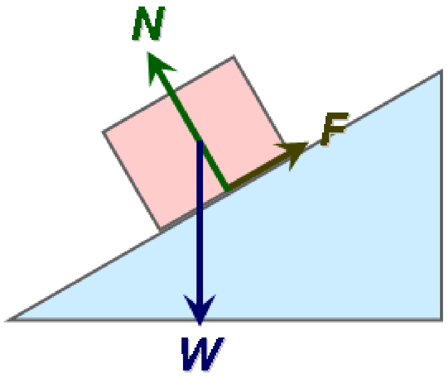




couplings to many d.o.f.

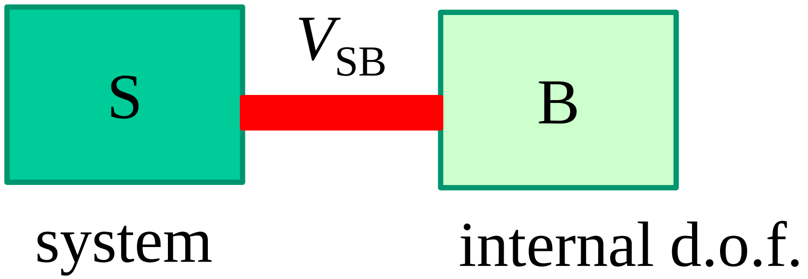
Fusion from a viewpoint of open quantum systems

classical mechanics



heat generation when a rigid body stops

quantum mechanics



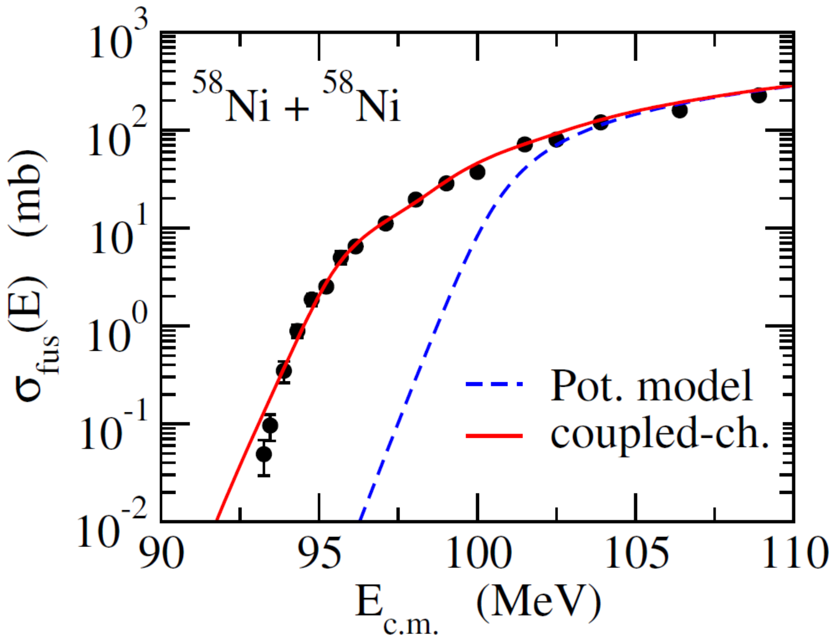
Caldeira-Leggett model

$$H_S = \frac{p^2}{2m} + V(q)$$

$$H_{\text{int}} = \sum_i \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 x_i^2$$

a collection of H.O.

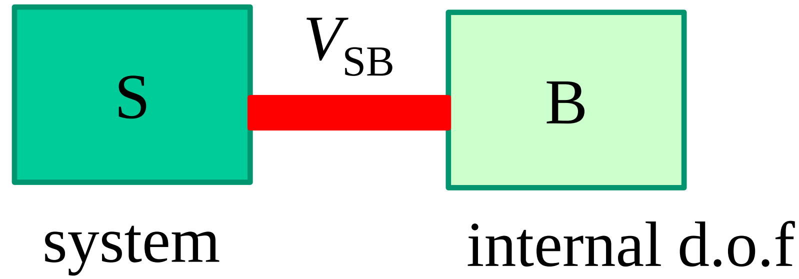
Fusion from a viewpoint of open quantum systems



cf. a vib. coupling in subbarrier fusion

2.90 MeV	———	$0^+, 2^+, 4^+$
1.45 MeV	———	2^+
	———	0^+
	^{58}Ni	

quantum mechanics



Caldeira-Leggett model

$$H_S = \frac{p^2}{2m} + V(q)$$

$$H_{\rm int} = \sum_i \frac{p_i^2}{2m_i} + \frac{1}{2} m_i \omega_i^2 x_i^2$$

a collection of H.O.

