Heavy-Ion Fusion Experiments and their possible Astrophysical Interest

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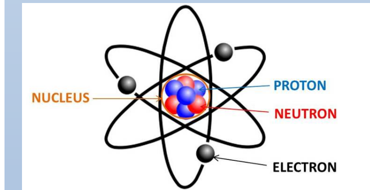
Nuclear Physics



Heavy-Ion fusion

Sub-barrier hindrance

Light systems

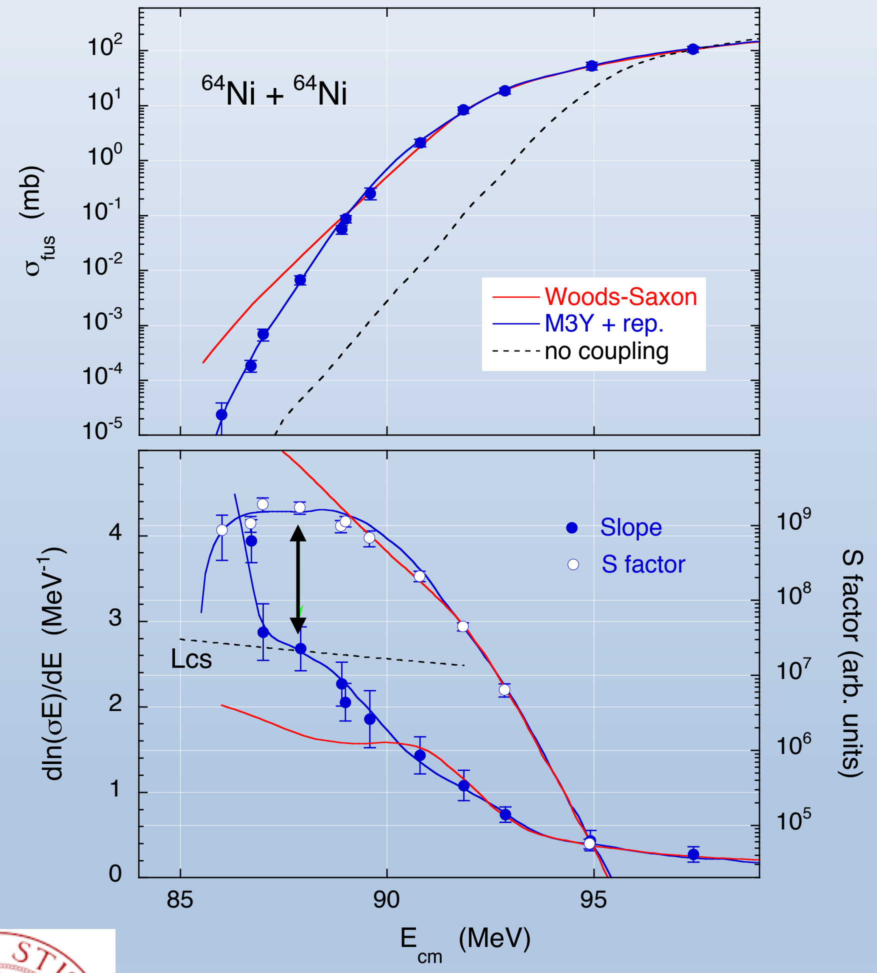
Stellar evolution

Astrophysics

Layout

- The phenomenon of fusion hindrance in sub-barrier heavy-ion reactions
- Fusion hindrance as a general phenomenon
- The case of the $^{12}C + ^{30}Si$ system: sub-barrier trends of the excitation function and of the S-factor
- Other near-by cases: evidence for systematic behaviors
- Towards light systems and consequences for stellar evolution
- Summary

Fusion hindrance far below the barrier



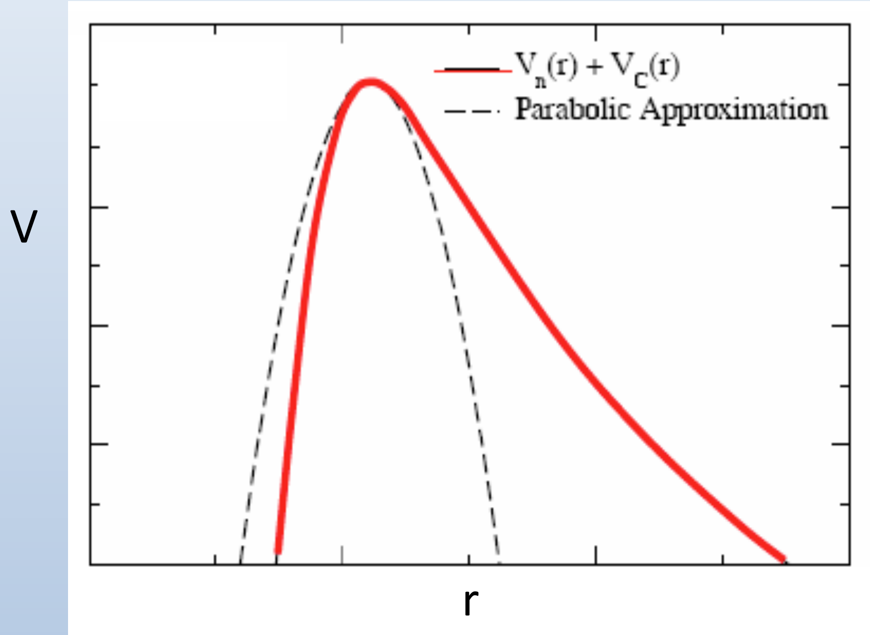
The "classical" case ^{64}Ni+^{64}Ni

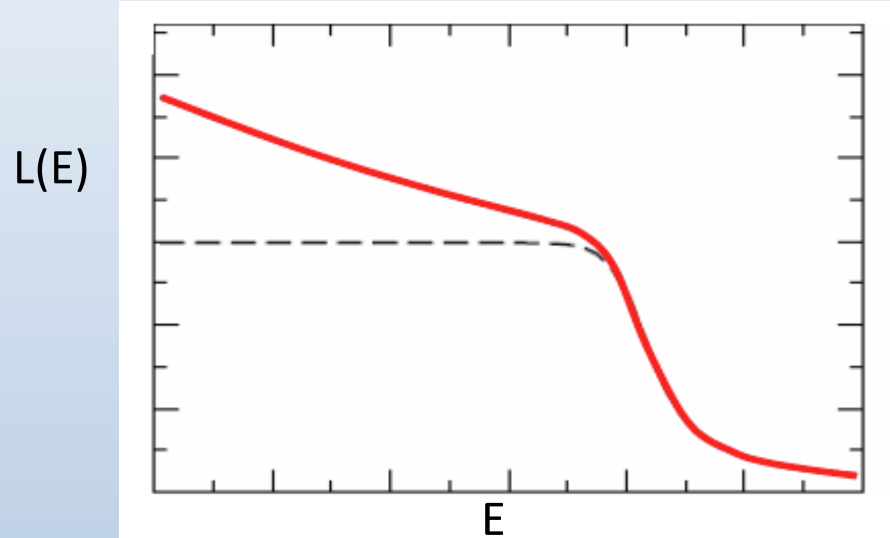
Standard CC calculations based on a Woods-Saxon potential overpredict the excitation function

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

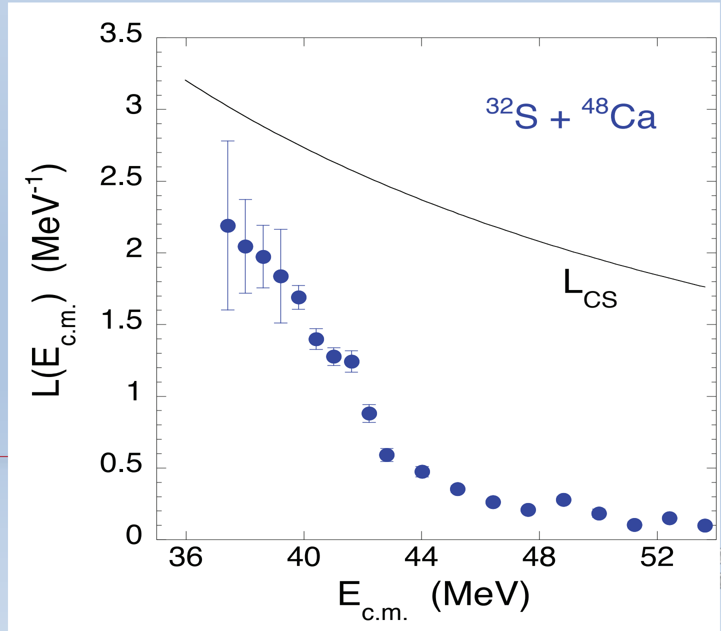
The logarithmic derivative (or slope) L(E) = dln(Eσ)/dE is a useful quantity, because it allows plotting the trend of cross sections extending over several decades in a linear scale





