Smooth transition from sudden to adiabatic states in deep-subbarrier incident energies

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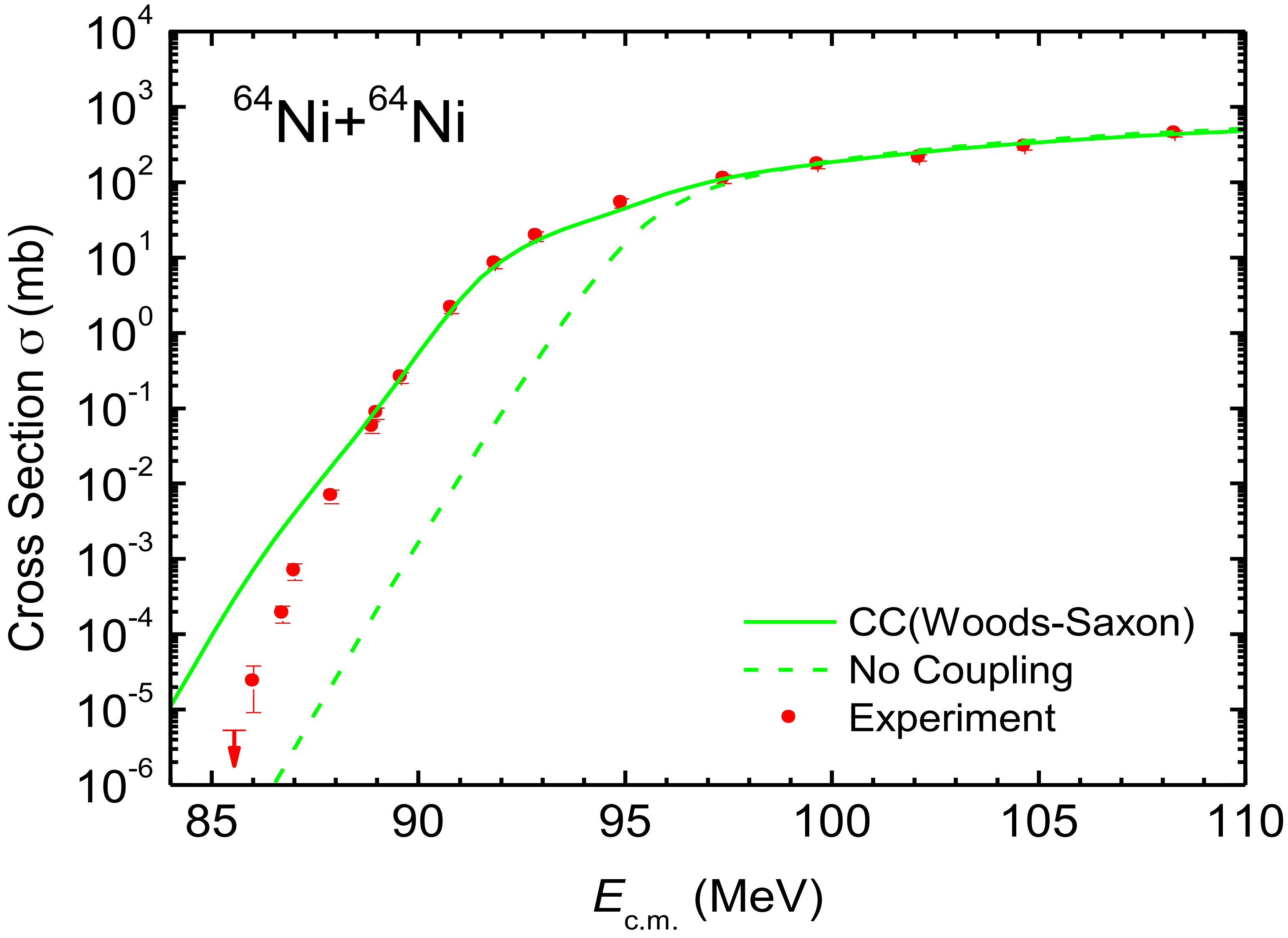
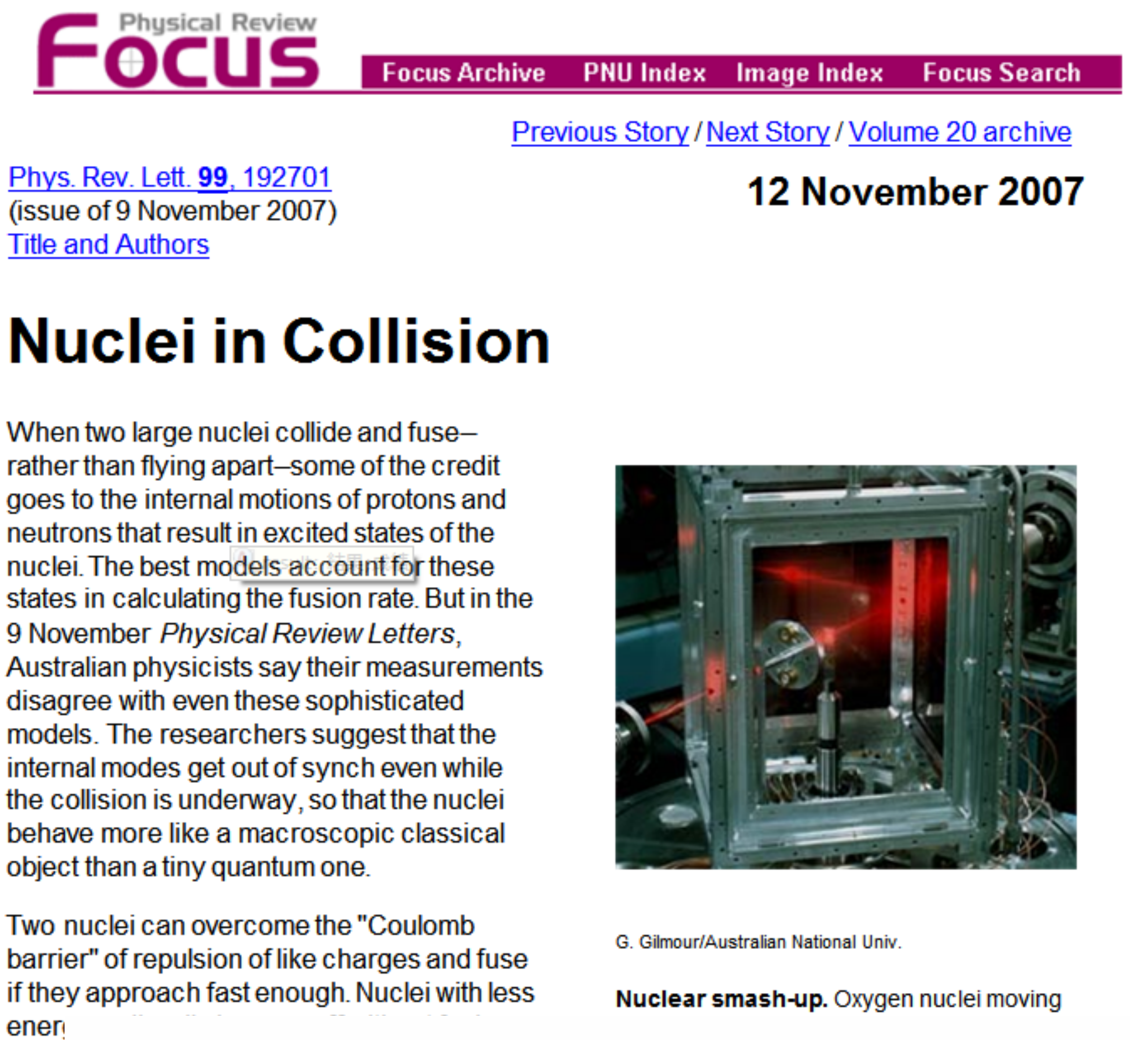
Steep falloff of fusion cross sections

Standard CC calculations largely deviate from experimental data at below a certain threshold incident energy

C. L. Jiang *et al.*, Phys. Rev. Lett. **93**, 012701 (2004)



^{16}O + ^{208}Pb (Mass-asymmetric system)



Phys. Rev. Lett. **99**, 192701
(issue of 9 November 2007)
Title and Authors

12 November 2007

Nuclei in Collision

When two large nuclei collide and fuse–rather than flying apart–some of the credit goes to the internal motions of protons and neutrons that result in excited states of the nuclei. The best models account for these states in calculating the fusion rate. But in the 9 November *Physical Review Letters*, Australian physicists say their measurements disagree with even these sophisticated models. The researchers suggest that the internal modes get out of synch even while the collision is underway, so that the nuclei behave more like a macroscopic classical object than a tiny quantum one.

G. Gilmour/Australian National Univ.

Nuclear smash-up. Oxygen nuclei moving

Two nuclei can overcome the "Coulomb barrier" of repulsion of like charges and fuse if they approach fast enough. Nuclei with less
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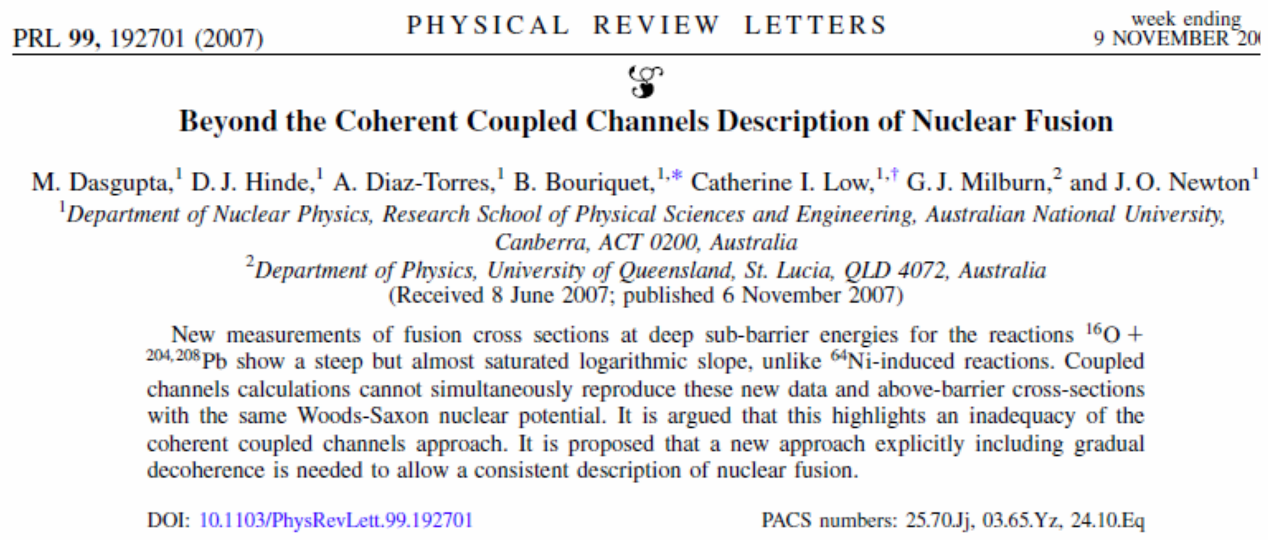

