Sub- and near-barrier fusion reactions experimental results

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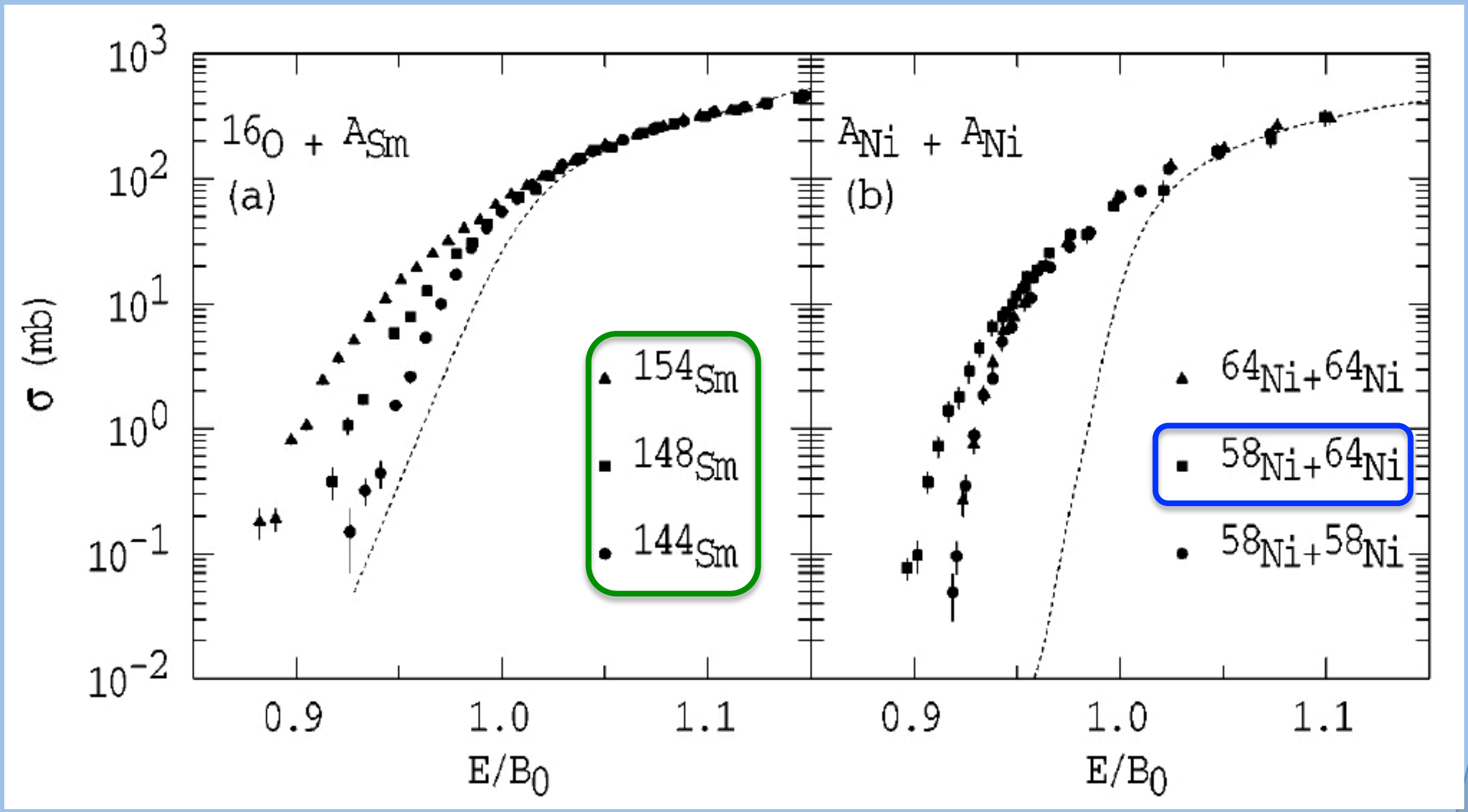
Layout

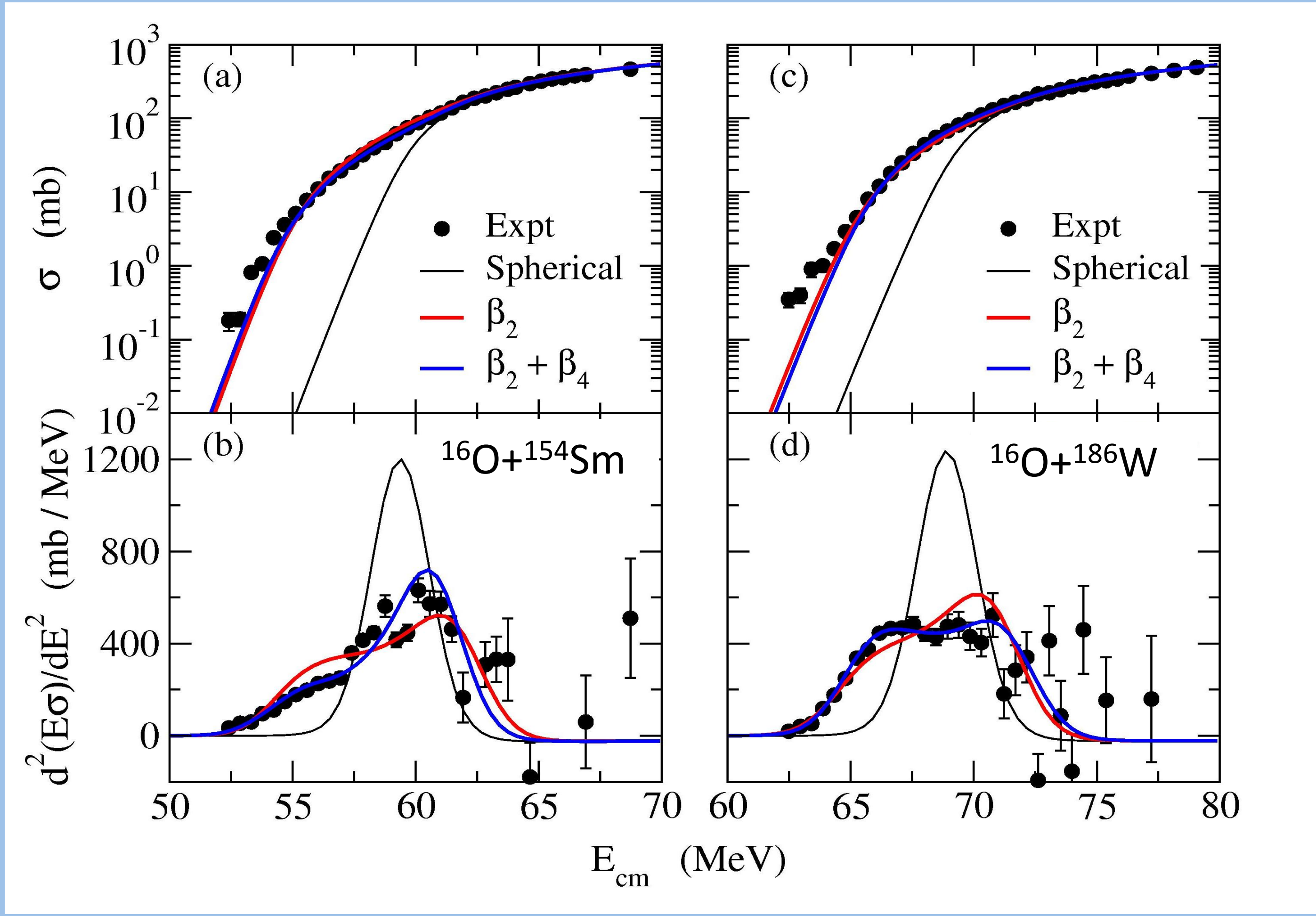
- The various features of near- and sub-barrier heavy-ion fusion: enhancements, barrier distributions and hindrance
- Fusion hindrance as a general phenomenon
- Coupling to transfer channels
- The case of the $^{28,30}Si + ^{28,30}Si$ systems: sub-barrier trends and fusion oscillations
- Some perspectives

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



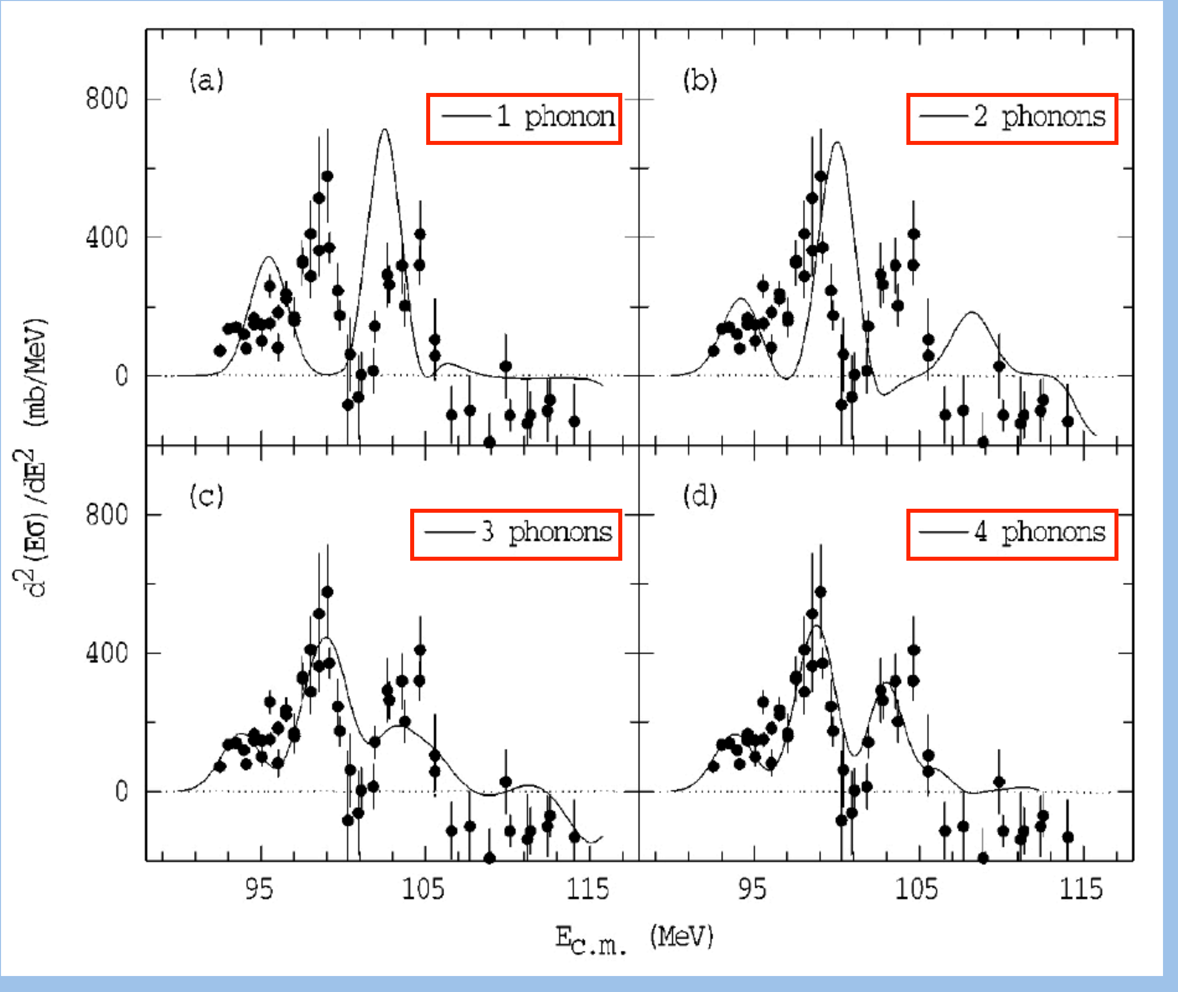
W.Reisdorf et al.,NPA 438 (1985) 212 M.Beckerman et al.,Phys. Rev.Lett. 45, 1472 (1980)