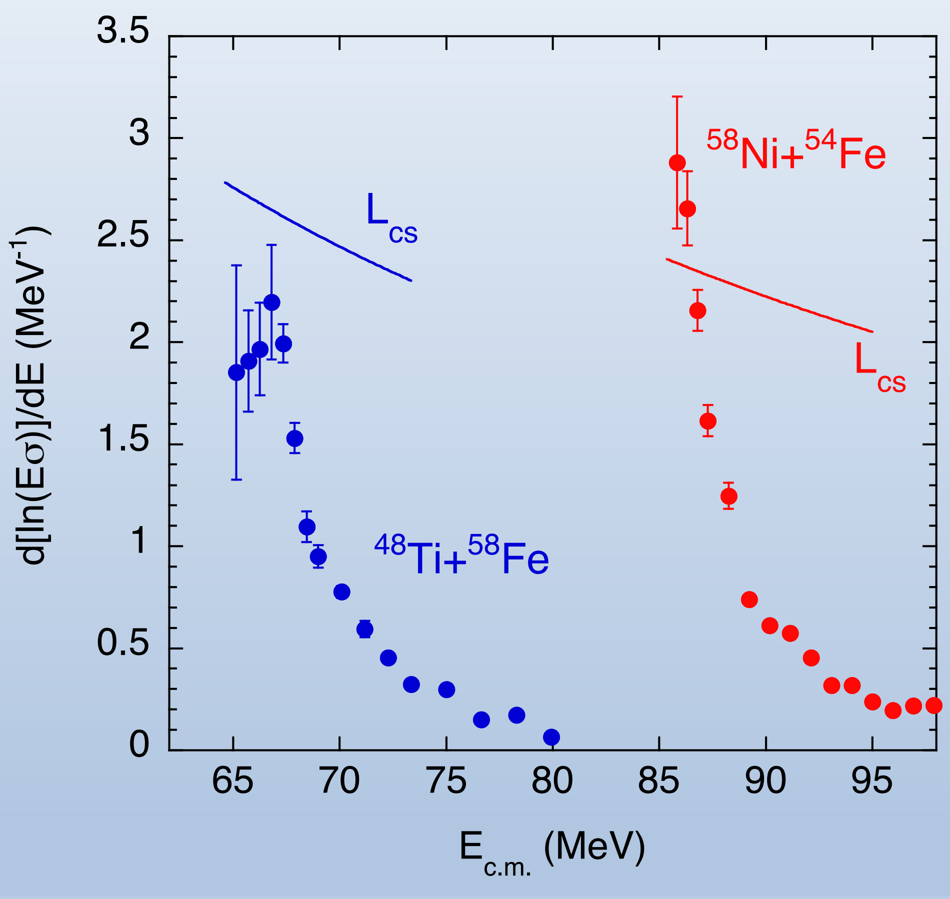
For a parabolic barrier L(E) = 2π/ħω is constant below the barrier. For a realistic barrier L(E) increases with decreasing energy.

K.Hagino et al, PRC67, 054603 (2003)

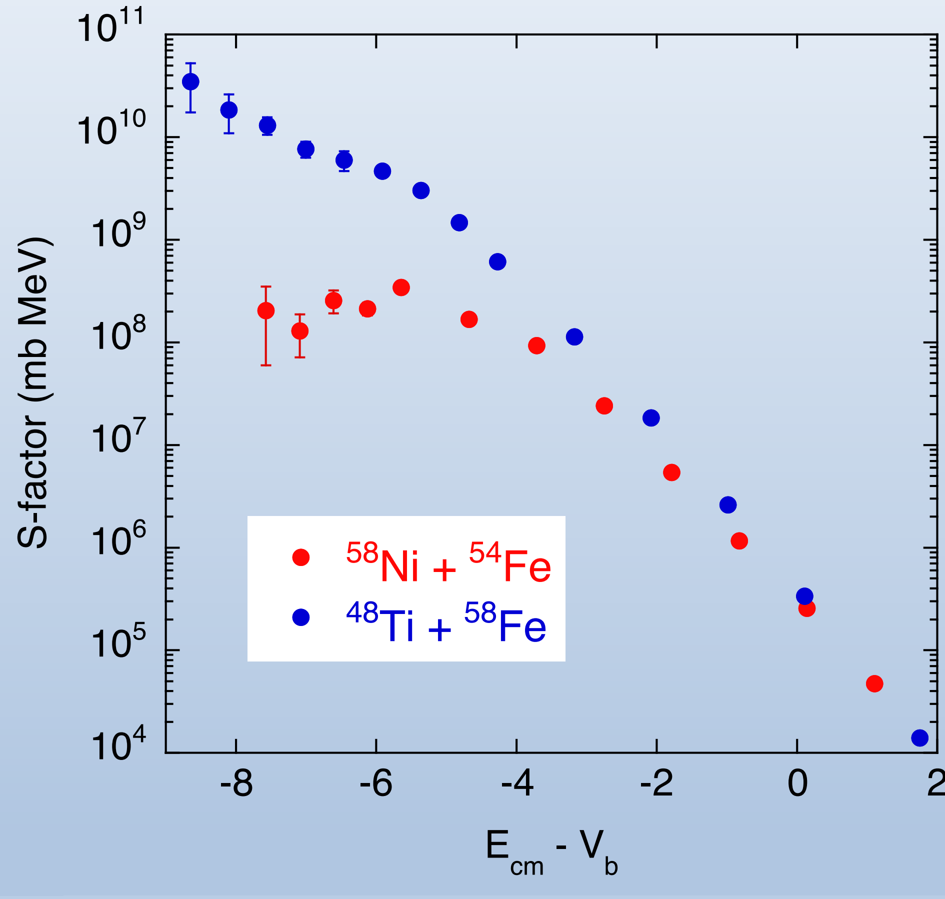


G.M. et al., PRC87, 014611 (2013)

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

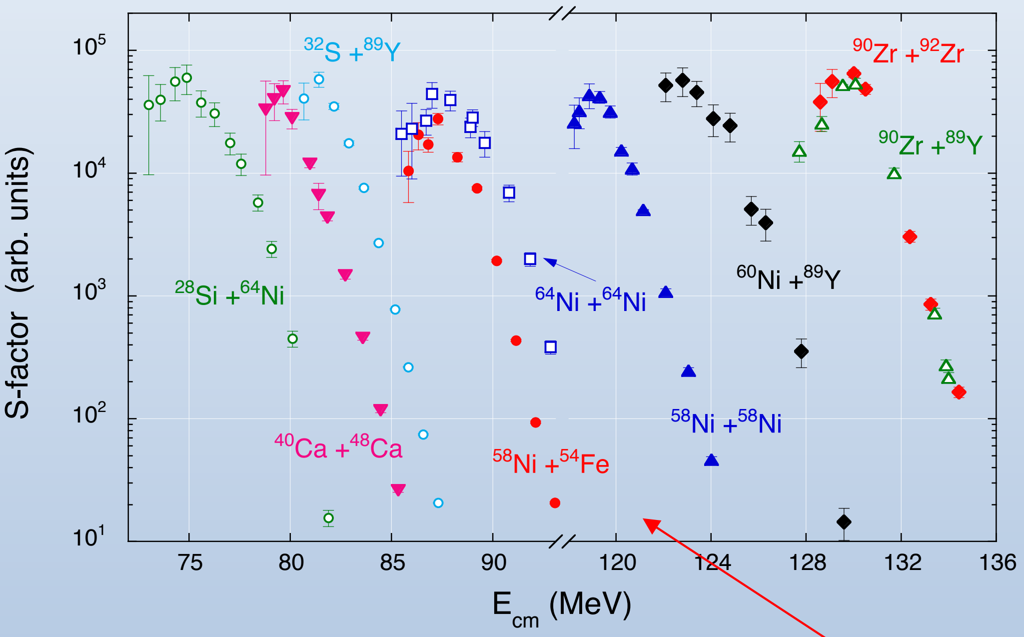


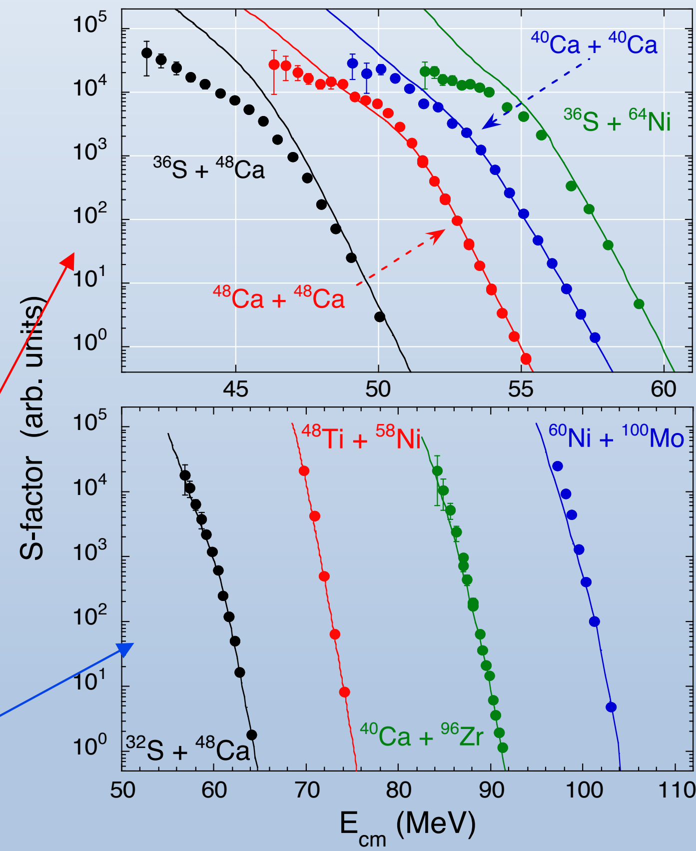
The slope of $^{48}Ti+^{58}Fe$ saturates below the barrier, while it keeps increasing for $^{58}Ni+^{54}Fe$



