Fusion Hindrance and Pauli Blocking in $^{58}Ni + ^{64}Ni$

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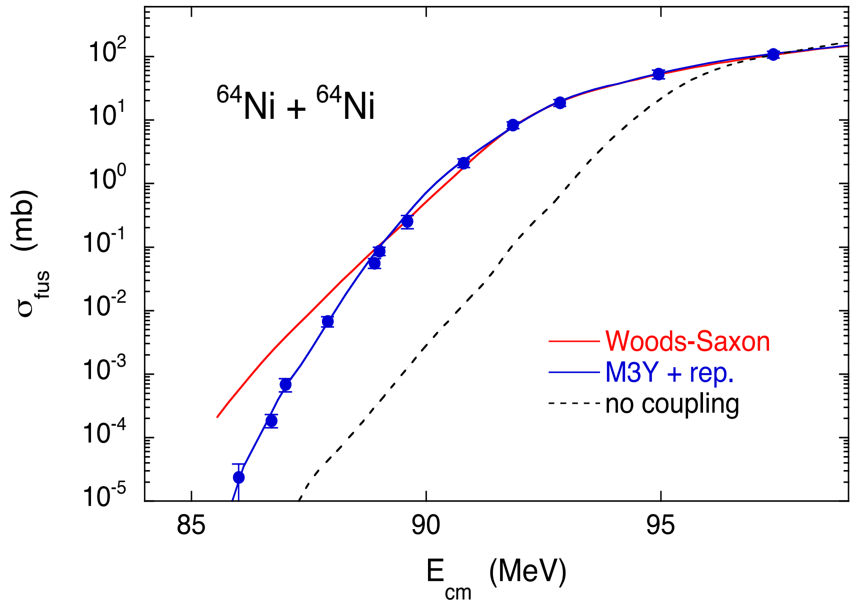
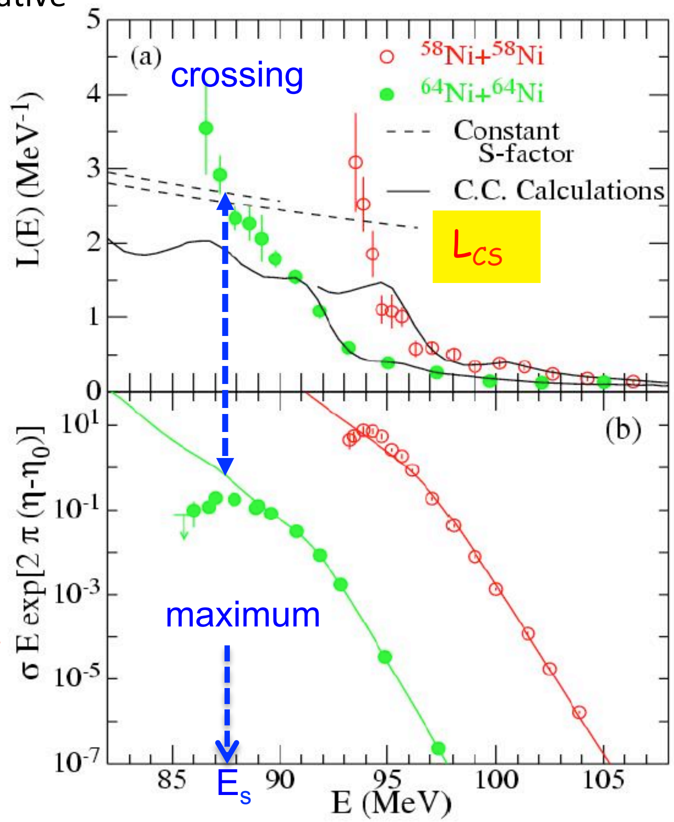
The phenomenon of fusion hindrance at deep sub-barrier energies



Logarithmic derivative
= d[ln(Eσ)]/dE



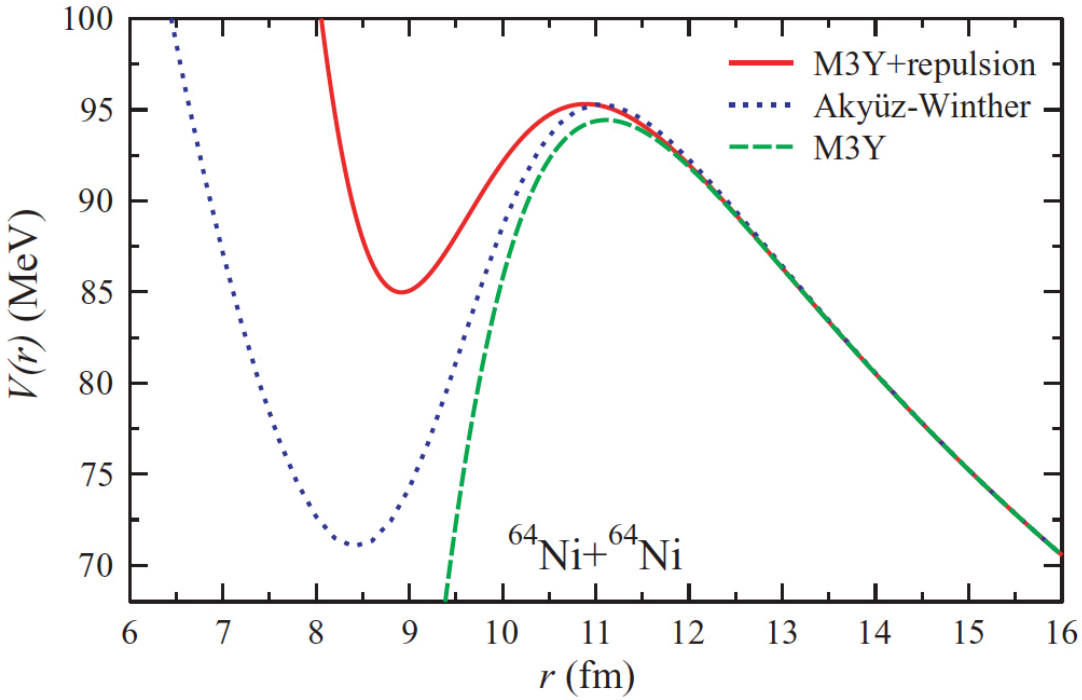
S-factor

C.L.Jiang et al., PRL 93, 012701 (2004)

S has a maximum when (if) $L(E) = \pi\eta/E = L_{CS}$

Theoretical interpretation of fusion hindrance

A successful model: shallow pocket developing inside the barrier due to the saturation properties of nuclear matter