PRL **99**, 192701 (2007) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 20

Beyond the Coherent Coupled Channels Description of Nuclear Fusion

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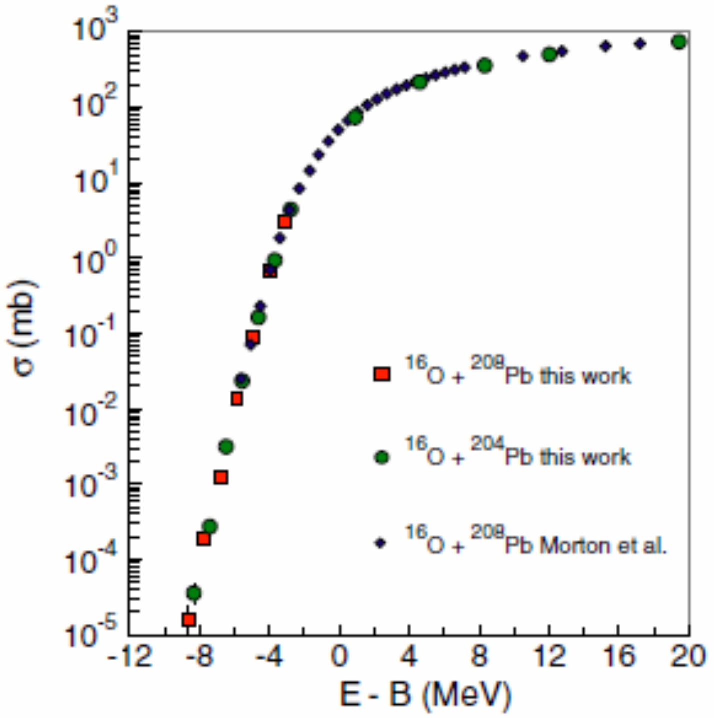
New measurements of fusion cross sections at deep sub-barrier energies for the reactions ^{16}O + ^{204,208}Pb show a steep but almost saturated logarithmic slope, unlike ^{64}Ni-induced reactions. Coupled channels calculations cannot simultaneously reproduce these new data and above-barrier cross-sections with the same Woods-Saxon nuclear potential. It is argued that this highlights an inadequacy of the coherent coupled channels approach. It is proposed that a new approach explicitly including gradual decoherence is needed to allow a consistent description of nuclear fusion.

DOI: 10.1103/PhysRevLett.99.192701 PACS numbers: 25.70.Jj, 03.65.Yz, 24.10.Eq



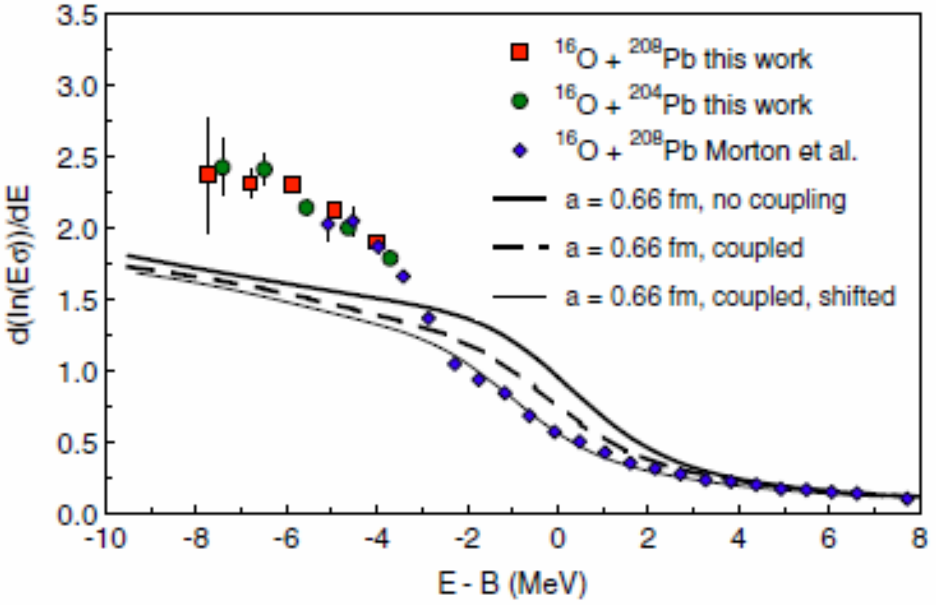
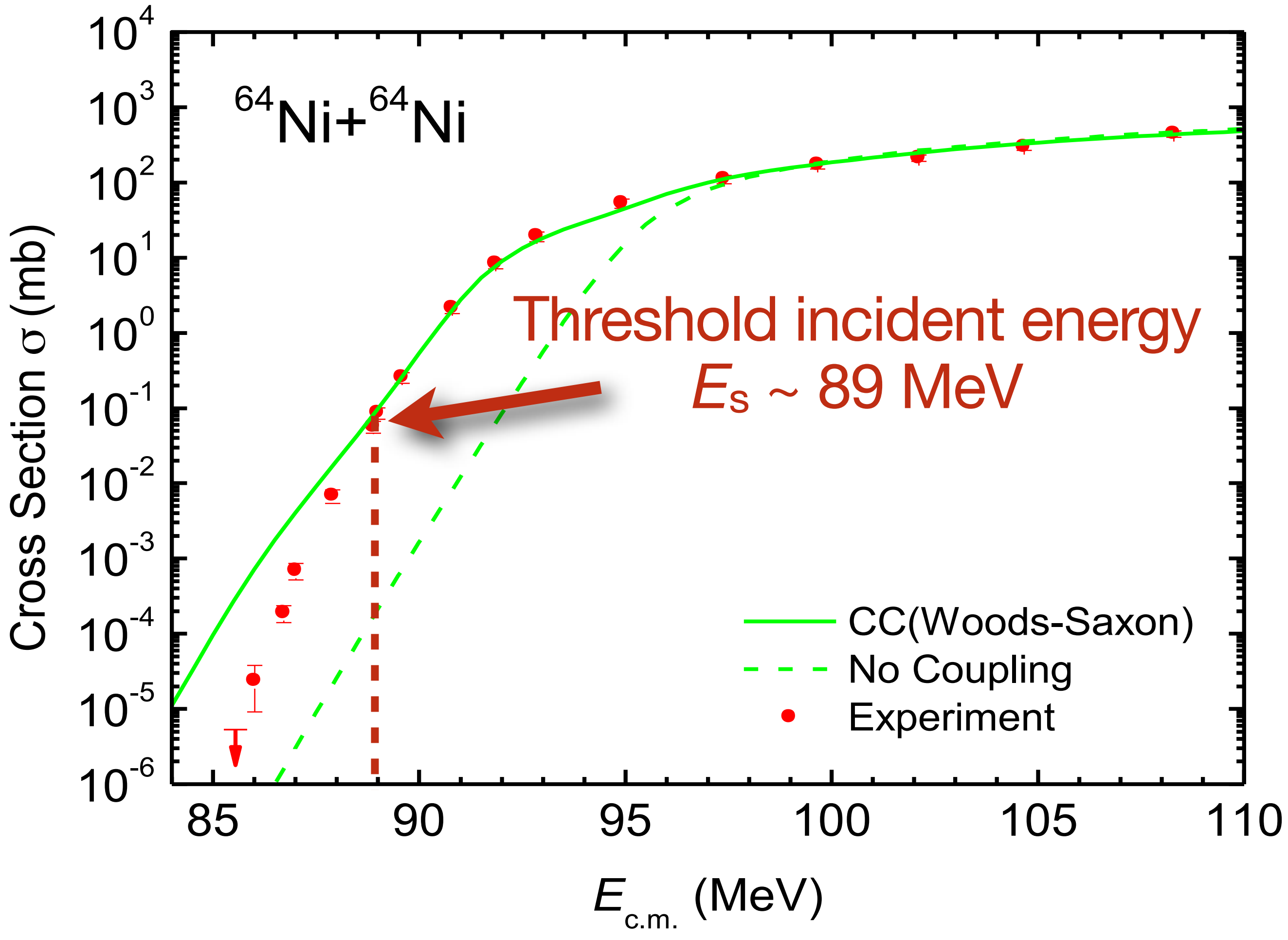


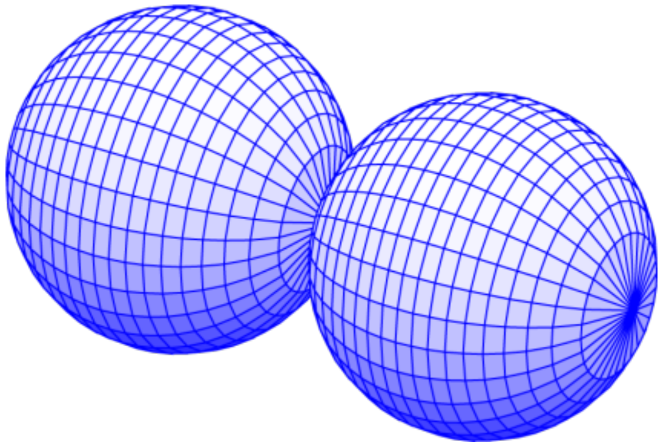
FIG. 3 (color online). Logarithmic slope as a function of energy with respect to the barrier. Calculation with standard parameters fail to match the measurements at low energy.