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



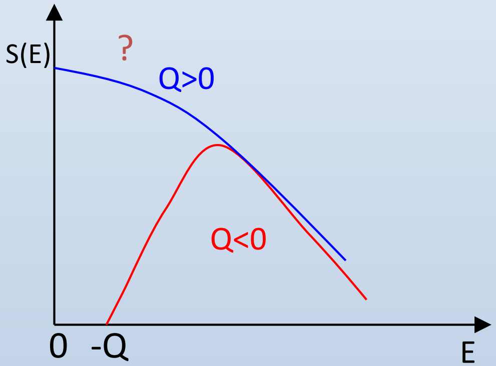


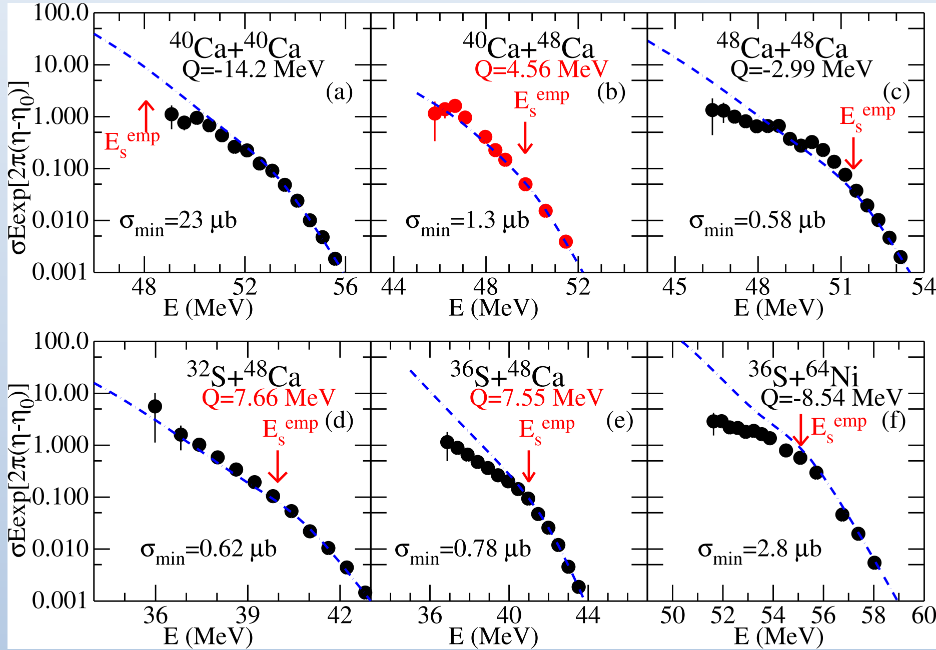
S factor maximum	YES	Hindrance	YES

S factor maximum	NO	Hindrance	YES
S factor maximum	NO	Hindrance	NO

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

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

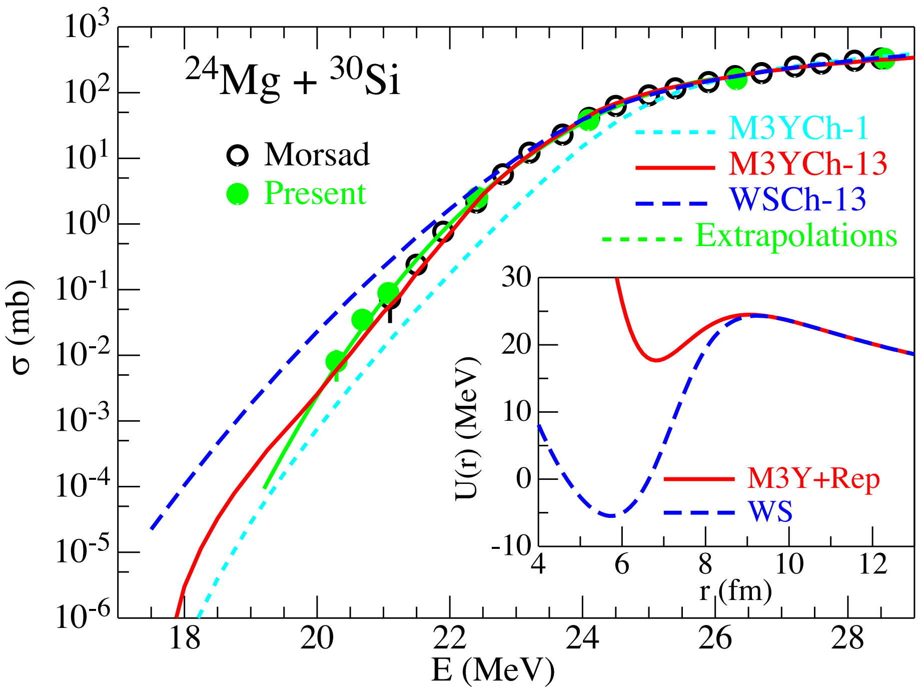




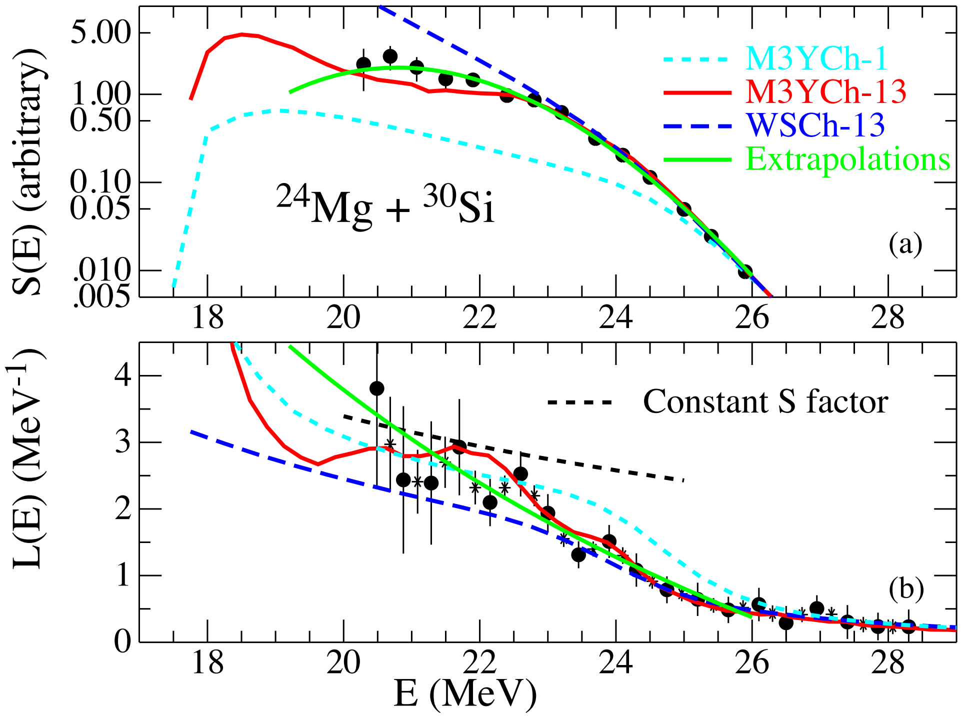
	E_{min}	$e^{2\pi\eta}$	S(E)
Q<0	-Q	finite	0
Q>0	0	→∞	finite ?

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

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

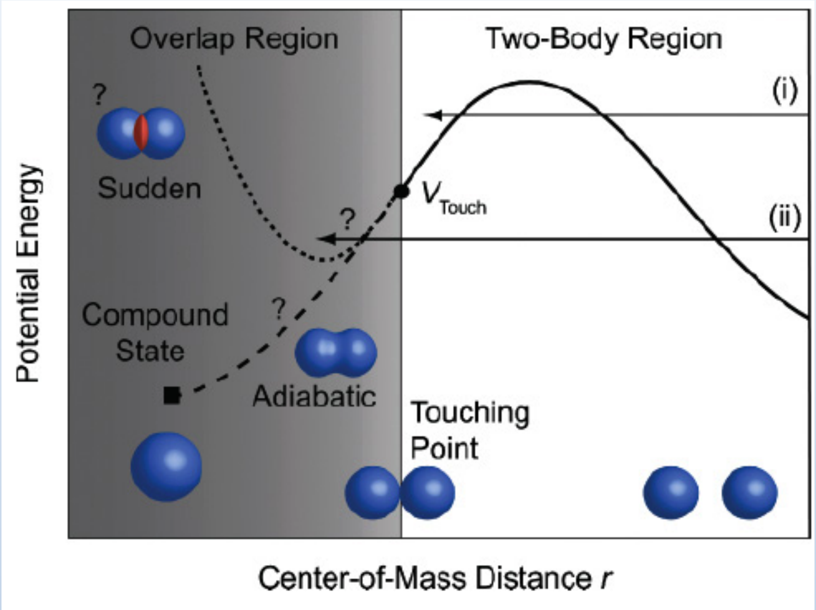


An S-factor maximum has been observed for ^{24}Mg + ^{30}Si (Q_{fus} = +17.89 MeV)



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

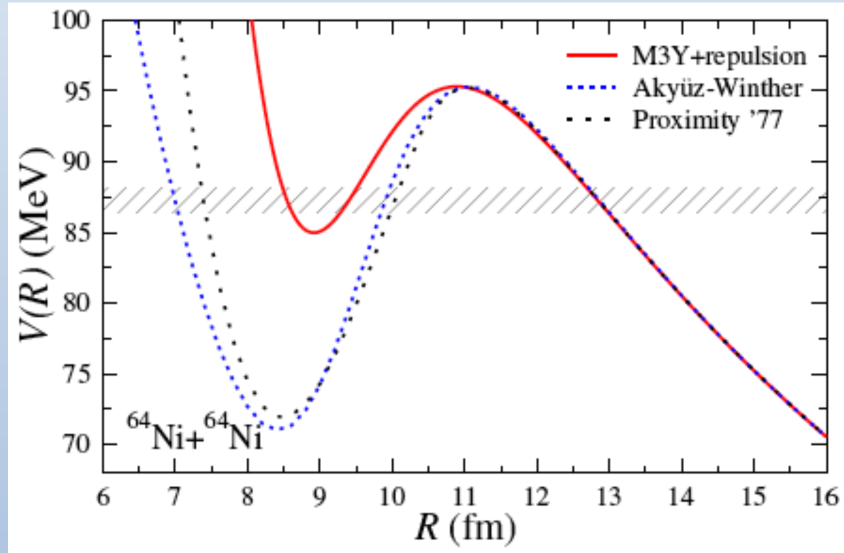
The system evolves in the classically forbidden region towards the compound nucleus



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

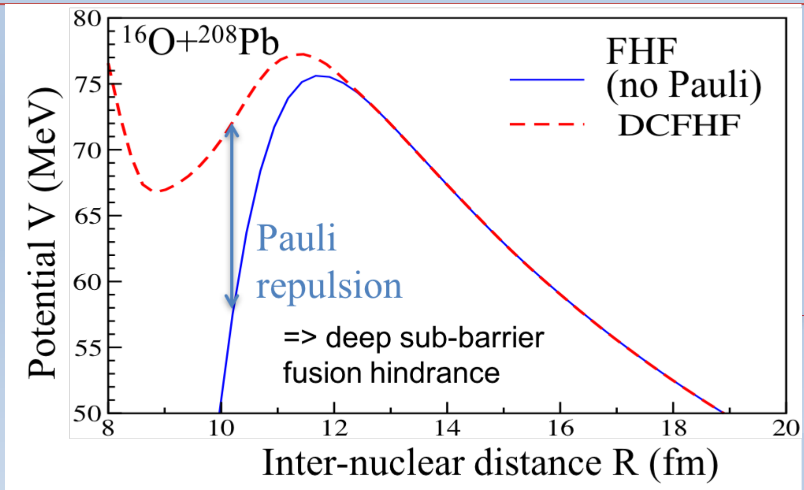
How does one understand the fusion hindrance effect ?

