Effects of Nuclear Incompressibility on Heavy-ion Fusion

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- Heavy-ion fusion is hindered at extreme subbarrier energies (Jiang et al., Argonne).

  The hindrance was first recognized in comparison with calculations.
  It can be characterized in terms of the S-factor, which develops a maximum
  at 10 - 20 MeV below the Coulomb barrier, and $E^*_{\rm CN}$ = 20 - 40 MeV.

- Challenge: explain the fusion hindrance by the coupled-channels calculations.

  The hindrance phenomenon is expected to be an entrance channel phenomenon.
  It cannot be explained by using a conventional ion-ion potential,
  such as the Akyüz-Winther (AW) or the proximity potential.

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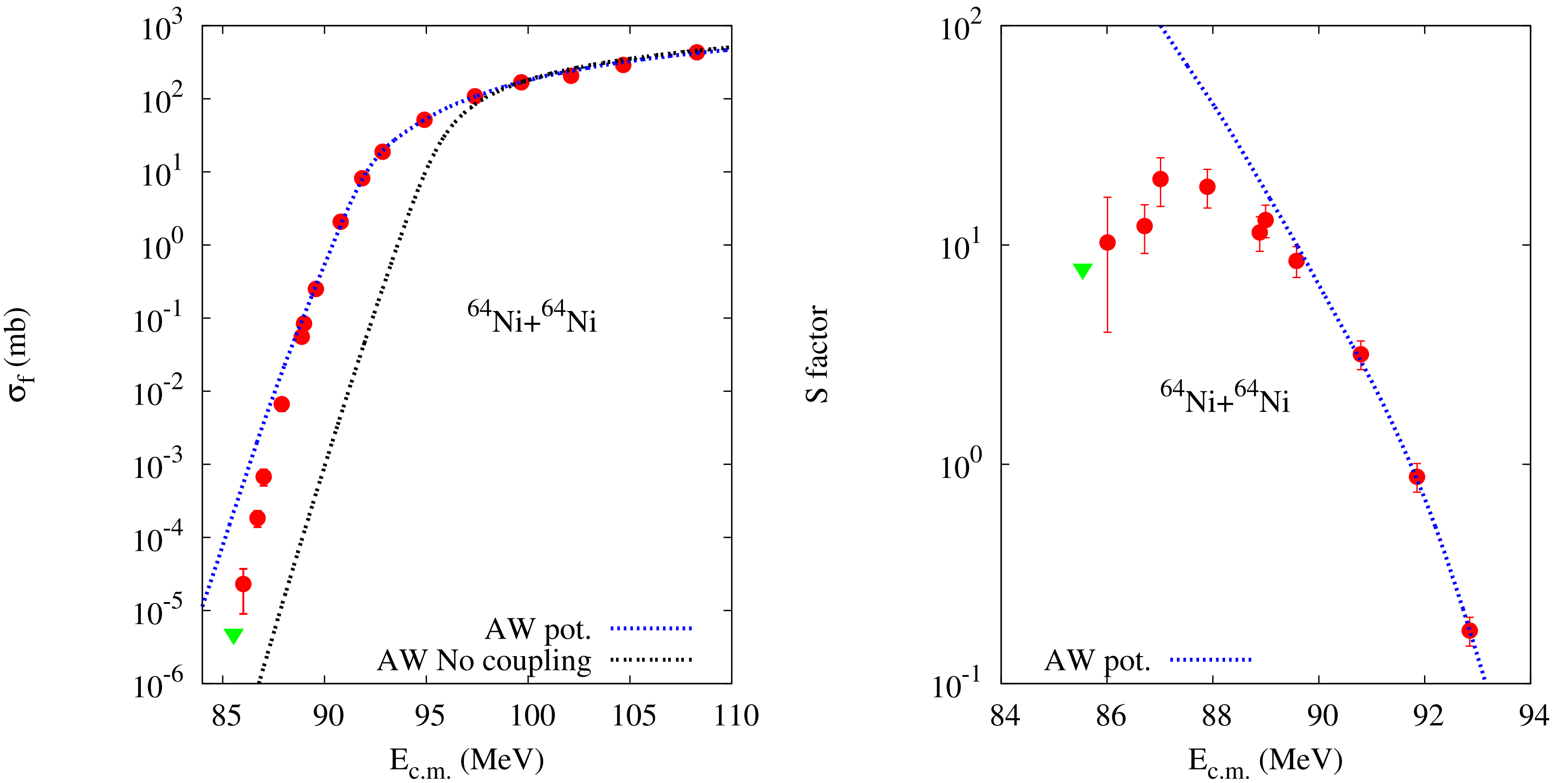
Example: ^{64}Ni+^{64}Ni fusion at ATLAS, Jiang et al., PRL 93, 012701 (2004).