Steep falloff of fusion cross sections

Energy at touching configuration coincides with threshold incident energy E_s



Threshold incident energy
$E_s \sim 89$ MeV

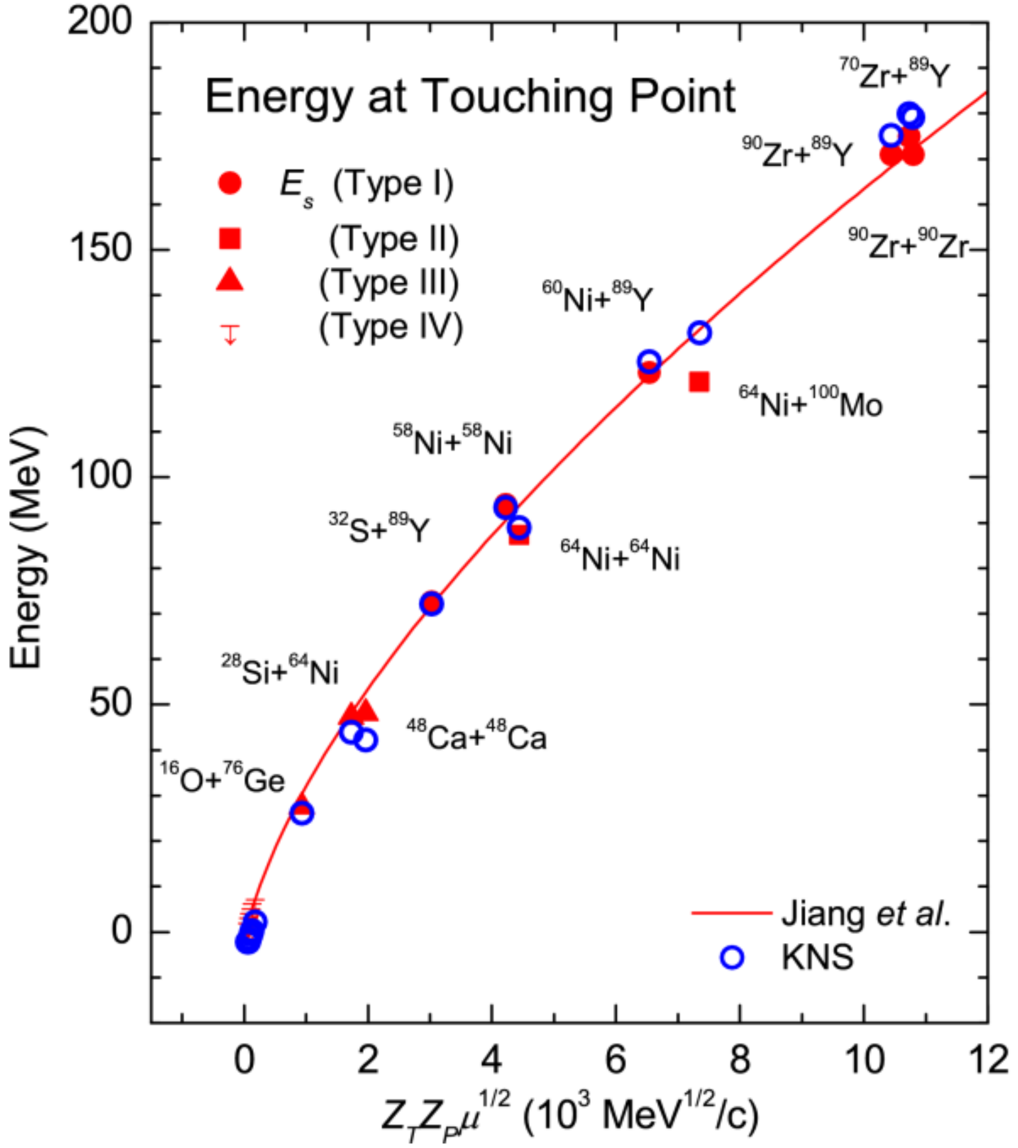


Energy at touching point
$V_{touch} = 88.61$ MeV(YPE)

Correlation between E_s and V_{touch}

Energy at touching configuration, V_{touch}, strongly correlates with threshold incident energy E_s

TI, KH, and AI, Phys. Rev. C **75**, 064612 (2007)

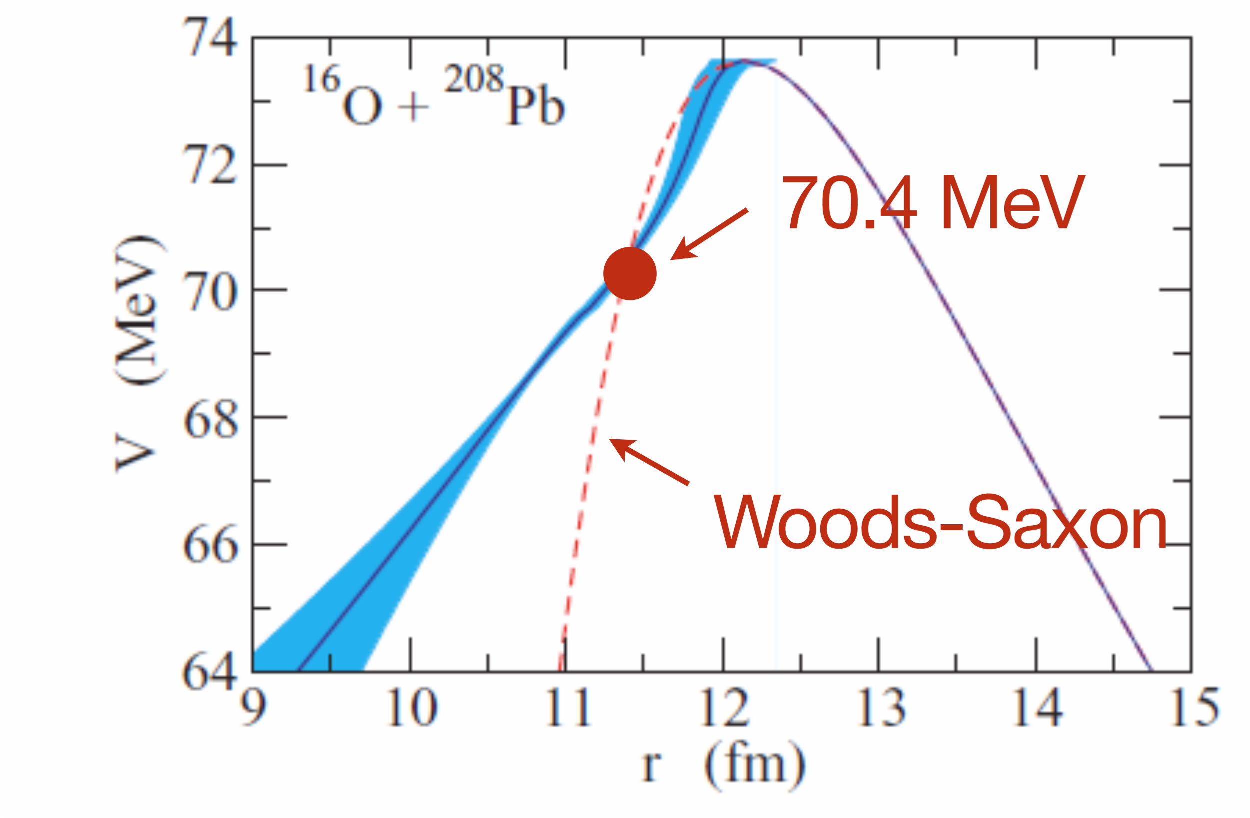


- **Estimate potential energy at touching configuration V_{touch} (YPE model)**
  - E_s → Energy at the peak position of the *S*-factor
  - Red curve
    → Systematic curve
    Jiang *et al.*, Phys. Rev. Lett. **93**, 012701 (2004)

Potential inversion method

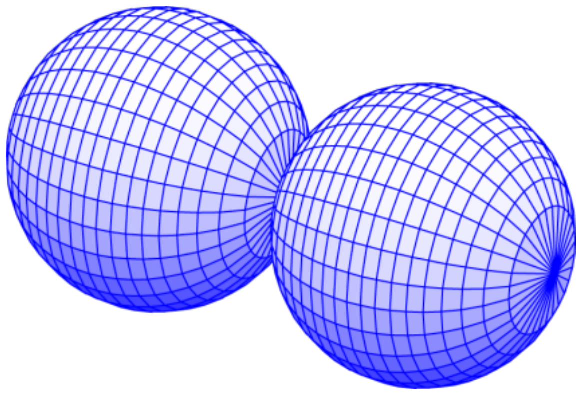
- **Extract the lowest eigen-potential for coupled channel calculations from experimental data**

K. H and Watanabe, Phys. Rev. C76, 021601(R) (2007)



70.4 MeV

Woods-Saxon

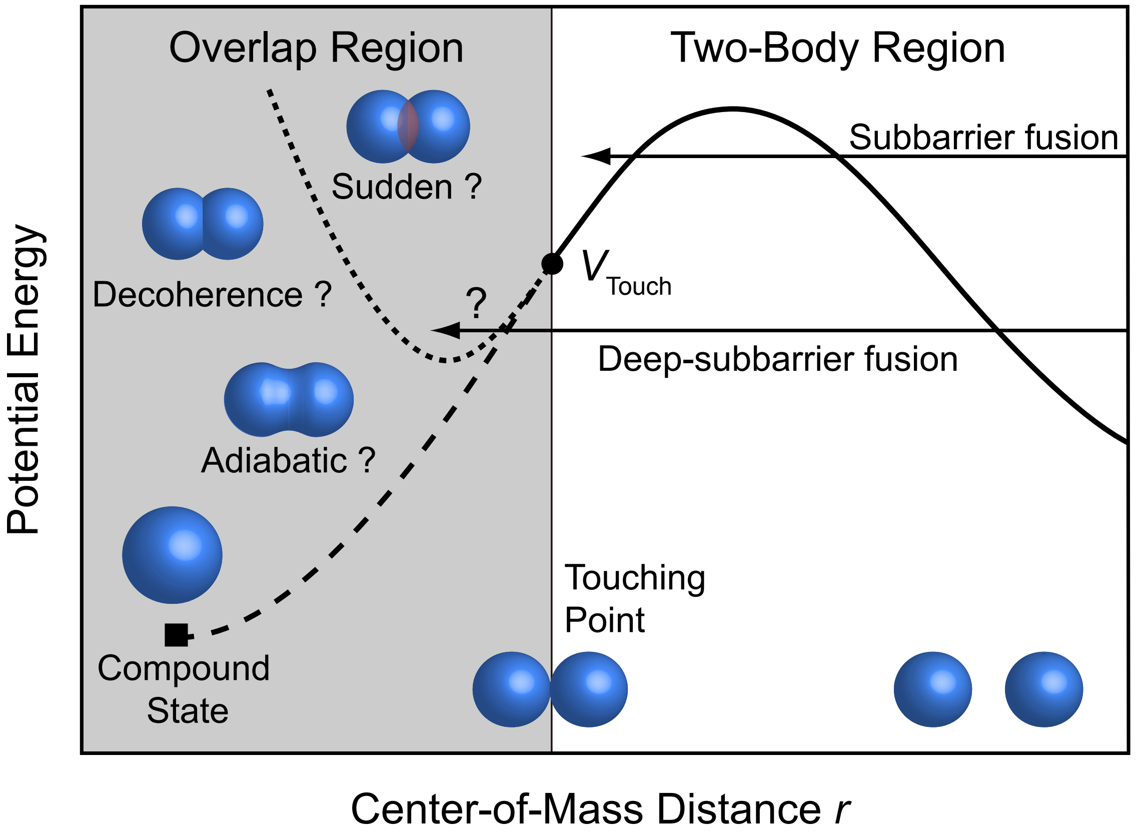


Energy at touching point
V_{touch} = 70.5 MeV(YPE)

What happen below energy at touching point?

