Fusion hindrance in light and heavy systems

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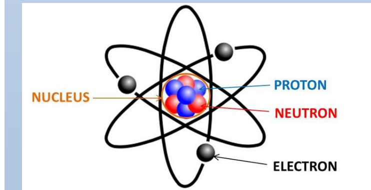
Nuclear Physics

Heavy-Ion fusion



Sub-barrier hindrance

Light systems

Stellar evolution

Astrophysics

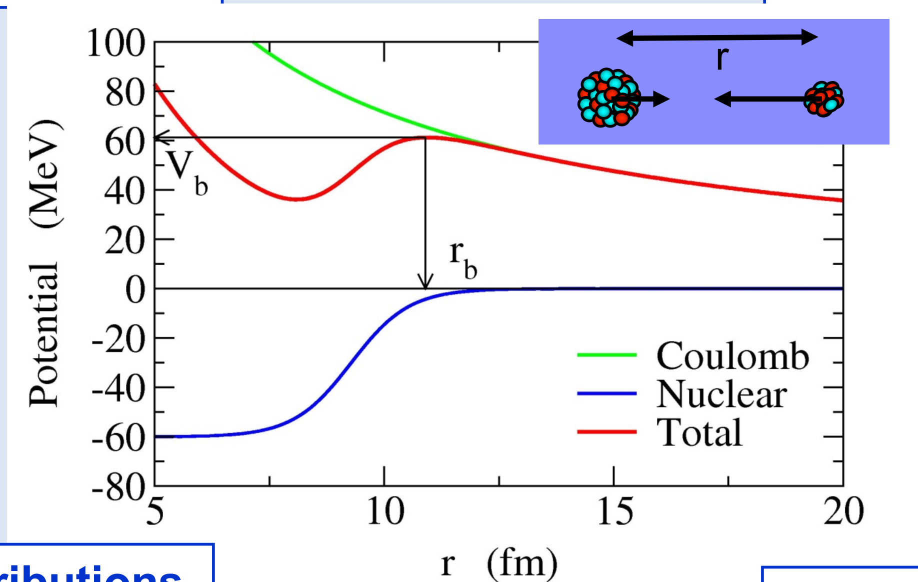
Layout

- The various features of near- and sub-barrier heavy-ion fusion: enhancements and barrier distributions
- The phenomenon of fusion hindrance at deep sub-barrier energies
- Fusion hindrance as a general phenomenon
- The two systems ^{12}C+ ^{30}Si, ^{24}Mg: sub-barrier trends of the excitation functions and of the S-factors
- Other near-by cases: evidence for systematic behaviors
- Towards light systems and possible consequences for astrophysics
- Summary

The many features of Heavy-Ion fusion reactions

Quantum tunneling of many-body systems

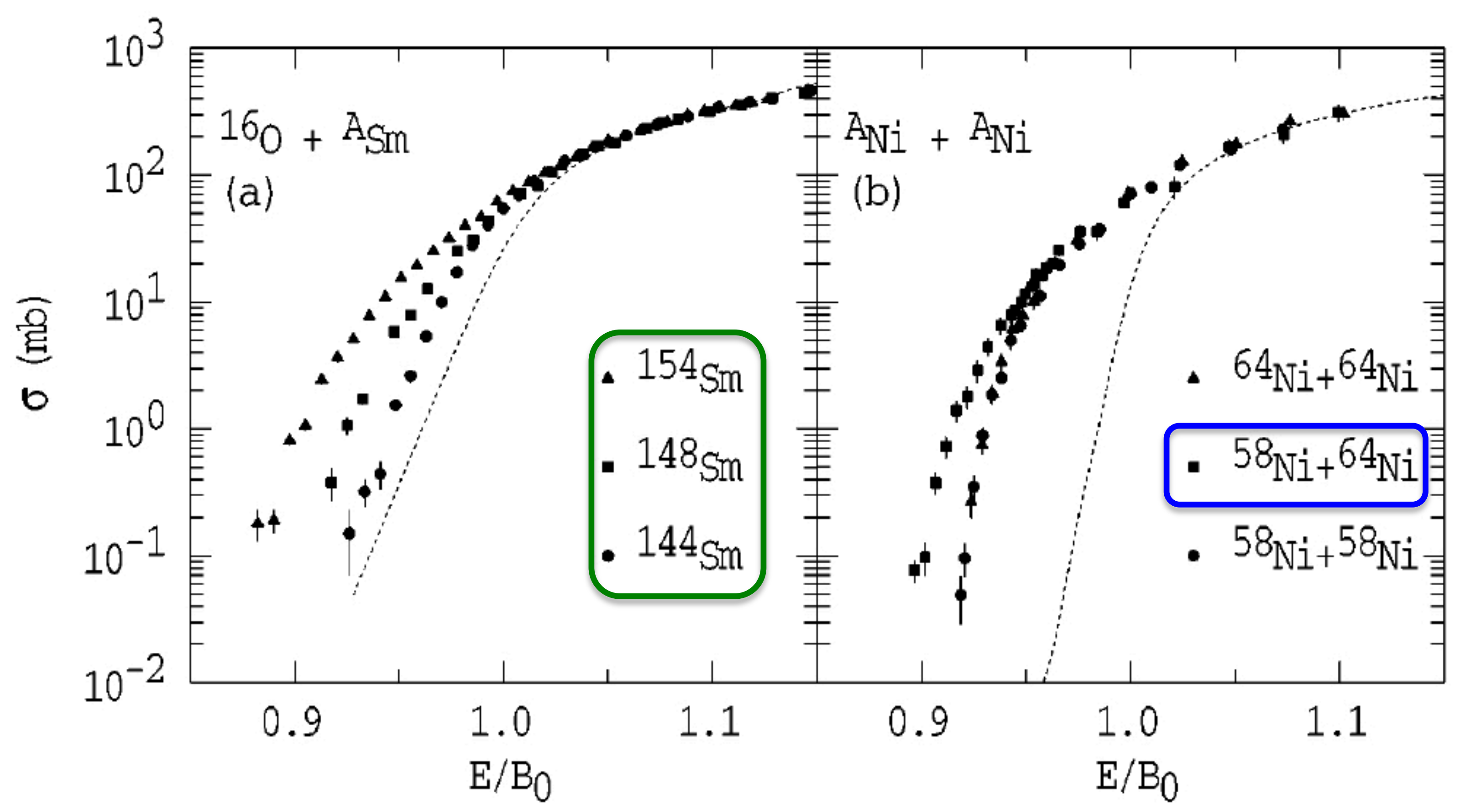
Enhancement due to coupled degrees of freedom



Interplay of dynamics and nuclear structure

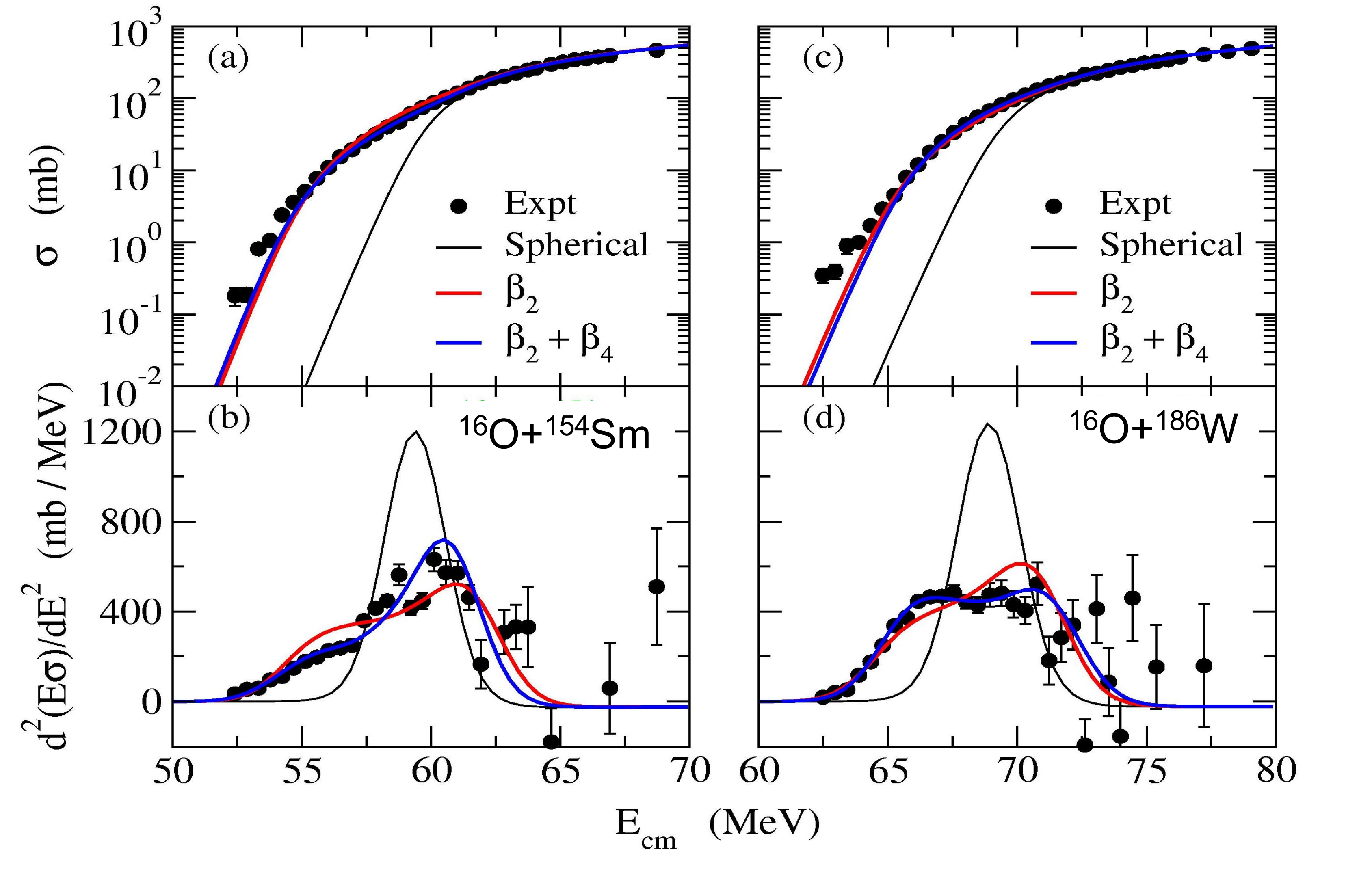
Fusion barrier distributions and hindrance far below the barrier

Early studies of sub-barrier fusion teached us that cross sections may strongly depend on the structure of colliding nuclei and on couplings to transfer channels



W.Reisdorf et al.,NPA 438 (1985) 212 M.Beckerman et al.,Phys. Rev.Lett. 45, 1472 (1980)

The concept of a "fusion barrier distribution" was exploited: its sensitivity to the static nuclear deformation was evidenced ...