$S-$ factor: $S = E_{c.m.}\ \sigma_f\ exp(2\pi[\eta - \eta_0])$, where $\eta = \frac{Z_1 Z_2 e^2}{\hbar v}$.

The hindrance occurs at $E^*_{CN} \approx 40$ MeV. Most likely an entrance channel phenomenon.

Triangle: 1 count (none were seen).

- The Akyüz-Winther (AW) ion-ion potential is parametrized as

$$U_{\rm AW}(r) = \frac{-16\pi\gamma a R_{aA}}{1+exp[(r-R_a-R_A)/a]}.$$

  It has the correct liquid drop form for touching spheres (γ is the surface tension.)

- Our goal is to explain the low-energy fusion data by constructing a shallow potential in the entrance channel. We start with the M3Y double-folding potential,

$$U_N(\mathbf{r}) = \int d\mathbf{r}_1\, d\mathbf{r}_2\, \rho_a(\mathbf{r}_1)\, \rho_A(\mathbf{r}_2)\, v_{NN}(\mathbf{r}+\mathbf{r}_2-\mathbf{r}_1).$$

  and supplement the effective M3Y interaction with a repulsive contact term, $v_{NN}^{\rm rep} = V_{\rm rep}\, \delta(\mathbf{r}+\mathbf{r}_2-\mathbf{r}_1)$.

- The strength of the repulsive interaction, $V_{\rm rep}$, is adjusted so that the total nuclear interaction for overlapping nuclei,

$$U_N(r=0) = 2A_a[\epsilon(2\rho)-\epsilon(\rho)] \approx \frac{A_a}{9}K,$$

  gives a reasonable value for the nuclear incompressibility: $K \approx 230$ MeV.

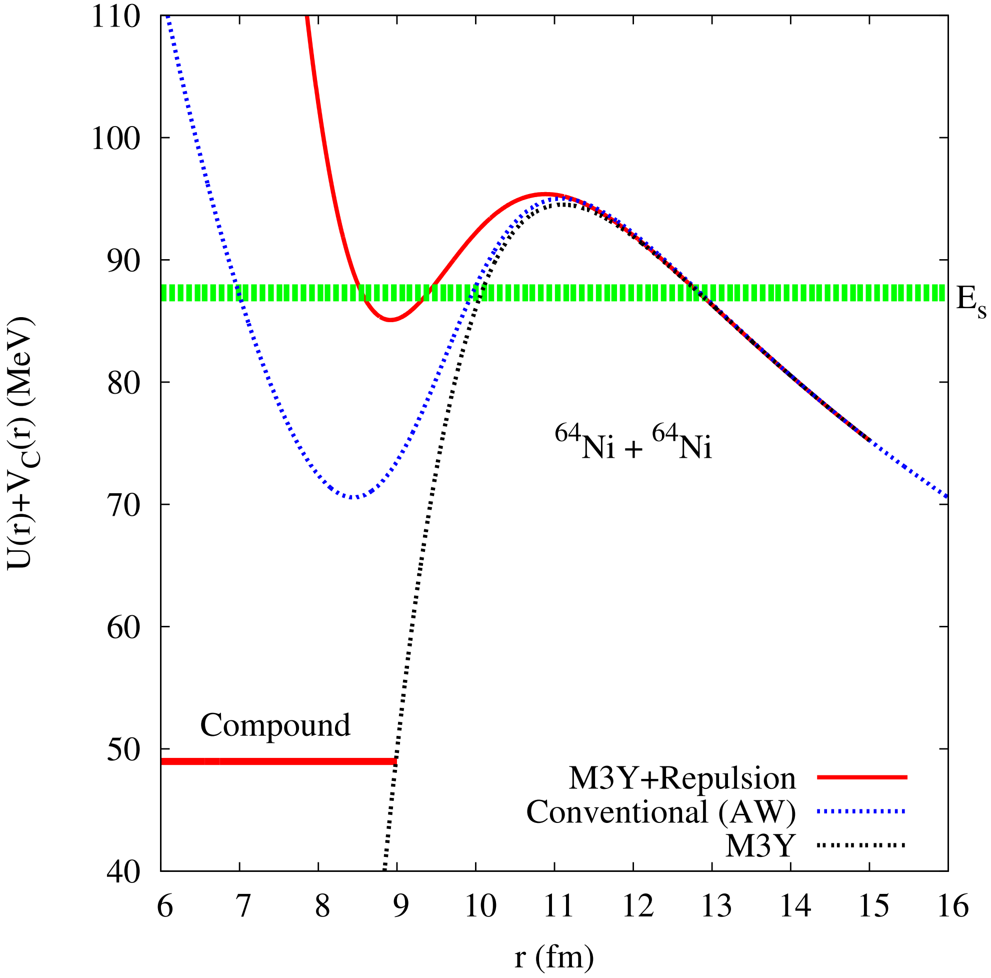
Example: ^{64}Ni+^{64}Ni. Mişicu and Esbensen, PRL 96, 112701 (2006).