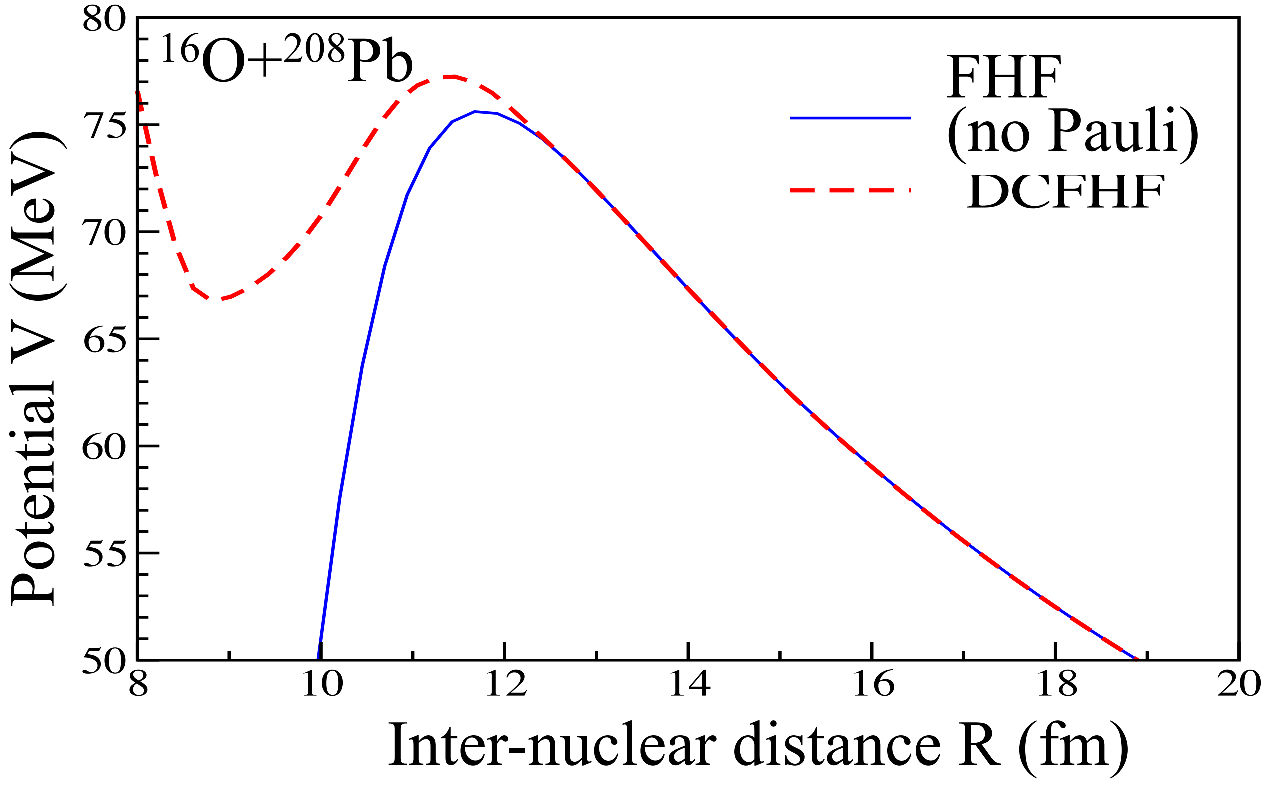
- using the double-folding potential based on the Reid parametrization of the M3Y interaction
- supplemented with a repulsive potential that takes into account the incompressibility of the nuclear matter

- CC calculations are able to reproduce the experimental data for several systems

S.Misicu and H.Esbensen PRC75, 034606 (2007)

The Pauli exclusion principle affects fusion of atomic nuclei

- a novel microscopic method (density-constrained frozen Hartree-Fock DCFHF method) is used to compute the interaction between nuclei, while accounting exactly for the Pauli exclusion principle between nucleons



C.Simenel et al., PRC 95, 031601(R) (2017)

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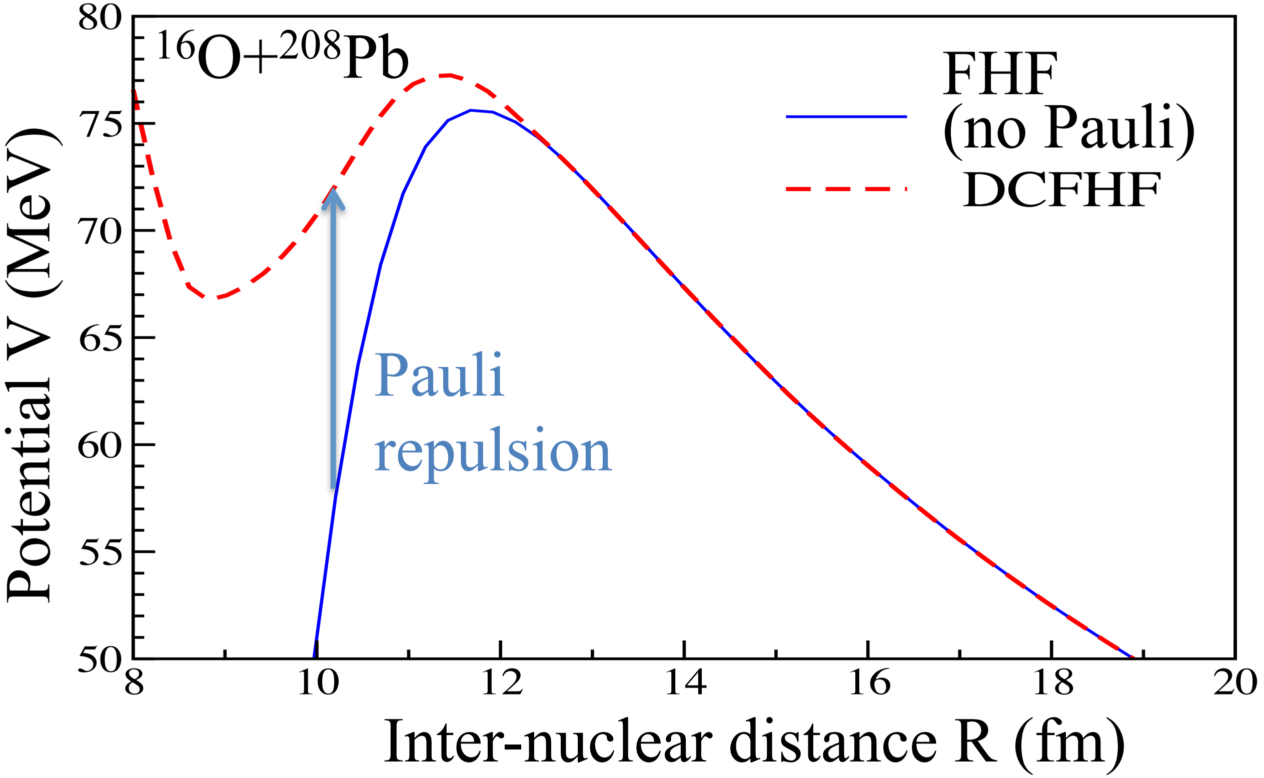
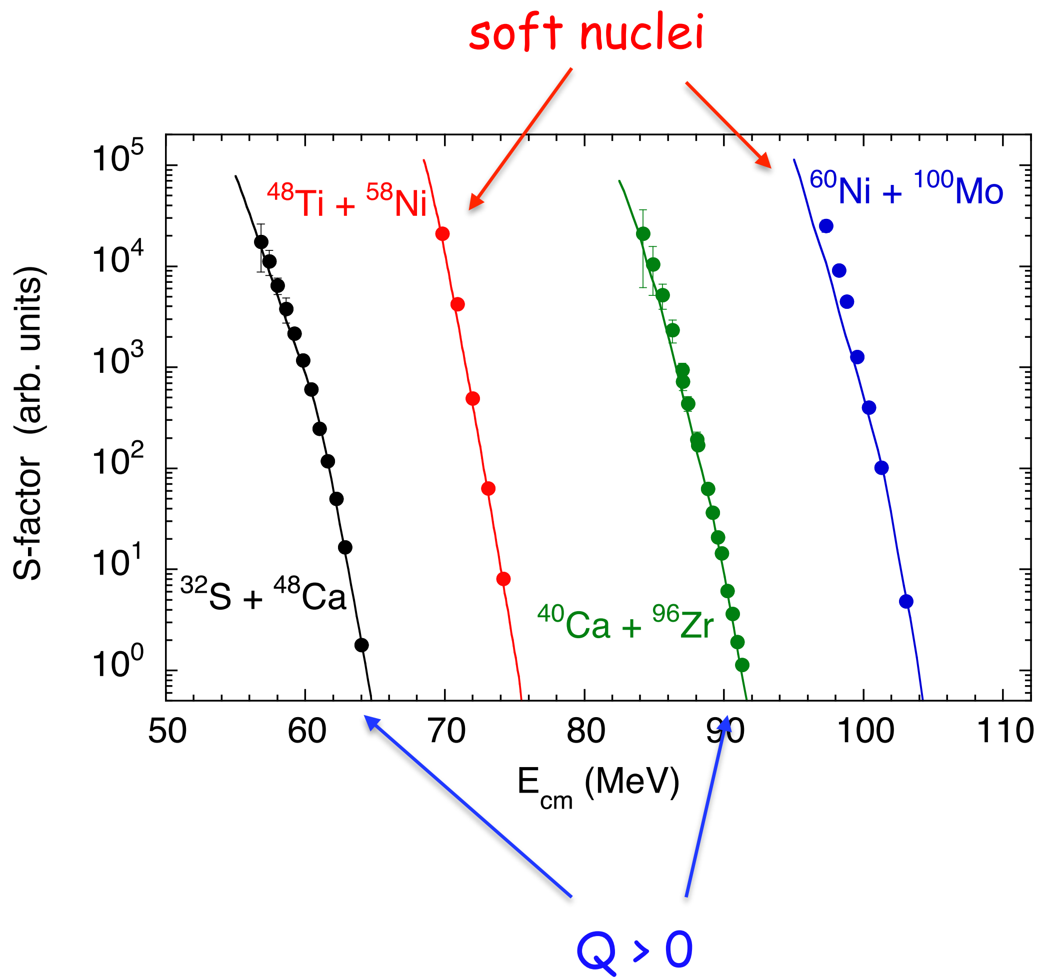