Motivation

Steep fall-off phenomenon can be attributed to dynamics after target and projectile touch with each other



- **Subbarrier energies (E > V_{touch})**
  - Inner turning point
    → Outside of touching point
- **Deep subbarrier energies (E < V_{touch})**
  - Inner turning point
    →In the overlap region

Sudden approach → Fusion takes place so rapidly

Adiabatic approach → Dynamical change in the density

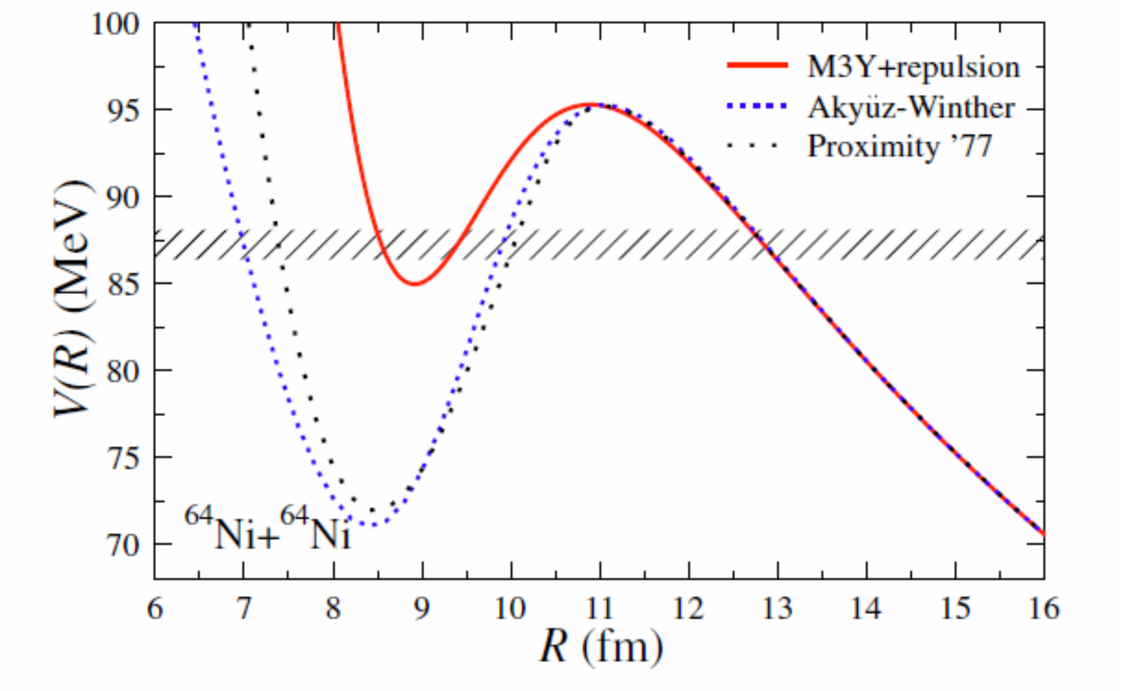
Sudden and adiabatic approaches

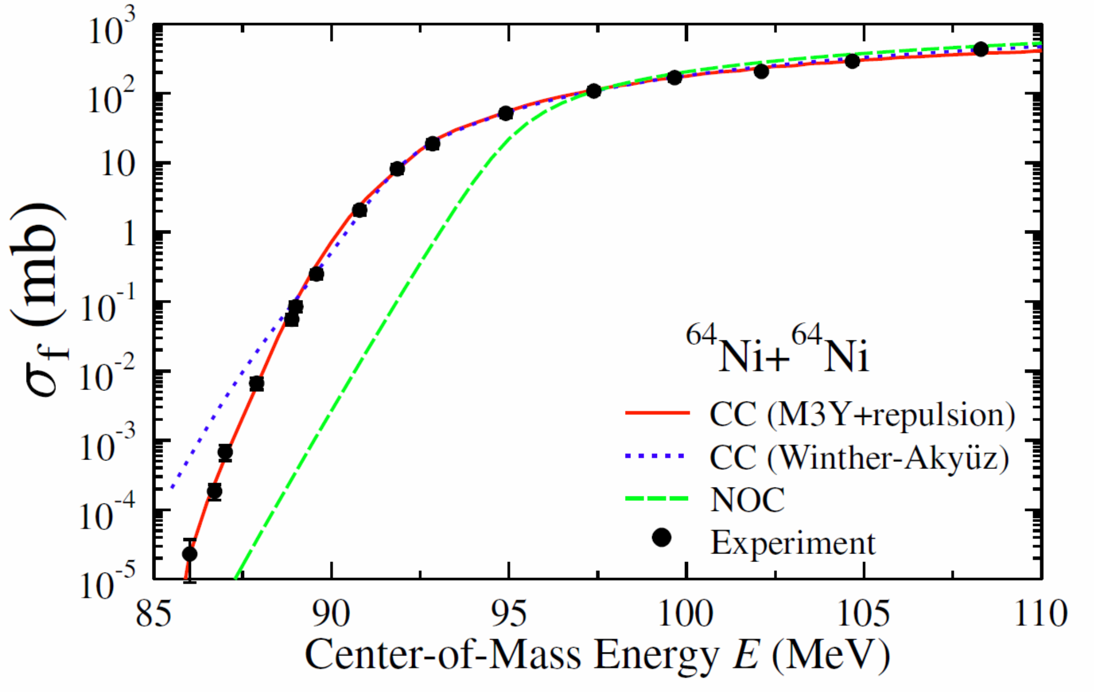
- **Sudden Approach**

  →Shallow potential pocket

  - Frozen density approximation
    Mişicu and Esbensen

Ş. Mişicu and H. Esbensen, Phys. Rev. Lett. **96**, 112701 (2006)





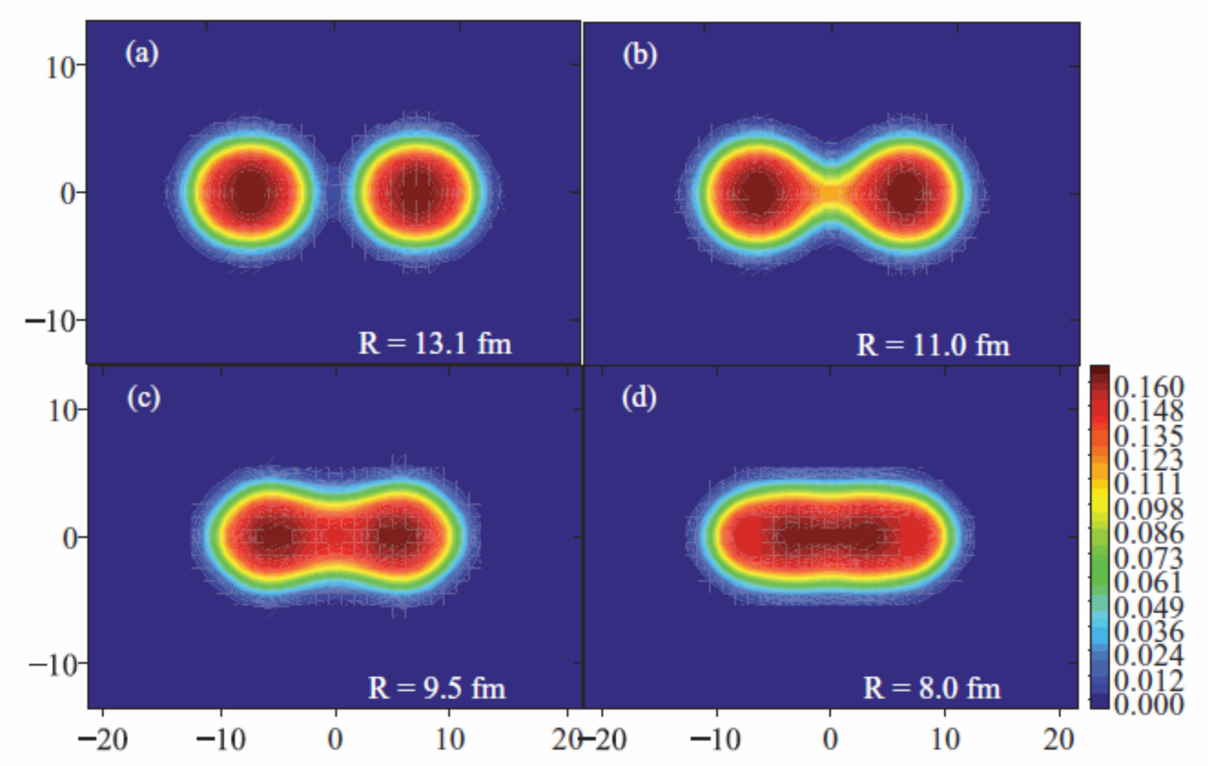
Sudden and adiabatic approaches

- **Adiabatic approach**
  →Neck formations

  - Density-constraint time-dependent Hatree-Fock model
    Umar and Oberacker

  - Macrosopic-microscopic model

A.S. Umar, V.E. Oberacker, Phys. Rev. C**77**, 064605 (2008)