The fusion data have a maximum S-factor at E_S, the green band.

The conventional M3Y double-folding potential is too deep. It is even deeper than the GS of the compound nucleus.

The AW potential is not as deep but it cannot explain the fusion data.

The shallow M3Y+Repulsion potential, which has been corrected for the effect of the nuclear incompressibility, explains the data quite well.



Coupled-channels calculations.

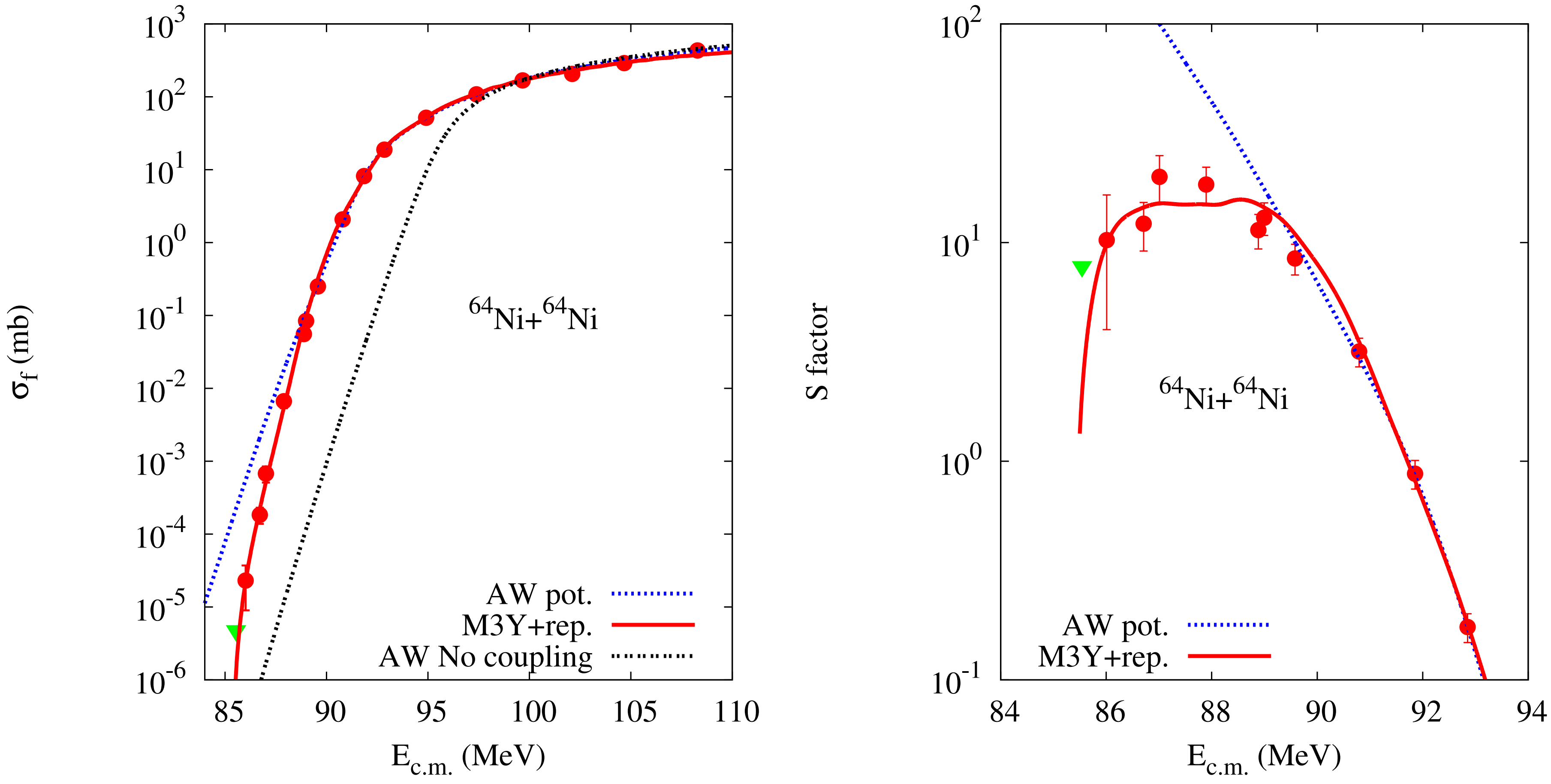
- We include couplings to the low-lying 2^+ and 3^- states in projectile and target, as well as the mutual and two-phonon excitations of these states.
- We include nuclear couplings up to second order in the (dynamic) surface displacement $\delta s = R \sum \alpha_{\lambda\mu} Y^*_{\lambda\mu}(\hat{r})$,