C.Simenel et al., PRC 95, 031601(R) (2017)

No hindrance observed down to about 1 μb in several cases



may be a consequence of different influence of nuclear structure and/or strong transfer couplings, that probably push the hindrance threshold below the lowest measured energy

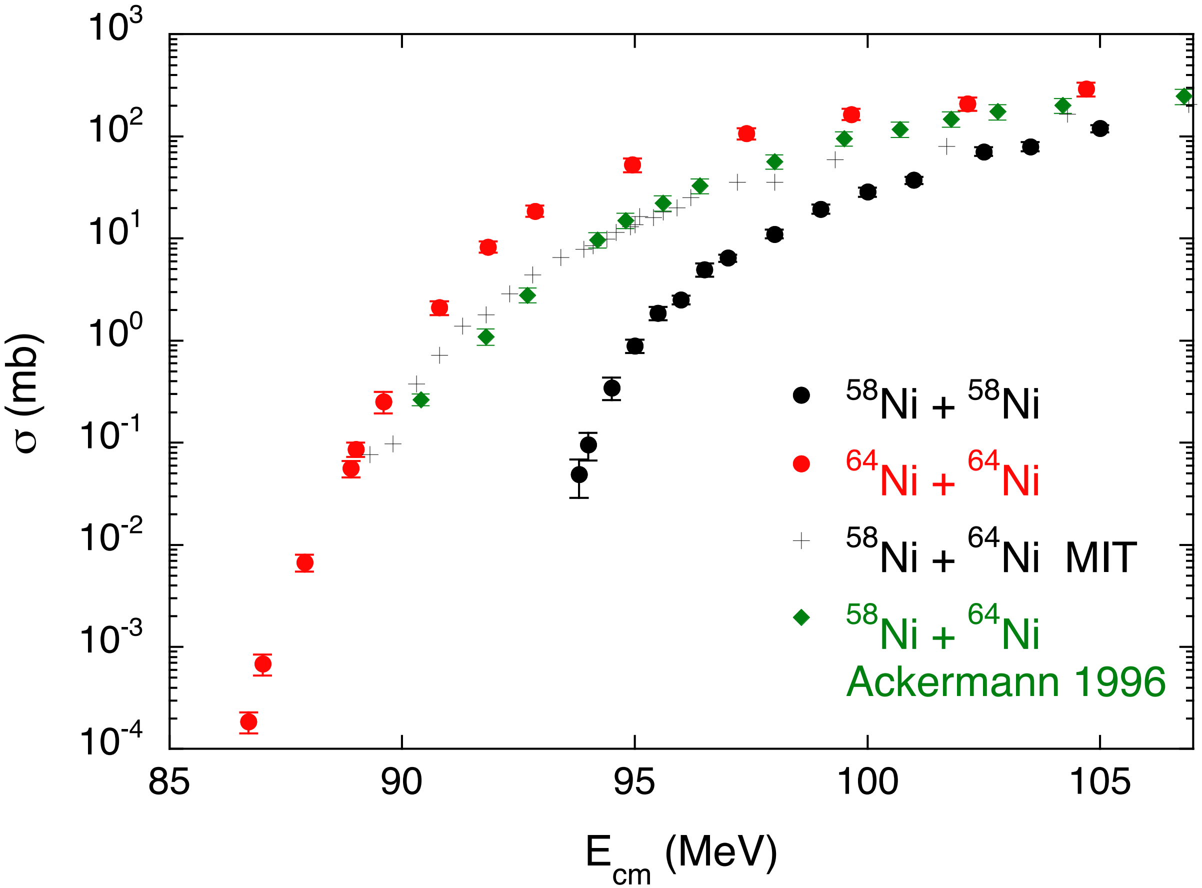
The present experiment: behavior of $^{58}Ni + {}^{64}Ni$ at very low energies

Ground state transfer Q-values for $^{58}Ni + ^{64}Ni$ and two other systems

System	+1n	+2n	+3n	+4n
$^{58}Ni + ^{64}Ni$	-0.65	+3.89	+1.12	+3.89
$^{32}S + ^{48}Ca$	-1.30	+2.84	-0.57	+1.90
$^{40}Ca + ^{96}Zr$	+0.51	+5.53	+5.24	+9.64