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



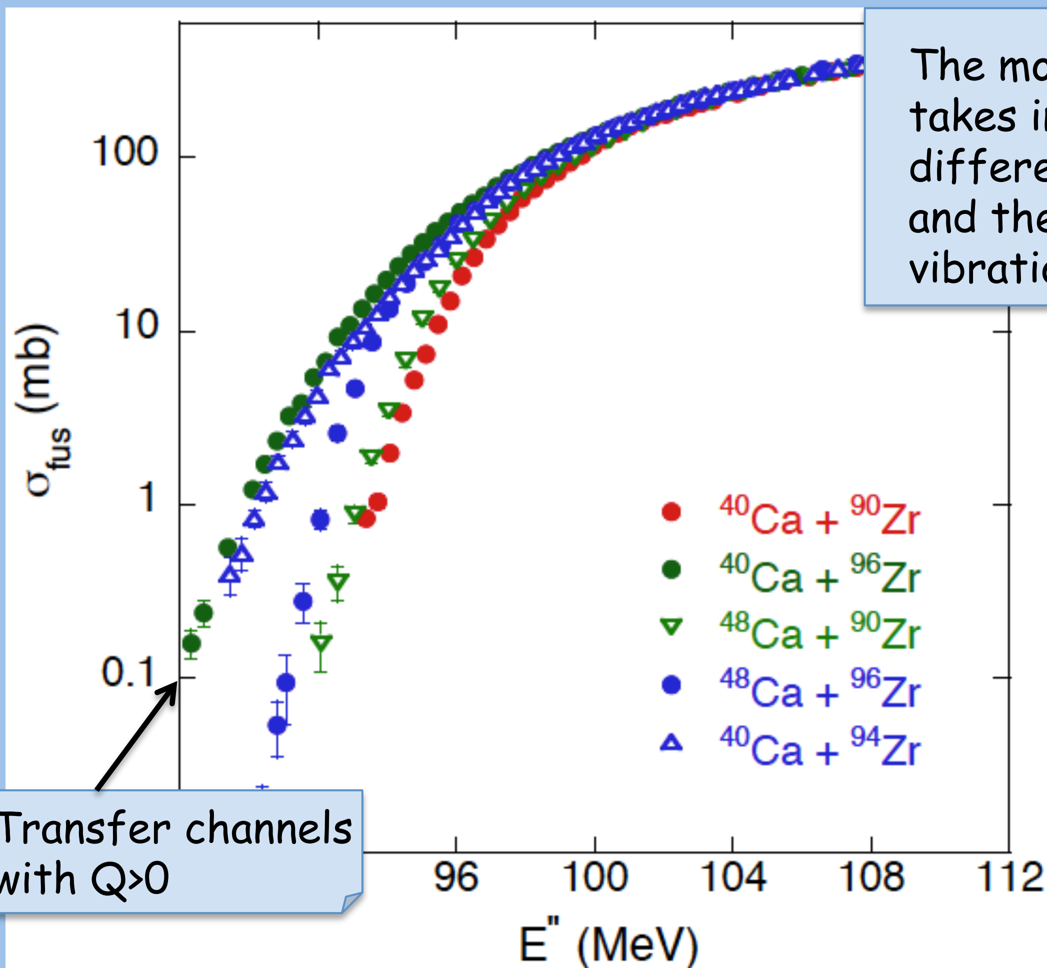
J.Leigh et al., Phys. Rev. C 52, 3151 (1995)

… 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.



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

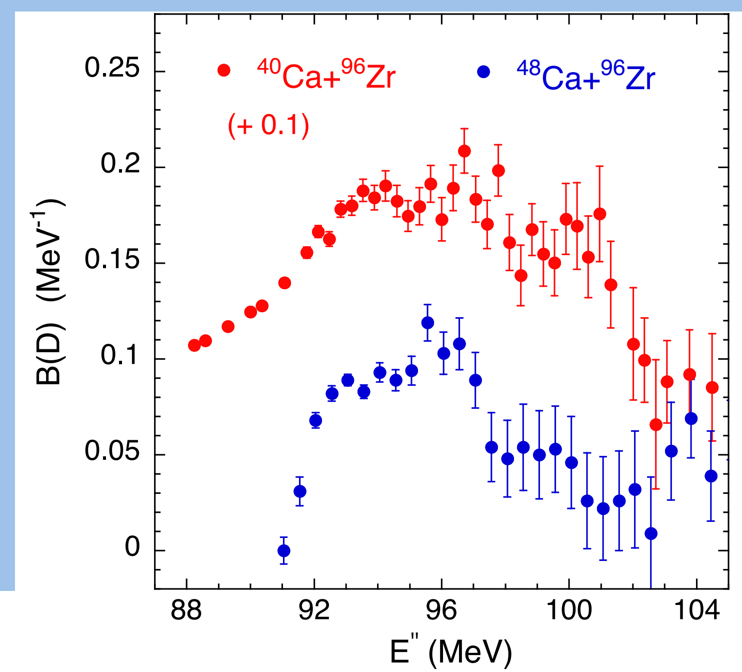
The effect of coupling to transfer channels in several Ca+Zr systems



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

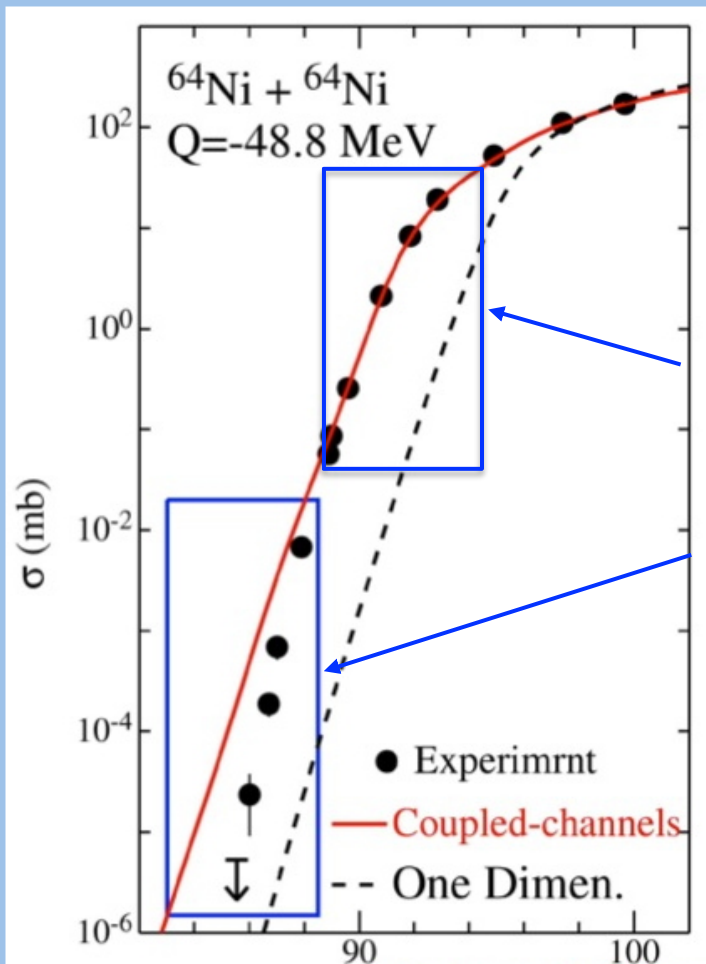
Barrier distributions



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

Hindrance vs. enhancement

Enhancement and hindrance of fusion near and below the barrier - Argonne



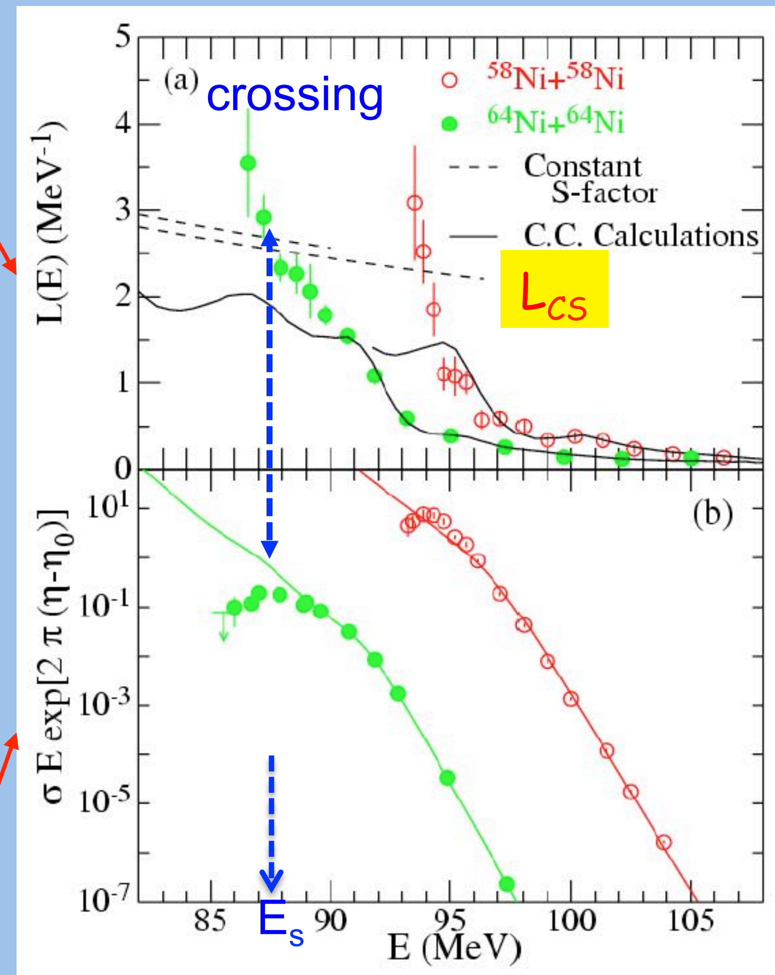
E(MeV)

