Sub-barrier Fusion Excitation Functions of Heavy-Ion Systems

A. M. Stefanini

INFN – Laboratori Nazionali di Legnaro, Italy

The Scrovegni Chapel by Giotto, Padova

ANPC, 29 Nov.-3 Dec. 2023

UNIVERSITAS · STUDII PADUANI
MCCXXII

INFN
Istituto Nazionale di Fisica Nucleare

Question

Which kind of information can we extract from the heavy-ion fusion cross sections below the Coulomb barrier ?

We are going to see that

the slopes of experimental excitation functions throw light on the dynamics of quantum tunnelling in heavy-ion sub-barrier fusion, which is strongly connected to the intrinsic degrees of freedom of the colliding nuclei, i.e. their nuclear structure and the dynamics of inelastic scattering and quasi-elastic transfer reactions

50 years ago … the Wong formula

The Wong formula at sub-barrier energies reduces to

$$E\sigma_{fus}(E) = \frac{\hbar\omega R_b^2}{2} exp\left[\frac{2\pi}{\hbar\omega}(E - V_b)\right]$$

its derivative with respect to the energy is

$$\frac{d(E\sigma_{fus})}{dE} = \frac{\hbar\omega R_b^2}{2} exp\left[\frac{2\pi}{\hbar\omega}(E - V_b)\right]\frac{2\pi}{\hbar\omega} = \frac{2\pi}{\hbar\omega}E\sigma_{fus}$$

The derivative varies linearly with $E\sigma_{fus}$ with a slope

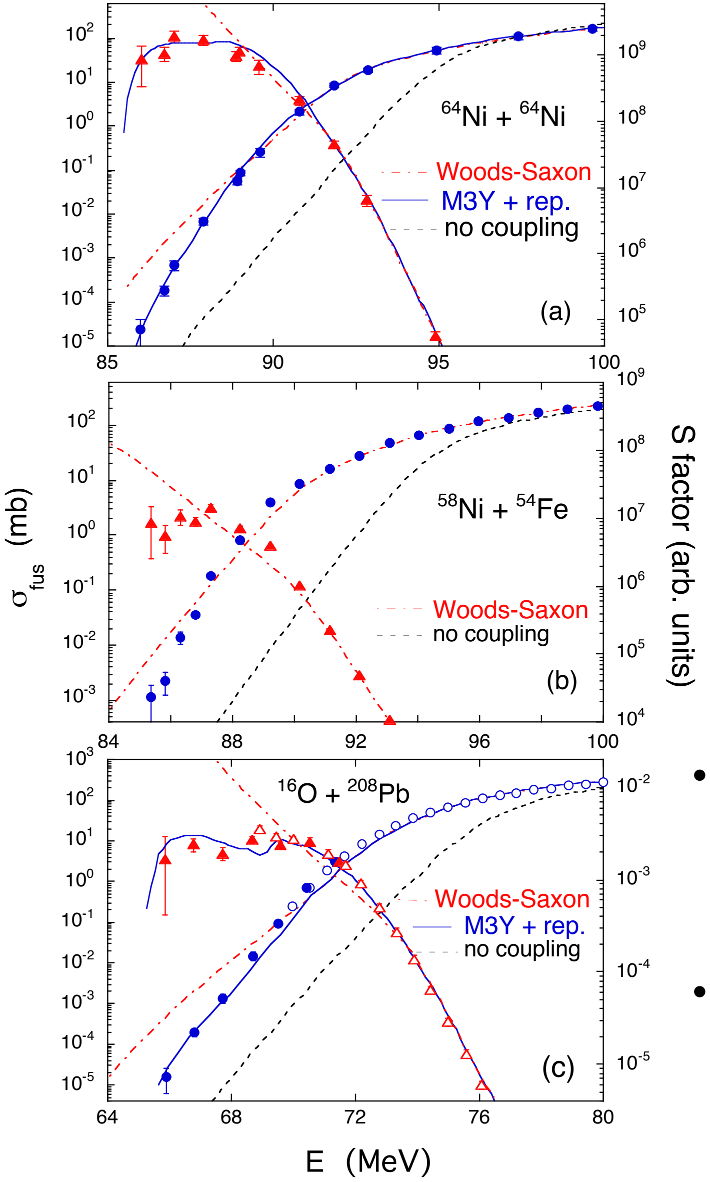
$$\frac{1}{E\sigma_{fus}}\frac{d(E\sigma_{fus})}{dE} = \frac{2\pi}{\hbar\omega} = \frac{dln(E\sigma_{fus})}{dE}$$