J.Leigh et al., Phys. Rev. C 52, 3151 (1995)

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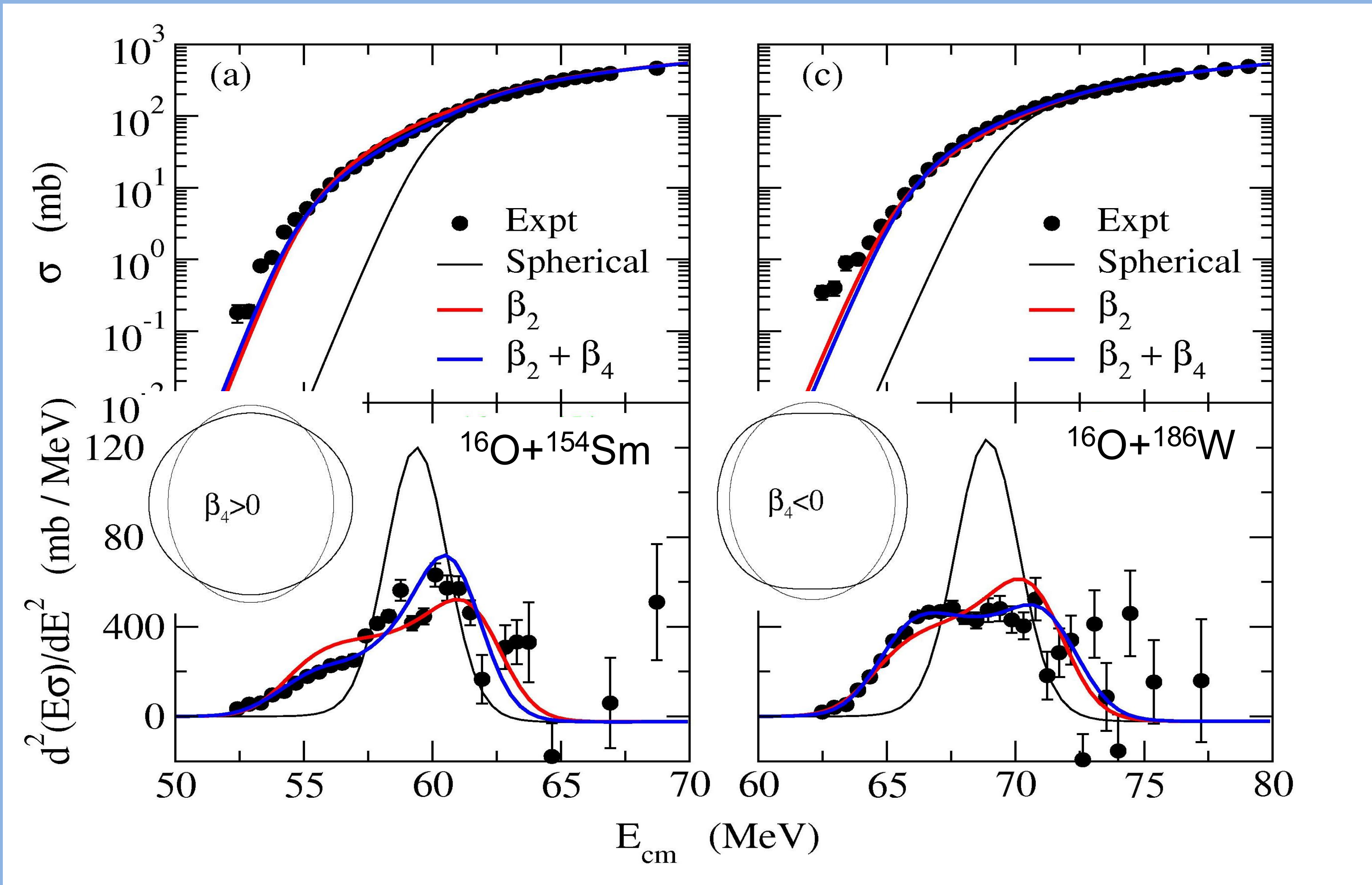
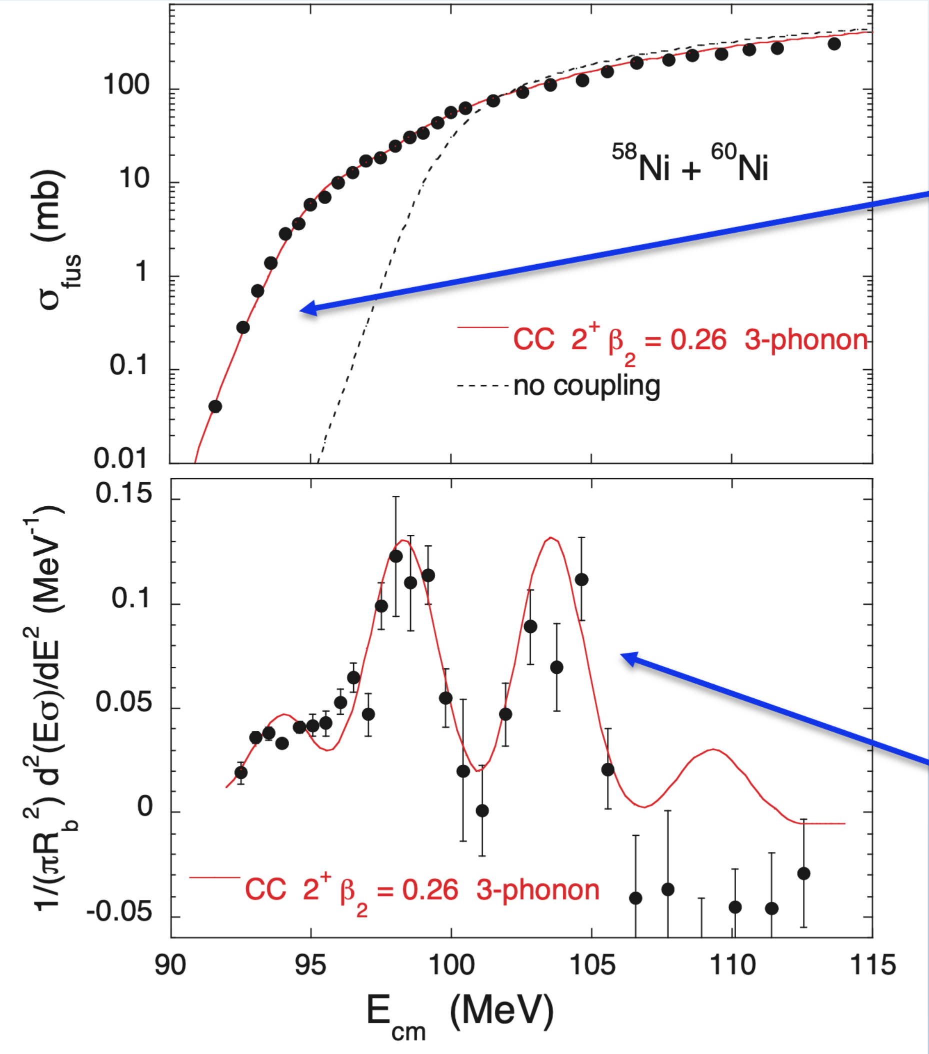


J.Leigh et al., Phys. Rev. C 52, 3151 (1995)

… and the study of ^{58}Ni+^{60}Ni revealed for the first time the existence of a barrier distribution with several well-defined peaks explained by multi-phonon couplings.



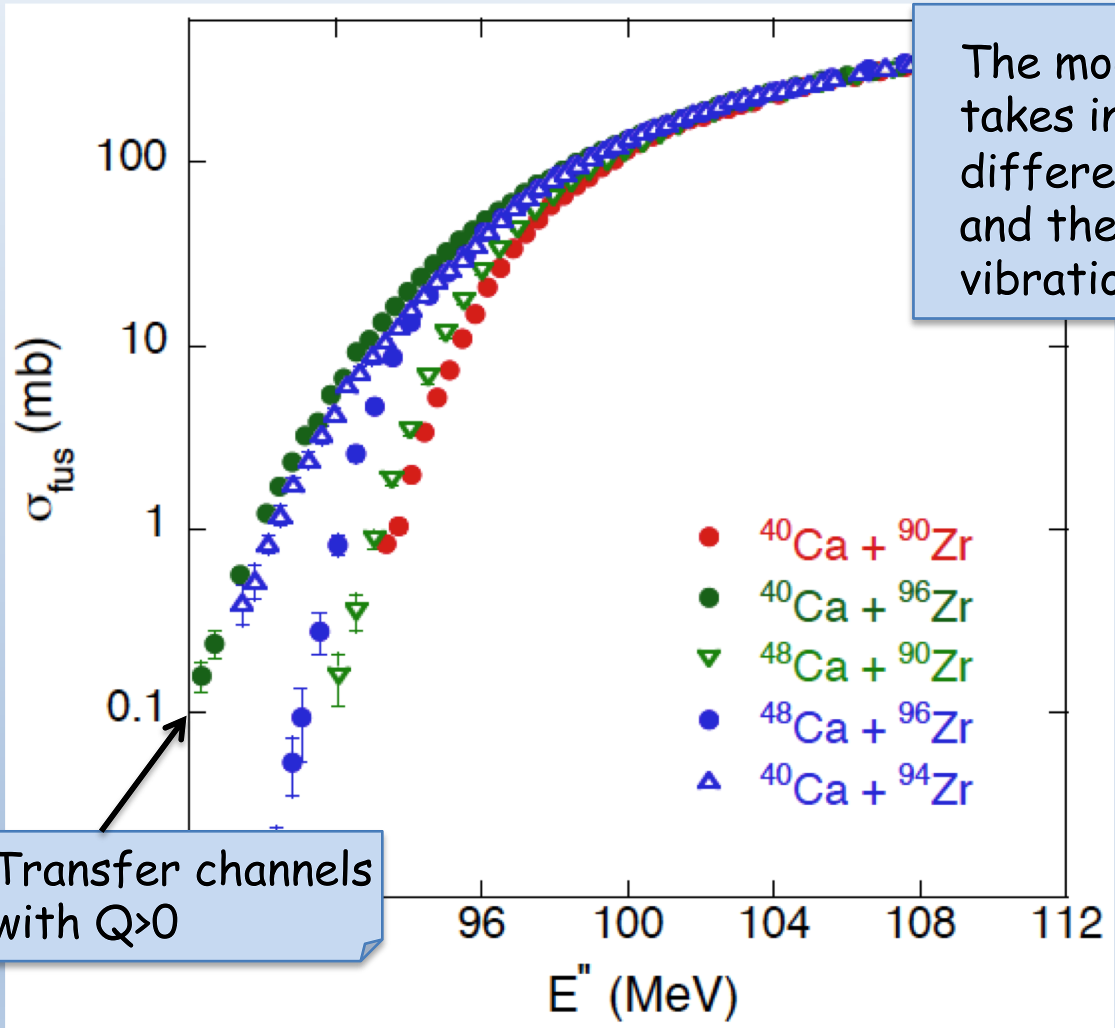
The fusion cross sections near and below the barrier show a huge enhancement with respect to the one-dimensional barrier limit

The excitation function seems to be structureless and it is not easy to identify the channel coupling(s) producing such enhancement.

This is best revealed by the barrier distribution that displays a clear structure with three well-defined peaks.

A.M.Stefanini et al., PRL 74, 864 (1995)

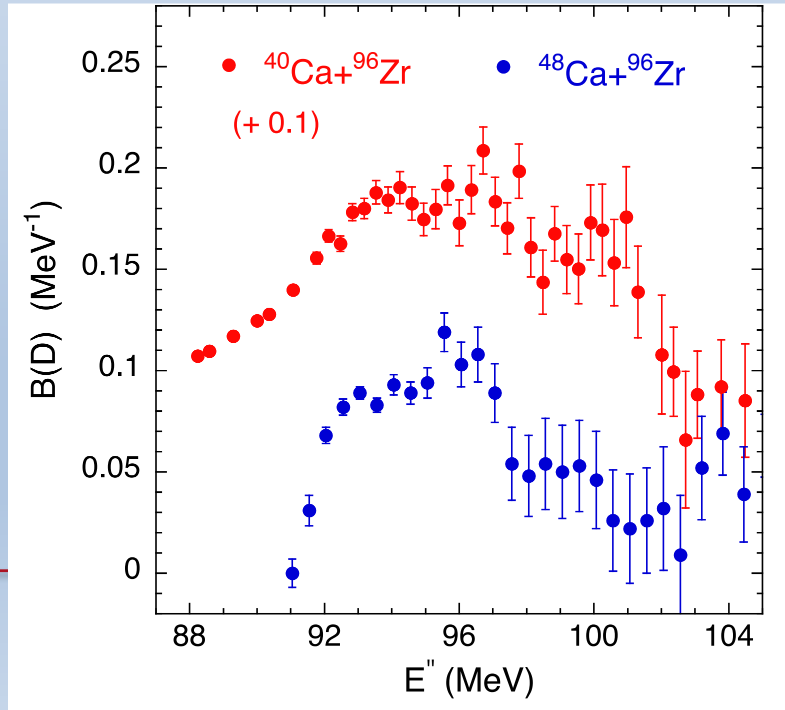
The effect of coupling to transfer channels in several Ca+Zr systems



The modified energy scale E" takes into account the different Coulomb barriers and the high energy octupole vibrations of ^{40}Ca and ^{48}Ca