→ C.C. calculations

Fusion from a viewpoint of open quantum systems

Caldeira-Leggett model

$$H_S = \frac{p^2}{2m} + V(q)$$

$$H_{\rm int} = \sum_{i=1}^{\infty} (a_i^\dagger a_i + 1/2)\hbar\omega_i$$

how to deal with a huge number of phonon modes?

→ an efficient truncation scheme

$$b_k^\dagger = \sum_{i=1}^{\infty} C_{ki}\, a_i^\dagger \qquad (k = 1, \cdots K)$$

$$e^{-i\omega t} \sim \sum_{k=0}^{K} \eta_k(\omega) J_k(t)$$

$$\rightarrow b_k^\dagger = \sum_i \left[\frac{d_i}{\hbar}\eta_k(\omega_i)\right] a_i^\dagger$$

cf. a "two-phonon" state

2.90 MeV — $0^+, 2^+, 4^+$

1.45 MeV — 2^+

0^+

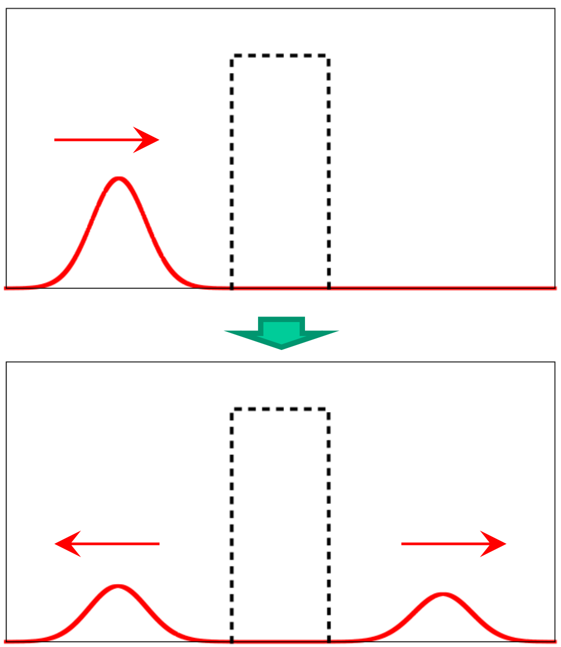
^{58}Ni

$$|2ph\rangle = \sum_I \langle 2020|I0\rangle |\phi_I\rangle$$

M. Tokieda and K. Hagino,
Ann. of Phys. 412 (2020) 168005
Front. in Phys. 8 (2020) 8.

Application to heavy-ion fusion reactions

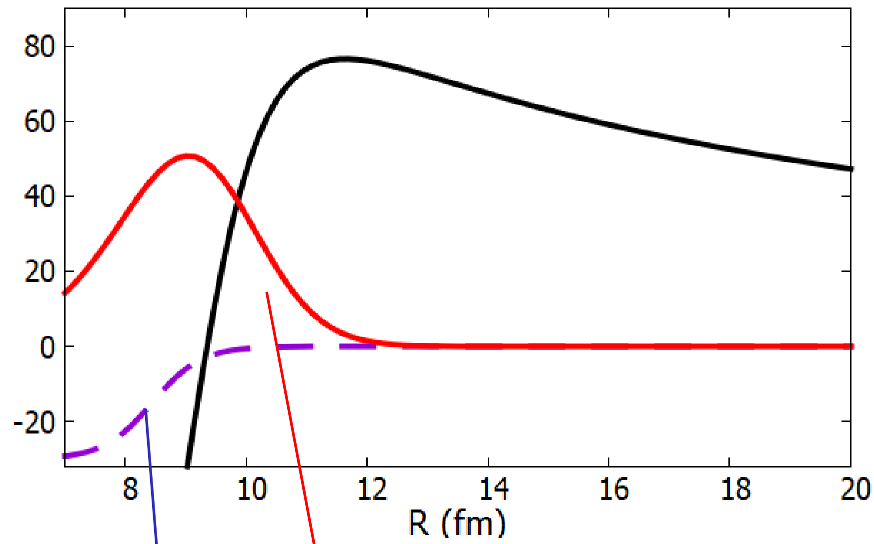
time-dep. wave packet approach



$$R(E) \propto \langle \psi_R(t_f) | \delta(H - E) | \psi_R(t_f) \rangle$$

3D: radial coordinate for each partial wave
(NB. no tangential friction)