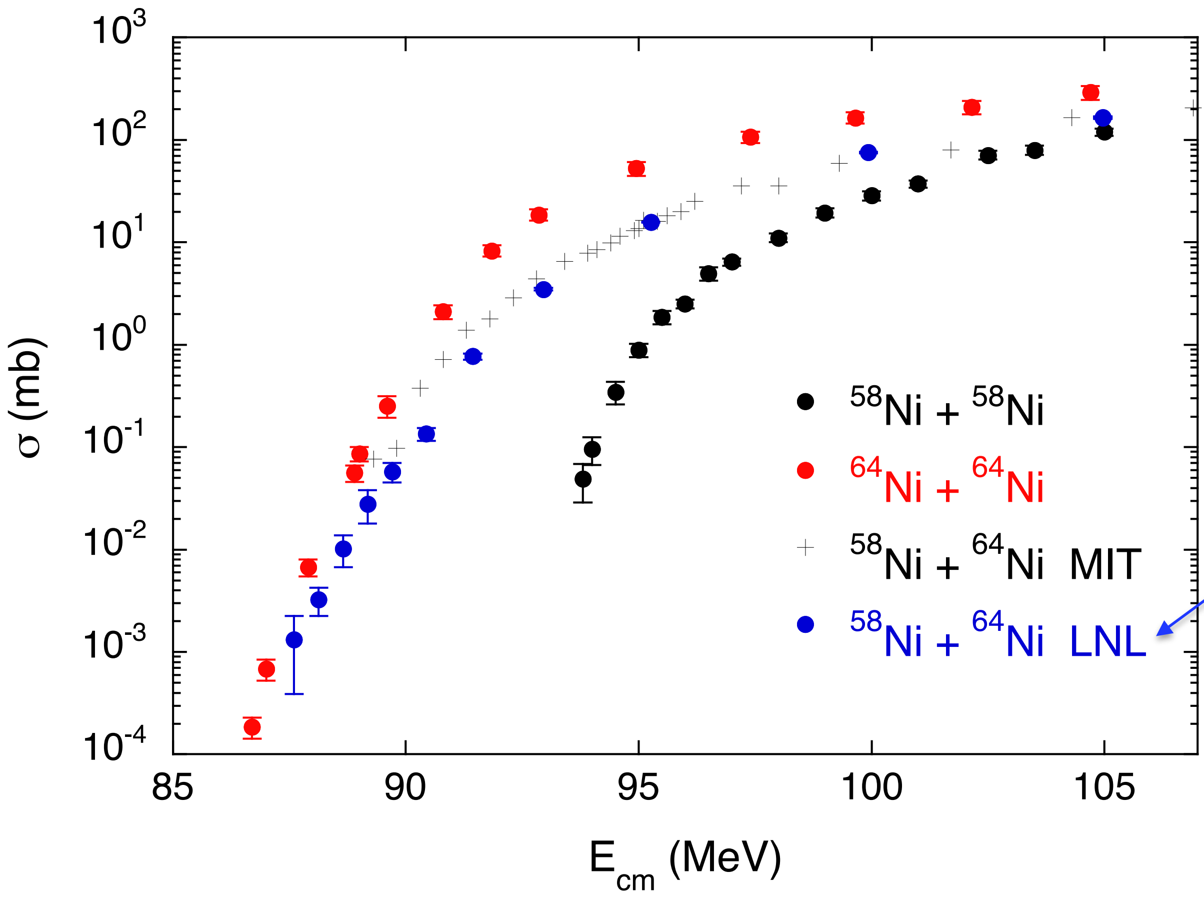
In these three cases the 2-neutron pick-up Q-value is positive. Indeed, their excitation functions have similar trends at sub-barrier energies.

Excitation functions of Ni + Ni systems



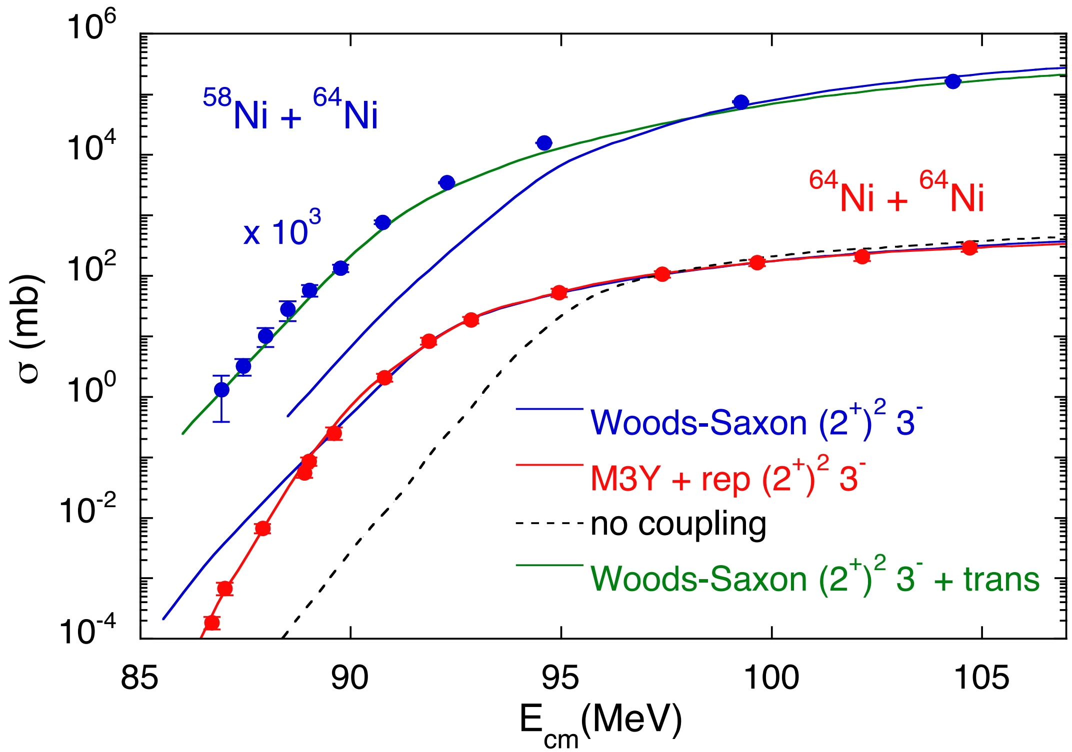
M.Beckerman et al.,Phys. Rev.Lett. 45, 1472 (1980)
C.L.Jiang et al., PRL 93, 012701 (2004)
D.Ackermann et al., Nucl. Phys. A609, 91 (1996)