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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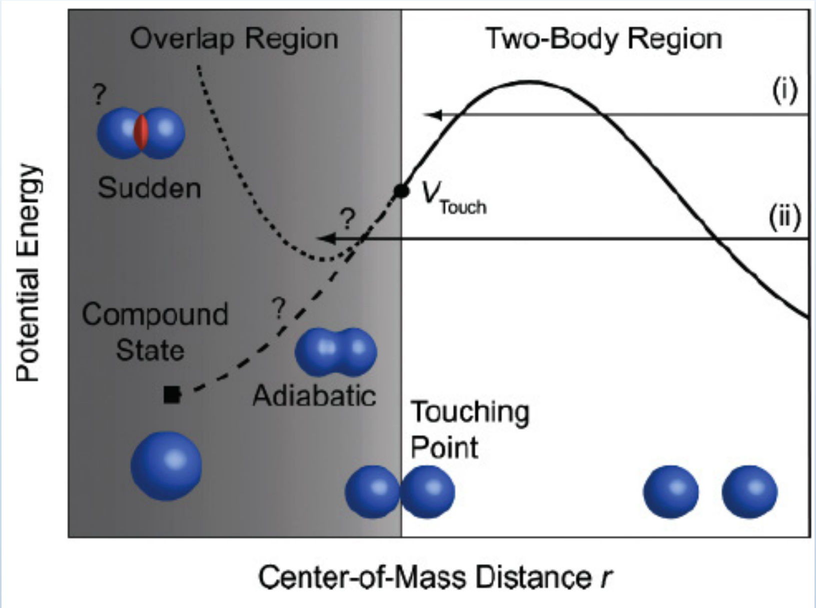

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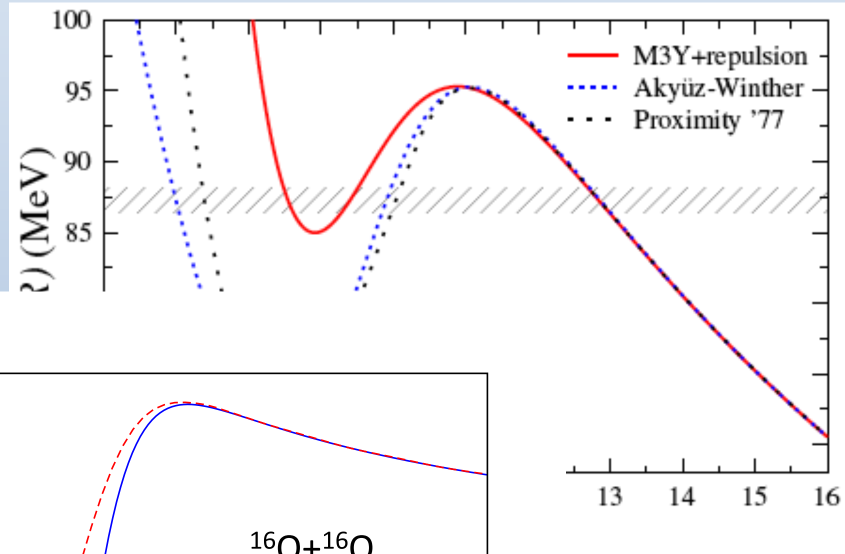

034606 (2007)

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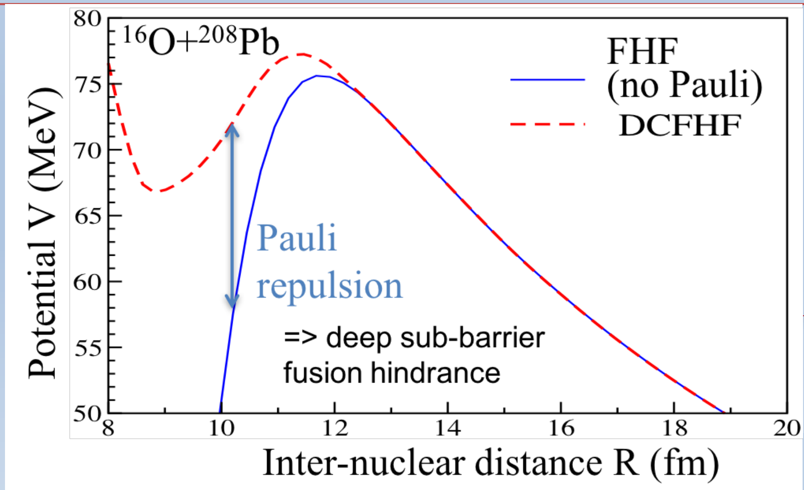