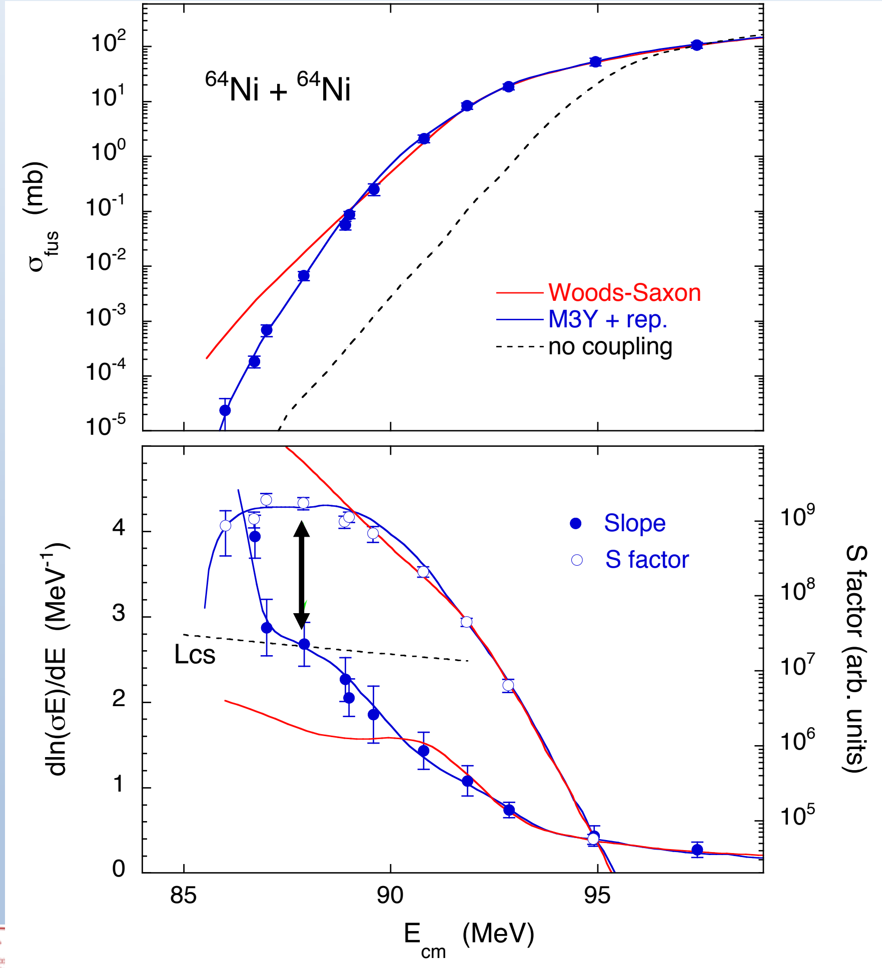
Transfer channels with Q>0

Barrier distributions



A.M. Stefanini et al., PRC76, 014610(2007)

Fusion hindrance far below the barrier



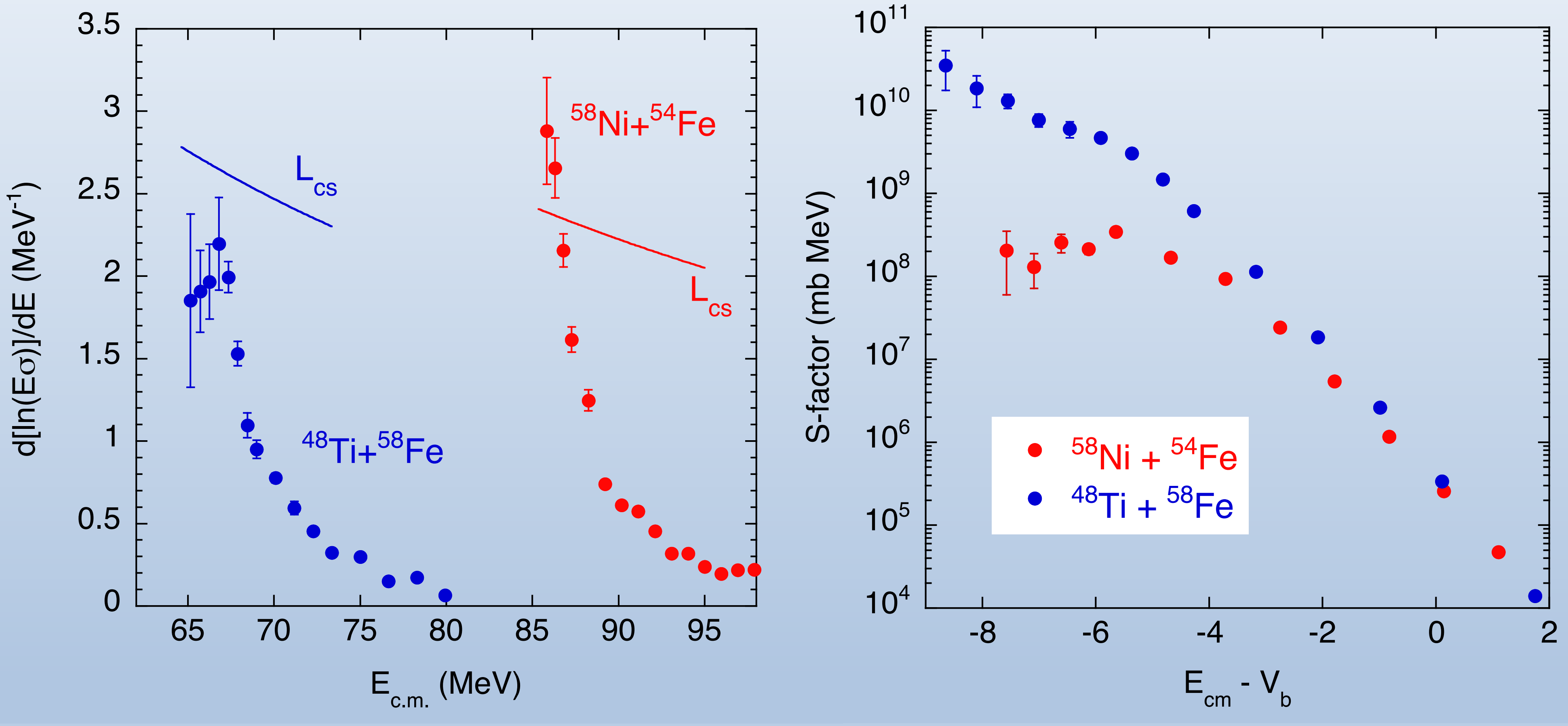
The "classical" case ^{64}Ni+^{64}Ni

Standard CC calculations based on a Woods-Saxon potential overpredict the excitation function

The astrophysical S factor develops a maximum at the energy where the logarithmic slope reaches the value $L_{CS} = \pi\eta/E$

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

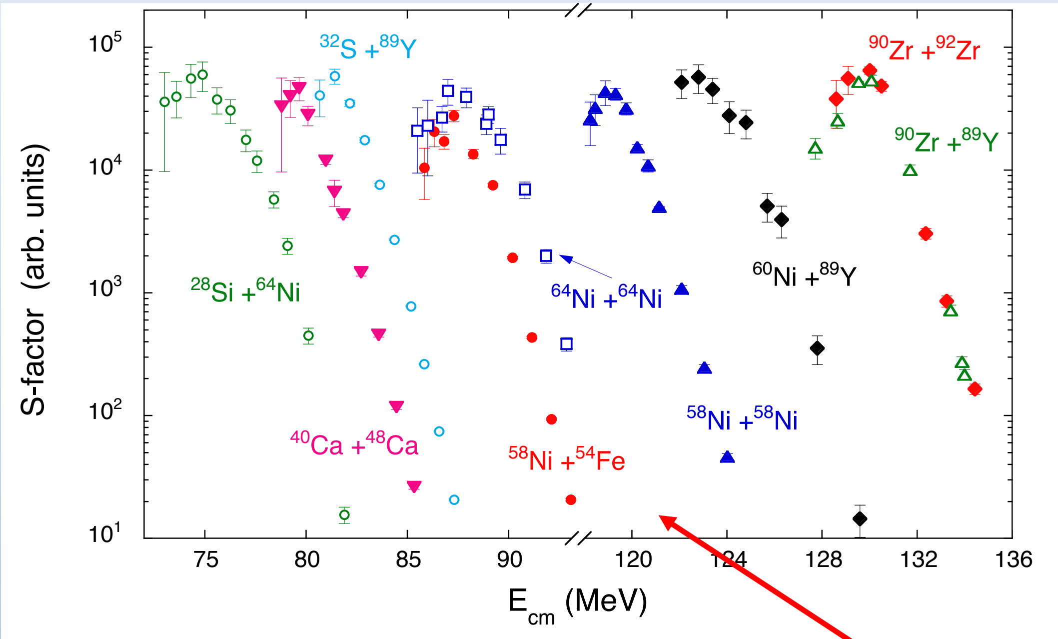
Logarithmic derivative of the fusion excitation function of ^{48}Ti+^{58}Fe and ^{58}Ni+^{54}Fe, and comparison of the S-factors for the two systems

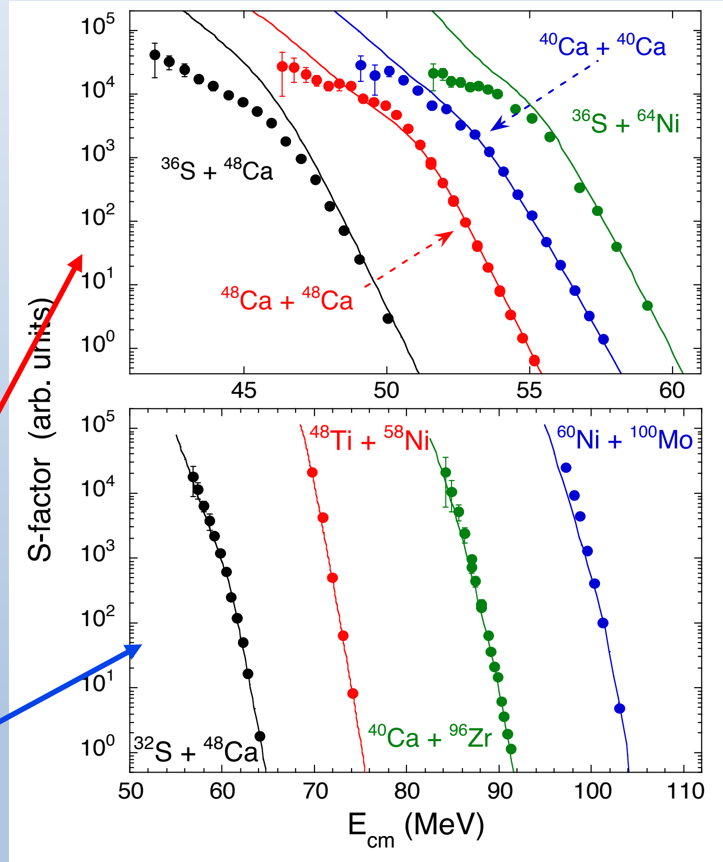


The slope of ^{48}Ti+^{58}Fe saturates below the barrier, while it keeps increasing for ^{58}Ni+^{54}Fe

A clear maximum of the S-factor develops for ^{58}Ni+^{54}Fe, but no maximum is observed for ^{48}Ti+^{58}Fe

Several cases involving medium-mass nuclei



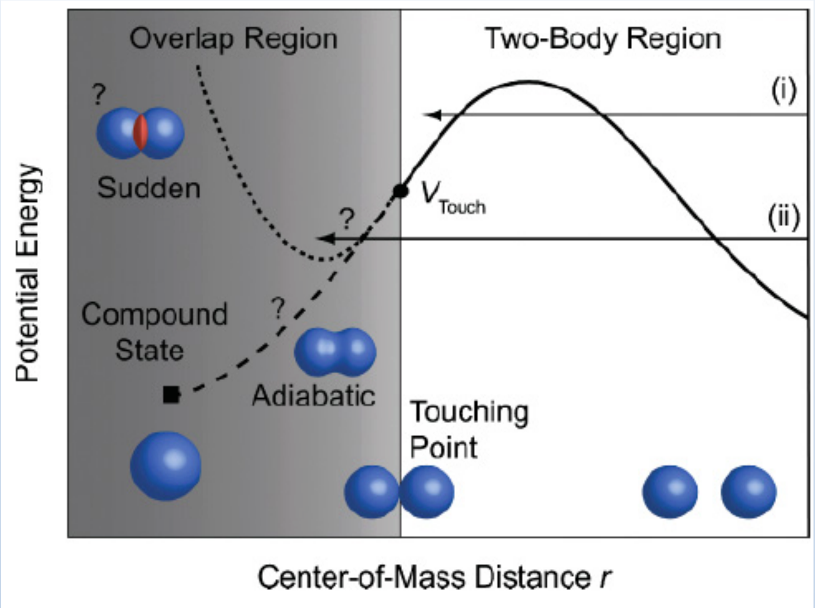


S factor maximum YES Hindrance YES

S factor maximum NO Hindrance YES

S factor maximum NO Hindrance NO

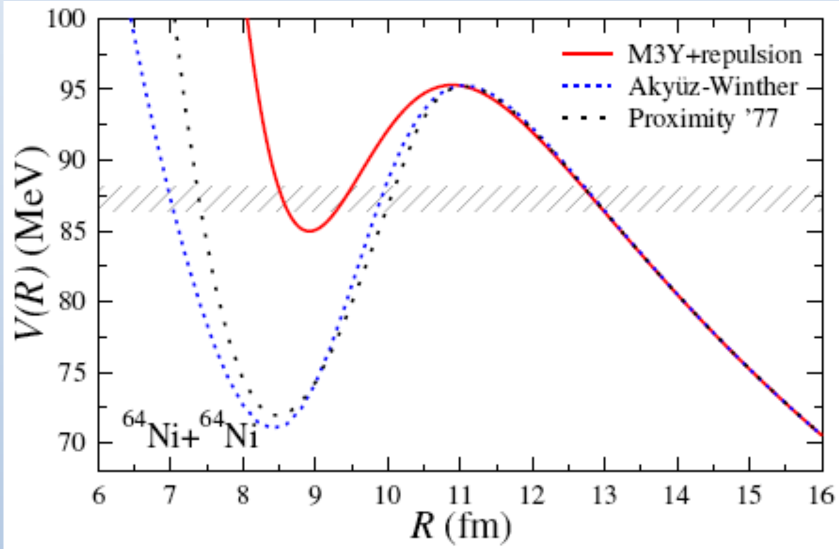
The system evolves in the classically forbidden region towards the compound nucleus