Excitation functions of Ni + Ni systems



New data points measured in Nov. 2019

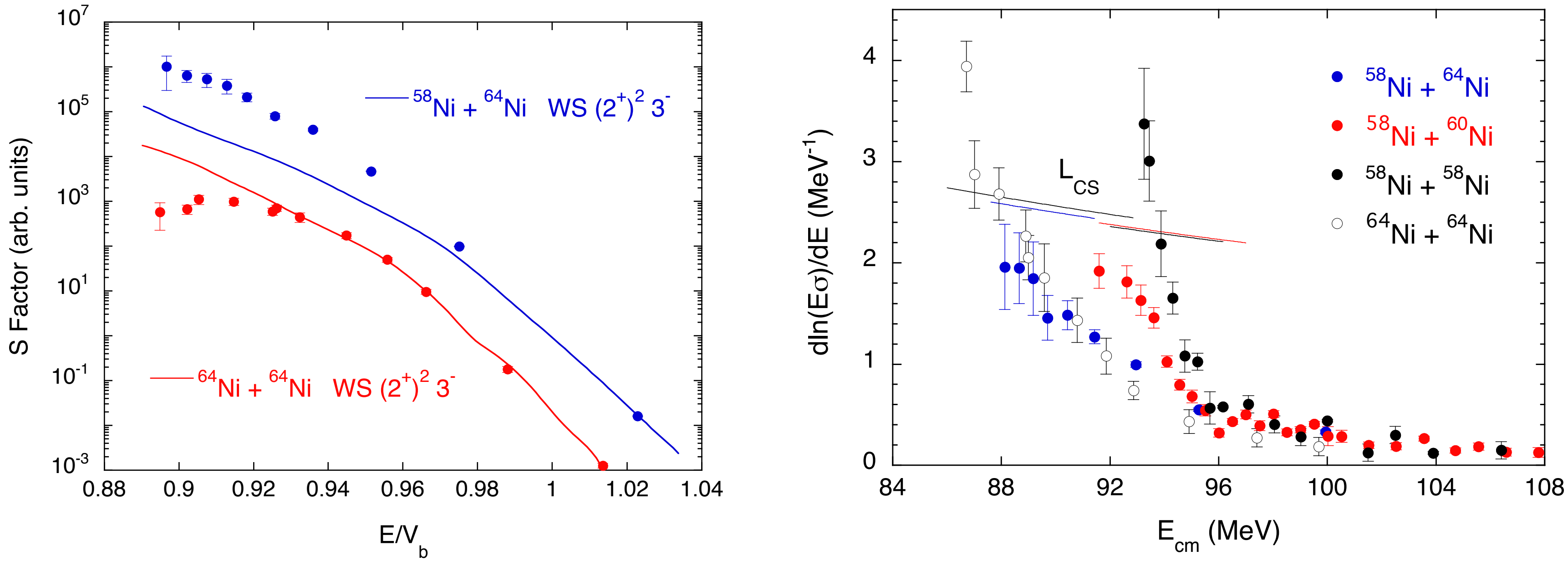
Fusion cross sections of $^{58,64}Ni + ^{64}Ni$ compared to CC calculations



- We have measured deep sub-barrier fusion cross sections for $^{58}Ni + ^{64}Ni$.
- No fusion hindrance has been observed down to about 1 μb, probably due to the influence of positive Q-value transfer channels.
- The behaviour is very different from $^{64}Ni + ^{64}Ni$ where hindrance shows up very clearly.

A.M.Stefanini, G.Montagnoli et al., in preparation

S-factors and logarithmic slopes for ^{58,64}Ni + ^{64}Ni and other Ni + Ni systems



The difference is due to the existence of Q>0 transfer channels in ^{58}Ni +^{64}Ni, given the very similar low-energy vibrational nature of the two nuclei.

This is even more clear in the S-factor representation (left), and in the trend of the logarithmic derivatives (right).

Fusion of ^{32}S + ^{48}Ca

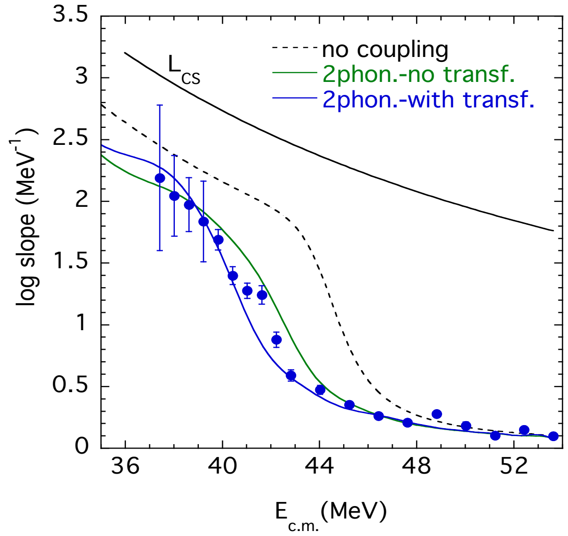
- Fusion of ^{32}S + ^{48}Ca was measured down to very low energies (σ_{fus}= 800 nb)

- Cross sections decrease smoothly below the barrier, and the log slope increases slowly

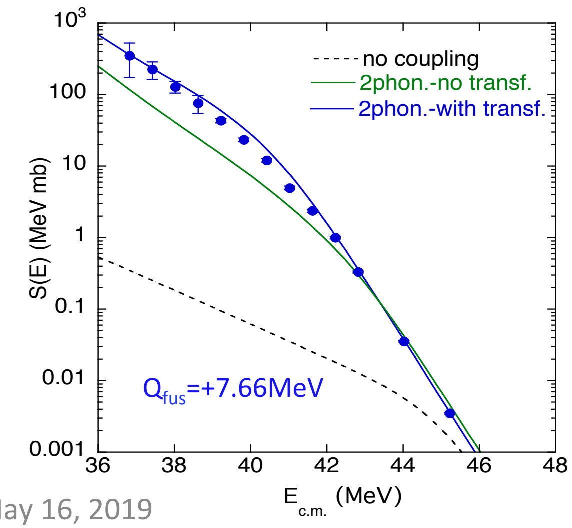
- No maximum of the astrophysical S-factor is observed

- CC calculations based on a standard WS potential well fit the data, provided the 2 neutron pick-up channel is considered

- Fusion hindrance does not show up for ^{32}S + ^{48}Ca in the measured energy range