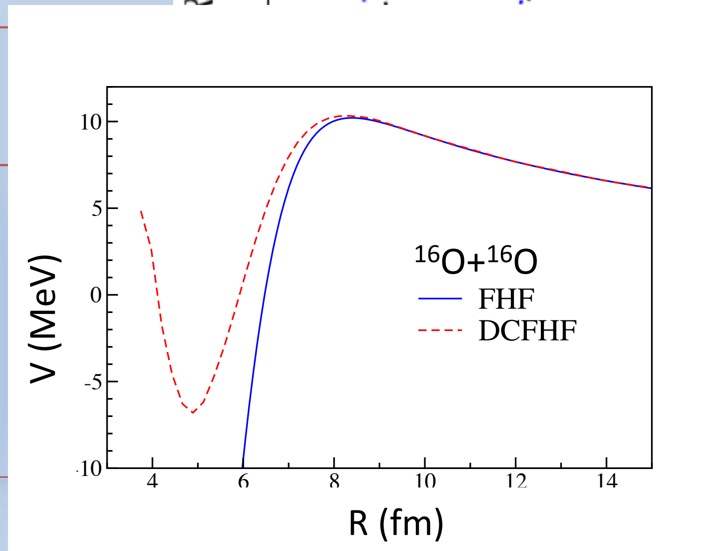

C. Simenel et al. PRC95, 031601(R) (2017)

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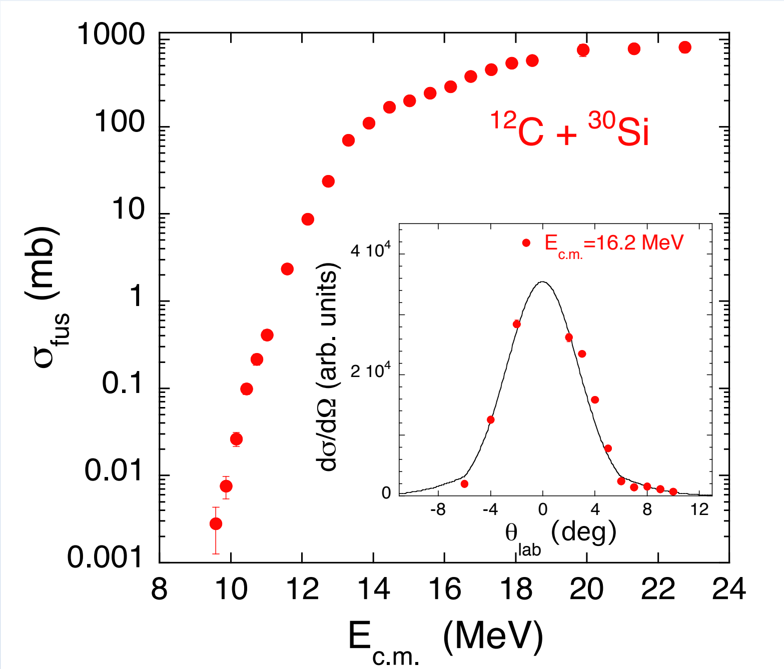
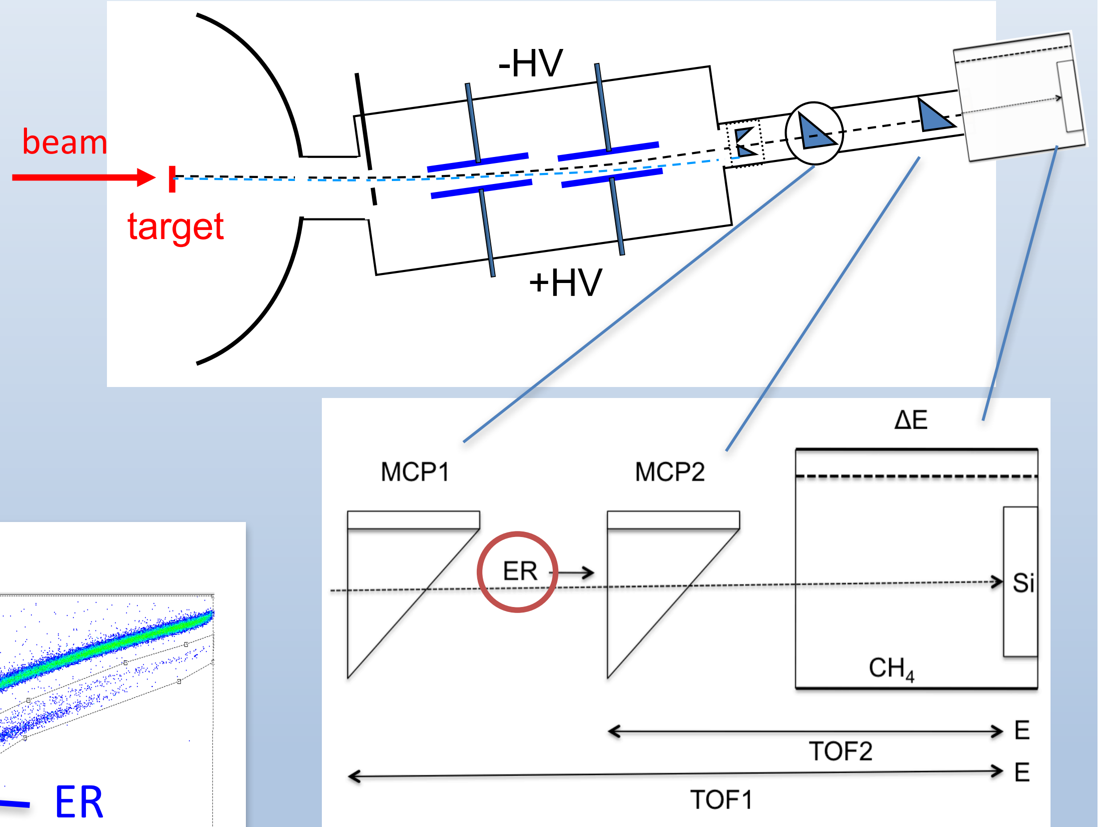
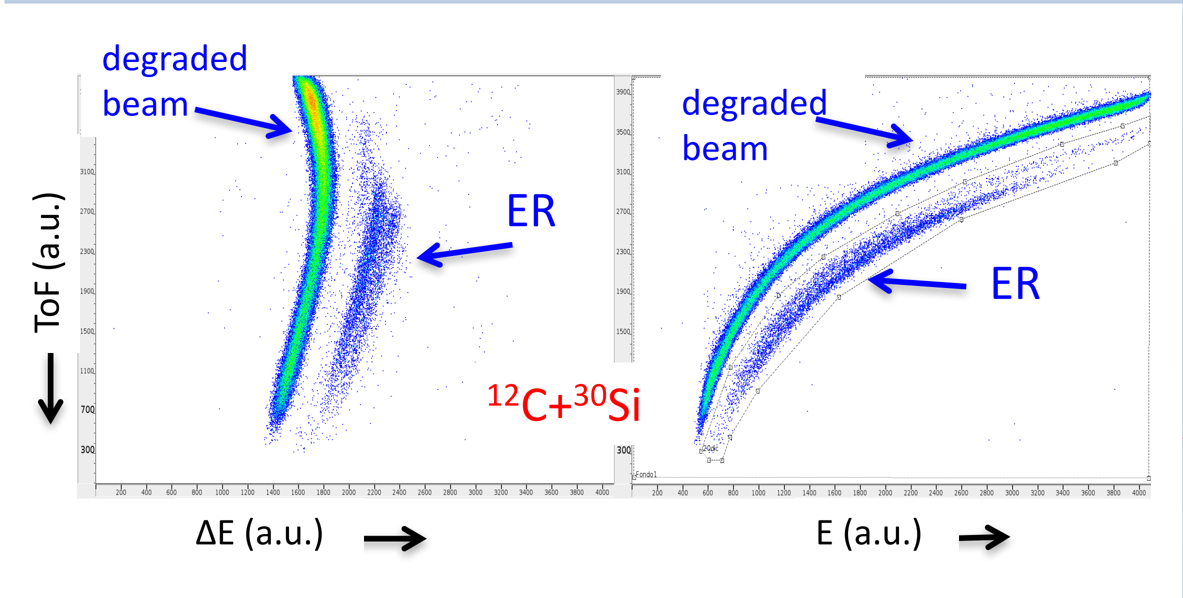
The recent measurement of $^{12}C + ^{30}Si$: fusion cross sections

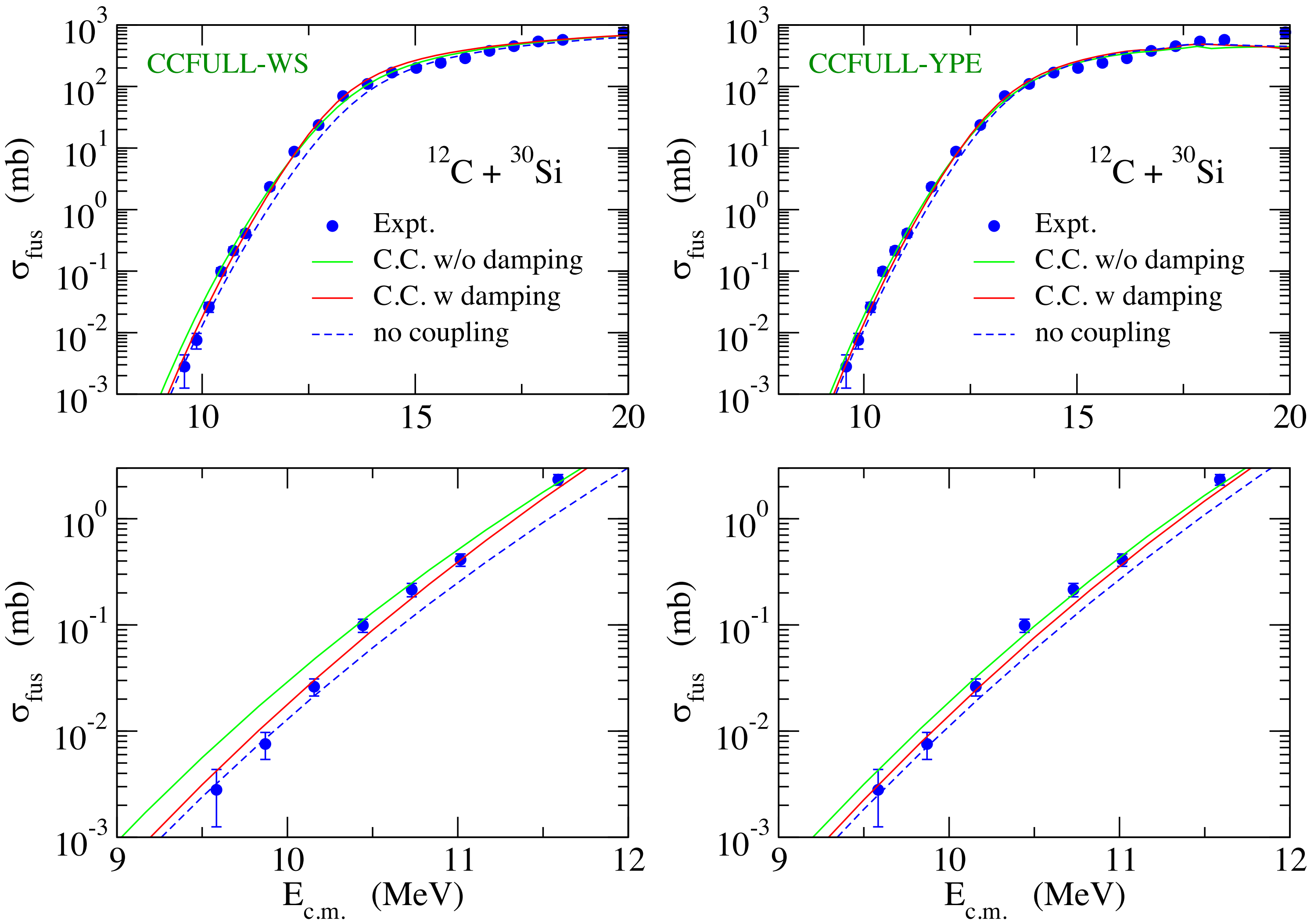




(lowest measurable cross section ≈ 0.5-1 μb)