T.Ichikawa et al. PRC75, 064612 (2007)

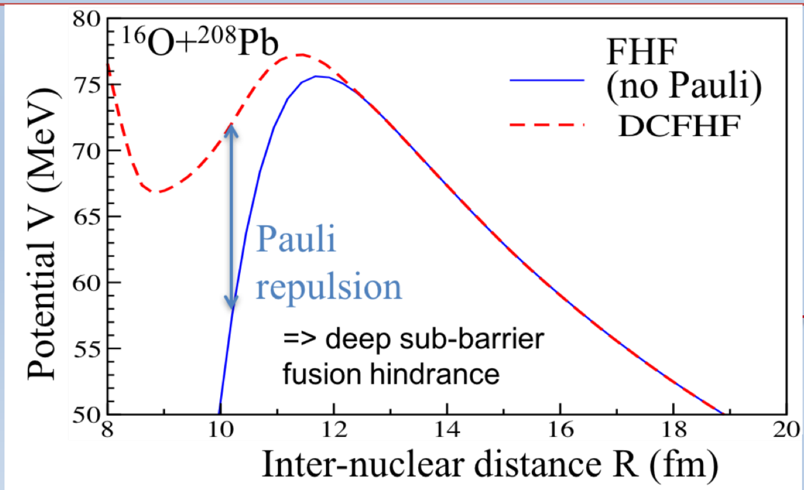
How does one understand the fusion hindrance effect ?

A shallow pocket develops inside the barrier due to the saturation properties of nuclear matter



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

Nucleus-Nucleus potential: the barrier is thicker when the Pauli principle is taken into account



C. Simenel et al. PRC95, 031601(R) (2017)

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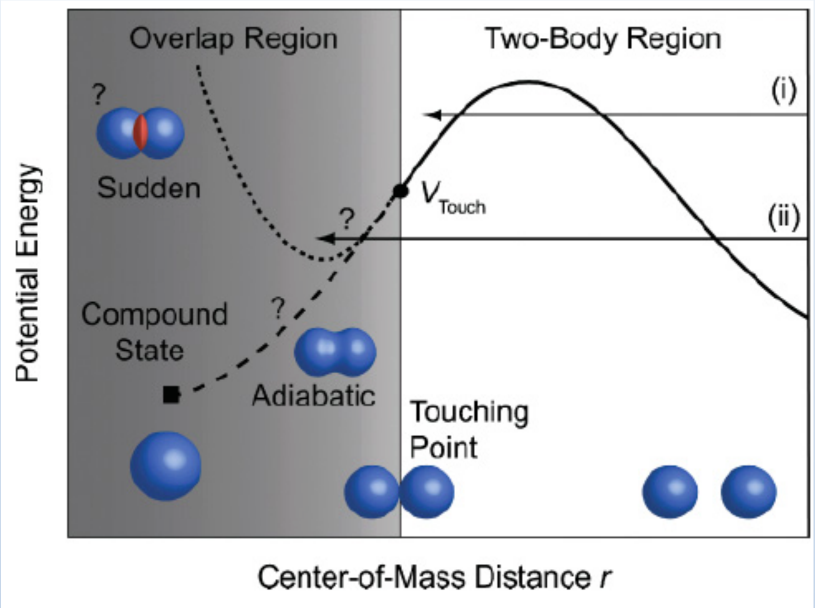

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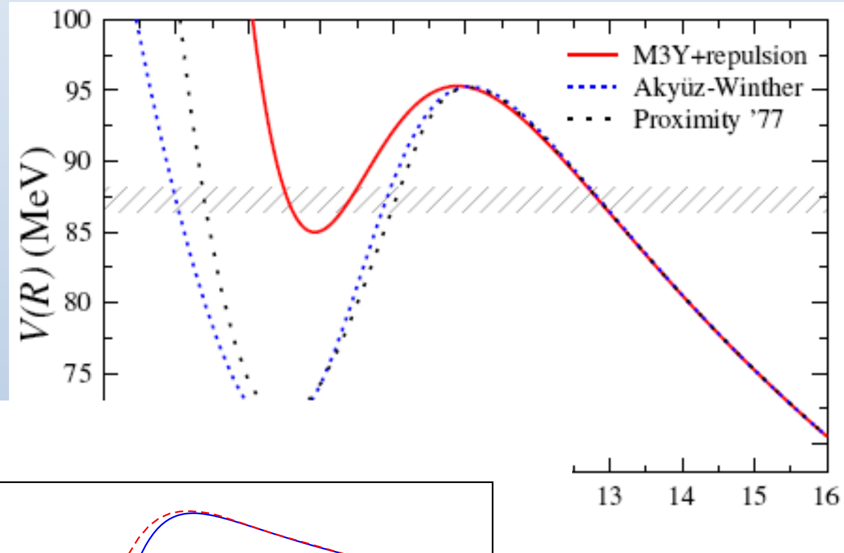

034606 (2007)

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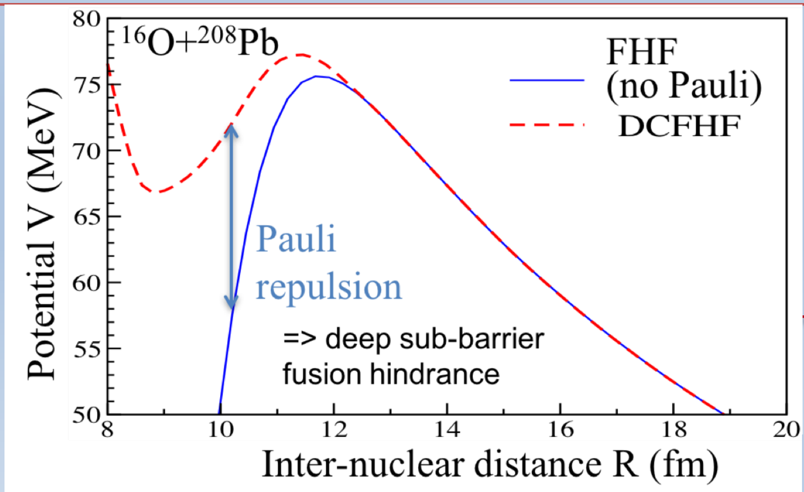
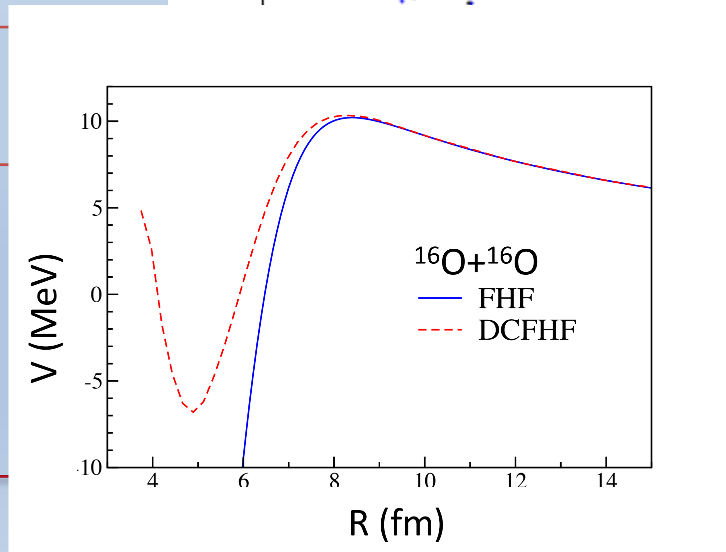
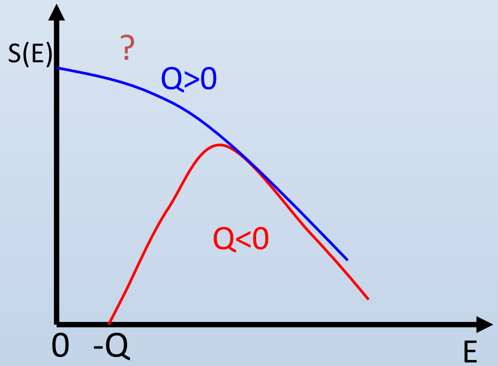


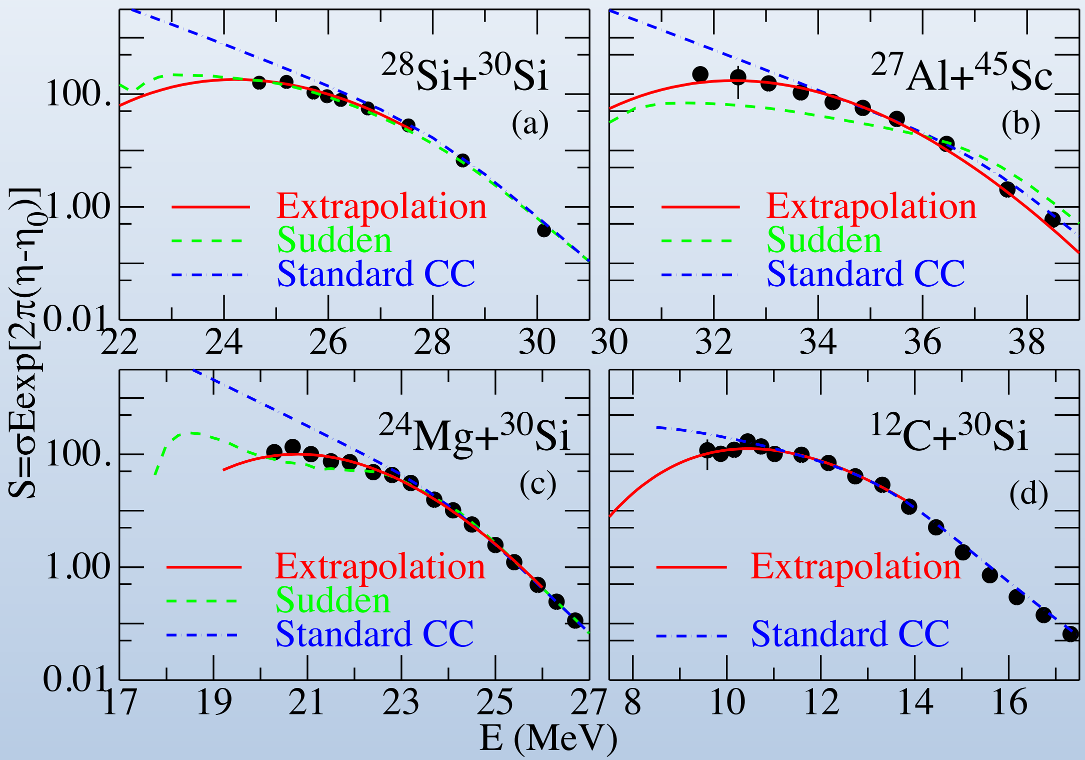


C. Simenel et al. PRC95, 031601(R) (2017)

Is there something special with systems having $Q_{fus} > 0$?