$^{16}O + ^{208}Pb$



coupling to the bath

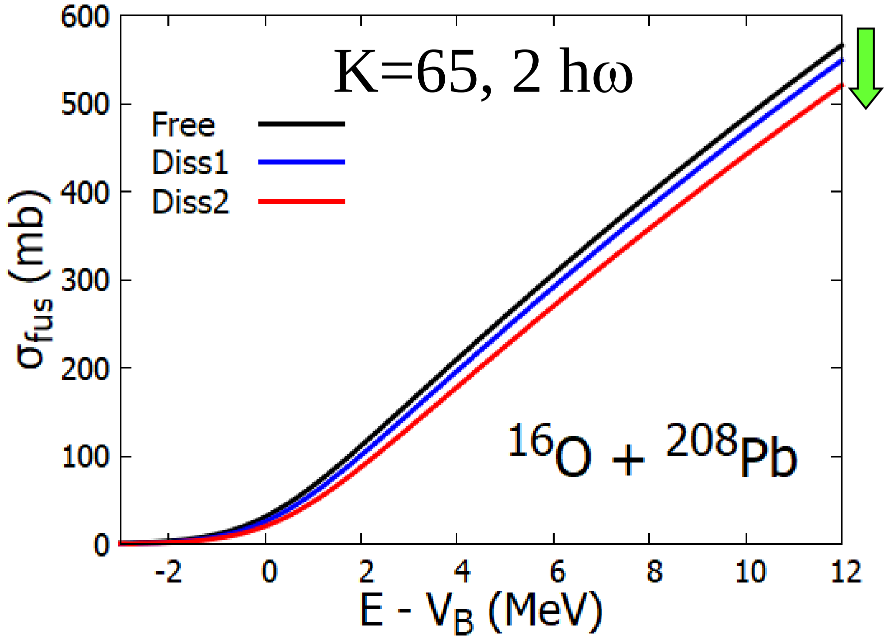
$$h(r) \propto V_N'(r)^2$$

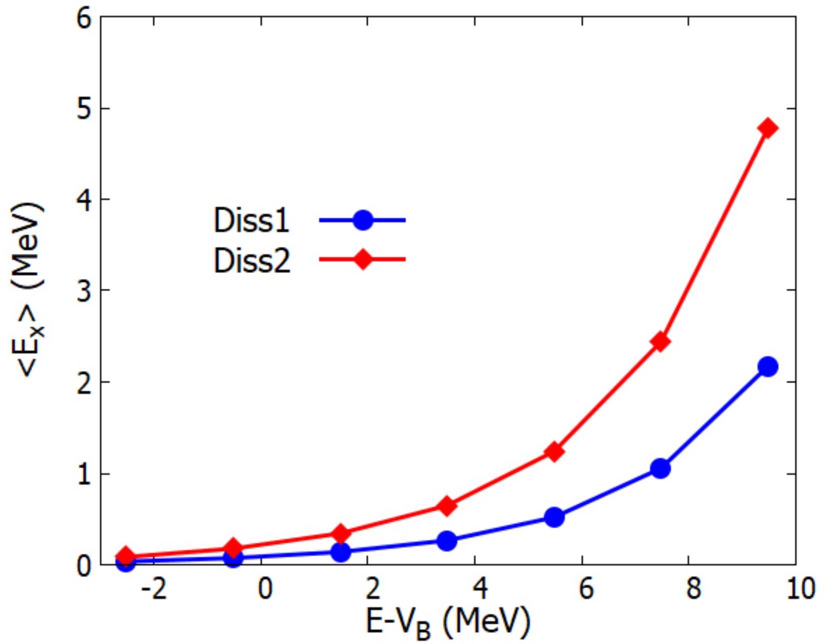
cf. the surface friction model

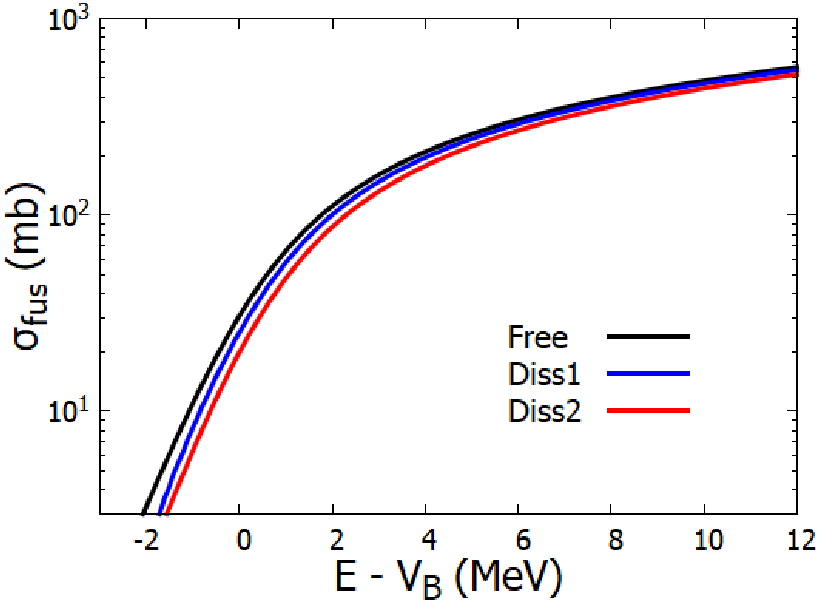
absorption to simulate fusion

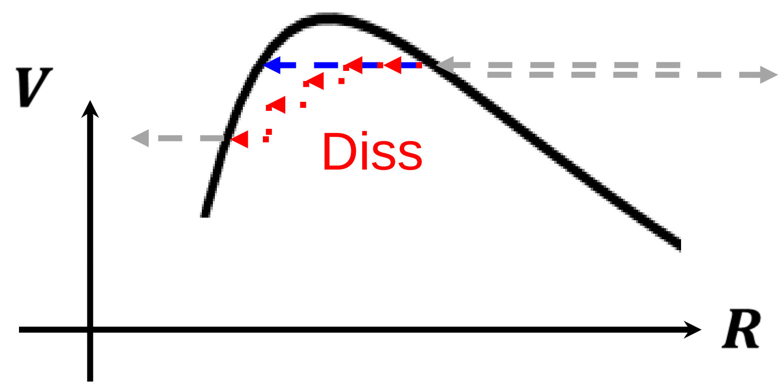
fusion cross sections

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





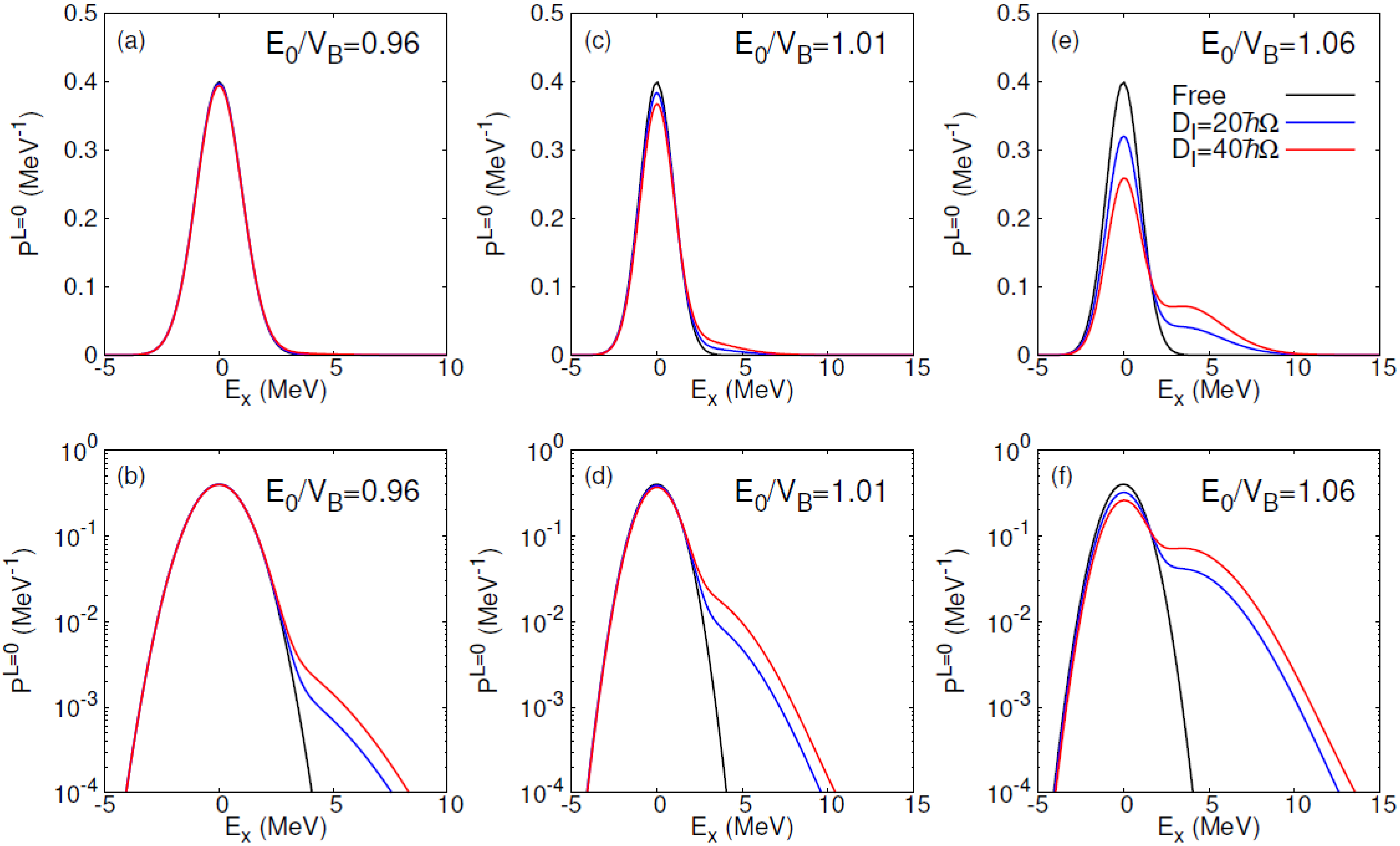




M. Tokieda, Ph.D. thesis (2021), Tohoku University

Q-value distribution