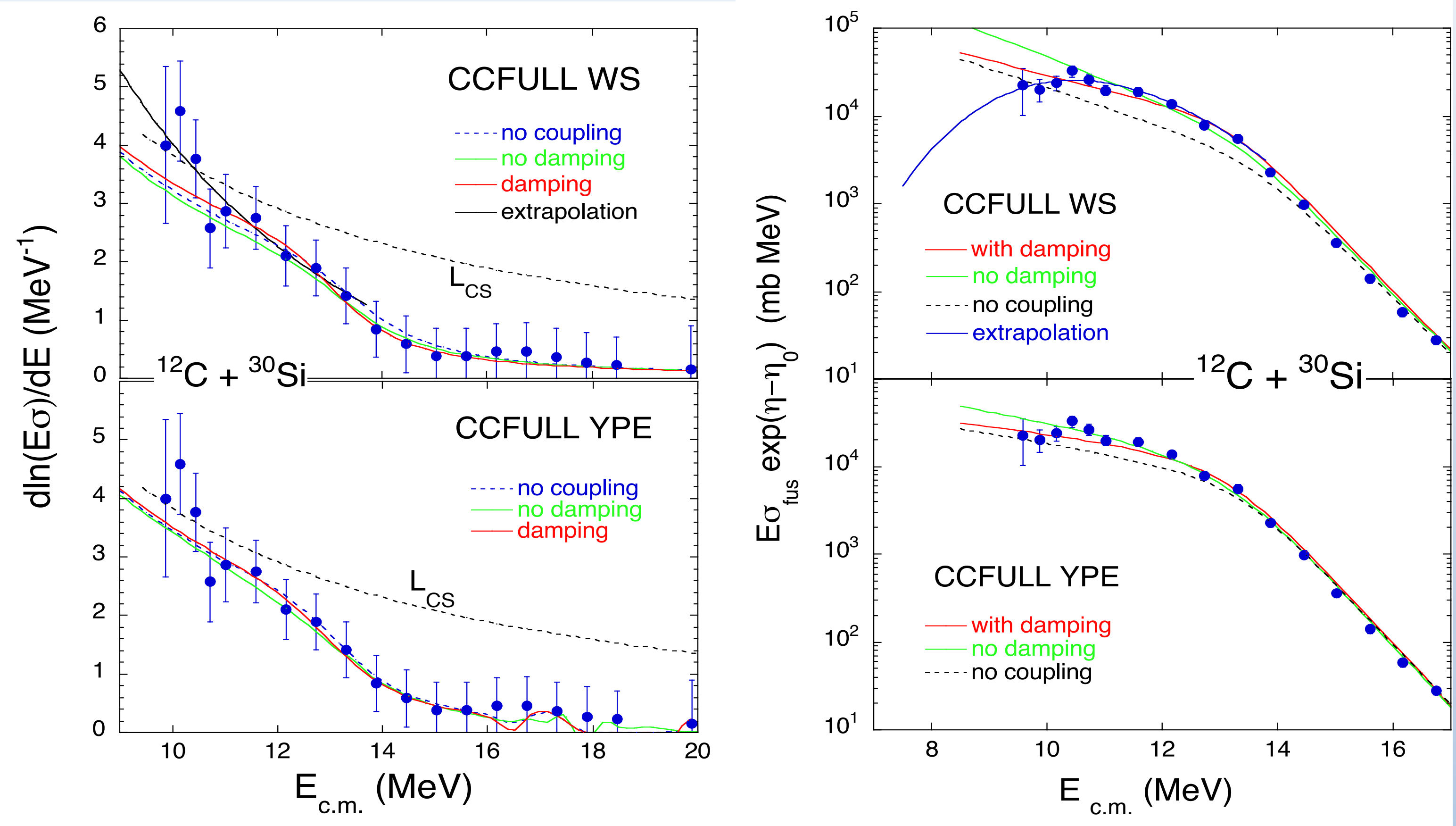


Excitation function compared with CC calculations



The CC calculations employ Woods-Saxon (left) and Yukawa plus exponential (right) potentials, with and without damping of the coupling strengths

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)

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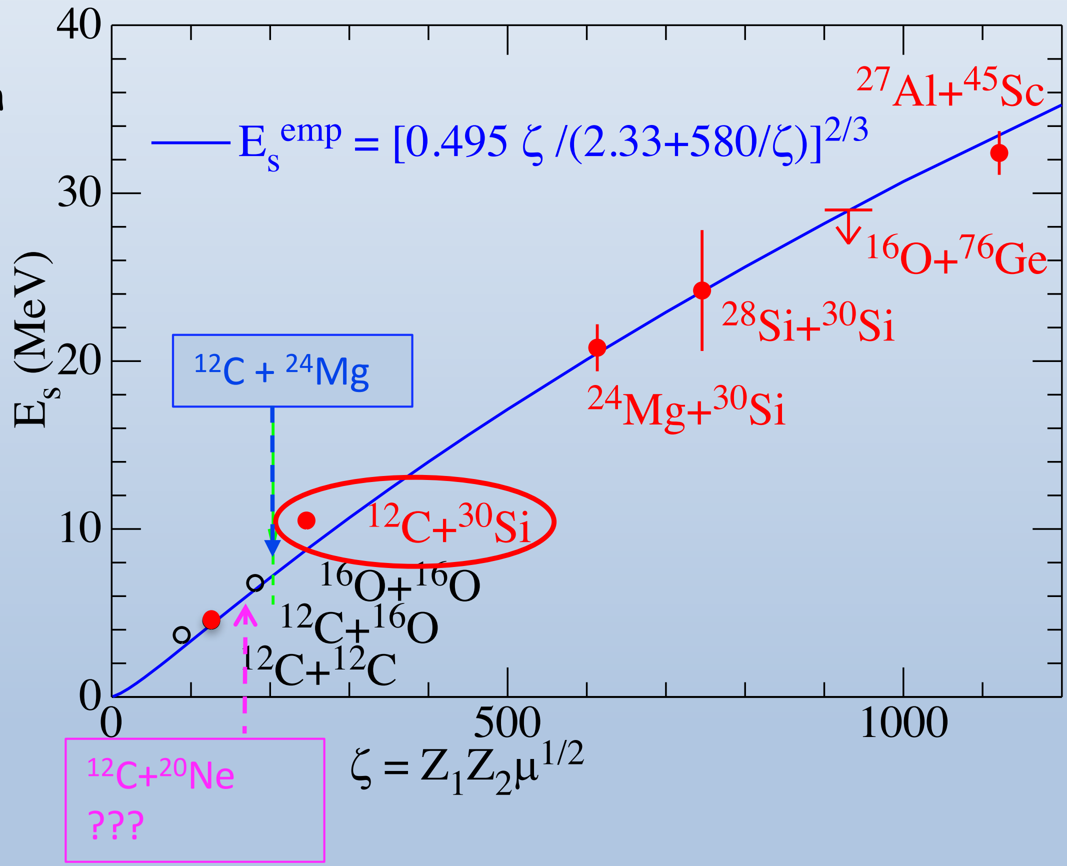
Threshold energies for hindrance in light systems

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)

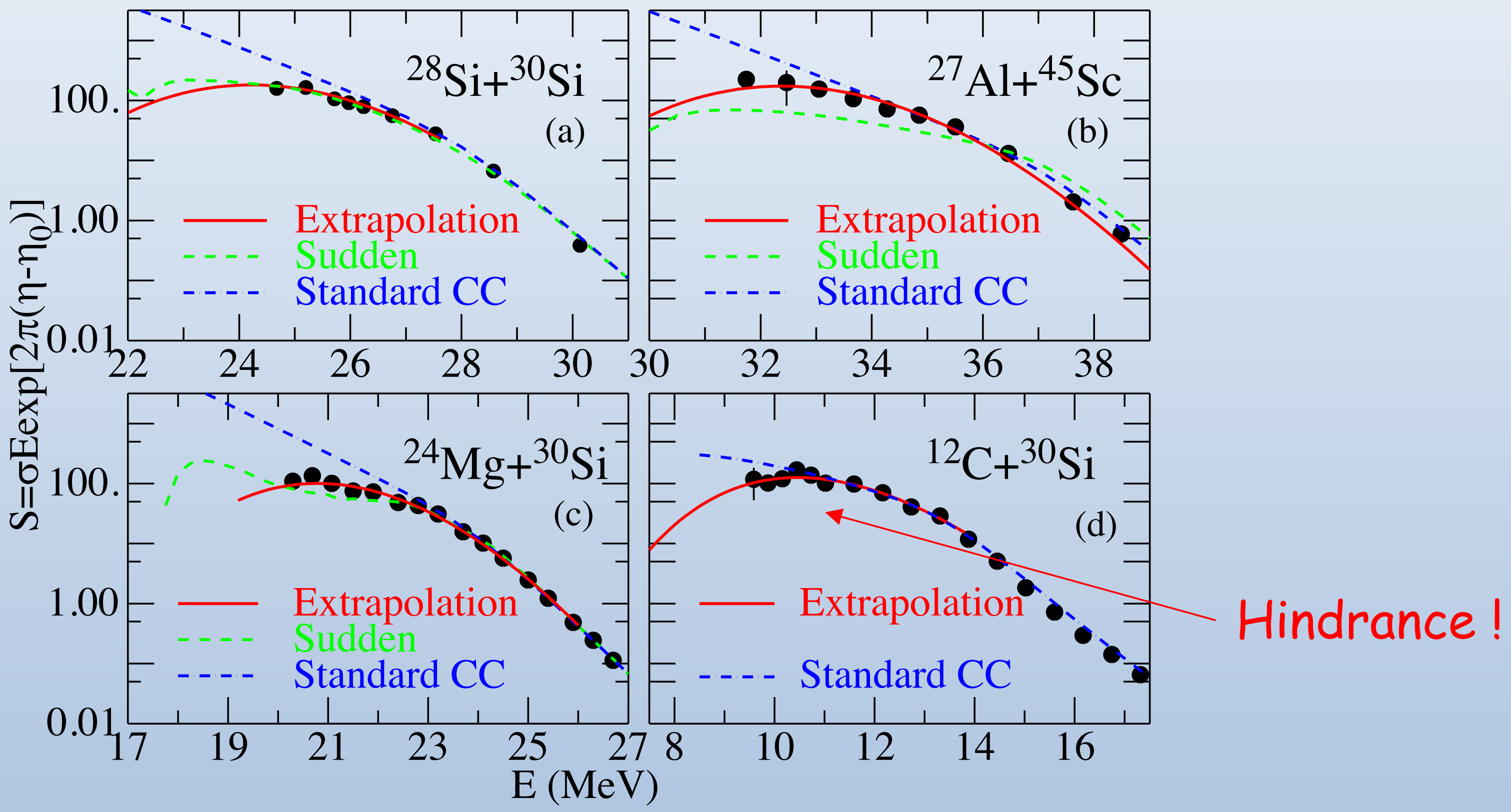
^{12}C + ^{24}Mg (Q=+16.3 MeV), is even nearer to the light systems and has not been measured

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

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



S factors trend for medium-light systems with positive fusion Q-value

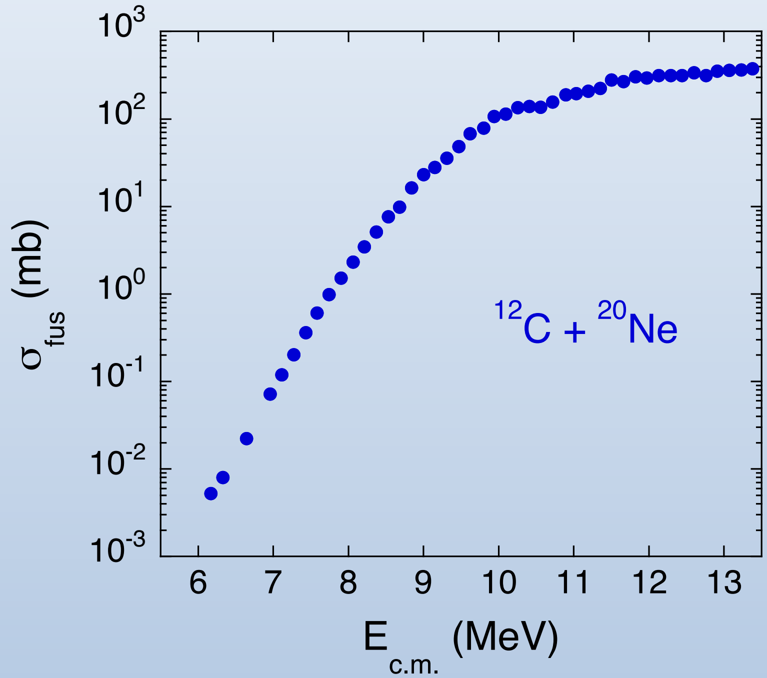


There is some evidence for an **S** -factor maximum, but the energy range covered in these experiments is limited and so the possible existence of that maximum is not so clear.