The astrophysical
S-factor $S(E) = E\sigma(E)e^{2\pi\eta}$



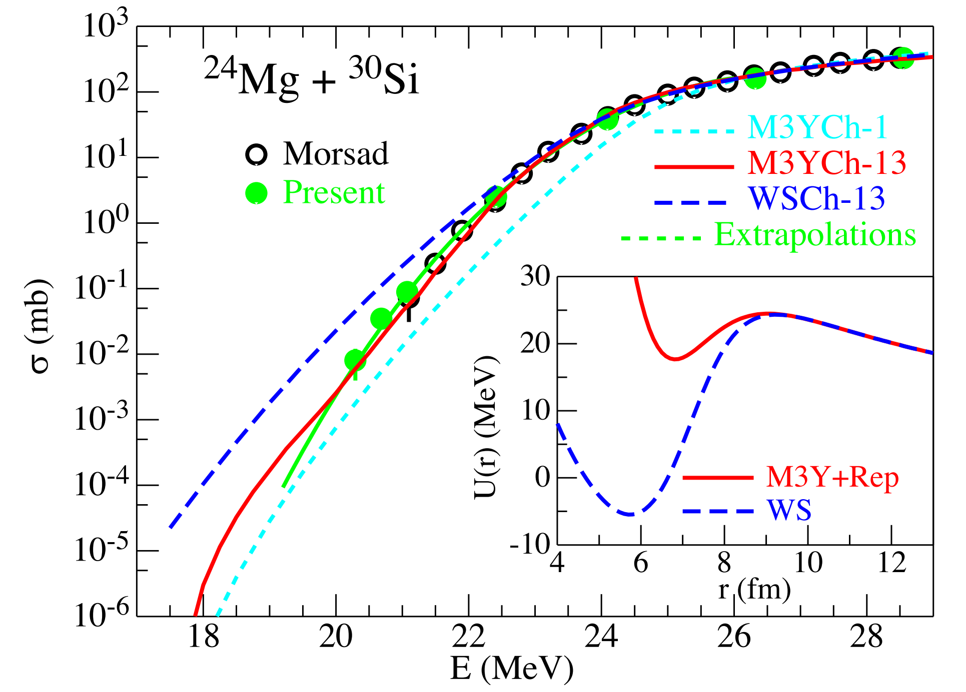


	E_{min}	$e^{2\pi\eta}$	S(E)
Q<0	-Q	finite	0
Q>0	0	$\rightarrow\infty$	finite ?

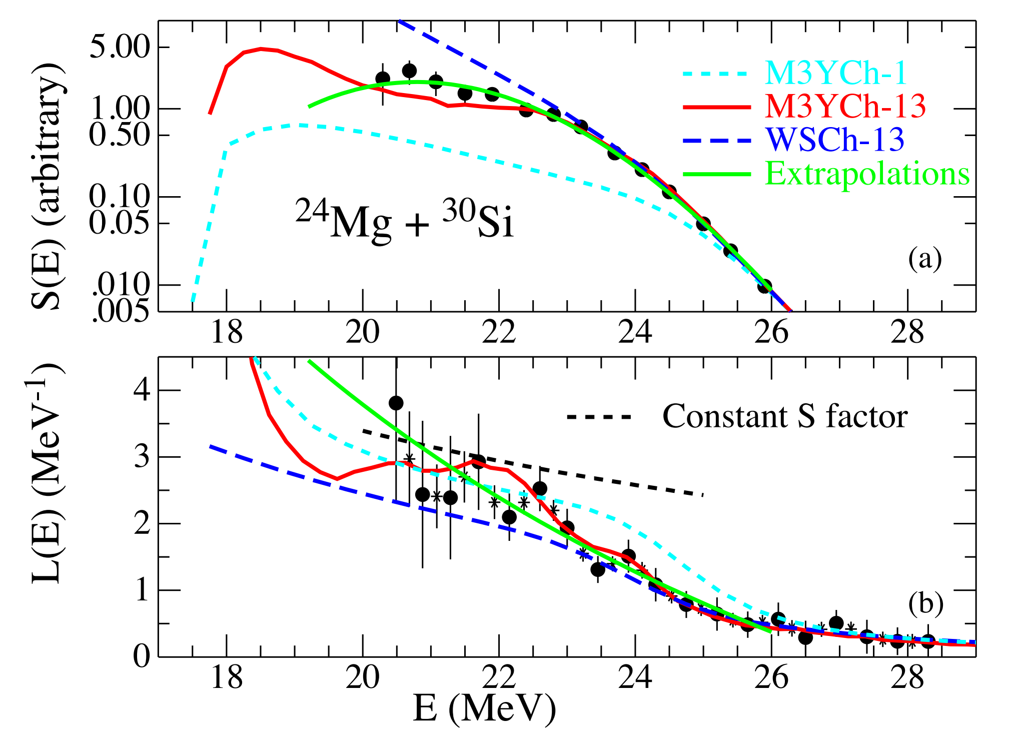
There is some evidence for an **S** -factor maximum, but the possible existence of that maximum is not so clear.
G.M. and A.M. Stefanini, EPJA 53, 169 (2017)

For $Q_{fus} > 0$ S(E) may not show any maximum !

Light systems with Q>0: the case of $^{24}Mg + ^{30}Si$

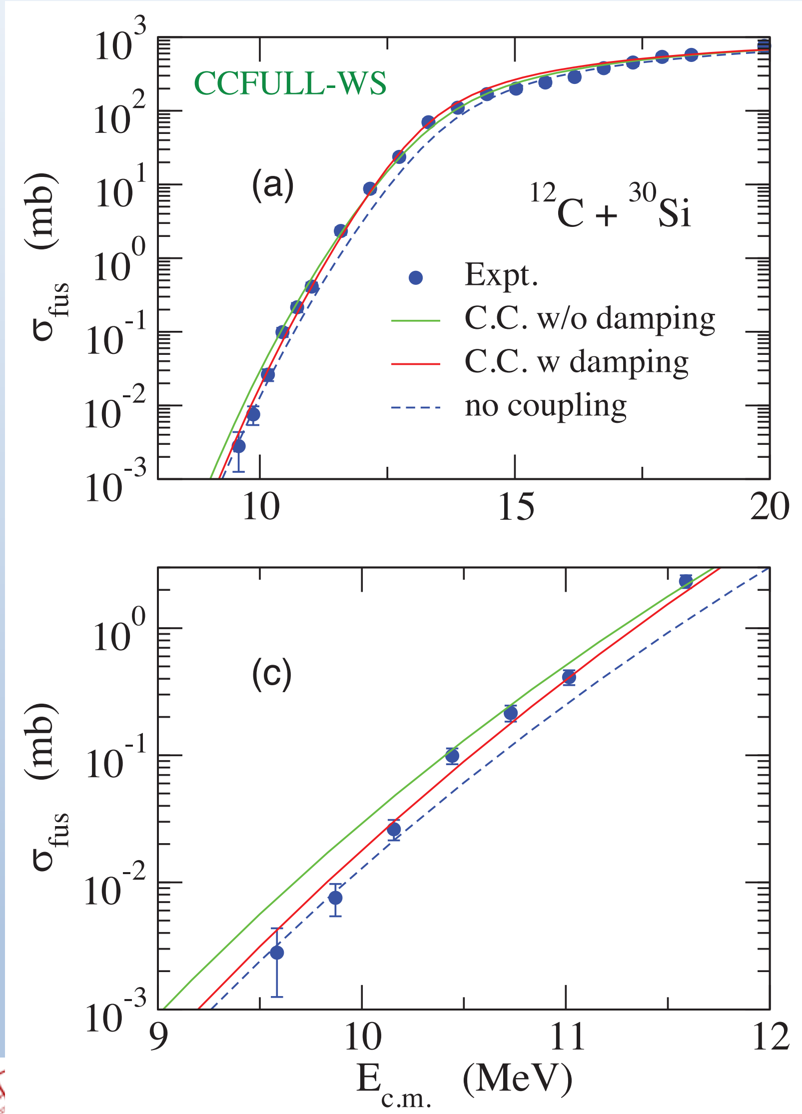


An S-factor maximum has been observed for $^{24}Mg + ^{30}Si$ (Q_{fus} = +17.89 MeV)



C.L.Jiang, A.M.Stefanini, H.Esbensen et al., Phys. Rev. Lett. 113, 022701 (2014)

Excitation function compared with CC calculations



The fusion excitation function of ^{12}C + ^{30}Si has been measured with high statistical accuracy, Q_{fus}=+14.1 MeV.

Calculations were performed within the Hagino-Ichikawa model that considers a damping of the coupling strength well inside the Coulomb barrier.

The calculations give a good account of the data, although the degree of hindrance is much smaller than in heavier systems.

G. M. et al., Phys. Rev. C 97, 024610 (2018)

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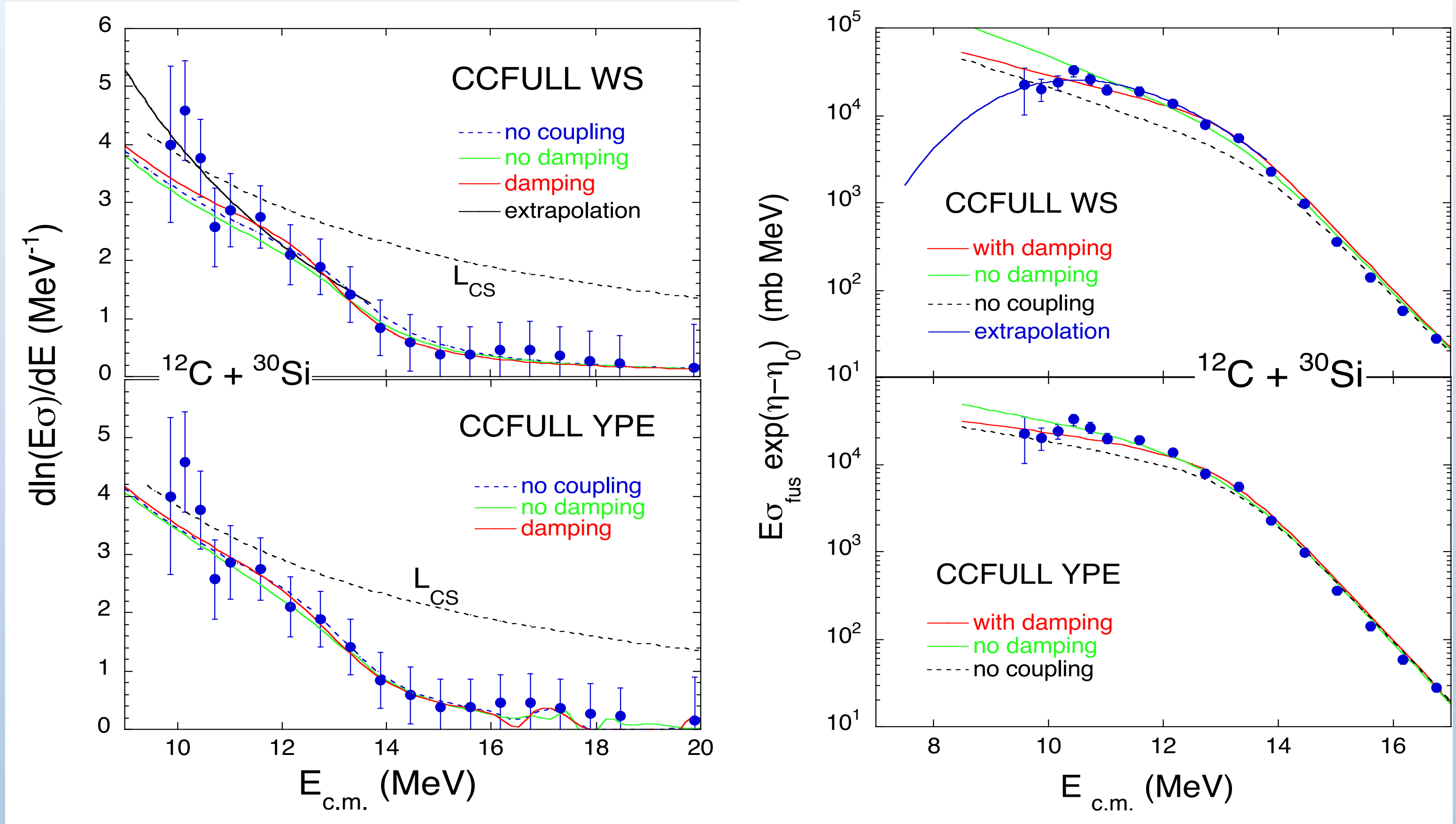
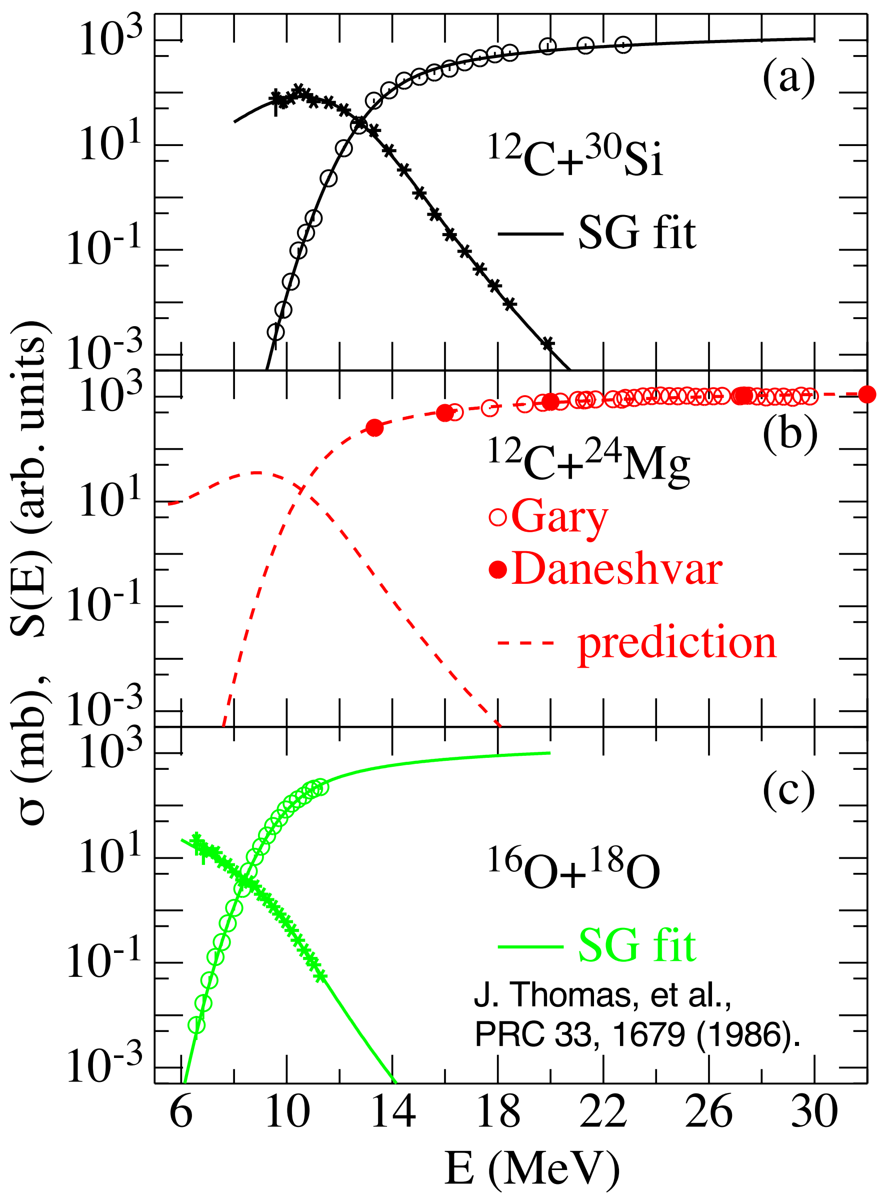
Logarithmic slope and S factor for $^{12}C+^{30}Si$