enhancement

hindrance

Logarithmic derivative
= d[ln(Eσ)]/dE

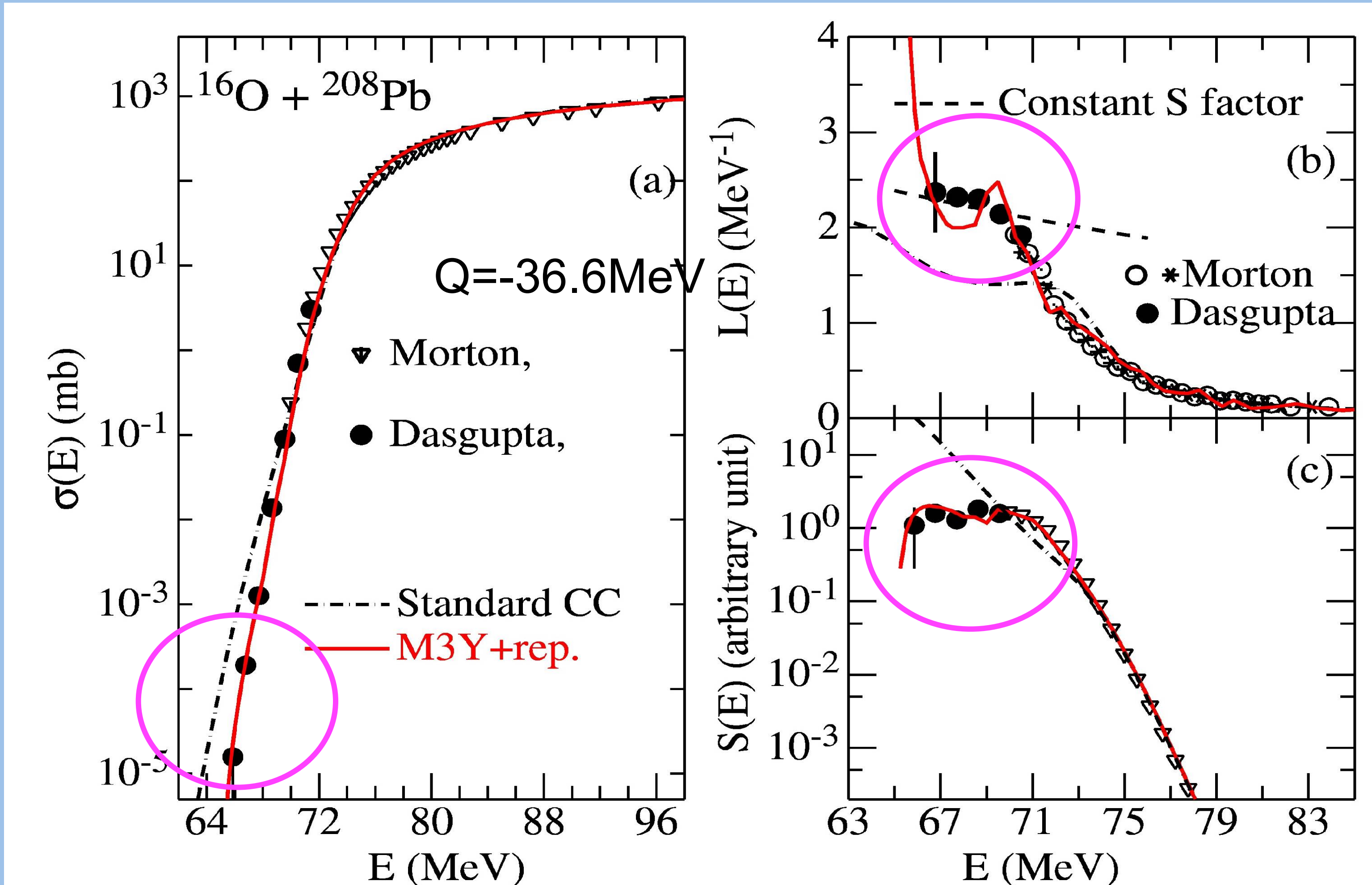
S-factor



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

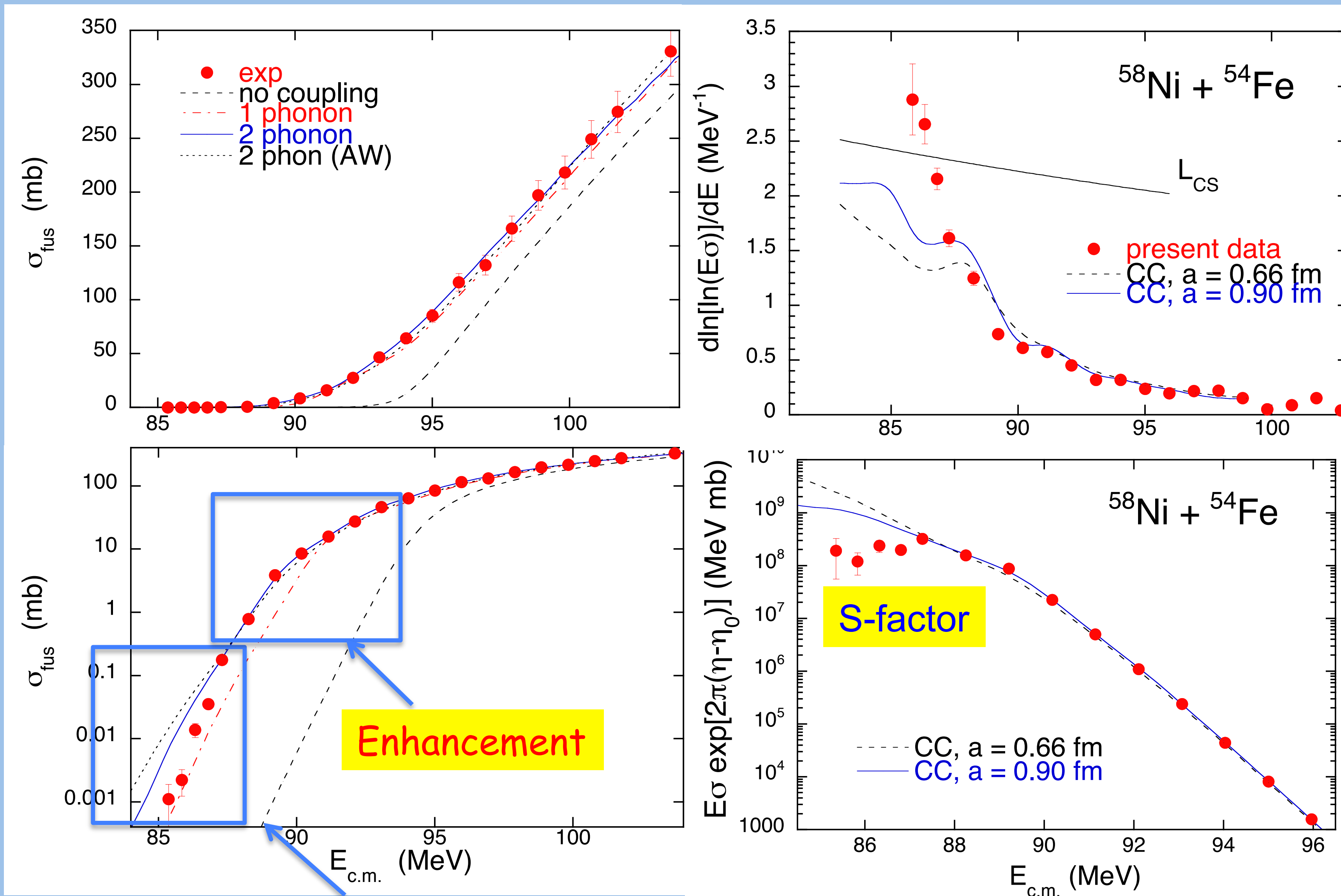
C.L.Jiang et al., PRL 93, 012701 (2004)
PRC 73, 014613 (2006)