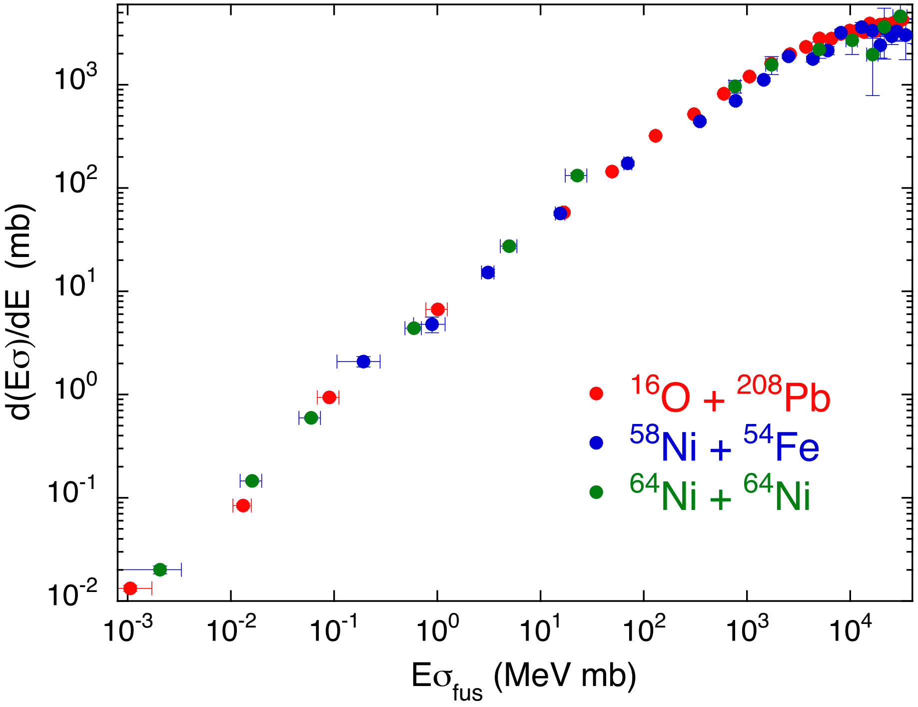
given by the logarithmic derivative and
proportional to the (parabolic) barrier width

C.Y. Wong, PRL 31, 766 (1973).

The representation d(Eσ)/dE *vs* Eσ

- we remove the effect of the varying Coulomb barrier when comparing different systems