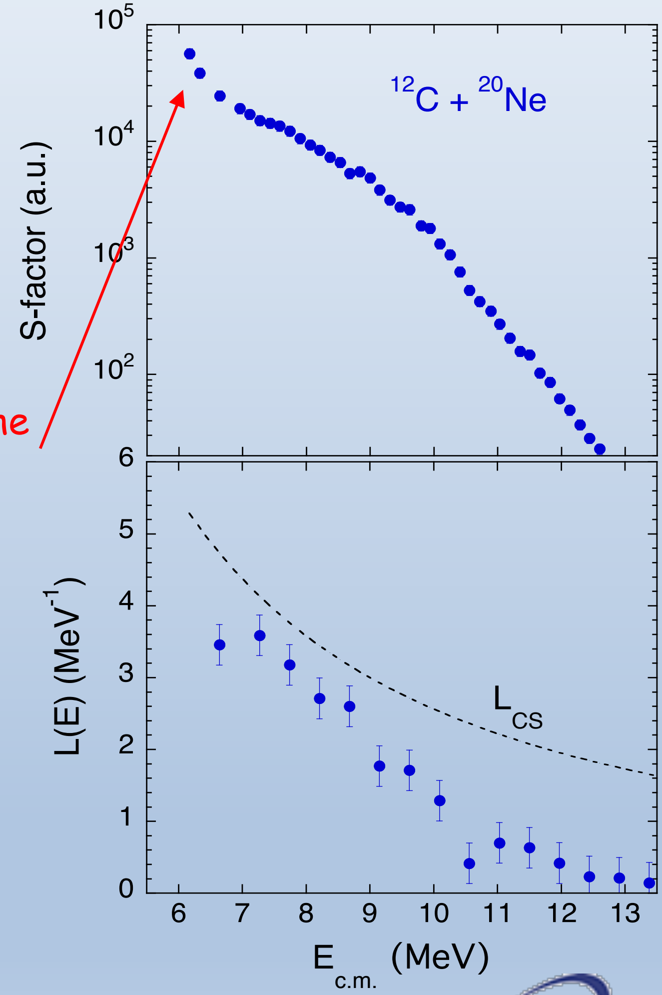
The clearest case is $^{12}C+^{30}Si$

G.M. and A.M. Stefanini, EPJA 53, 169 (2017)

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



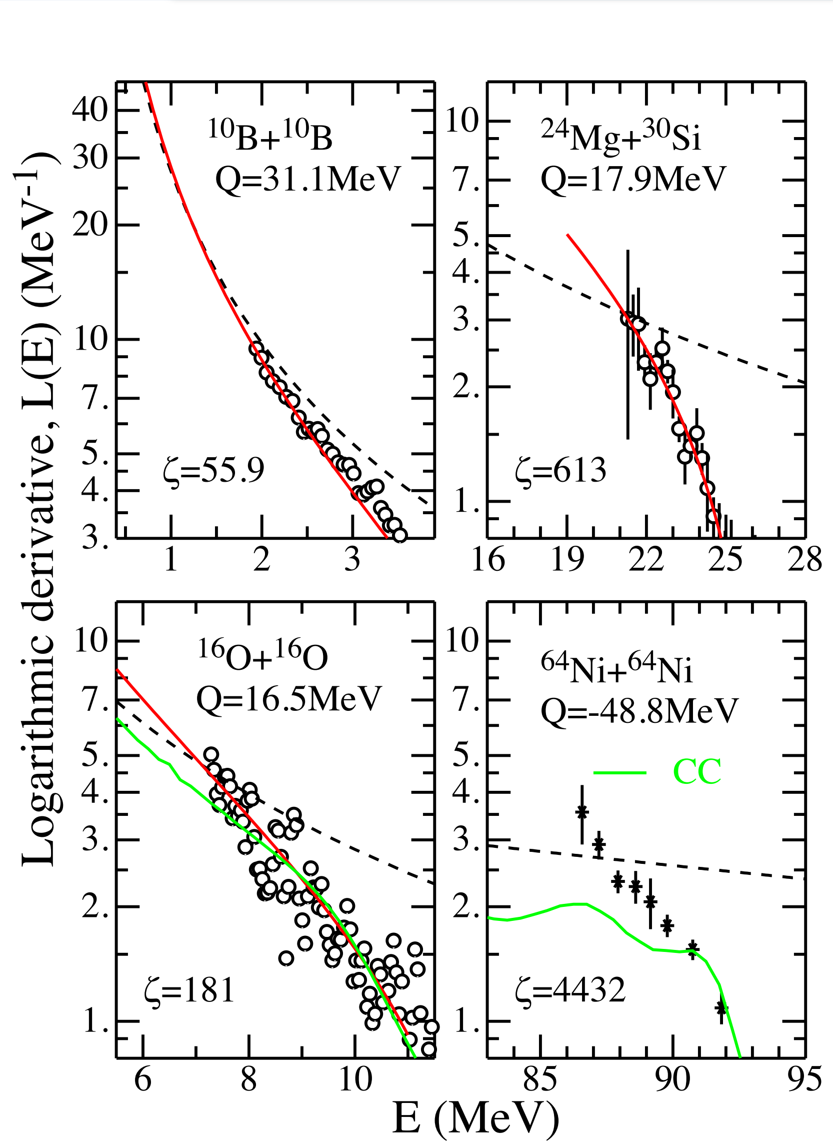
Increase of the S factor !?



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

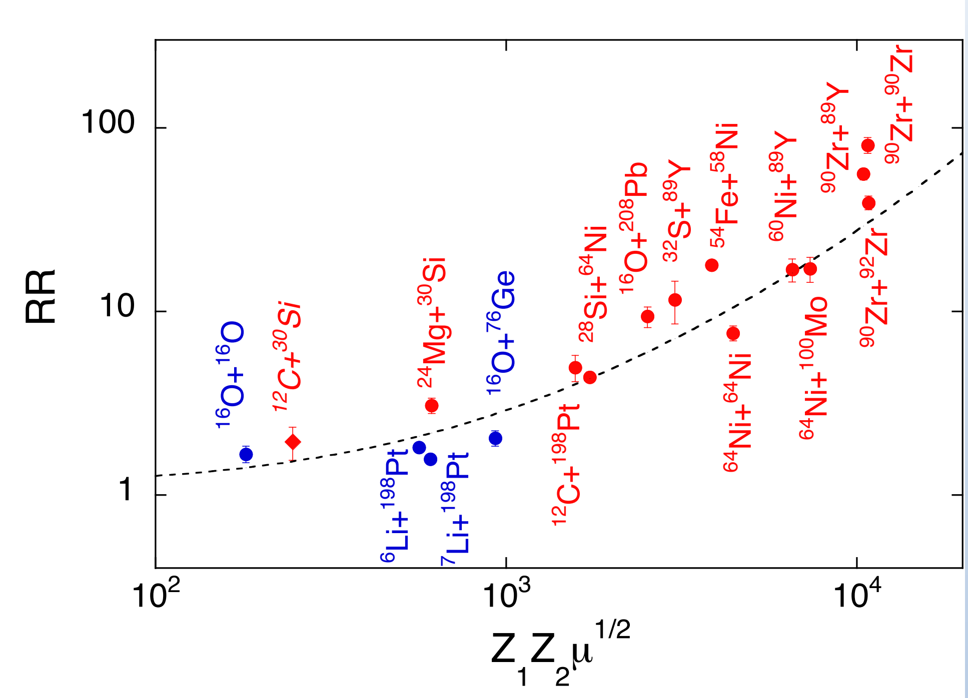
G. Hulke et al., Z. Physik A 297, 161 (1980)