Sudden picture works well at before touching point

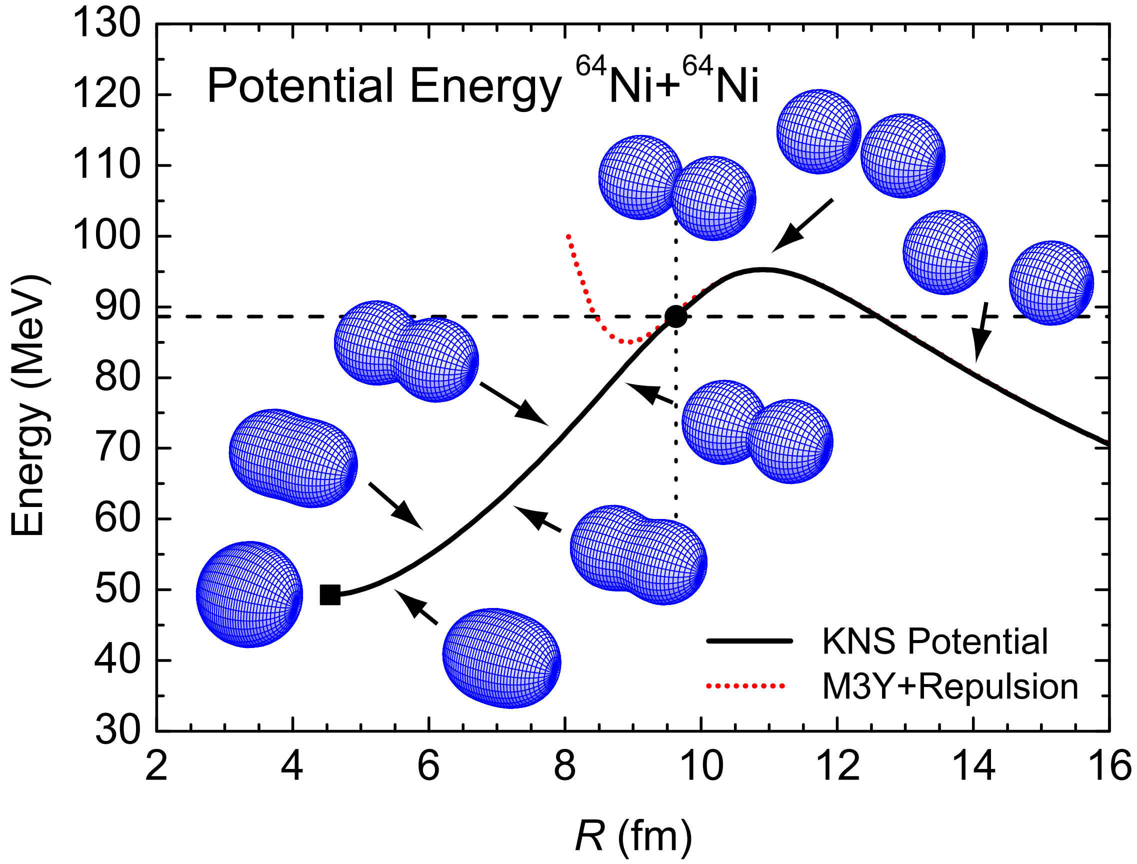
Adiabatic potential energy

Connect smoothly between one- and two-body potential energies

- **Total potential energy**

→ Lemniscatoid parametrization

$$E(r) = E_V + E_C(r) + E_N(r)$$



- Yukawa-plus-Exponential (YPE) model

$$E_N = -\frac{C_s}{8\pi^2 r_0 a^3}\int\int\left(\frac{\sigma}{a}-2\right)\frac{e^{-\sigma/a}}{\sigma}d^3r d^3r$$

$$C_s = a_s(1-\kappa_s I^2) \quad I = (N-Z)/A$$

$a = 0.68$ fm, $a_s = 21.33$ MeV, $\kappa_s = 2.3785$
(parameter set: FRLDM2002)

Difficulties in adiabatic approach

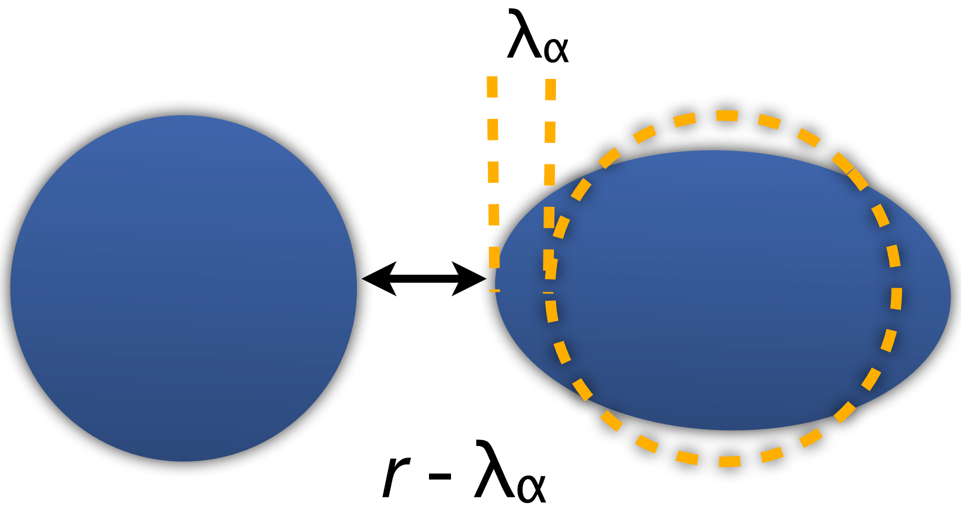
Extension of the standard coupled-channel equation

- **How do we describe the total wave function in the one-body system?**
  - The total wave function is expanded by the asymptotic intrinsic basis of the isolated nuclei
  - Require to include all the intrinsic basis in the complete set
    →Almost impossible in practice
- **Double counting of CC effects**
  - Adiabatic one-body potential with neck formations already includes a large part of the channel coupling effects

Standard coupled-channel model

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2}+\frac{J(J+1)}{2\mu r^2}+V(r)+\epsilon_n-E\right]u_n(r)+\sum_n\left\langle\phi_n\middle|V_{\mathrm{coup}}\middle|\phi_n\right\rangle u_n(r)=0$$

- Vibrational coupling $\left\langle\phi_n\middle|V_{\mathrm{coup}}\middle|\phi_n\right\rangle$



$$V_{\mathrm{coup}}(r,\hat{O})=V^{(N)}_{\mathrm{coup}}(r,\hat{O})+V^{(C)}_{\mathrm{coup}}(r,\hat{O})$$

$$V_{nm}=\left\langle I0\middle|V_N(r,\hat{O})\middle|I'0\right\rangle-V_N^{(0)}(r)\delta_{nm}$$

$$=\sum_\alpha\langle I0|\alpha\rangle\langle\alpha|I'0\rangle V_N(r,\lambda_\alpha)-V_N^{(0)}(r)\delta_{nm}$$

Intrinsic state: $\hat{h}\,|\alpha\rangle=\epsilon_\alpha\,|\alpha\rangle$

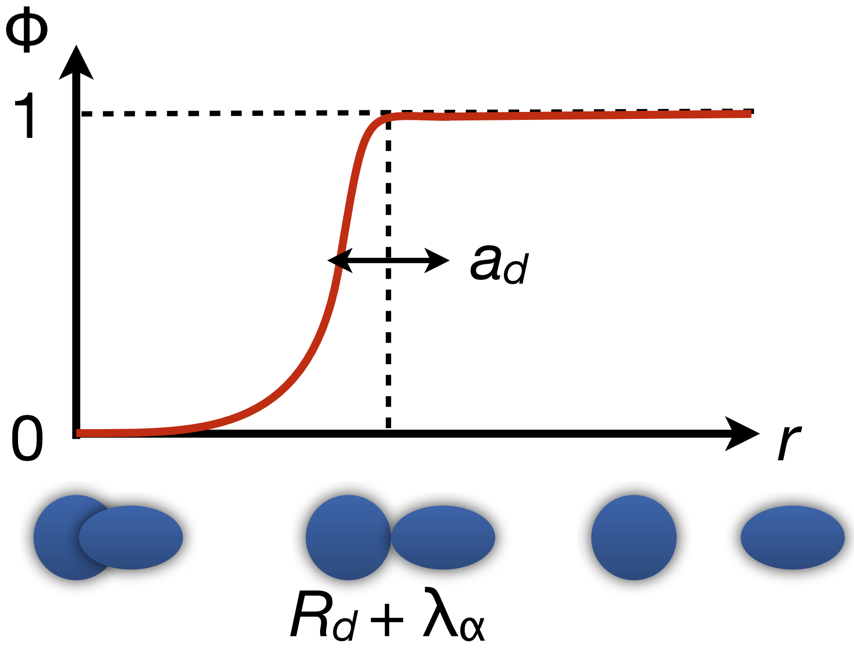
$$\hat{O}=\frac{\beta_\lambda}{\sqrt{4\pi}}R_T\left(a^\dagger_{\lambda0}+a_{\lambda0}\right)$$

$$\hat{O}\,|\alpha\rangle=\lambda_\alpha\,|\alpha\rangle$$

$$\boxed{V_N(r,\lambda_\alpha)\sim V_N^{(0)}(r)-\frac{dV_N^{(0)}(r)}{dr}\lambda_\alpha+\frac{1}{2}\frac{d^2V_N^{(0)}(r)}{dr^2}\lambda_\alpha^2}$$

Extension of coupled-channel model

- Damping factor



$$\Phi(r,\lambda_\alpha) = \begin{cases} 1 & (r \geq R_d + \lambda_\alpha) \\ e^{-(r-R_d-\lambda_\alpha)^2/2a_d^2} & (r < R_d + \lambda_\alpha) \end{cases}$$

$$R_d = r_d(A_T^{1/3} + A_P^{1/3})$$

a_d: Damping factor

$$\boxed{V_N(r,\lambda_\alpha) \sim V_N^{(0)}(r) + \left[-\frac{dV_N^{(0)}(r)}{dr}\lambda_\alpha + \frac{1}{2}\frac{d^2V_N^{(0)}(r)}{dr^2}\lambda_\alpha^2\right]\Phi(r,\lambda_\alpha)}$$

Different touching point in each eigenchannel

Two body

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + \frac{J(J+1)}{2\mu r^2} + V(r) + \epsilon_n - E\right]u_n(r) + \sum_n \left\langle \phi_n \middle| V_{\text{coup}} \middle| \phi_n \right\rangle u_n(r) = 0$$

↓

Touching point

$$V_{nm}^{(N)} = \left\langle I0 \middle| V_N(r,\hat{O}) \middle| I'0 \right\rangle - V_N^{(0)}(r)\delta_{nm} \to 0$$

↓

One body

$$\left[-\frac{\hbar^2}{2\mu}\frac{d^2}{dr^2} + \frac{J(J+1)}{2\mu r^2} + V(r) + \epsilon_n - E\right]u_n(r) = 0$$

Input parameters

- **CC calculation CCFULL (K. Hagino)**
  - ^{64}Ni+^{64}Ni: C.L. Jiang *et al.*, Phys. Rev. Lett. **93**, 012701 (2004)

    2^+: $E_x = 1.35$ MeV, β_c=0.165, $\beta_N = 0.185$, 2ph

    3^-: $E_x = 3.56$ MeV, β_c=0.193, $\beta_N = 0.20$, 1ph
  - ^{58}Ni+^{58}Ni: H. Esbensen *et al.*, Phys. Rev. C35, 2090 (1987).