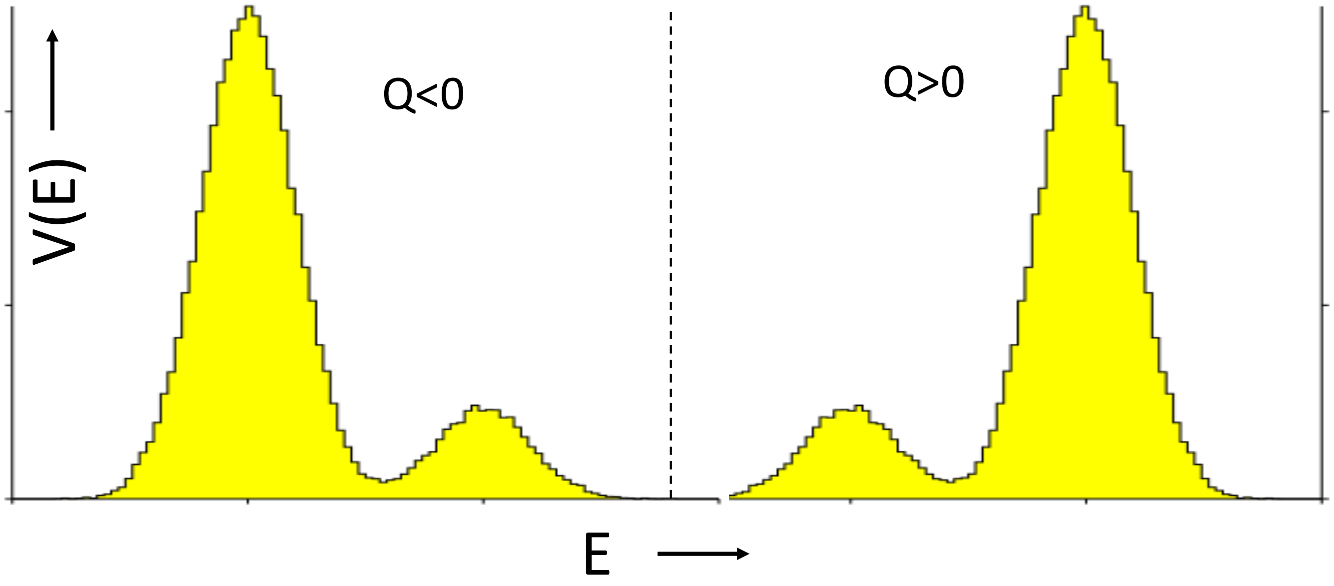


- The behaviour of these three systems is very similar, even if they strongly differ in mass asymmetry and nuclear structure

- *A* good starting point to look at other cases where inelastic excitations and/or nucleon transfer channels influence the sub-barrier fusion cross sections

From the Coupled-Channels model …

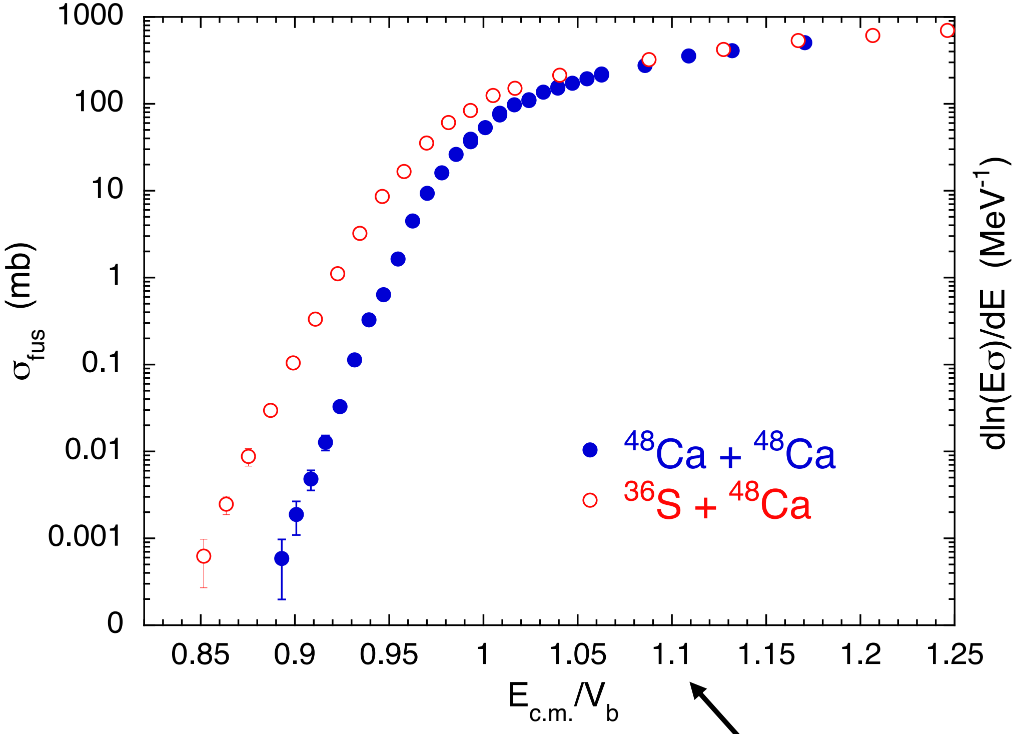
Schematic barrier distributions predicted by the CC model for coupling to one channel with $Q < 0$ (left) and $Q > 0$ (right)