$$U(r, \delta s) = U_N(r) - \frac{dU_N}{dr}\delta s + \frac{1}{2}\frac{d^2U_N}{dr^2}(\delta s^2 - \langle \delta s^2 \rangle),$$

  and Coulomb couplings up to first order in δs.
- The calculations are performed in the rotating frame approximation, i. e., we consider only the $\mu = 0$ magnetic sub-states for spherical nuclei.
- Fusion is simulated by ingoing-wave boundary conditions (IWBC), which are imposed at the minimum of the pocket in the entrance channel potential.

The IWBC are sometimes supplemented with a weak, short-ranged absorption.

^{64}Ni+^{64}Ni fusion data, Jiang et al., PRL 93, 012701 (2004).

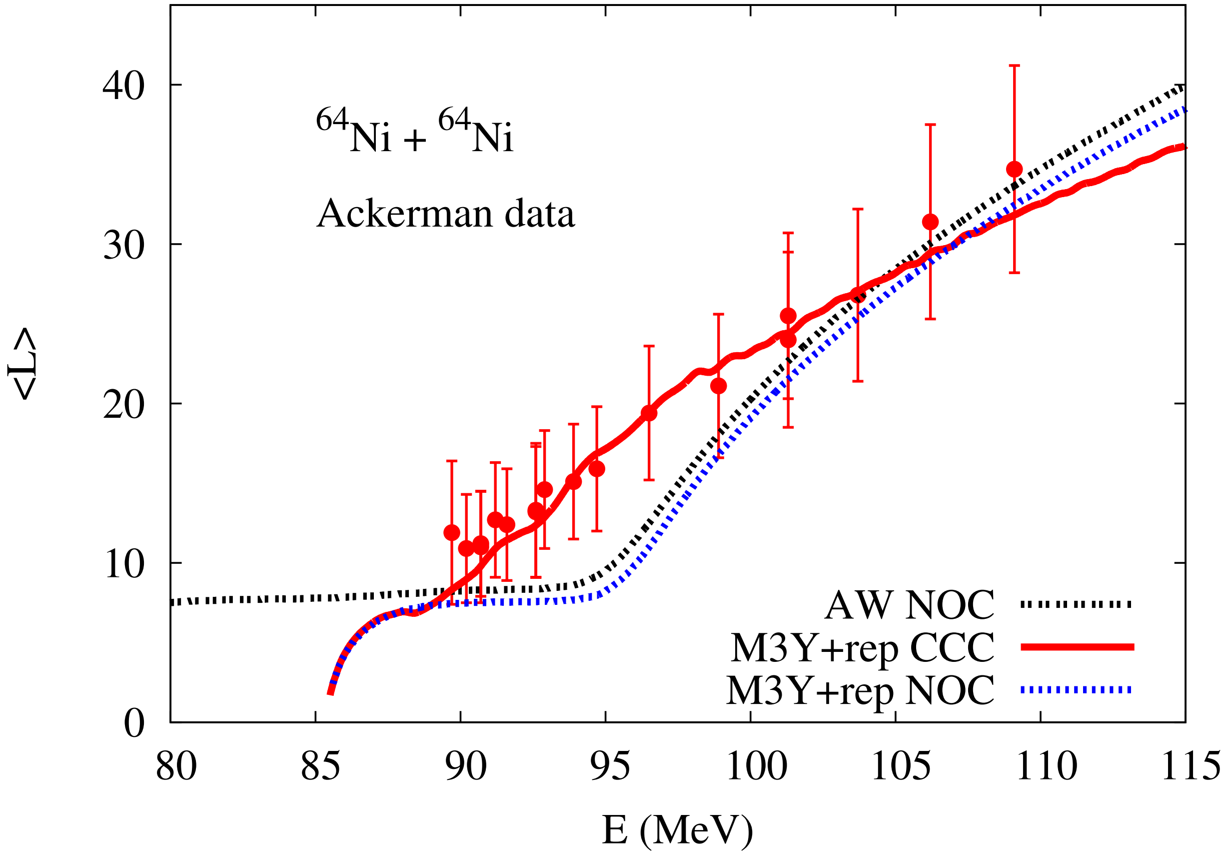


The M3Y+Repulsion potential has the minimum pocket energy: V_{pocket} = 85.4 MeV.