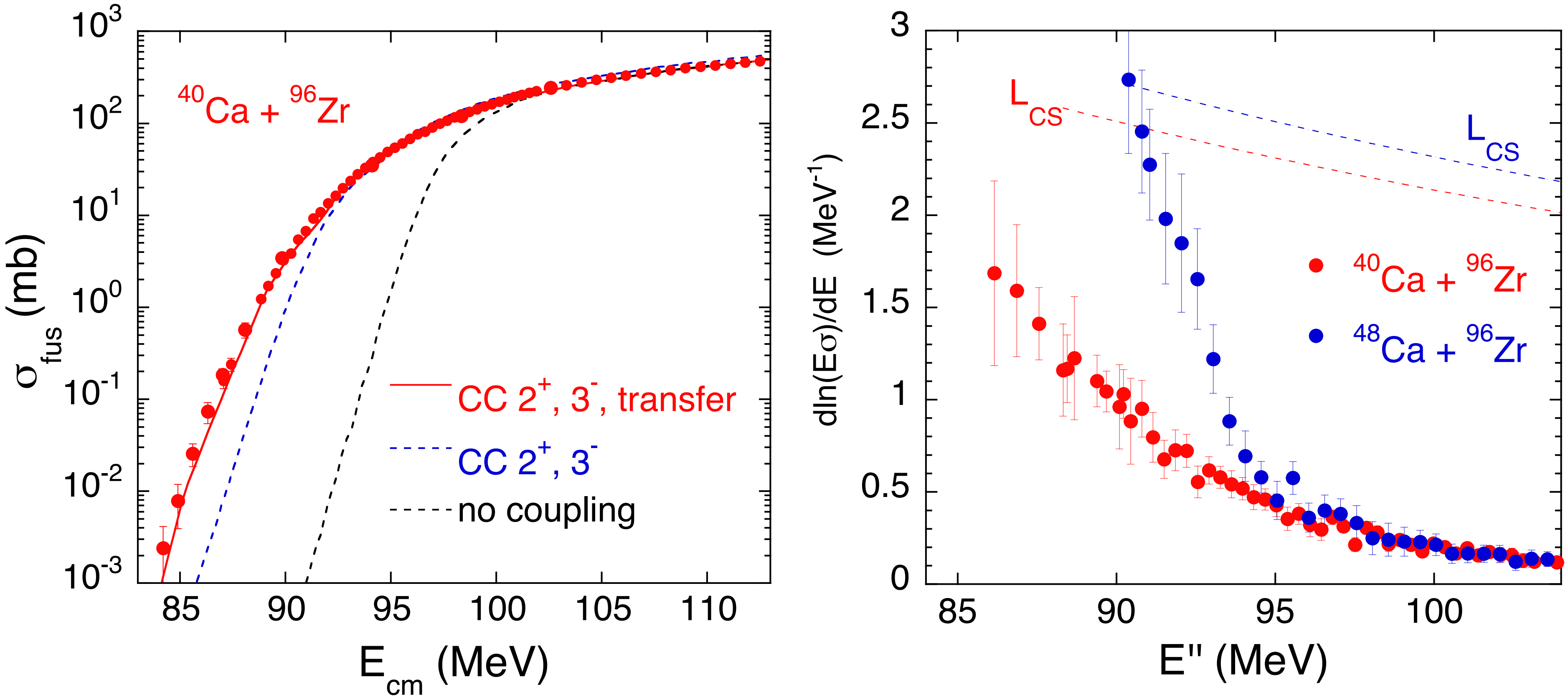
$$L(E) = \frac{d\ln(E\sigma)}{dE}$$



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

G. Montagnoli et al., PRC 87, 014611 (2013)

$^{40}Ca + {}^{96}Zr$ and $^{48}Ca + {}^{96}Zr$

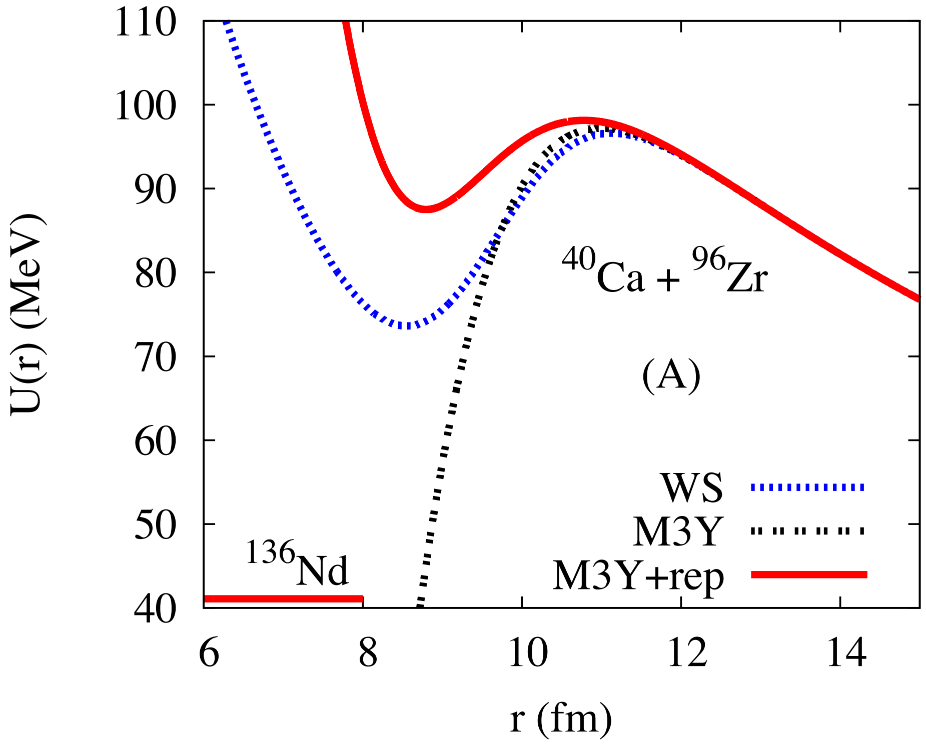


- The agrement with $^{40}Ca + {}^{96}Zr$ data is remarkably good.
- The calculations use a Woods-Saxon potential

no hindrance observed

H.Esbensen et al., PRC 93, 034609 (2016)

Barrier heights and ion-ion potentials



The hindrance phenomenon does not occur in $^{40}Ca+^{96}Zr$, as in ^{32}S + ^{48}Ca.

The present data show that the same is true for ^{58}Ni + ^{64}Ni down to a few μb

Agreement with data is obtained using the WS or even the pure M3Y potential, and ignoring the repulsive part.

This is consistent with the Q-values for nucleon transfer being large and positive.

The valence nucleons can flow more freely from one nucleus to the other without being hindered by Pauli blocking that, in general, is expected to produce hindrance.

Summary

- The low-energy hindrance phenomenon is a general feature observed in heavy-ion fusion far below the barrier
- However, there are various cases where it does not show up down to very low cross sections
- We have recently measured the low-energy part of the excitation function of ^{58}Ni + ^{64}Ni
- It is very flat and no evidence of hindrance can be observed
- Standard CC calculations using a WS potential and coupling to the 2n pick-up channel give a very good account of the data

- In analogy with other cases like ^{32}S + ^{48}Ca or ^{40}Ca + ^{96}Zr, this reinforces the suggestion that the availability of several free states for transfer with $Q > 0$, effectively weakens or completely cancels the effect of Pauli repulsion that in general favors the hindrance of fusion