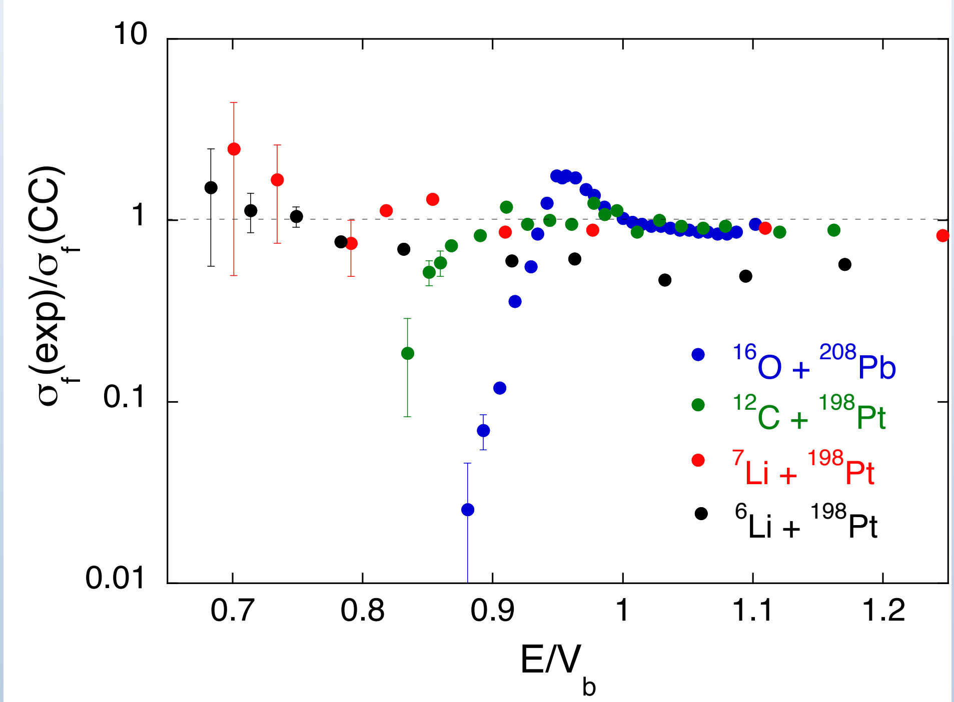
Logarithmic derivative for heavy and light systems



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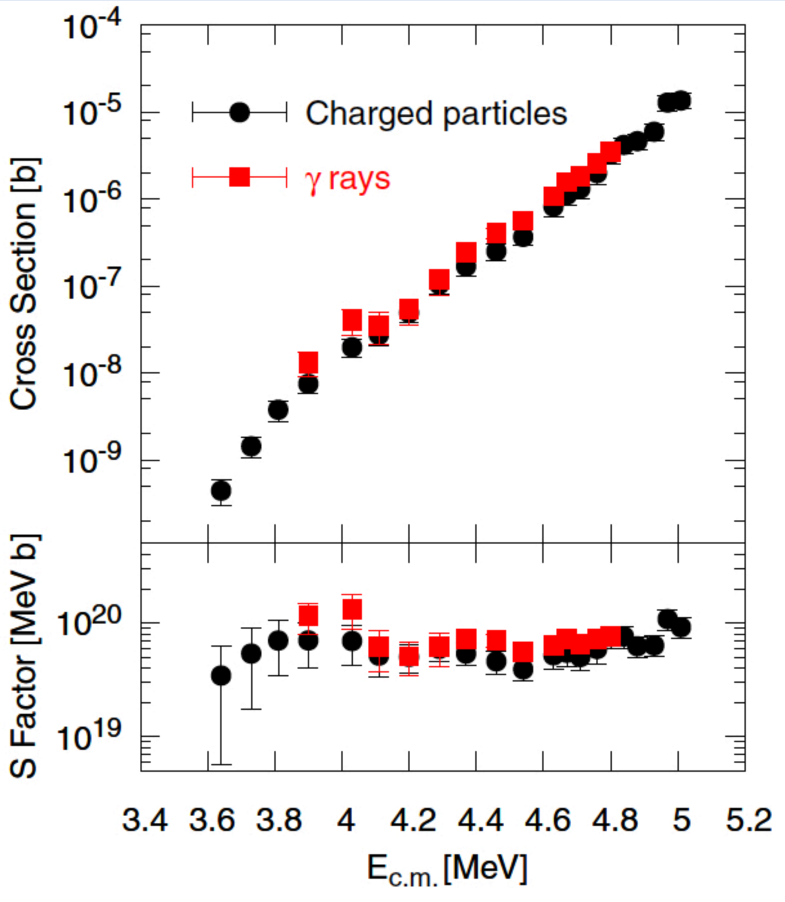
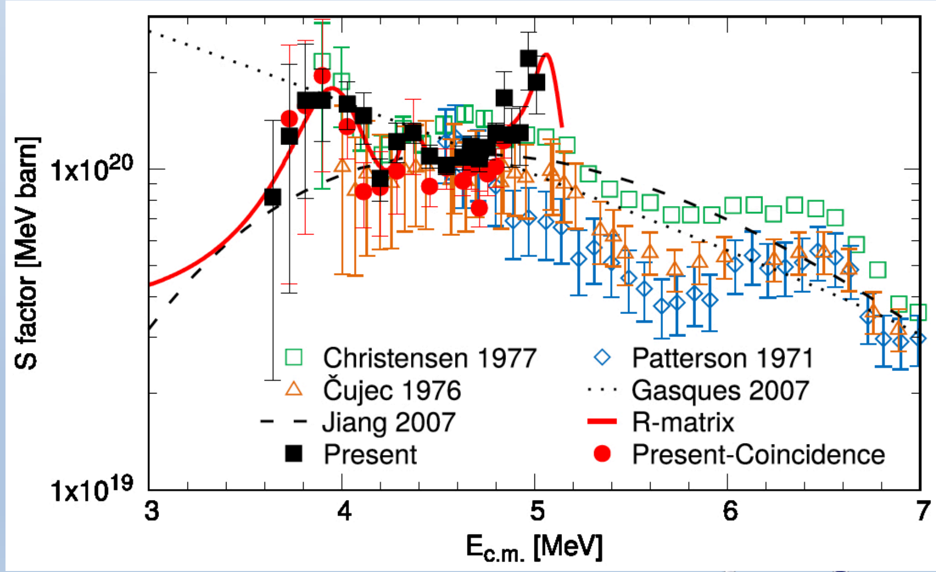
Fusion of the light system $^{12}C + ^{16}O$



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)

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.
- The case of the $^{12}C + ^{30}Si$ system: 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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J.Grebosz
Institute of Nuclear Physics, Cracow, Poland

end

Astrophysical S-factor and logarithmic slope L(E)

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

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

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

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(Eσ)]/dE

dS/dE = S(E)[L(E) – πη/E]

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

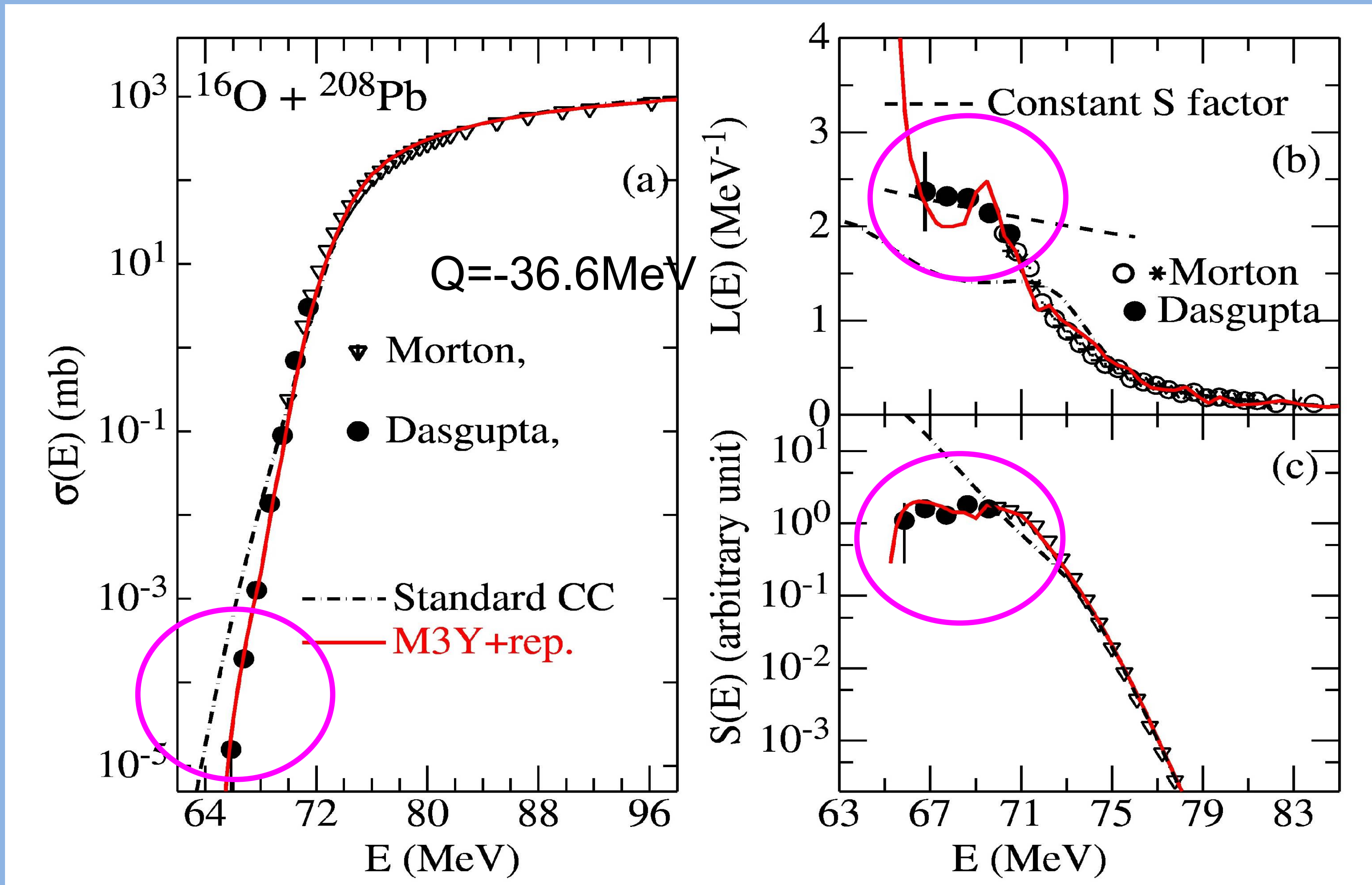
The energy E = E_S where this happens (if it happens !) has been usually taken as the threshold energy for hindrance.

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)

Australian National University- Canberra



M.Dasgupta et al., PRL 99, 192701 (2007)