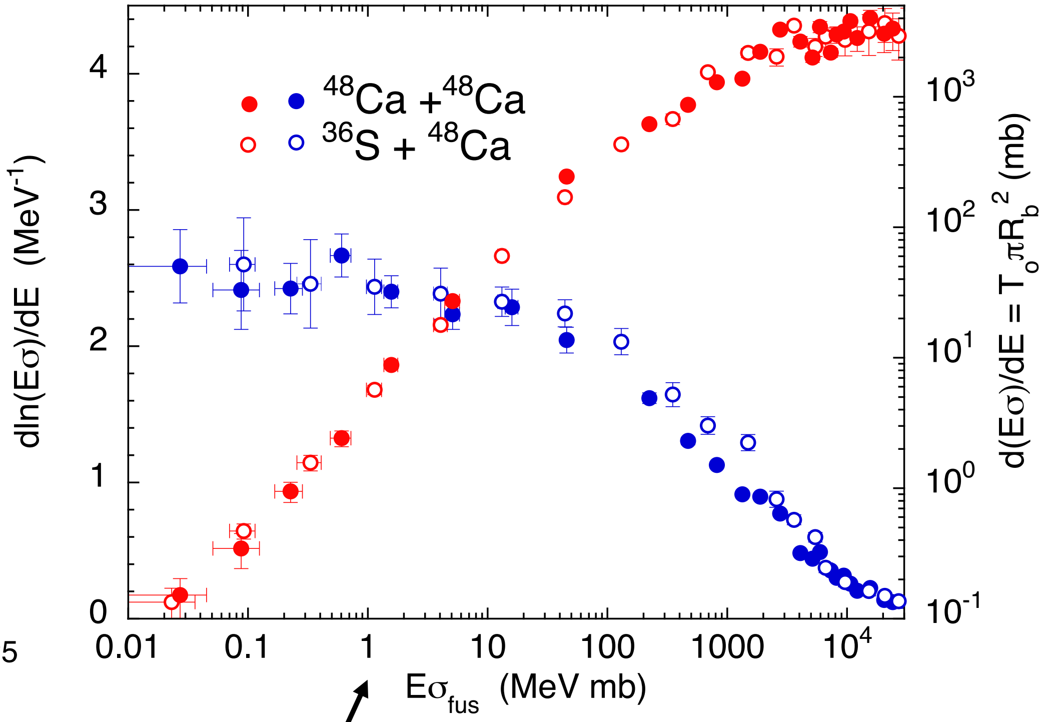


- The transmission coefficient, plotted vs energy, is smoother for couplings to $Q > 0$ channels, with respect to $Q < 0$ channels
- $d(E\sigma)/dE$ will be correspondingly smaller (larger)

C.H. Dasso, S. Landowne and A. Winther, NPA 405, 381 (1983)