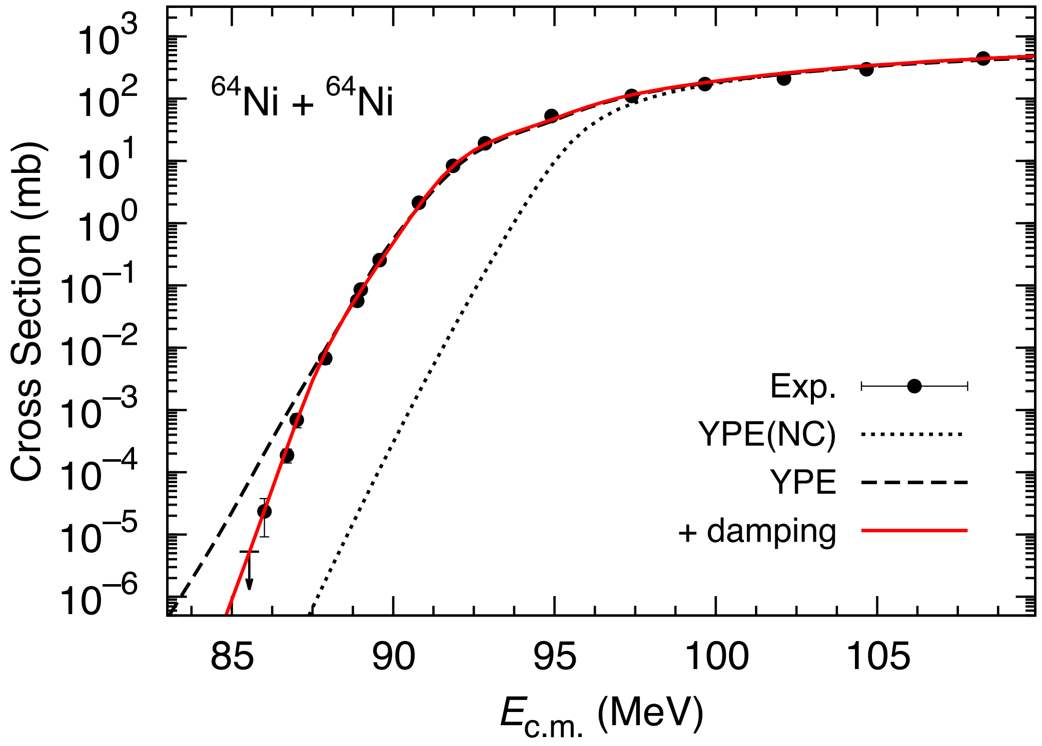
    2^+: 3ph, 3^-: 1ph
  - ^{16}O+^{208}Pb: C.R. Morton *et al.*, Phys. Rev. C**60**, 044608 (1999)

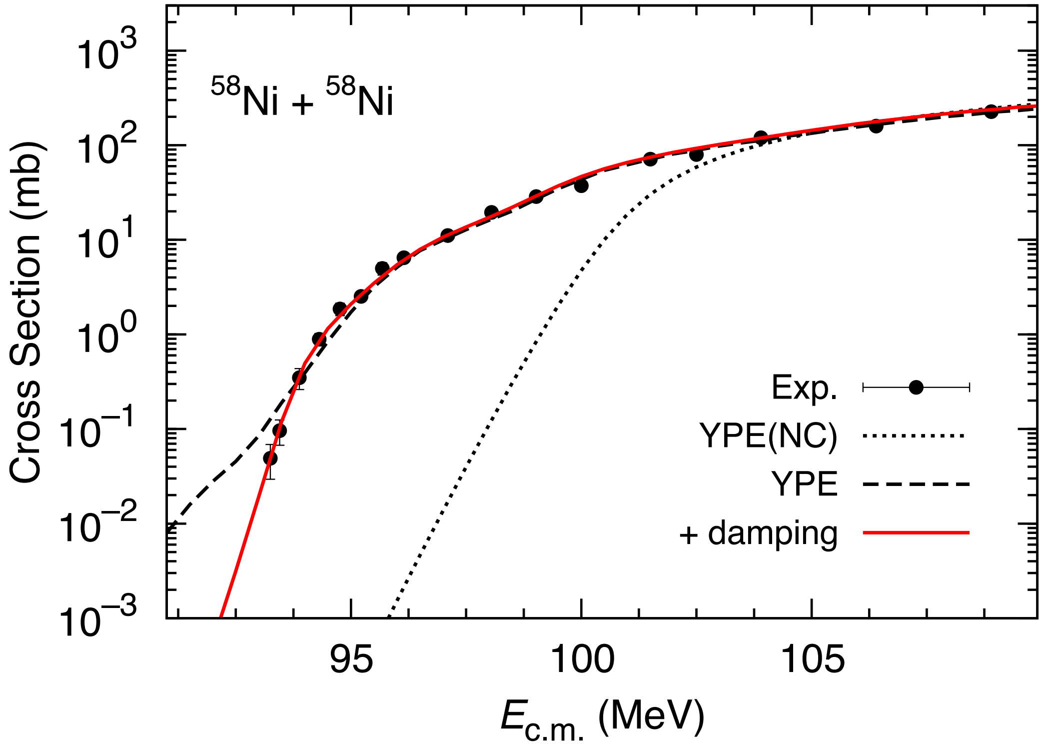
    ^{208}Pb → 3^-: $E_x = 2.615$ MeV, $\beta_c = 0.161$, $\beta_N = 0.733$, 2ph

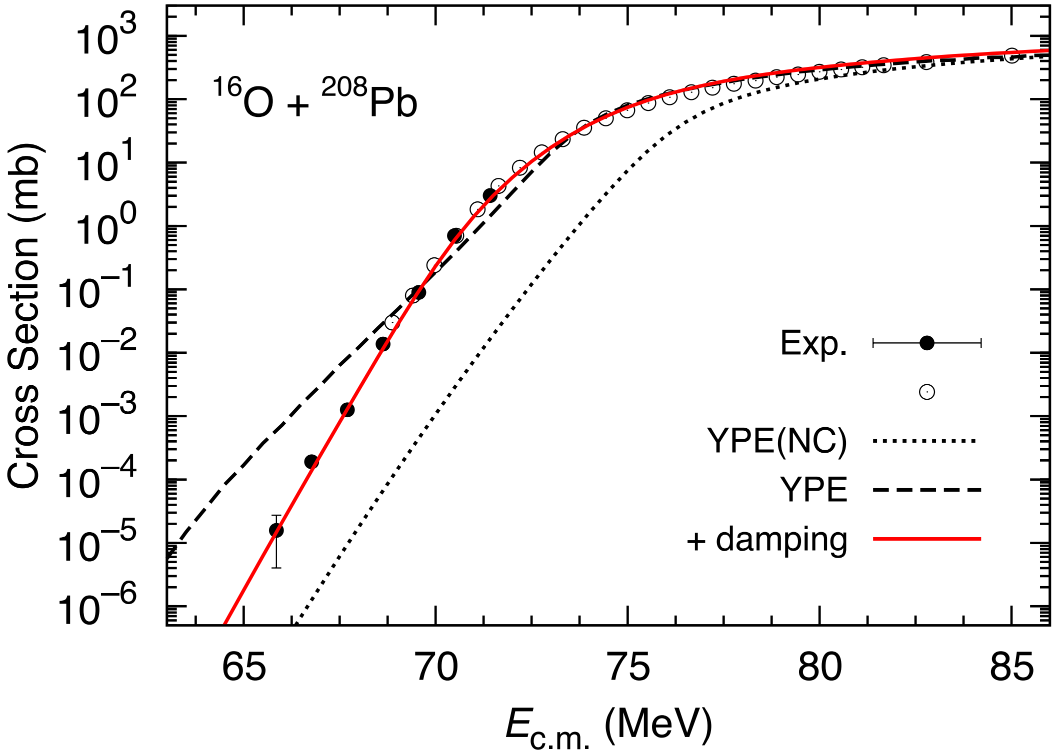
    ^{16}O → 3^-: $E_x = 6.13$ MeV, $\beta_c = 0.733$, $\beta_N = 0.733$, 2ph
- **Damping factor**
  - ^{64}Ni + ^{64}Ni: $r_d = 1.298$ fm, $a_d = 1.05$fm
  - ^{58}Ni + ^{58}Ni: $r_d = 1.3$ fm, $a_d = 1.3$ fm,
  - ^{16}O + ^{208}Pb: $r_d = 1.28$ fm, $a_d = 1.28$ fm