The logarithmic slope (left) crosses the L_{CS} value at the lowest energies where the S factor (right) appears to develop a maximum. In both cases a phenomenological extrapolation is shown, based on the systematics of C.L. Jiang

C.L.Jiang et al., PRC79, 044601 (2009)



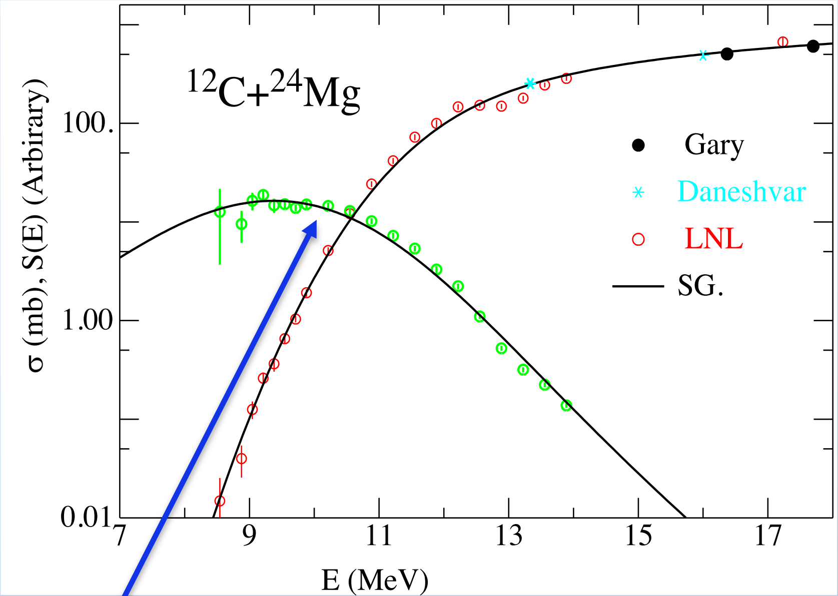
$^{12}C+^{30}Si$ and two lighter systems

The system $^{12}C+^{24}Mg$ is an interesting case but previous data do not extend below the barrier.

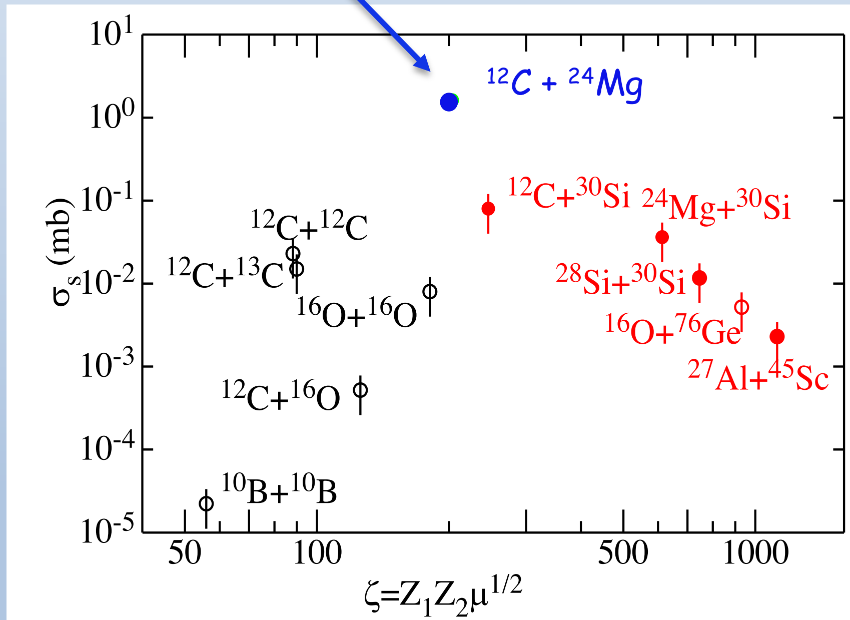
The curves for $^{16}O + ^{18}O$ and $^{12}C + ^{30}Si$ (SG) are the results of three-parameter fits of the barrier distributions* that have been interpolated to obtain the predic-tions for $^{12}C + ^{24}Mg$

* C.L. Jiang et al., EPJA 54, 218 (2018)

The case of $^{12}C + ^{24}Mg$ (preliminary data)



The threshold cross section is very high (σ_s=1.6mb) for this system, allowing to identify the hindrance phenomenon. It may be possible to extend the measurements further down in energy



The S-factor develops a clear maximum, indicating the presence of hindrance. The curves are least-square fits of the excitation function

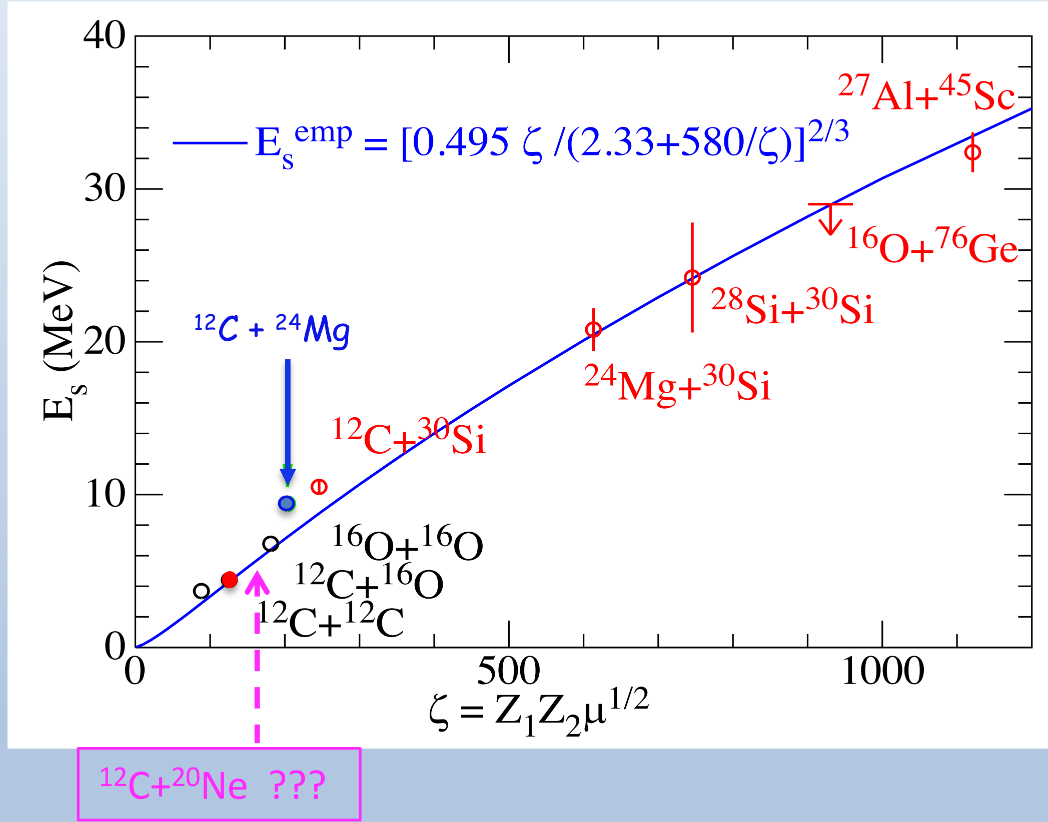
Threshold energies for hindrance in light systems

The system $^{12}C + {}^{30}Si$ has a ζ parameter very near to the lighter systems important for stellar evolution. Its Q-value for fusion is positive (Q=+14.1 MeV)

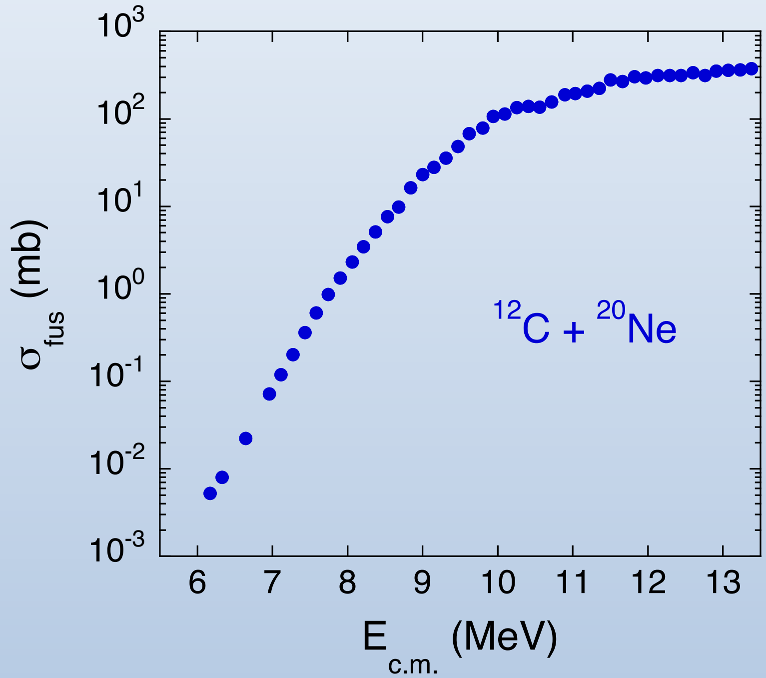
$^{12}C + {}^{24}Mg$ (Q=+16.3 MeV) is even closer to the light systems and has been measured very recently

The case of $^{12}C + {}^{20}Ne$ raises questions ….