Our collaboration for this experiment

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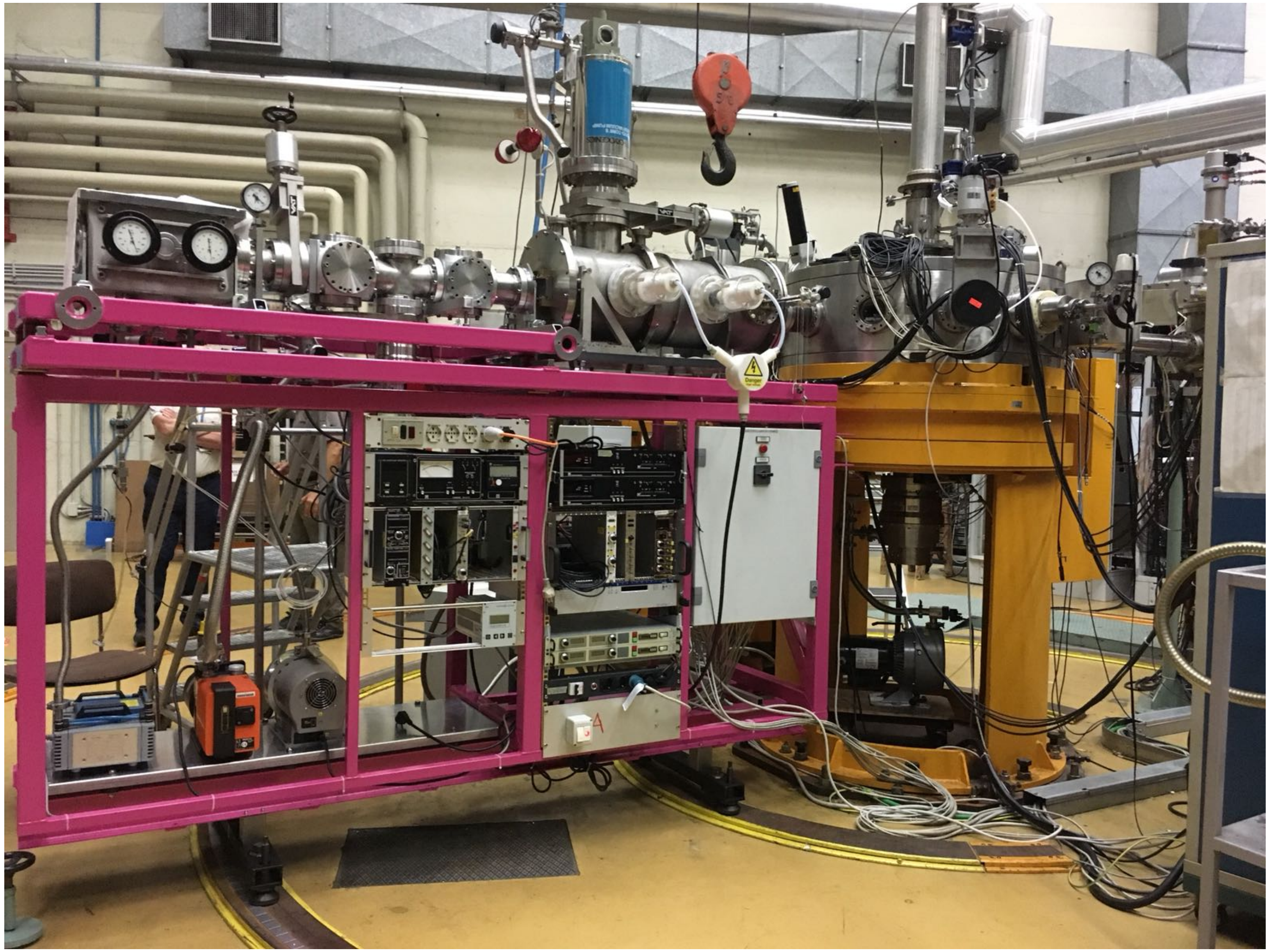
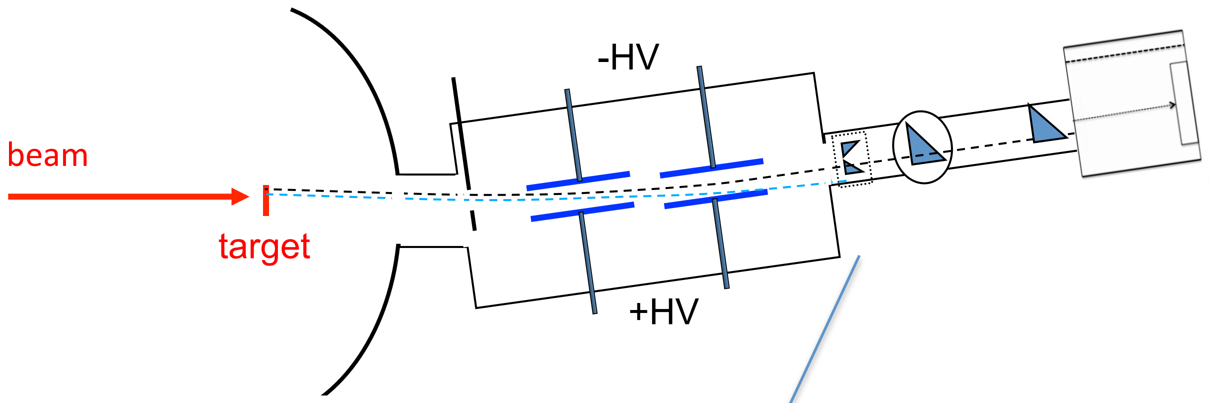
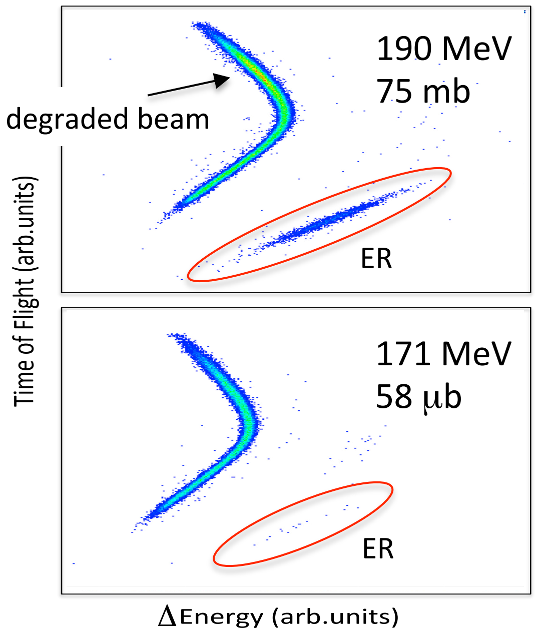
The Pisolo set-up