Radius parameters are almost the same as each system

Calculated results: fusion cross section

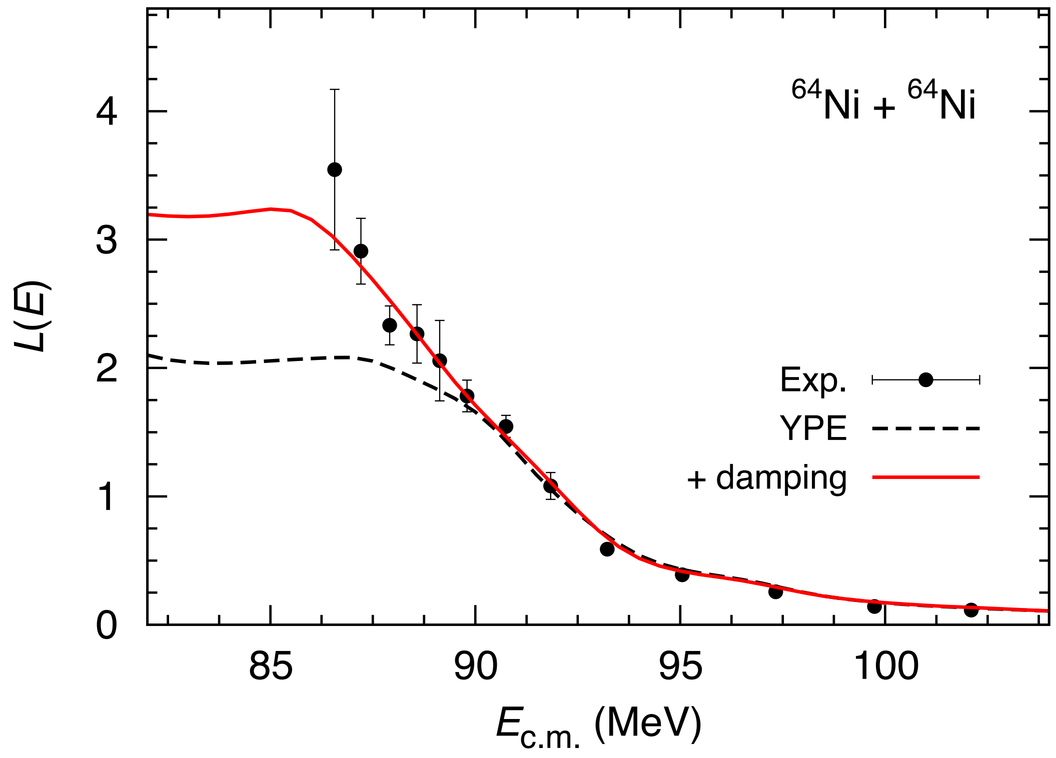


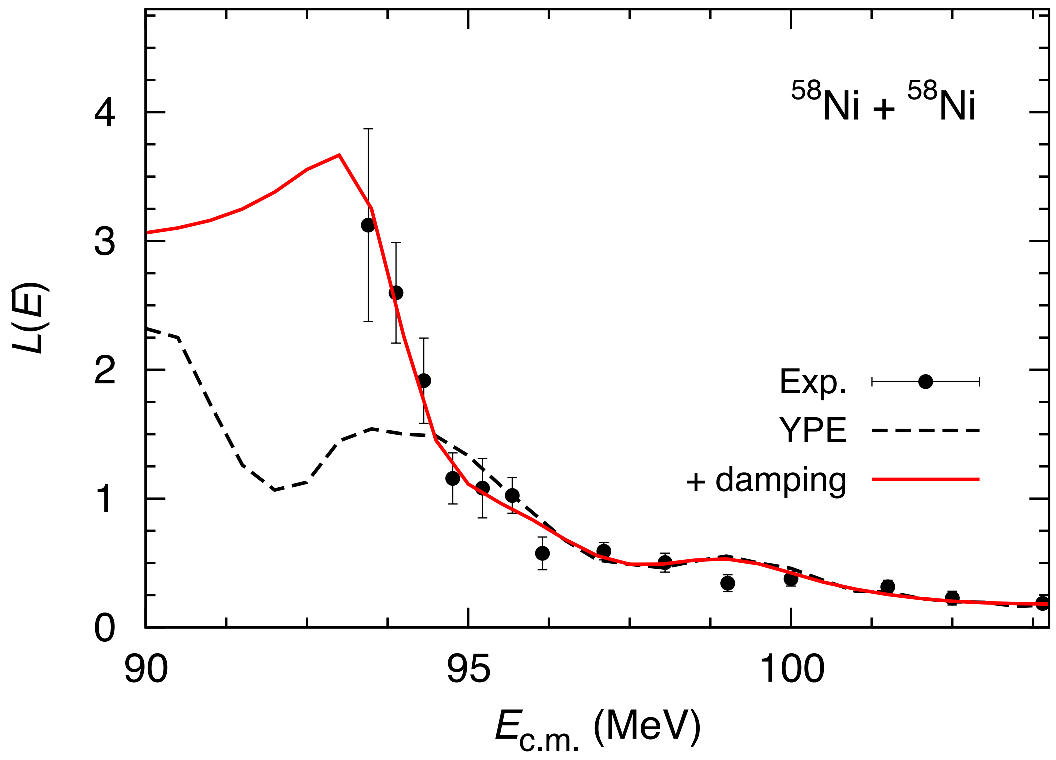


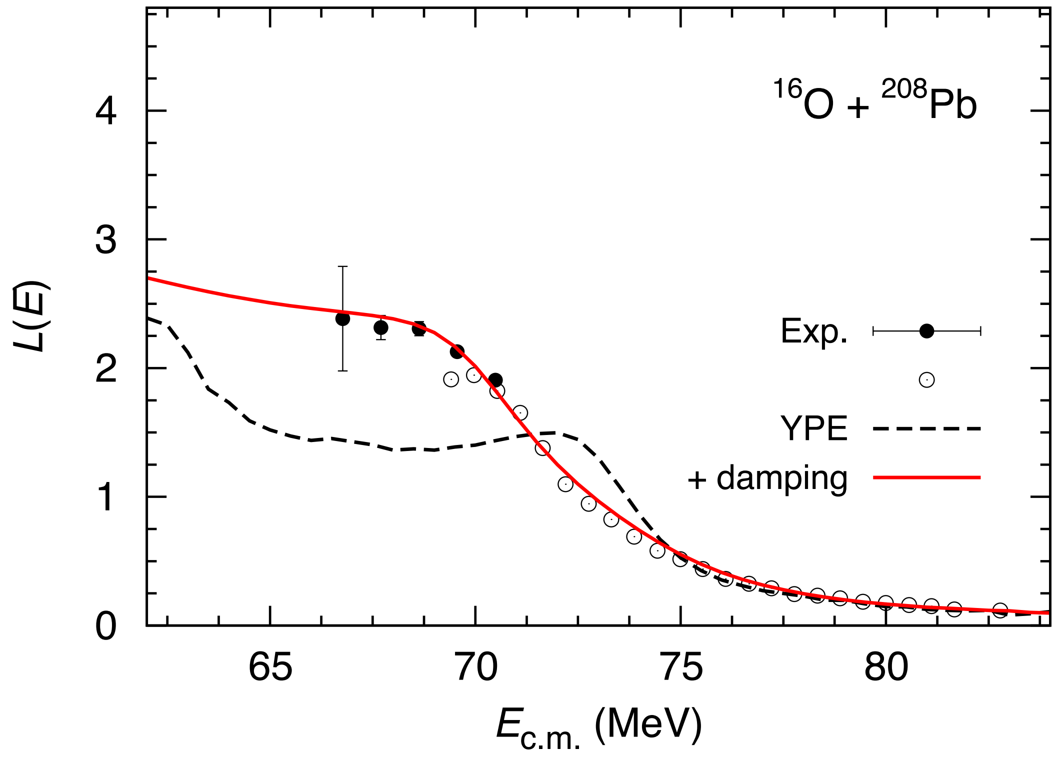


Drastic improvements are achieved by damping factor

First derivative of fusion cross section

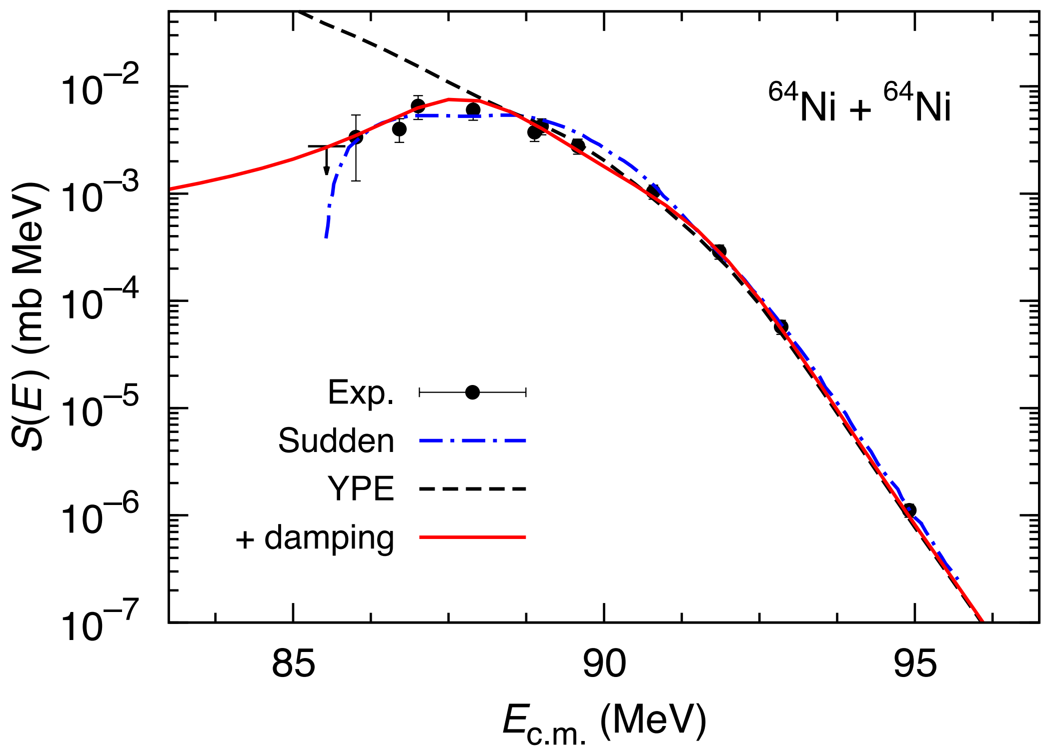


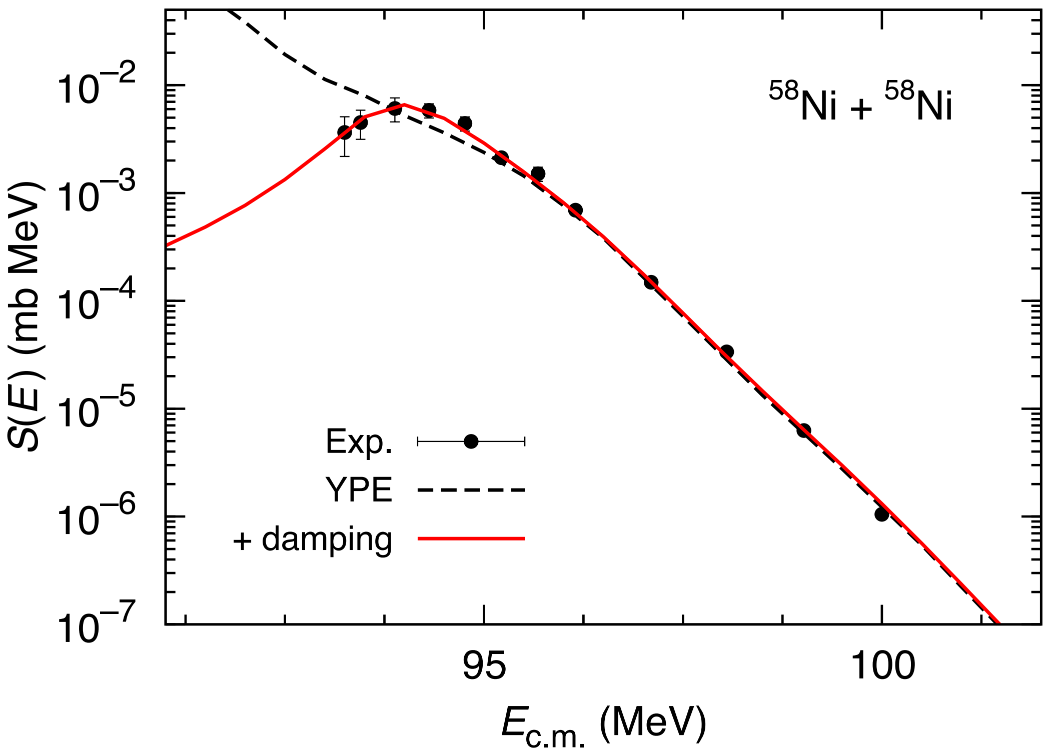


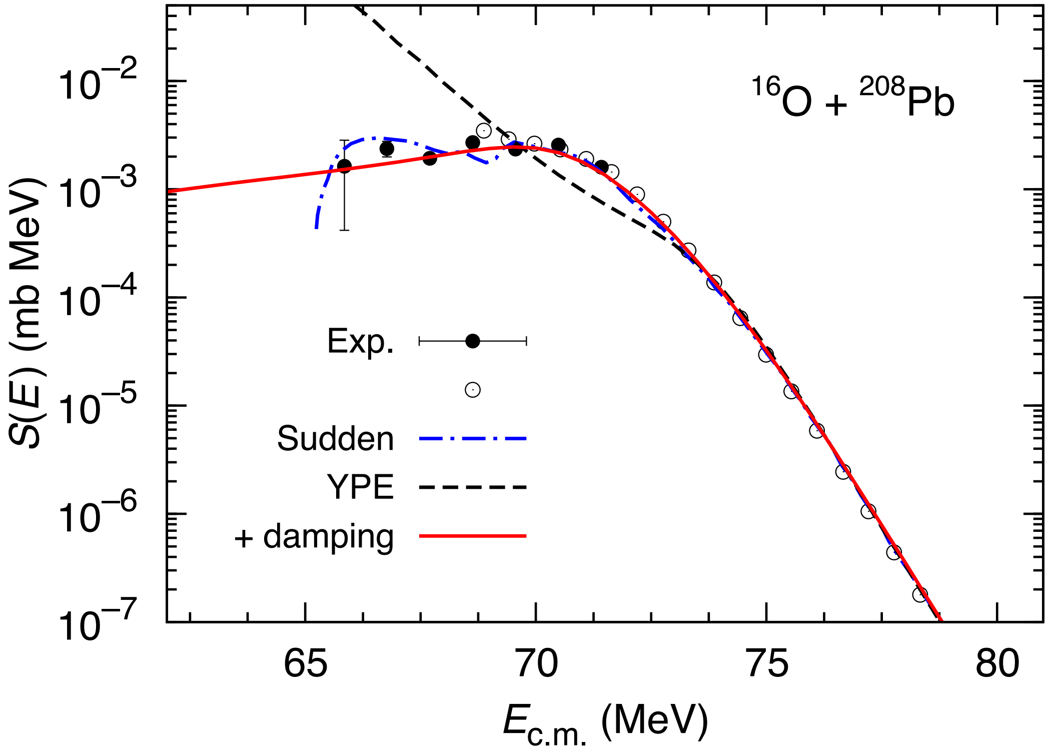


Reproduce the saturation at extremely low incident energies

Astrophysical S-factor



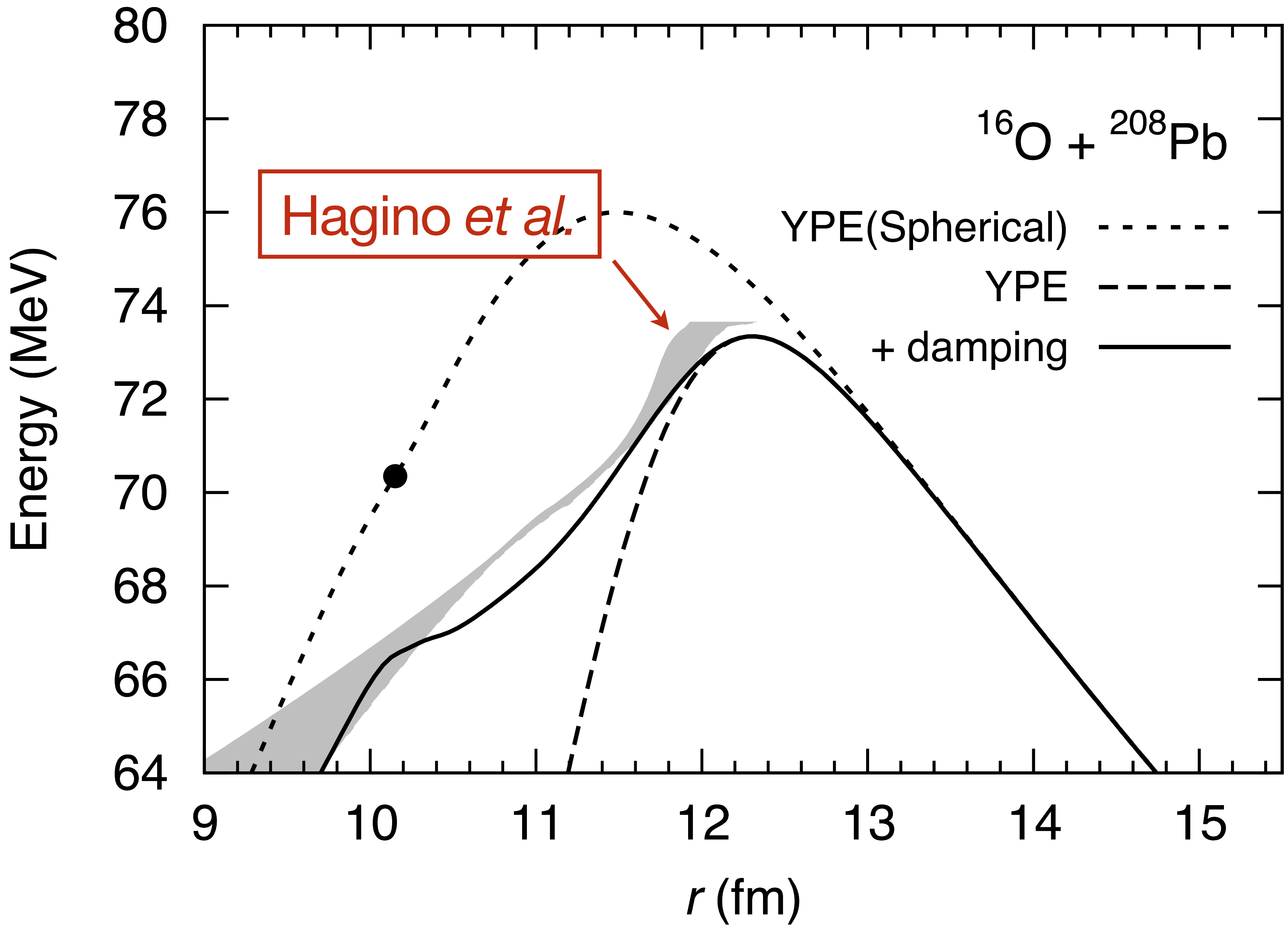




Differs considerably from sudden model

Adiabatic potential

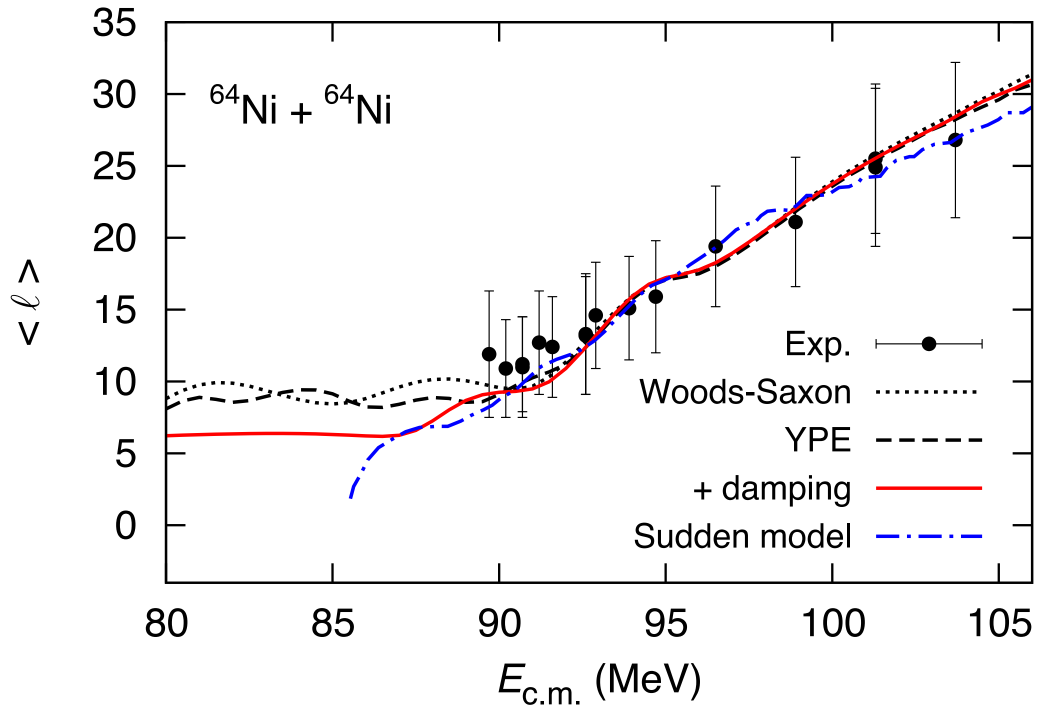
Reproduce the thickness of the CC adiabatic potential



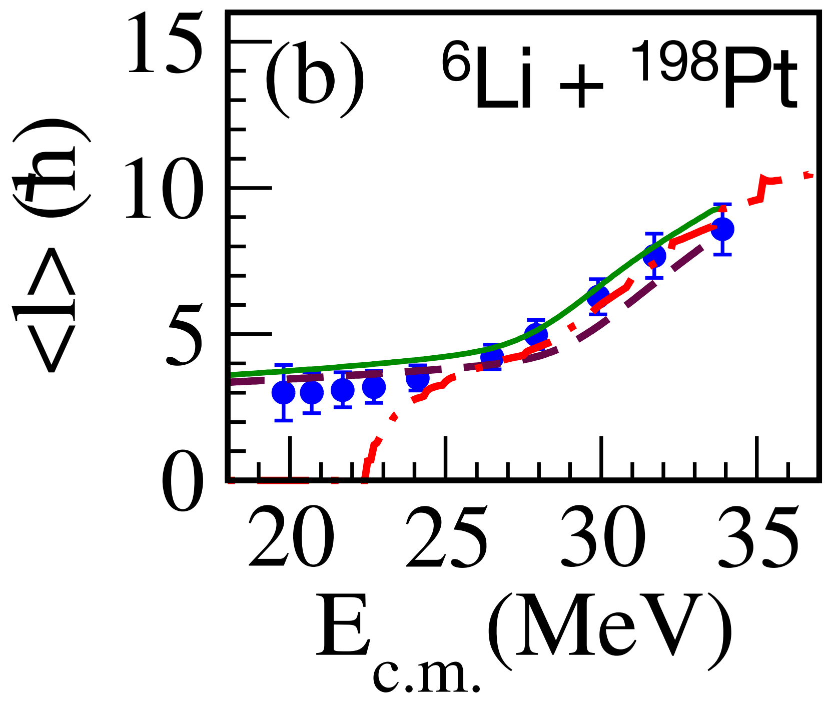
Difference between two approaches

- **Both the sudden and adiabatic models provide similar results for the fusion cross sections**
  - What is a difference between these two models?

→ Average angular momentum of compound nuclei



A. Shrivastava et al, Phys. Lev. Lett. 103, 232702 (2009)



By measuring average angular momentum, we can discriminate the two approaches

Summary

- **We have proposed a novel extension of the standard CC calculations based on the adiabatic approach**
  - Energy at touching point strongly correlates with threshold incident energy for steep-falloff of fusion cross sections
  - Introduce the damping of CC forme factor inside touching point, to simulate transition from sudden to adiabatic states
  - Sudden approximation works well before touching of two nuclei
  - Smooth transition from two-body to adiabatic one-body potential is responsible for steep falloff of fusion cross sections

T. Ichikawa, K. Hagino, and A. Iwamoto, Phys. Rev. C**75**, 057603 (2007): Phys. Rev. C**75**, 064612 (2007): Phys. Rev. Lett. **103**, 202701 (2009)