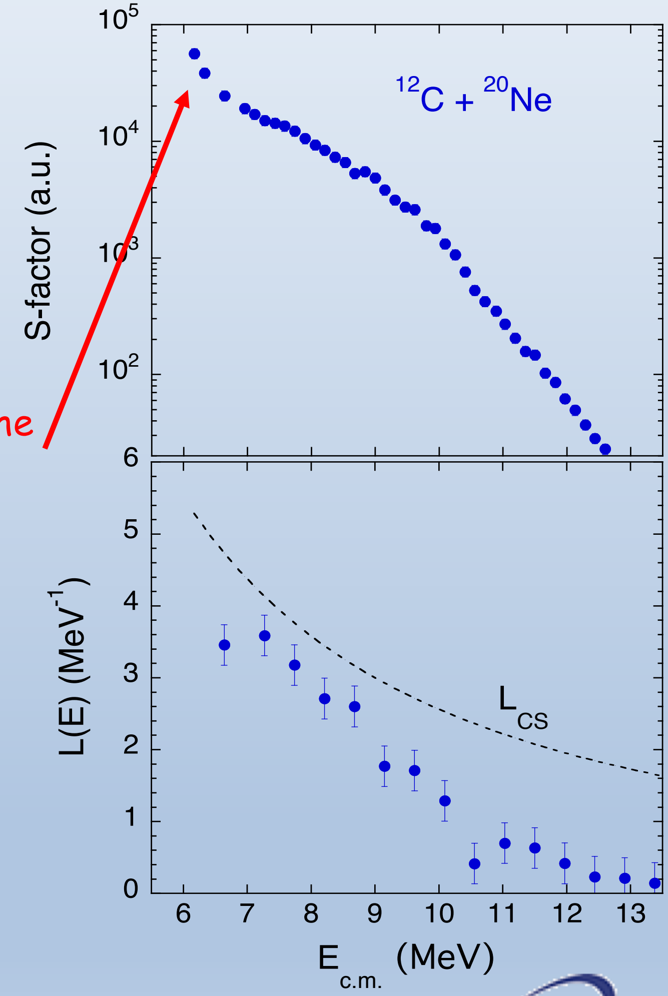
N.B. (the points of C+C and O+O are obtained only from extrapolations)



The case of $^{12}C + ^{20}Ne$



Increase of the S factor !?



This system was measured down to a few μb, but no hindrance seems to show up. Indeed from the systematics of Jiang one expects that the threshold is below 6 MeV where the cross section is probably ≈ 0.2-0.5 μb

G. Hulke et al., Z. Physik A 297, 161 (1980)

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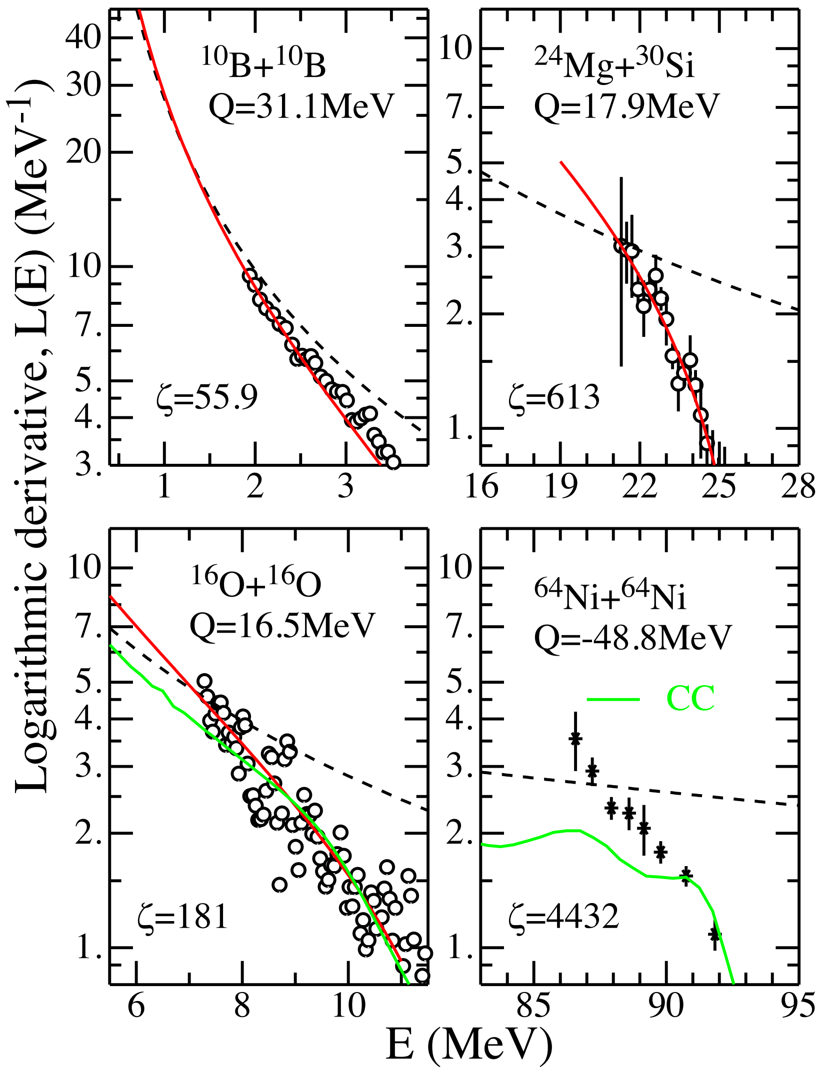
Logarithmic derivative for heavy and light systems

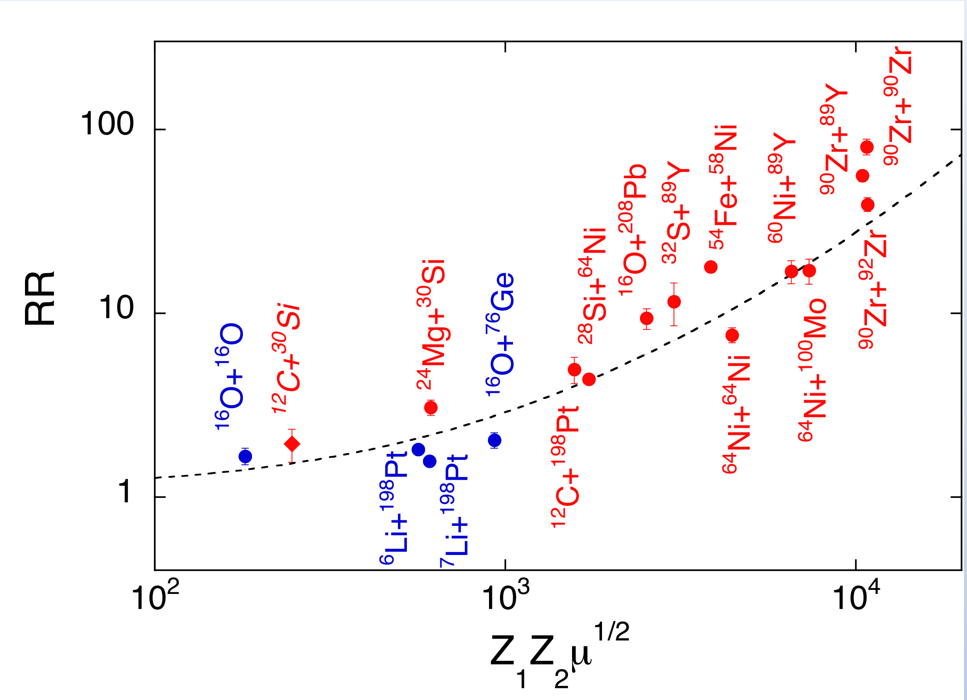


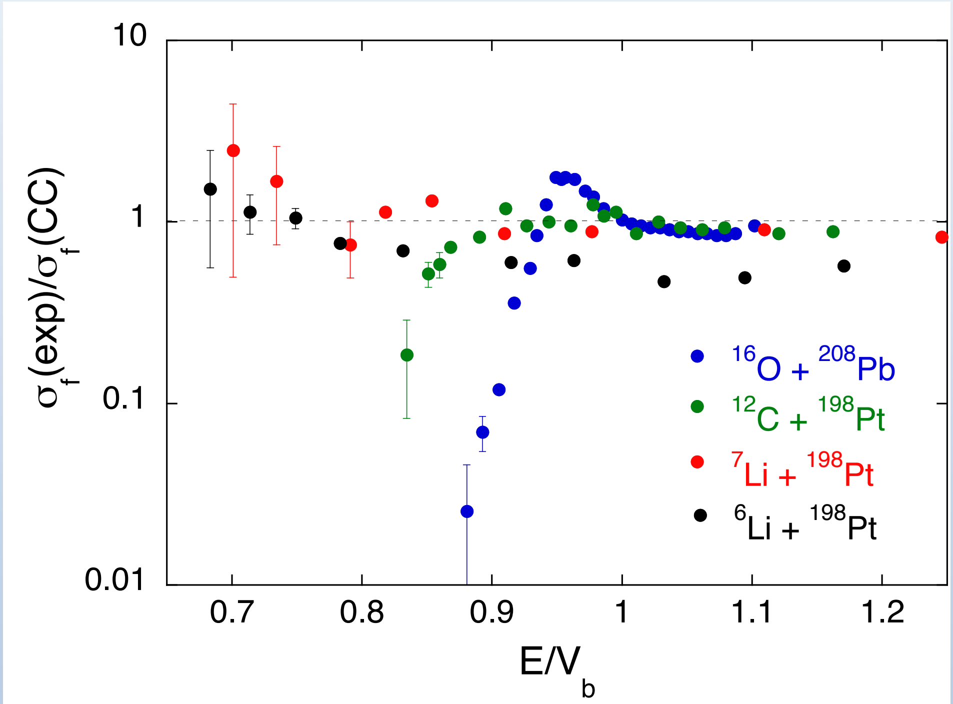
- Various heavy and light systems are represented here. In each case the Q value for fusion is indicated, as well as the system parameter ζ.

- The dashed line is $L_{CS}(E)$, the red one is a simple extrapolation and the green lines are standard CC calculations.