Australian National University- Canberra



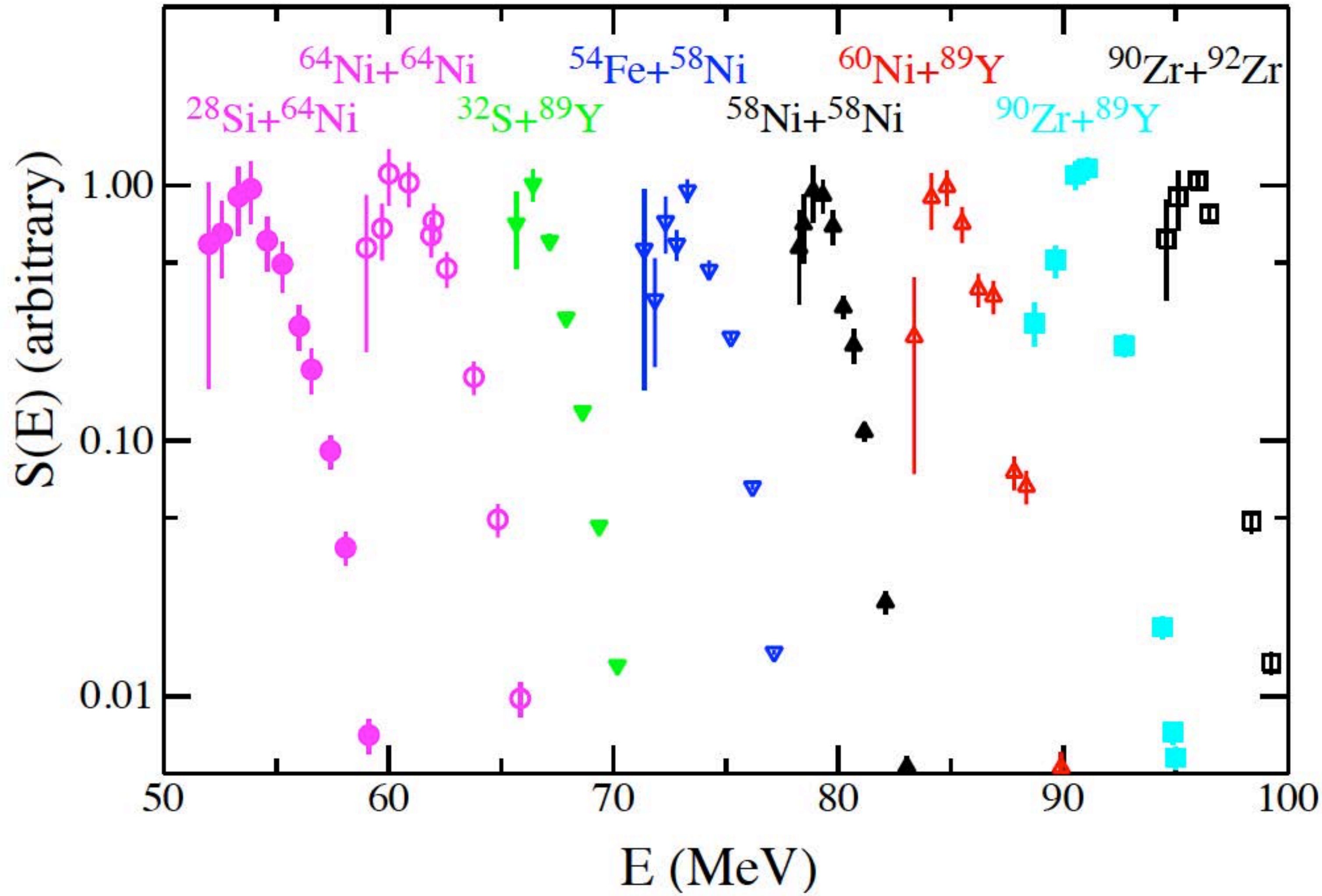
M.Dasgupta et al., PRL 99, 192701 (2007)

Fusion of stiff nuclei: the case of $^{58}Ni + ^{54}Fe$



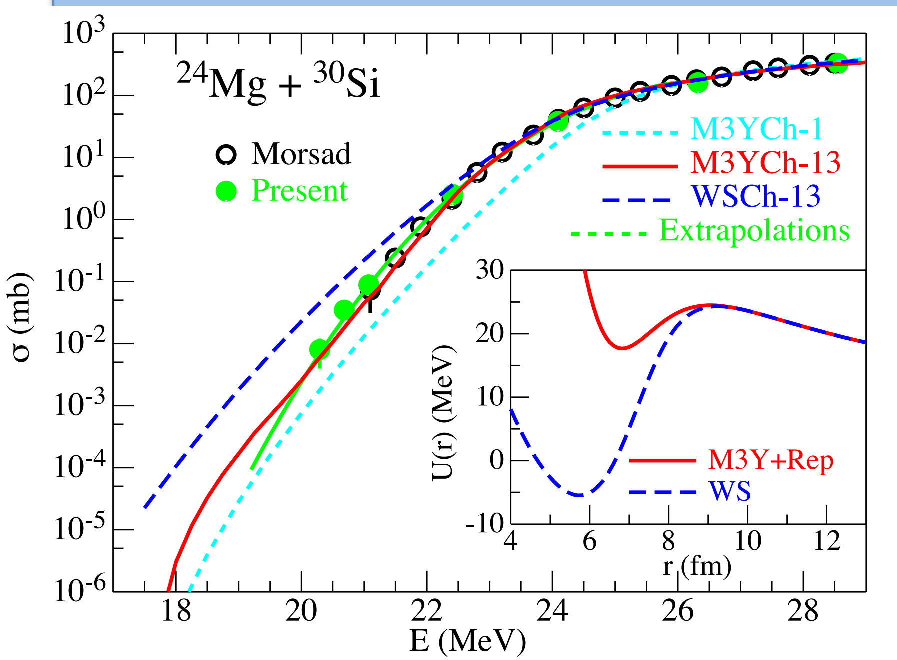
A.M.Stefanini et al., PR C81, 037601 (2010)

The "magnificent systems"

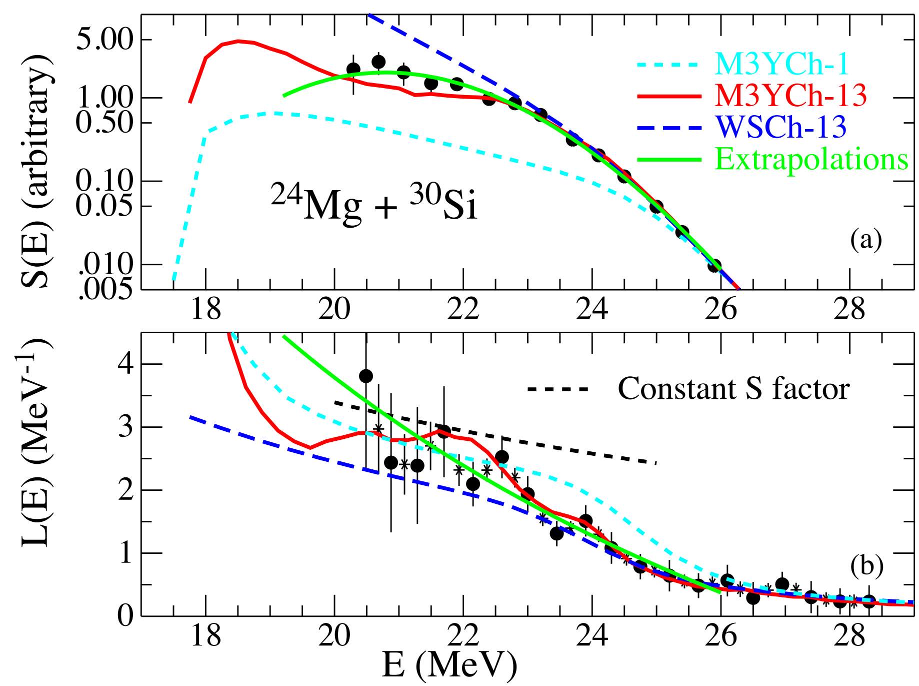


C.L.Jiang, private communication

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)

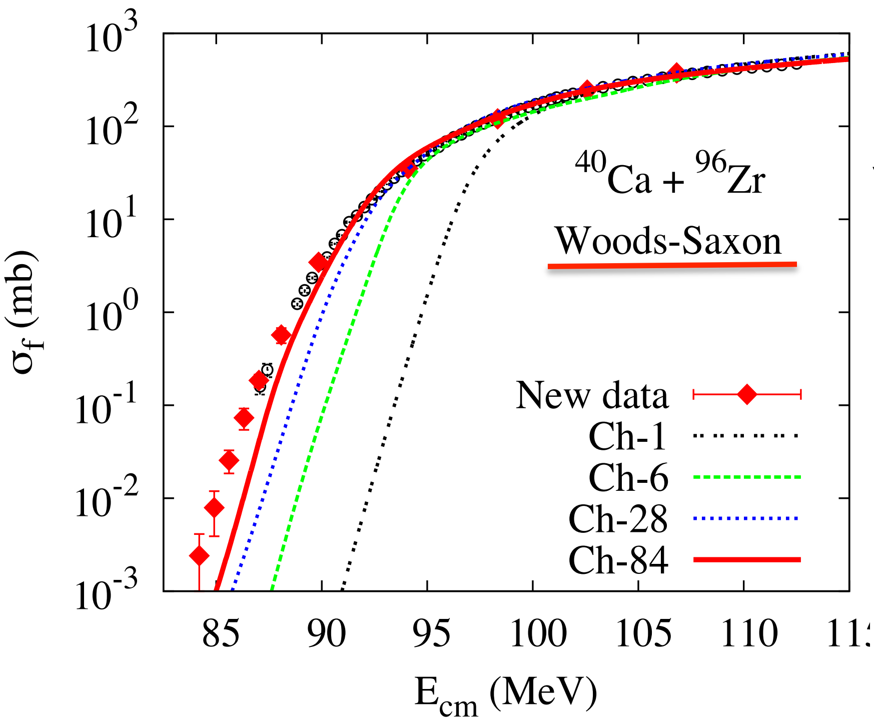


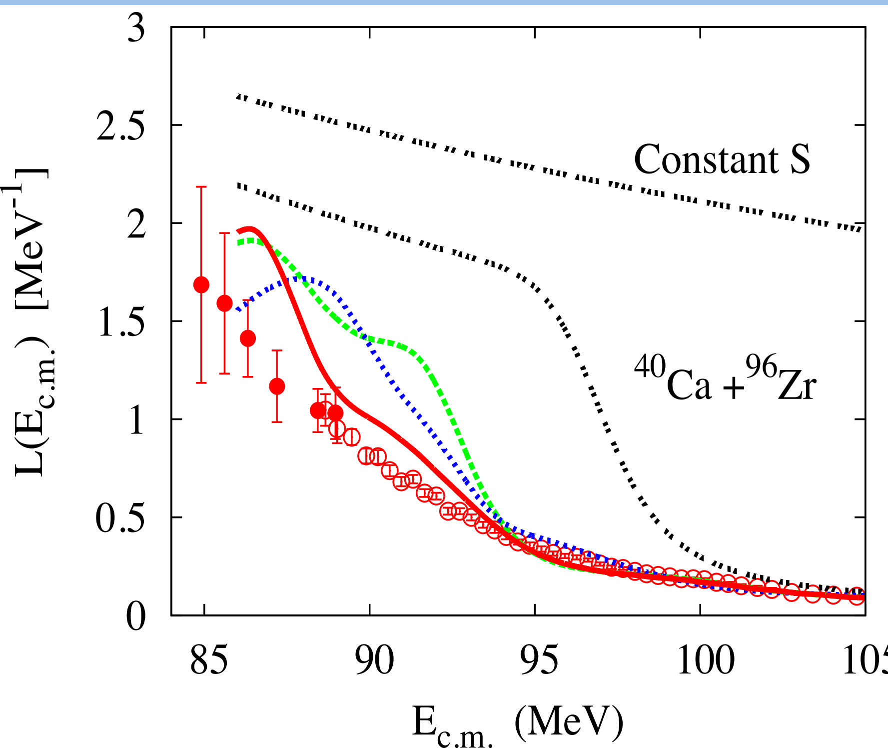
C.L.Jiang, A.M.Stefanini, H.Esbensen, K.E.Rehm, B.B.Back, G.M., L.Corradi, F.Scarlassara, E.Fioretto, …… Phys. Rev. Lett. 113, 022701 (2014)