The IWBC imply that $\sigma_f = 0$, for $E < V_{pocket}$.

Average spin for fusion

extracted from γ-ray multiplicities, Ackerman et al., NPA 609, 91 (1996).



The AW potential predicts an essentially constant average spin at low energy.

The M3Y+repulsion combined with IWBC produce a decreasing $\langle L \rangle$ at low energy.

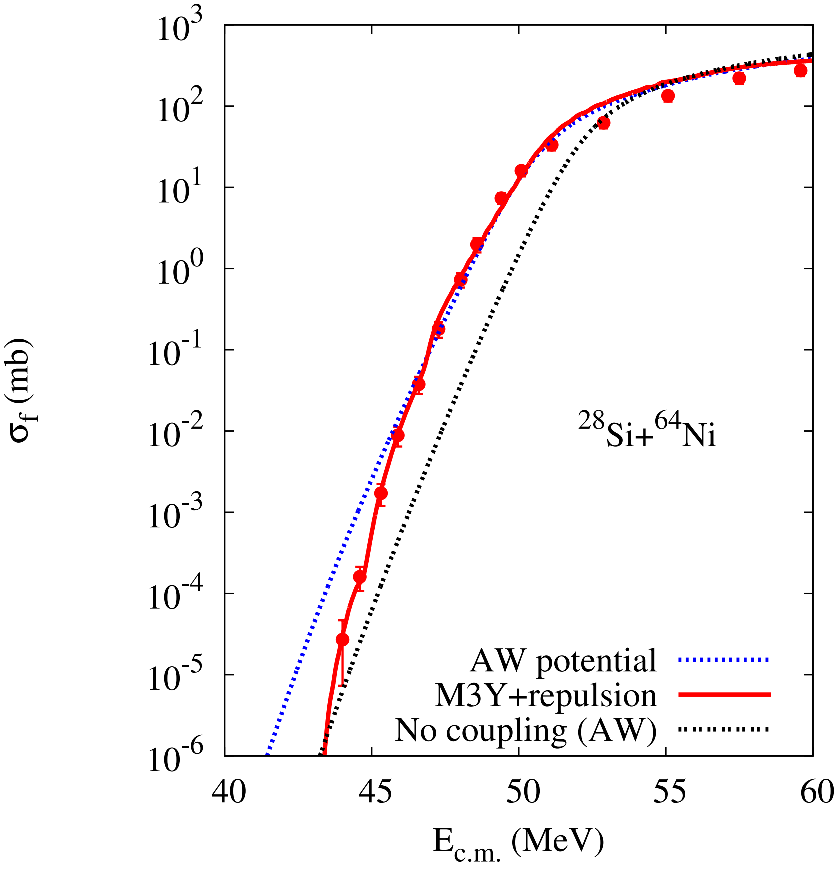
Mişicu and Esbensen, Phys. Rev. C 75, 034606 (2007).

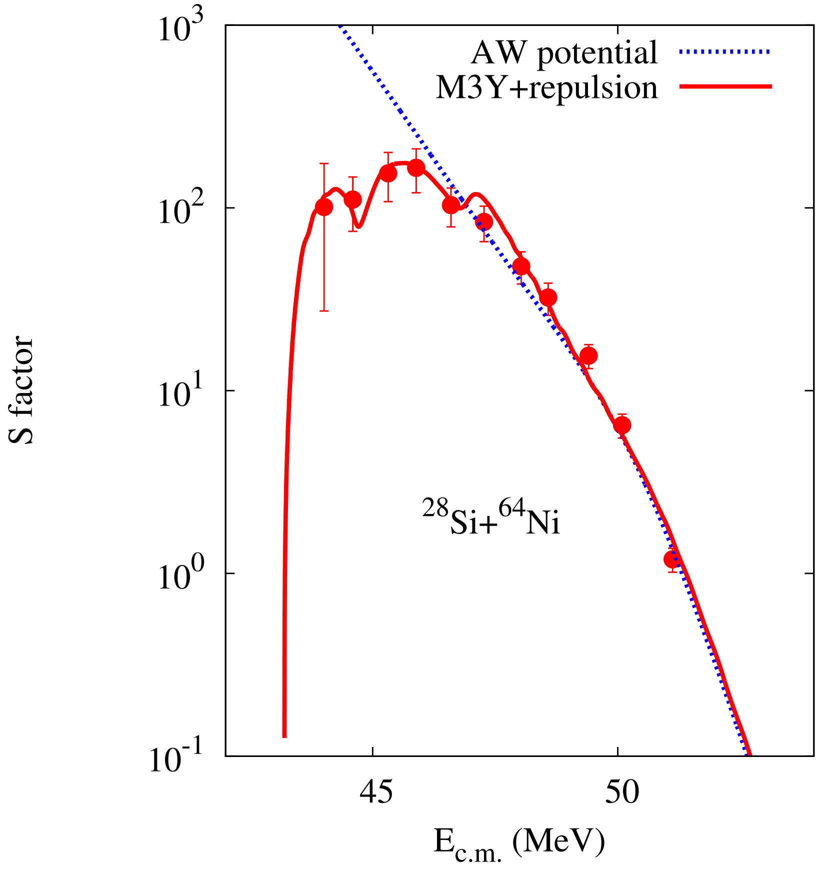
- The hindrance of fusion has been observed in other systems: ^{90}Zr+^{89}Y, +^{90,92}Zr, ^{28}Si+^{64}Ni, ^{58}Ni+^{58}Ni, ^{64}Ni+^{64}Ni, ^{32}S+^{89}Y, ^{60}Ni+^{89}Y, ^{64}Ni+^{100}Mo.