- For lighter systems, L(E) and $L_{cs}(E)$ are two nearly parallel or overlapping curves so the crossing point is rather undetermined and the S factor maximum becomes broader

Further systematic trends





RR is the ratio of energy derivatives of the slopes **L**(**E**) and $\mathbf{L}_{CS}$(E) at their crossing points, vs. the system parameter ζ

Measured vs. calculated fusion cross sections. Calculations have been performed with CCFULL using a standard WS potential

C.L. Jiang et al., PRC 75, (2007) 057604

A.Shrivastava et al., PLB 755 , (2016) 332

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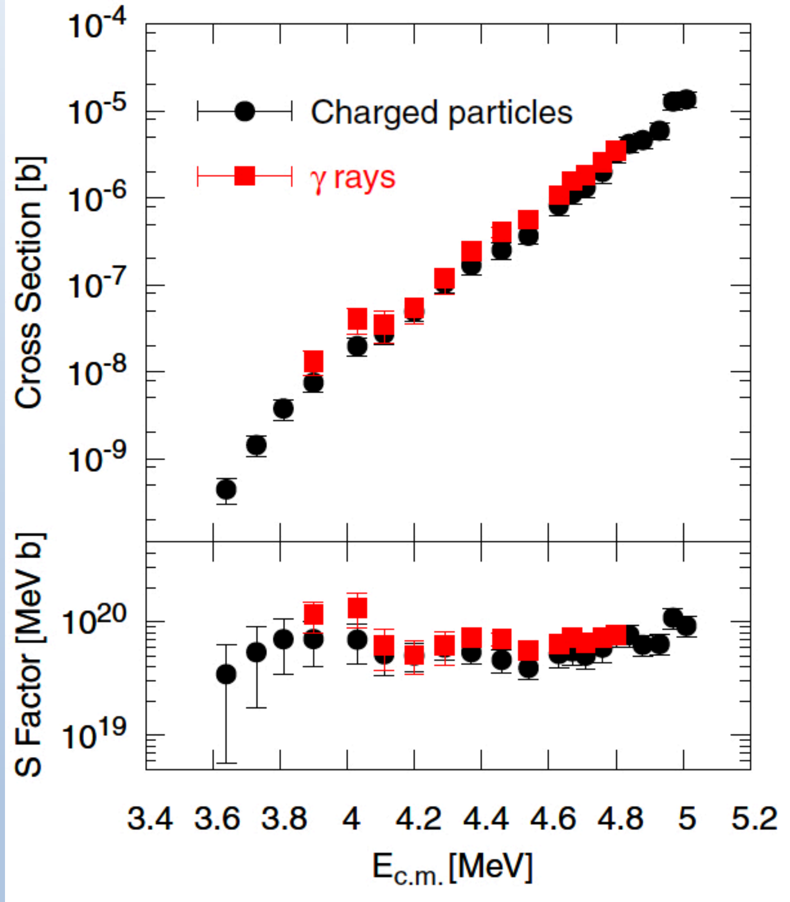
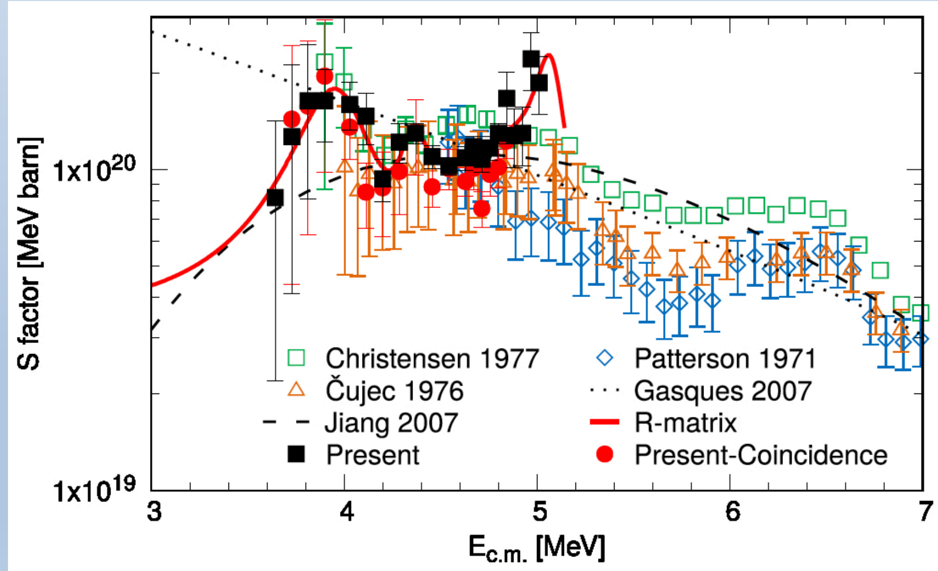
Fusion of the light system $^{12}C + ^{16}O$



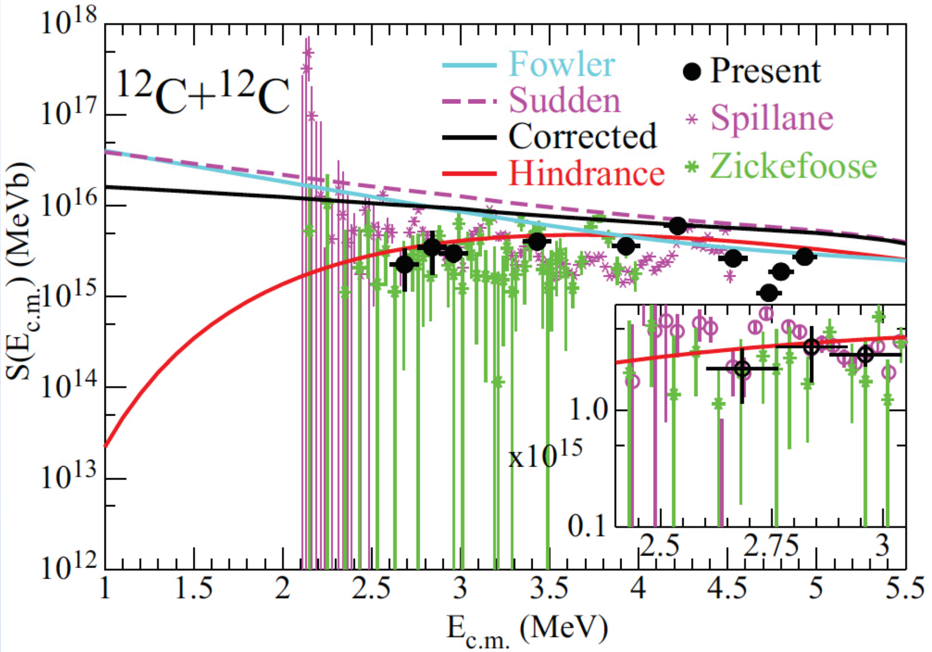
The $^{12}C + ^{16}O$ reaction may play an important role in both the carbon and oxygen burning phases of stars.

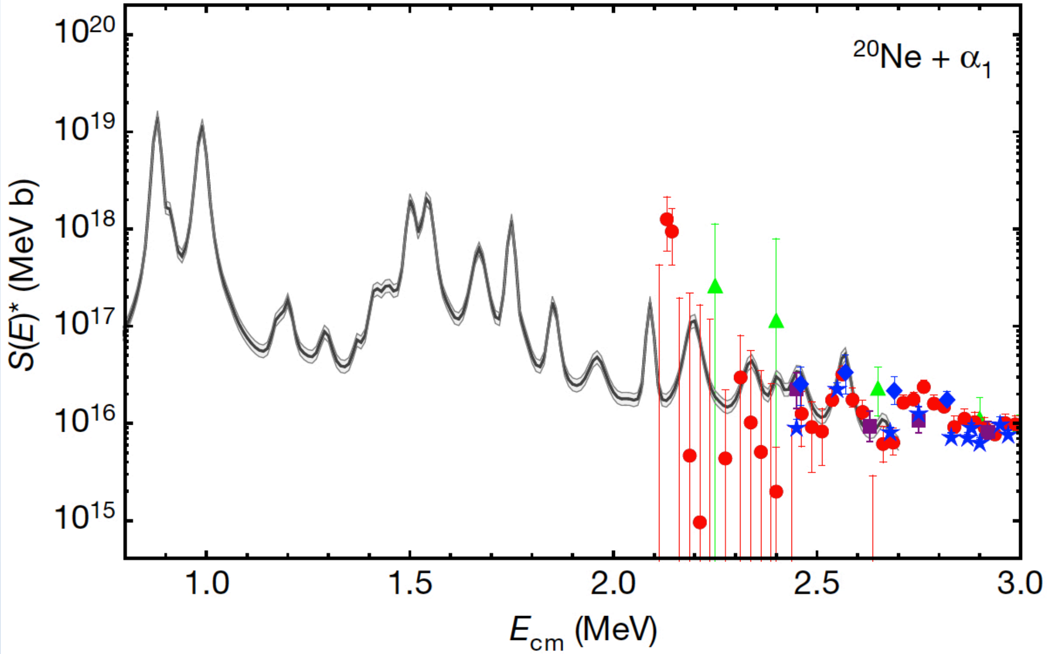
It seems that the low energy trend of the S factor is complicated by the possible evidence of resonances due to "*quasi-molecular states*"



X.Fang et al., PRC 96, 045804 (2017)

Recent results on $^{12}C+^{12}C$





Black points are S factors measured at ANL by C.L. Jiang. Magenta and green stars are results from other recent experiments The insert is a zoom around 2.7 MeV. The lines are various calculations and the red one is the empirical estimate of Jiang et al.

C.L. Jiang et al., PRC 97 (2018) 012801(R)

The black lines are the S factors for $^{12}C + ^{12}C$ fusion, evaporating one-particle, deduced by the Trojan Horse Method. The available direct data are reported as colored points.

A. Tumino et al., Nature 557 (2018) 687

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Summary

- The phenomenon of hindrance in sub-barrier heavy-ion fusion is a general phenomenon.
- It is recognized in many cases by the trend of the logarithmic slope and of the S factor at low energies.
- The comparison with standard CC calculations is a more quantitative evidence for its existence.
- Hindrance is observed even in light systems, independent of the sign of the Q-value, with different features.
- In the two cases $^{12}C + {}^{30}Si$, ^{24}Mg the hindrance effect is small but it is clearly recognized.
- Near-by cases show evidence for systematic behaviors.
- The consequences for the dynamics of stellar evolution have to be clarified by further experimental and theoretical work.

Our collaboration in recent experiments

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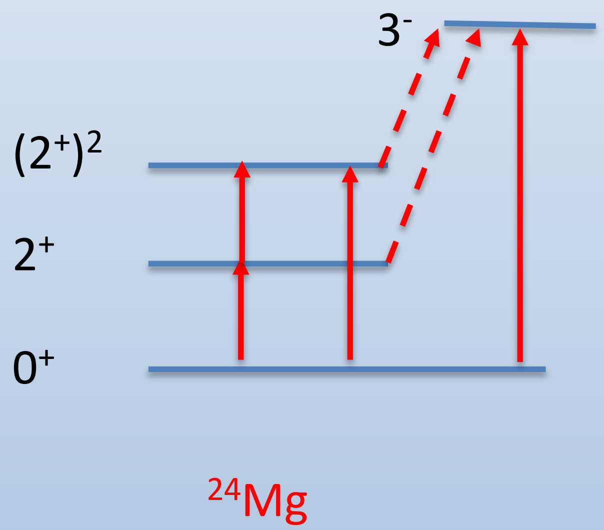
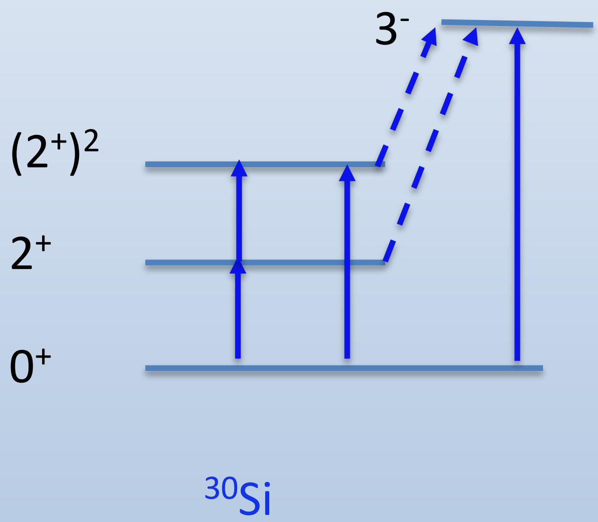
End


3-
(2+)2
2+
0+
24Mg


3-
(2+)2
2+
0+
30Si

Astrophysical S-factor and logarithmic slope L(E)

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

$$\eta = 0.157\frac{Z_1 Z_2}{\sqrt{\varepsilon}} \quad \text{where } \varepsilon = E/\mu$$

$$L(E) = \frac{d}{dE}\ln\left[S(E)\cdot e^{-2\pi\eta}\right] = \frac{1}{\left[S(E)\cdot e^{-2\pi\eta}\right]}\frac{d}{dE}\left[S(E)\cdot e^{-2\pi\eta}\right]$$

da cui

$$\frac{d}{dE}\left[S(E)\cdot e^{-2\pi\eta}\right] = e^{-2\pi\eta}\frac{dS(E)}{dE} + S(E)\frac{de^{-2\pi\eta}}{dE}$$

e quindi

$$\frac{dS(E)}{dE} = S(E)\cdot\left[L(E) + 2\pi\frac{d\eta}{dE}\right] = S(E)\cdot\left[L(E) - \frac{\pi\eta}{E}\right]$$

$L(E) = d[\ln(E\sigma)]/dE$

$dS/dE = S(E)[L(E) - \pi\eta/E]$

S has a maximum when $dS/dE = 0$, i.e. when $L(E) = \pi\eta/E = L_{CS}$

The energy $E = E_S$ where this happens (if it happens !) has been usually taken as the threshold energy for hindrance.

From the empirical systematics of Jiang et al. one obtains

$E_S \approx 0.356\ [Z_1 Z_2 \sqrt{\mu}]^{2/3}$ MeV

C.L.Jiang et al., PRC 73, 014613 (2006)