Istituto Nazionale di Fisica Nucleare

Coupling to transfer channels

Couplings to transfer channels in $^{40}Ca + ^{96}Zr$

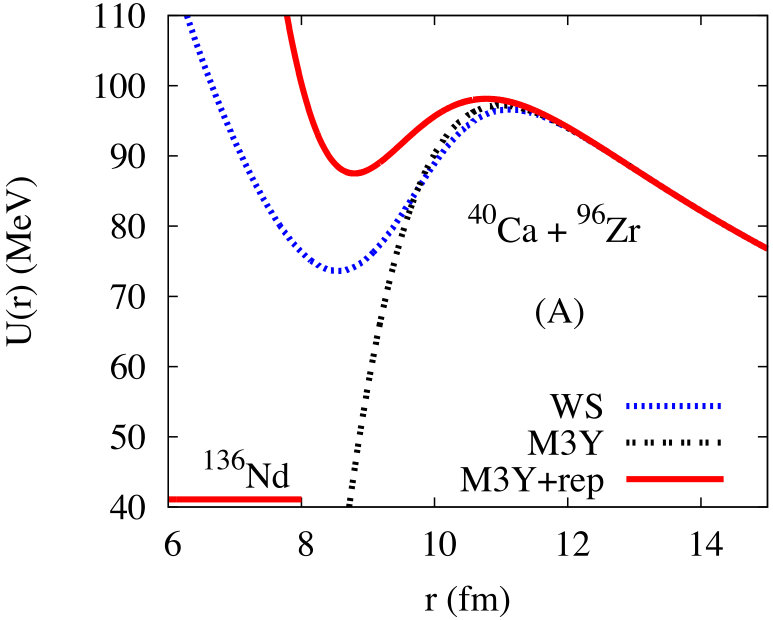


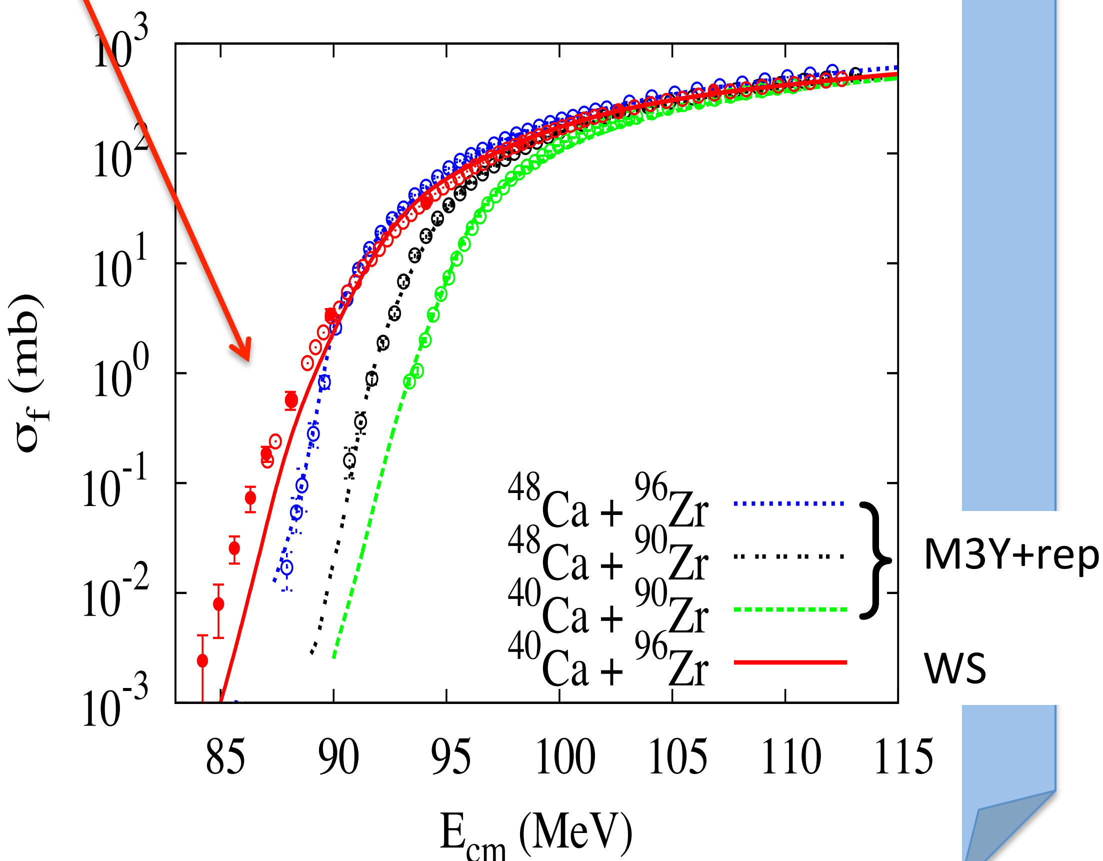


Ch-1 is no-coupling
Ch-6 one-phonon 2^+, 3^- couplings
Ch-28 two-phonon couplings
Ch-84 two-phonon, one- and two-nucleon transfer couplings

A.M.Stefanini et al., Phys. Lett. B728 (2014) 639
H. Esbensen and A.M. Stefanini, PRC 89,044616 (2014)

CC analysis: the hindrance phenomenon does not occur in $^{40}Ca+^{96}Zr$!



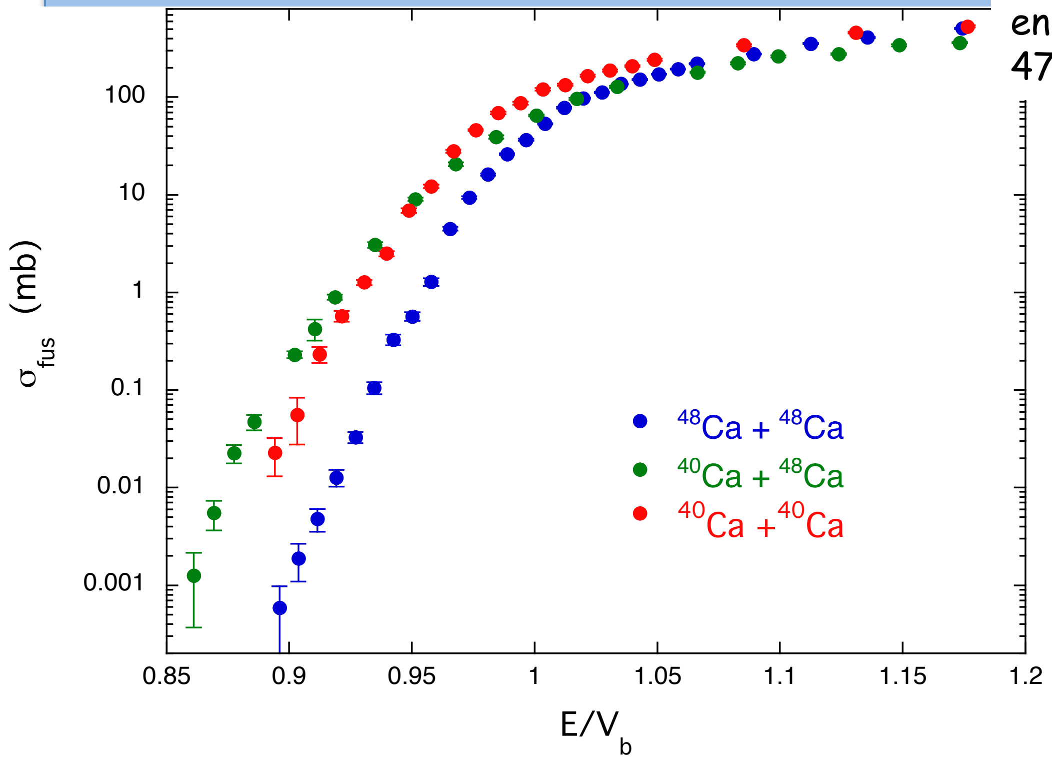


One has to use the WS or ignore the repulsive part of the M3Y potential, to get closer to the data.