  For systematics, see Jiang et al., Phys. Rev. C 73, 014613 (2006).

- ^{28}Si+^{64}Ni is the lightest system. The ground state Q-value: $Q_{gg} \approx 0$.

  Jiang et al., Phys. Lett. B 640, 18 (2006).





- New systems exhibiting fusion hindrance: ^{16}O+^{208}Pb (ANU), ^{48}Ca+^{96}Zr (Legnaro),...

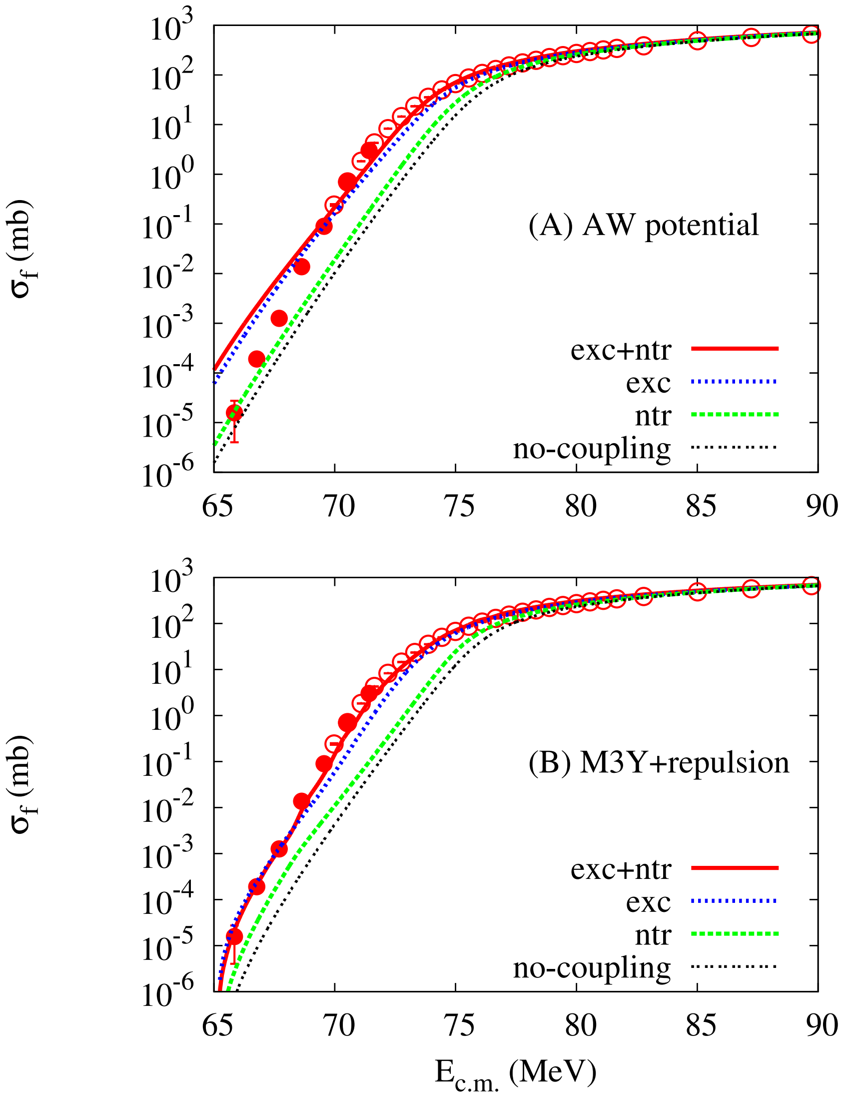
^{16}O+^{208}Pb fusion, Morton et al., Phys. Rev. C 60, 044608 (1999);
New data: Dasgupta et al., PRL 99, 192701 (2007).