Detector set-up and experimental matrices ΔE-ToF

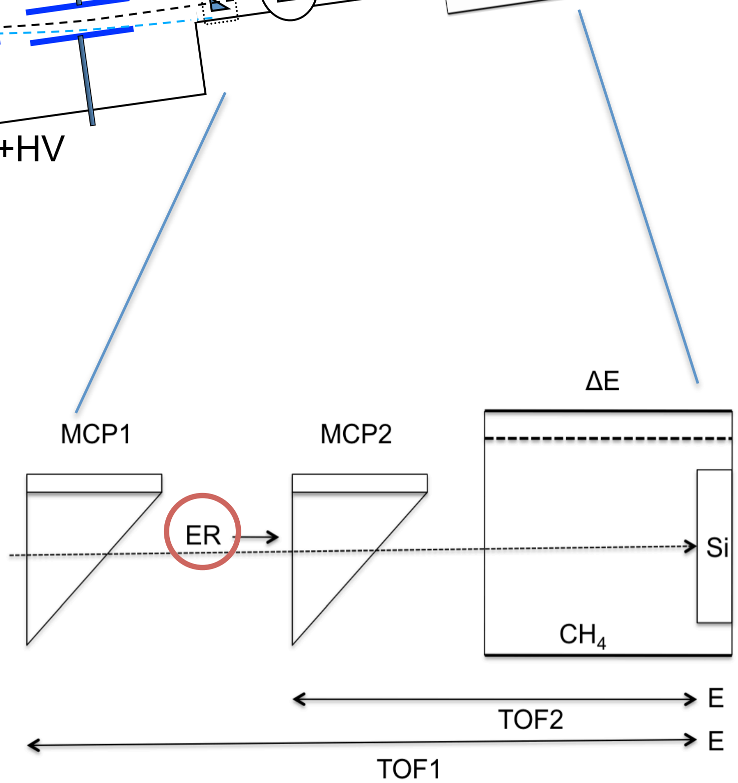


$^{58}Ni + ^{64}Ni$

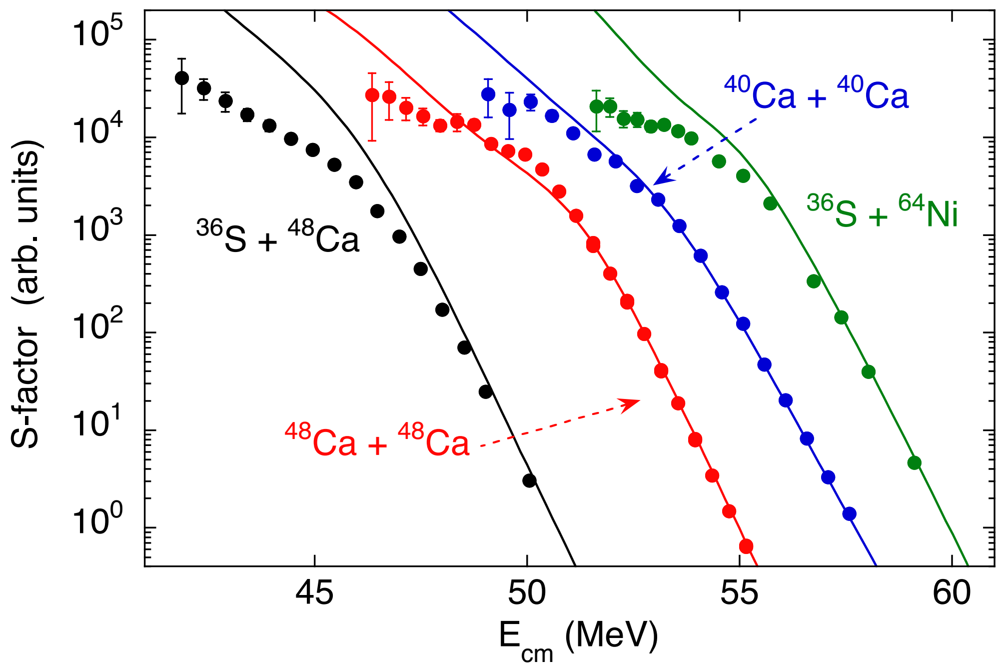


3 pnA
30 min
2200 ER

3 pnA
3 hours
14 ER



(lowest measurable cross section ≈ 0.5-1 μb)

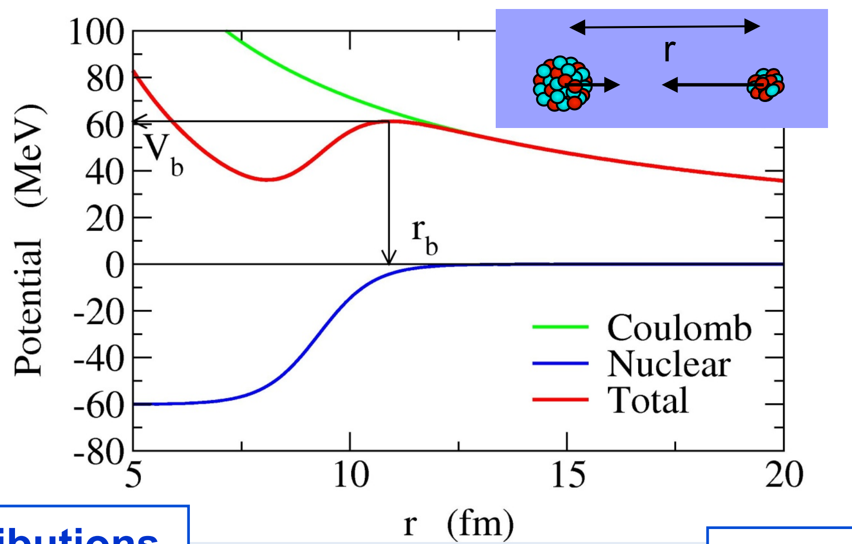


^{40}Ca + ^{40}Ca
^{36}S + ^{64}Ni
^{36}S + ^{48}Ca
^{48}Ca + ^{48}Ca
S-factor (arb. units)
E_{cm} (MeV)

The many features of Heavy-Ion fusion reactions

Quantum tunneling of many-body systems

Enhancement due to coupled degrees of freedom



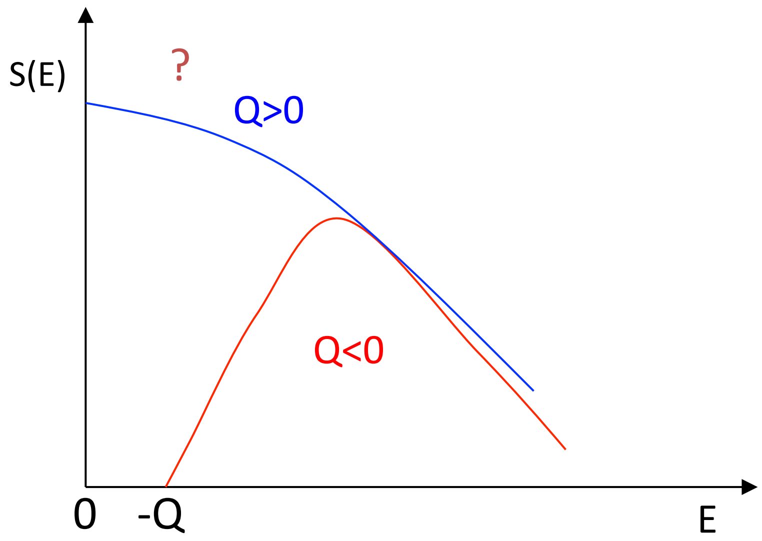
Interplay of dynamics and nuclear structure

Fusion barrier distributions and hindrance far below the barrier

We recently measured the fusion excitation function of $^{36}S + ^{48}Ca$ (Q-value=+7.6MeV)

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

	E_{min}	$e^{2\pi\eta}$	S(E)
Q<0	-Q	finite	0
Q>0	0	$\rightarrow\infty$	finite ?



For Q>0 S(E) may not show any maximum ⇒ no fusion hindrance!