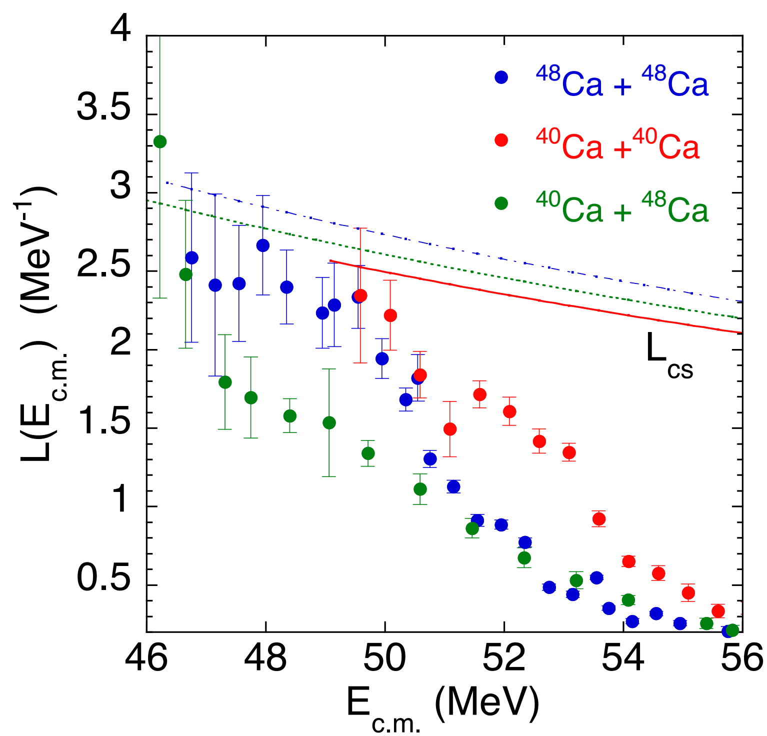
"Indeed, the Q-values for neutron transfer are large and positive. The valence nucleons can flow more freely from one nucleus to the other without being hindered by Pauli blocking"

H. Esbensen and A.M. Stefanini, PRC 89,044616 (2014)

Fusion of $^{40}Ca+^{40}Ca$, $^{40}Ca+^{48}Ca$ and $^{48}Ca+^{48}Ca$: octupole vibrations and Q>0 transfer couplings



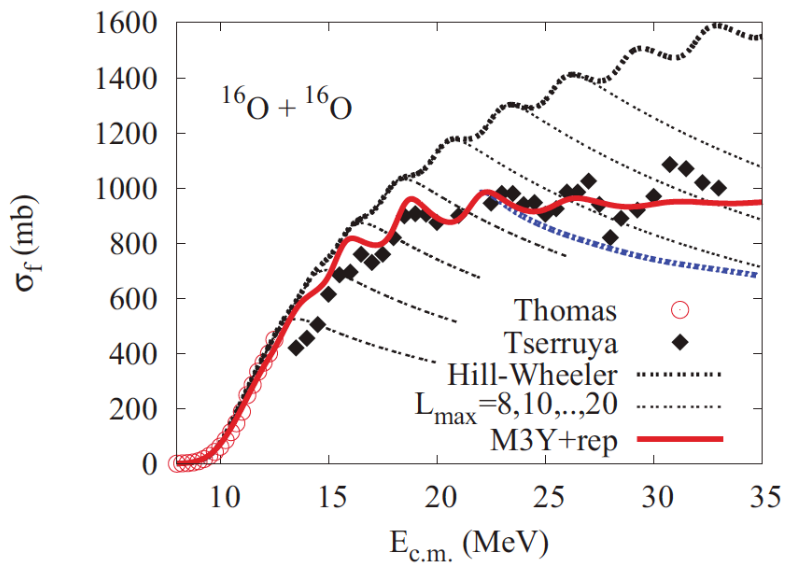
In spite of the large enhancement in the fusion of $^{40}Ca + ^{48}Ca$, hindrance does eventually occur but the onset is pushed down to very low energies, where it sets in rather abruptly below 47 MeV, where L(E) increases rapidly

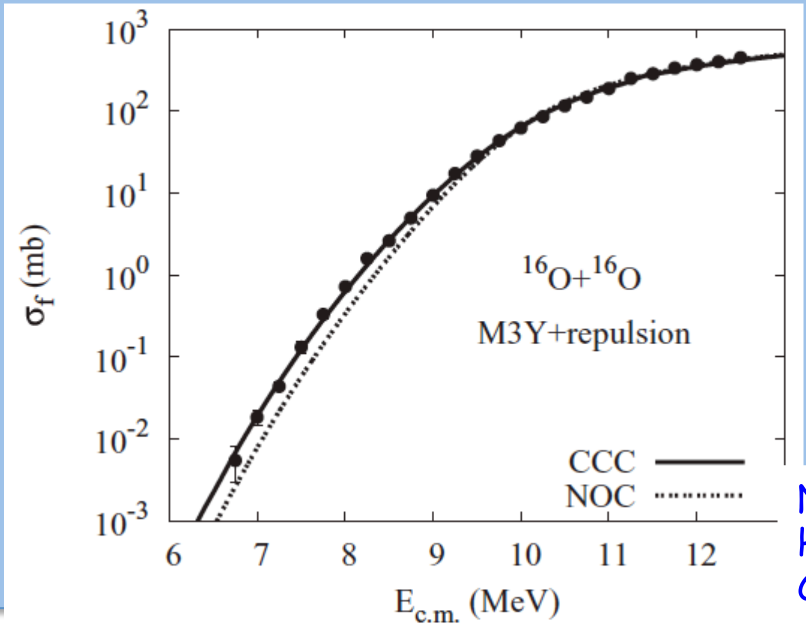


G.M. et al., PRC 85, 024607 (2012)
C.L.Jiang et al., PRC 82, 041601(R) (2010) A.M.Stefanini et al., PLB 679, 95 (2009)

The case of the $^{28,30}Si + ^{28,30}Si$ systems

Structures in the fusion excitation function of light systems





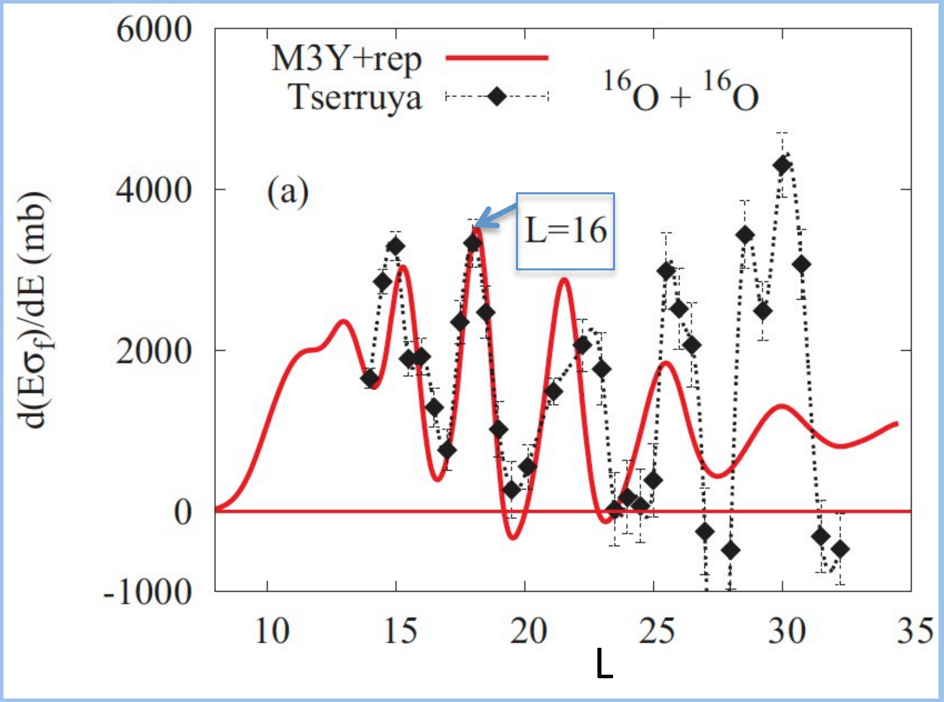
- oscillatory structures were observed long time ago
- a shallow ion-ion potential was employed to fit such data confirming the early suggestion that they are due to the penetration of successive centrifugal barriers
- the sub-barrier excitation function was reproduced as well

N. Poffe', N. Rowley and R. Lindsay, NPA 410, 498 (1983)
H.Esbensen, PRC85, 064611 (2012)
C. Simenel et al. PRC88, 024617 (2013)

Using the first derivative of the excitation function d(Eσ)/dE makes easier to observe oscillations

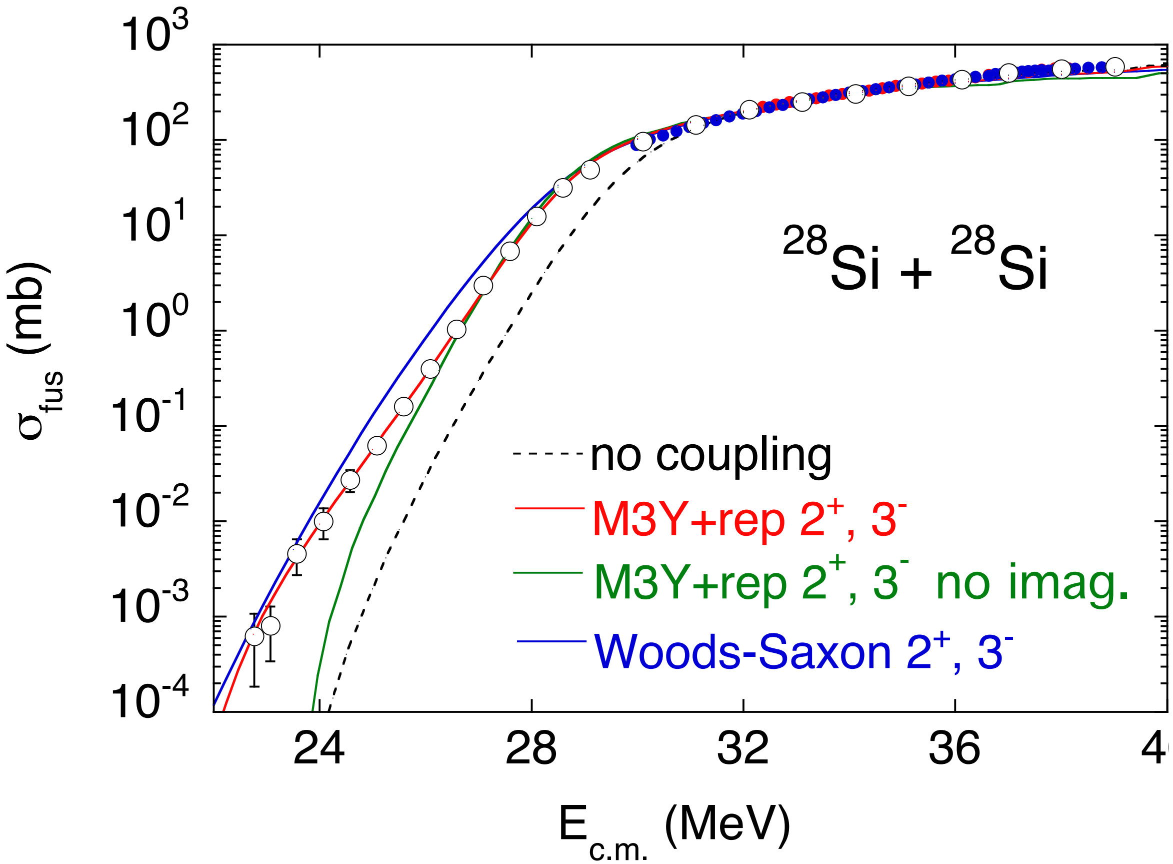
$$V_B(L) = V_{CB} + \frac{\hbar^2 L(L+1)}{2\mu R_{CB}^2}$$