The new data (solid points) confirm the hindrance phenomenon at low energy.

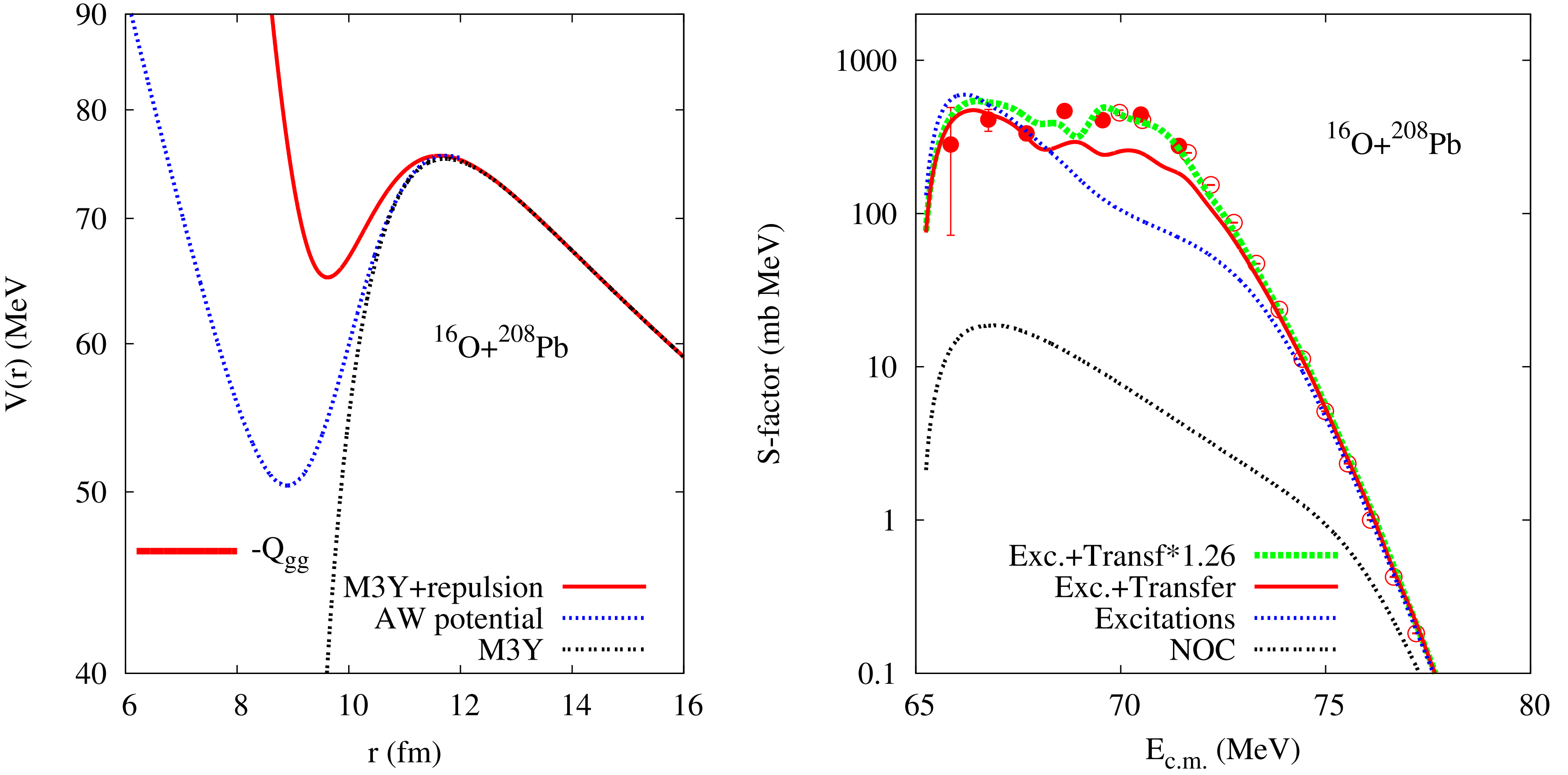
The AW potential is too deep and cannot explain the fusion hindrance.

The combination of a shallow pocket, a thicker barrier, and couplings to one-neutron transfer channels makes it possible to explain the low-energy data rather well.

Esbensen and Mişicu (unpublished).



Entrance channel potential and S-factor.