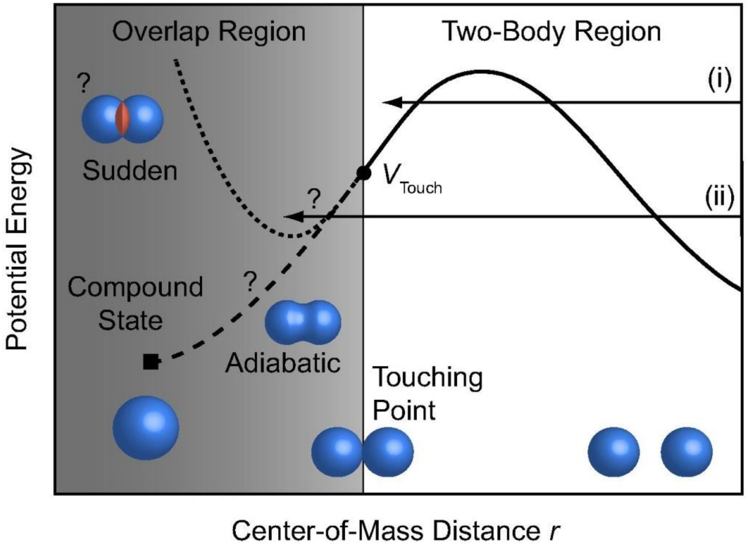
$$\langle E_x \rangle = \frac{\langle \psi_R(t_f) | \delta(H_B - E) | \psi_R(t_f) \rangle}{\langle \psi_R(t_f) | \psi_R(t_f) \rangle}$$



the next step: a comparison with the data

Summary

deep subbarrier fusion hindrance
→ dynamics after touching

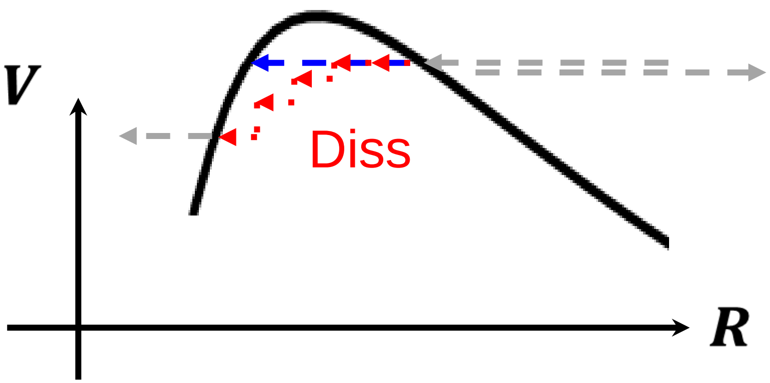


✓ couplings to internal degrees of freedom

→ coupled-channels calculations with many d.o.f.

- ✓ an efficient truncation scheme
- ✓ application to $^{16}O+^{208}Pb$
- ✓ role of energy dissipation

the next step: a comparison
to experimental data




FUSION20
November 15-20, 2020
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FUSION20

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November 14-21, 2021

Shizuoka, Japan

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FUSION23

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~~November 14-21, 2021~~
November, 2023
Shizuoka, Japan

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