The case of $^{16}O + ^{16}O$

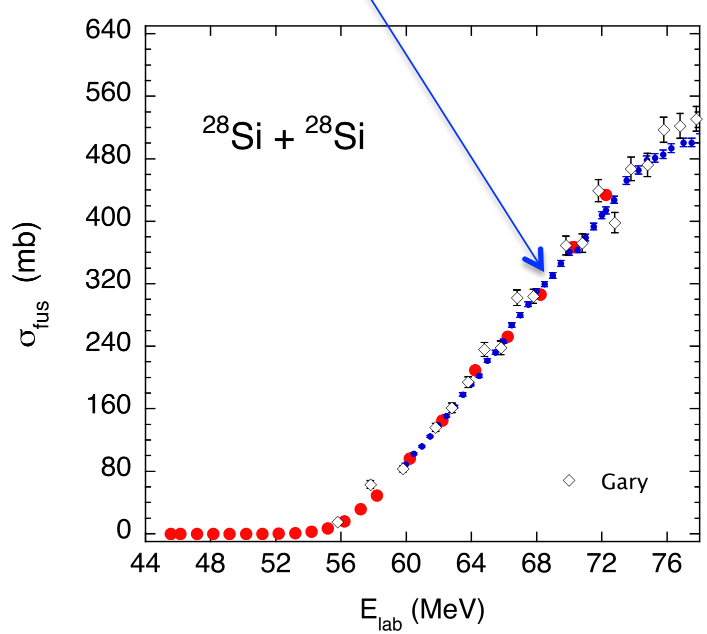


- in heavier systems sub-barrier enhancements/ hindrance are stronger
- do we observe oscillations in $^{28}Si + ^{28}Si$? this would provide very useful information on the potential and on coupling effects in a wide energy range

The fusion excitation function of $^{28}Si+^{28}Si$



(the blue points were measured with ΔE_{cm} = 0.5 MeV, and 1% statistical error)



The CC calculations include the low-lying 2^+ and 3^- states, and their mutual excitations. A weak and short-ranged imaginary potential (W_o=5 MeV, a=0.2 fm) is required at low energies.

G.M. et al, PRC 90, 044608 (2014)

S. Gary and C. Volant, PRC 25, 1877 (1982)

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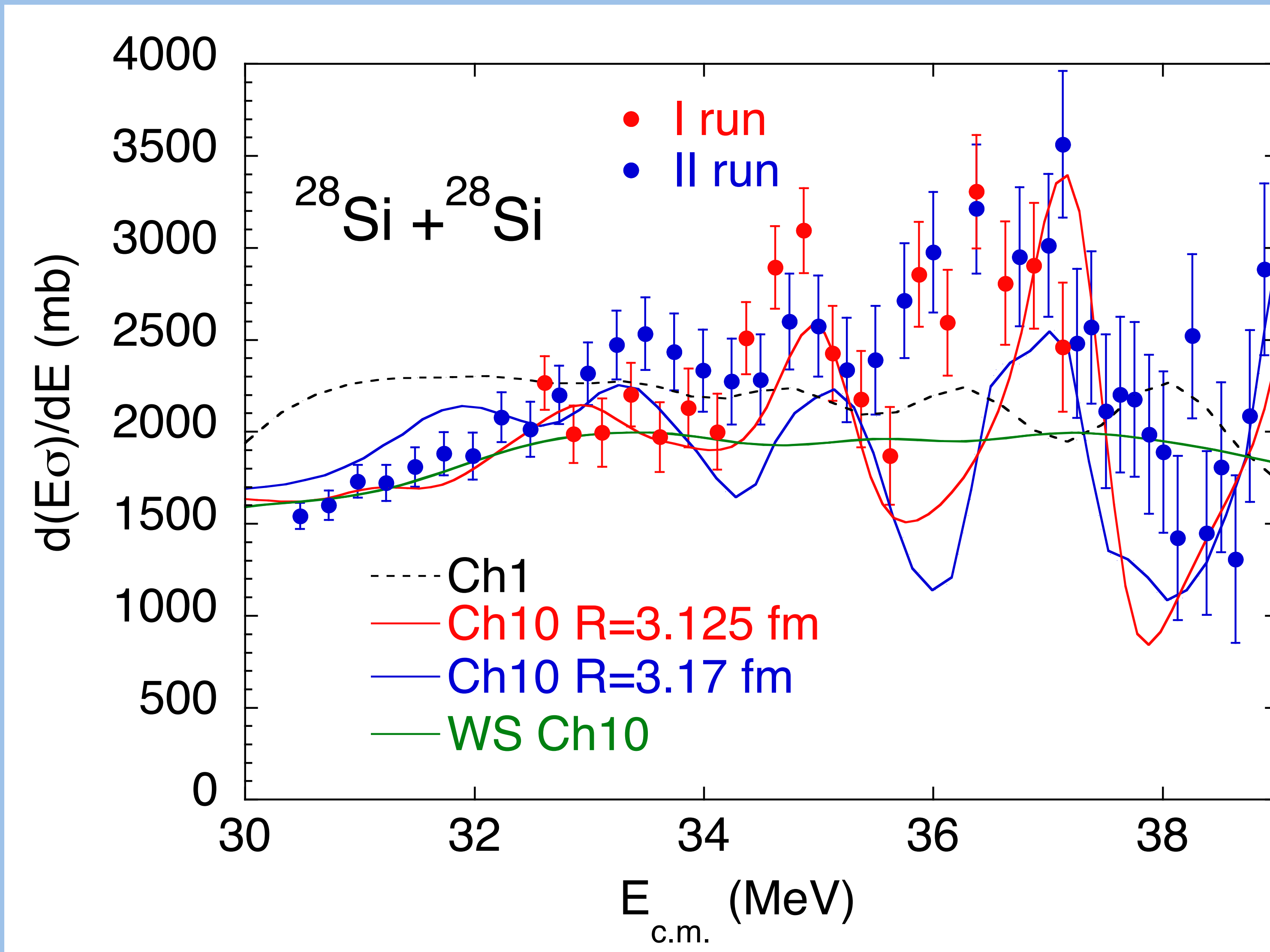
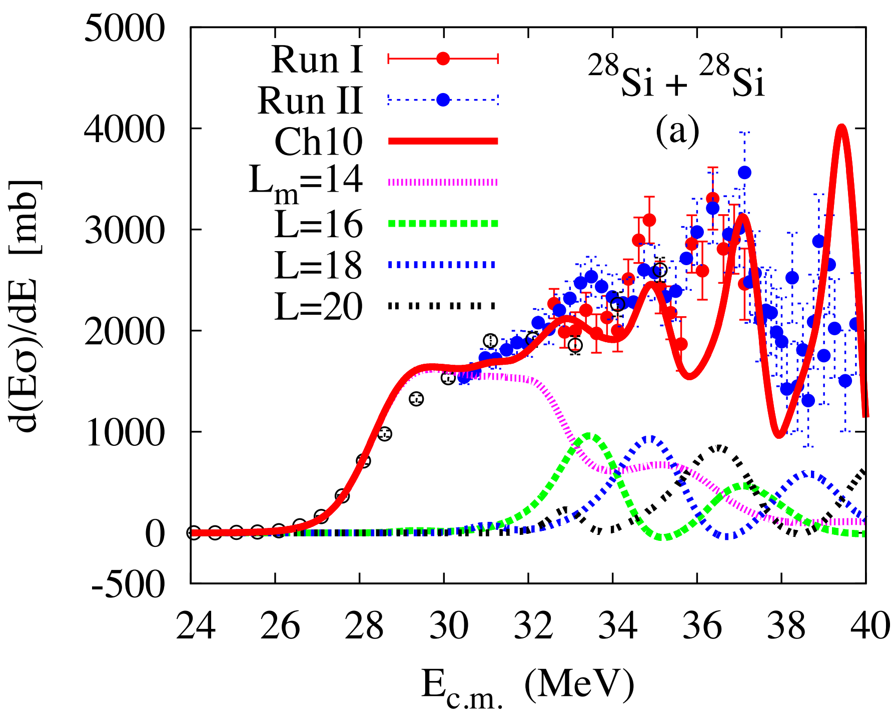
The first derivative d(Eσ)/dE shows distinct oscillations above the barrier



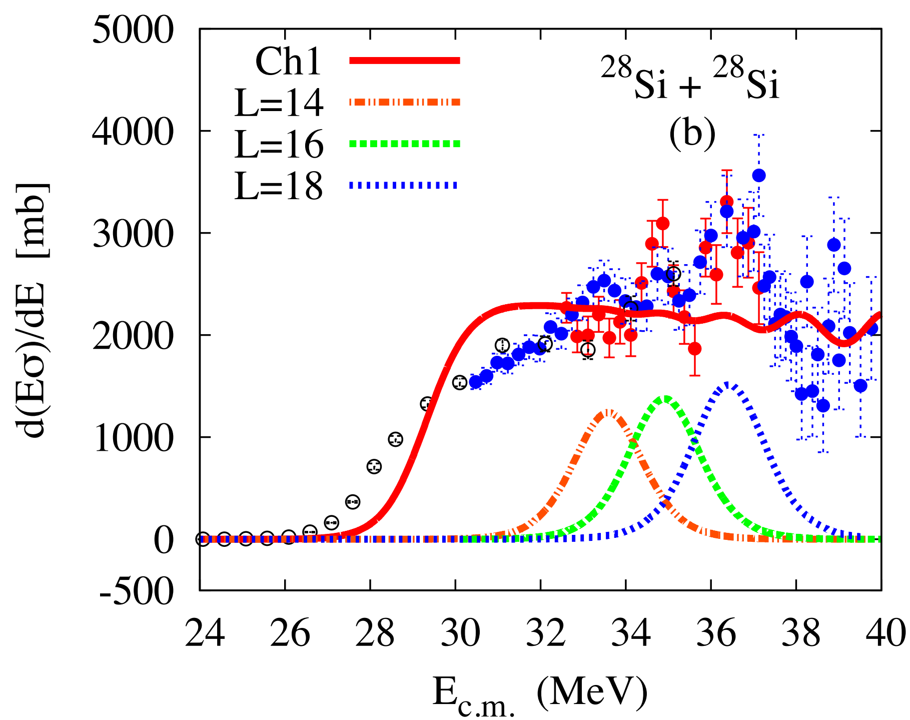
G.M. et al., PLB746, 300 (2015)