Two reference cases

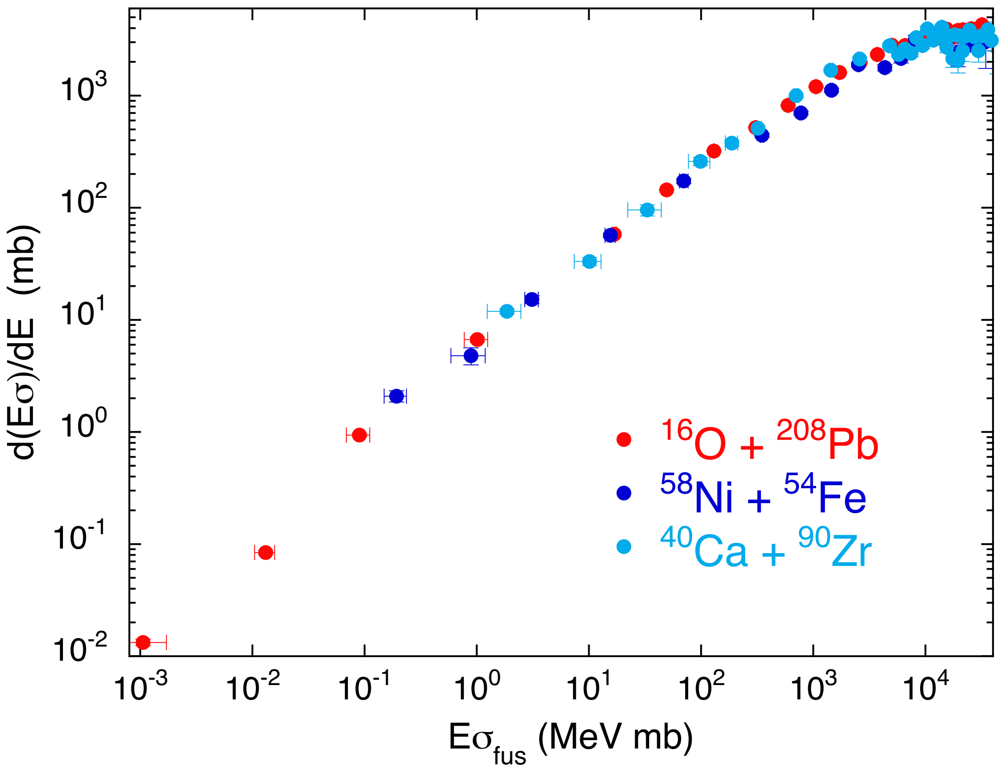


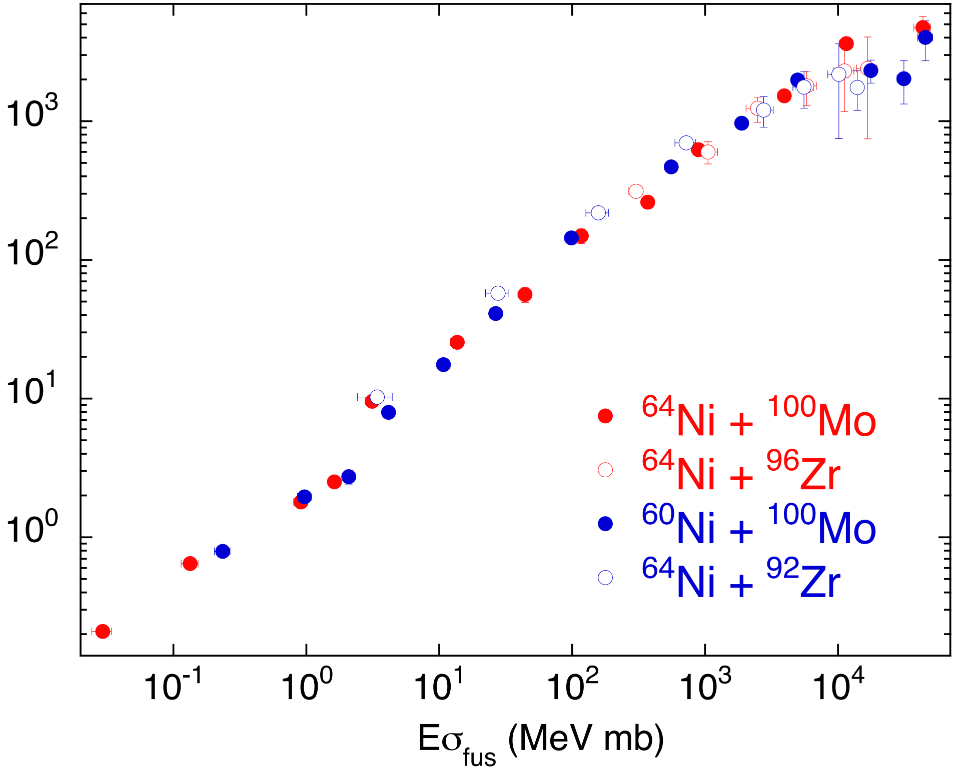


- Experimental fusion excitation functions, d[ln(Eσ)]/dE and d(Eσ)/dE vs σE the corresponding barriers
- The two barriers have approximately the same width
- N.B. in both cases, the measured barrier distributions are dominated by a single strong peak