The M3Y+repulsion potential has a pocket at 65.1 MeV.

Green curve: the one-neutron transfer strength was multiplied by 1.26.

This strength produces a realistic total reaction cross section.

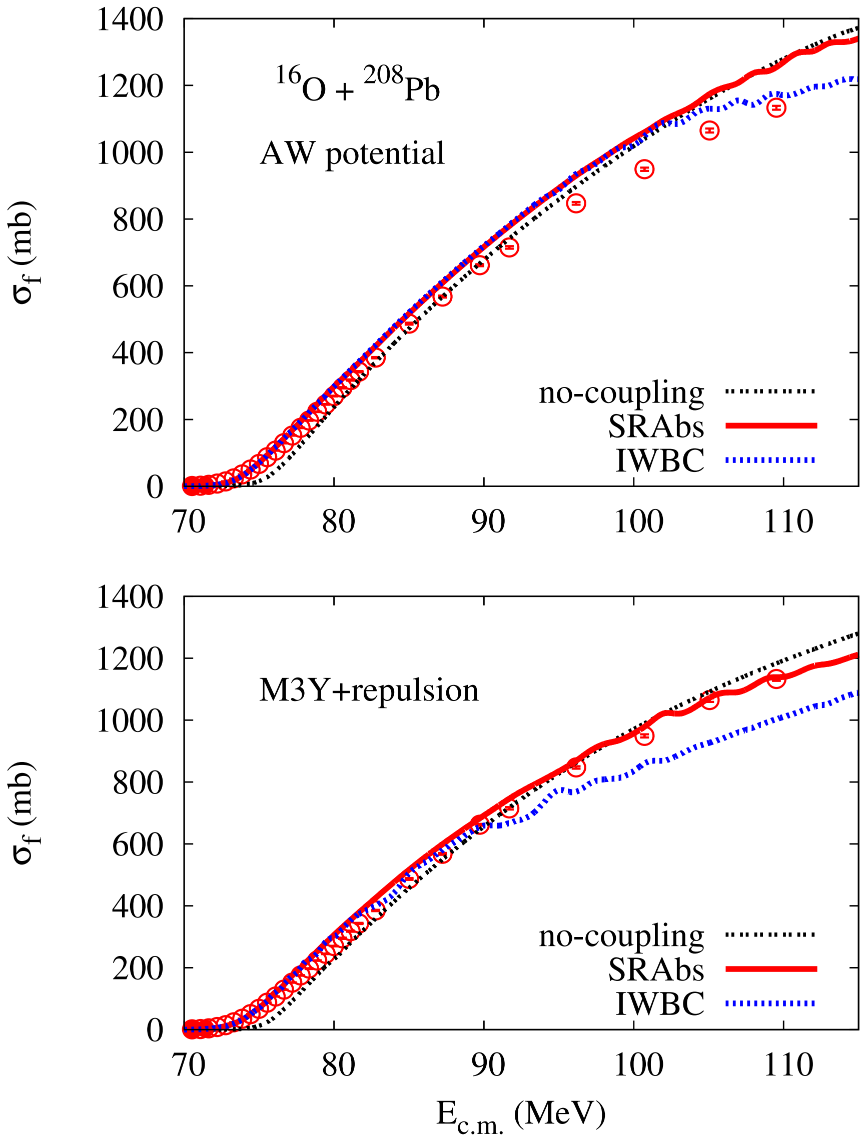
Linear plot of $^{16}O+^{208}Pb$ fusion.

The high energy data are suppressed
compared to the calculations based
on the AW potential.

The problem is sometimes fixed by
using a large diffuseness (a = 1.18 fm).

The calculation based on the M3Y+repulsion
potential and a weak, short-ranged absorption
(SRAbs) reproduces the high-energy.

The M3Y+repulsion potential helps resolve
the problem of a suppression at high energy.



Conclusion

- The hindrance of fusion far below the Coulomb barrier is a general phenomenon, which has been observed in many heavy-ion systems.
- It can be explained in terms of the shallow entrance channel potential we obtained by correcting the M3Y double-folding potential for the effect of nuclear incompressibility.
- A shallow entrance channel potential also helps resolve the problem of the suppression of high energy fusion data compared to (previous) calculations.

Open questions

- Expand the experimental and theoretical studies to lighter systems. WILL THE HINDRANCE PERSIST, and how will it affect the extrapolation to astrophysical reaction rates? (Gasques et al., PRC 76, 035802, 2007).
- What is the relation between the shallow potential and molecular resonances?
- How does a shallow potential affect the production of heavy elements?
- Model dynamics from capture to the compound nucleus (Iwamoto et al., PRC 75, 2007.)