In some detail …

Coupled channels 2^+, 3^-

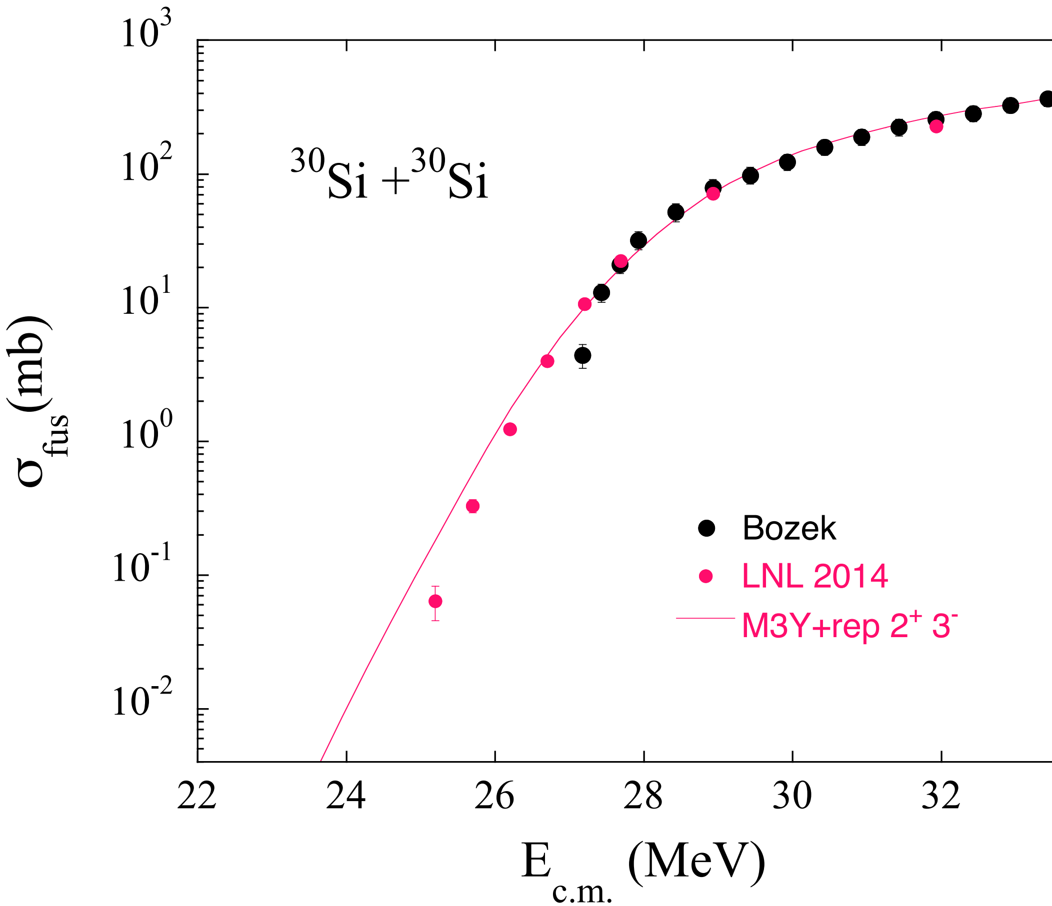


No couplings



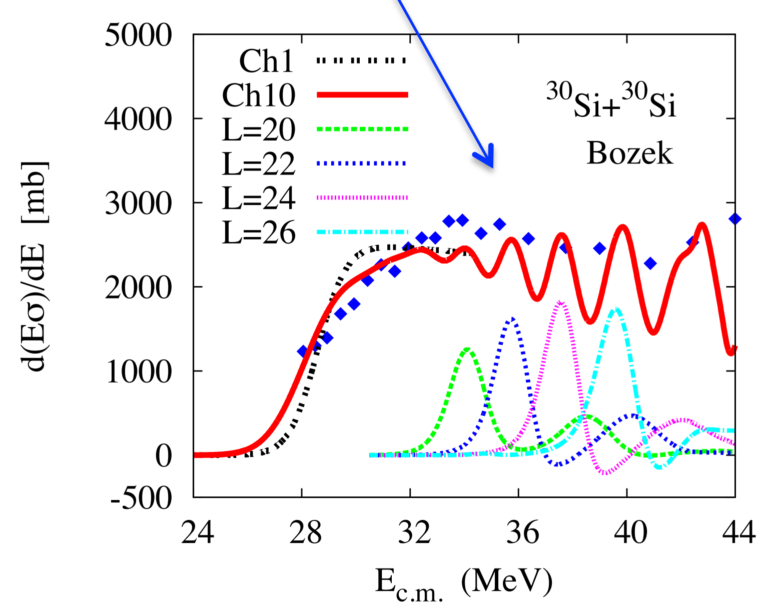
see also N.Rowley and K.Hagino
PRC 91, 044617 (2015)

The study of ^{30}Si + ^{30}Si is in progress



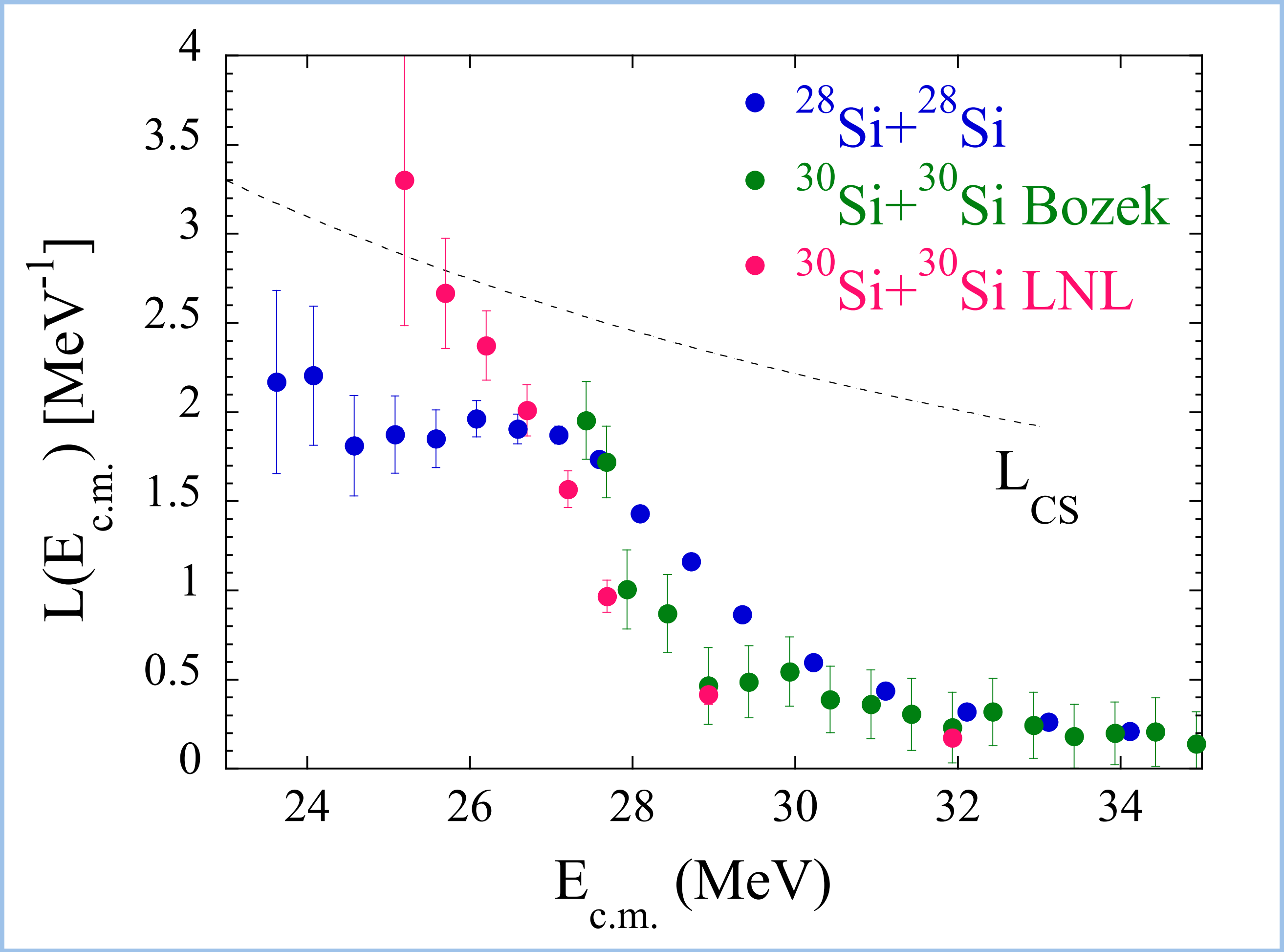
The CC calculation includes the low lying 2^+ and 3^- states, and their mutual excitations, but no imaginary potential.

Oscillations are predicted also in this case ...



E. Bozek et al. Nucl. Phys. A 451, 171 (1986)

The logarithmic derivatives of $^{28}Si+^{28}Si$ and $^{30}Si+^{30}Si$



What do we learn from the Si+Si systems

- the appearance of oscillations and the trend of sub-barrier cross sections in $^{28}Si + {}^{28}Si$ have been reproduced within the same theoretical frame, i.e., the CC model using the shallow M3Y+rep. potential
- within that model the existence of oscillations is tightly bound to channel couplings in this relatively heavy system, while in lighter cases the oscillations are related to the overcoming of successive centrifugal barriers well spaced in energy
- as a consequence, the one-to-one relation between each peak and the height of a centrifugal barrier is lost
- checking the importance of the oblate deformation of ^{28}Si in all this, calls for an analogous experiment on the near-by system $^{30}Si + {}^{30}Si$ because ^{30}Si is a spherical nucleus

Some perspectives

- Measurement of the average angular momentum and possibly of the spin distribution below the barrier
- Stable beams with high intensity and quality
- Experiments with heavy exotic beams
- New high efficiency set-ups
- The fusion hindrance phenomenon in systems of astrophysical interest

Our collaboration in recent experiments

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End