A.M. Stefanini, et al., PLB 679 (2009) 95; PRC 78 (2008) 044607

Couplings to inelastic channels

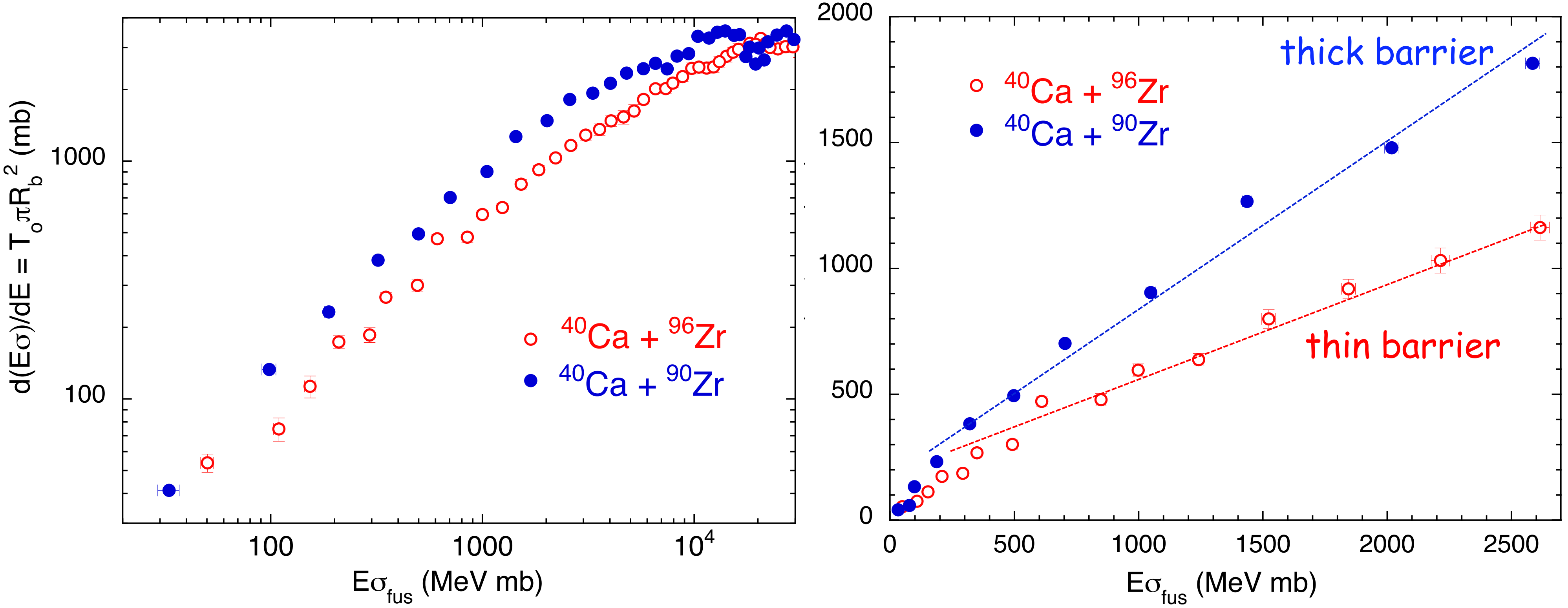




- $d(E\sigma)/dE$ does not essentially change when comparing systems where couplings to inelastic excitations are dominant

G. Montagnoli and A.M.Stefanini, EPJ A 59, 138 (2023)

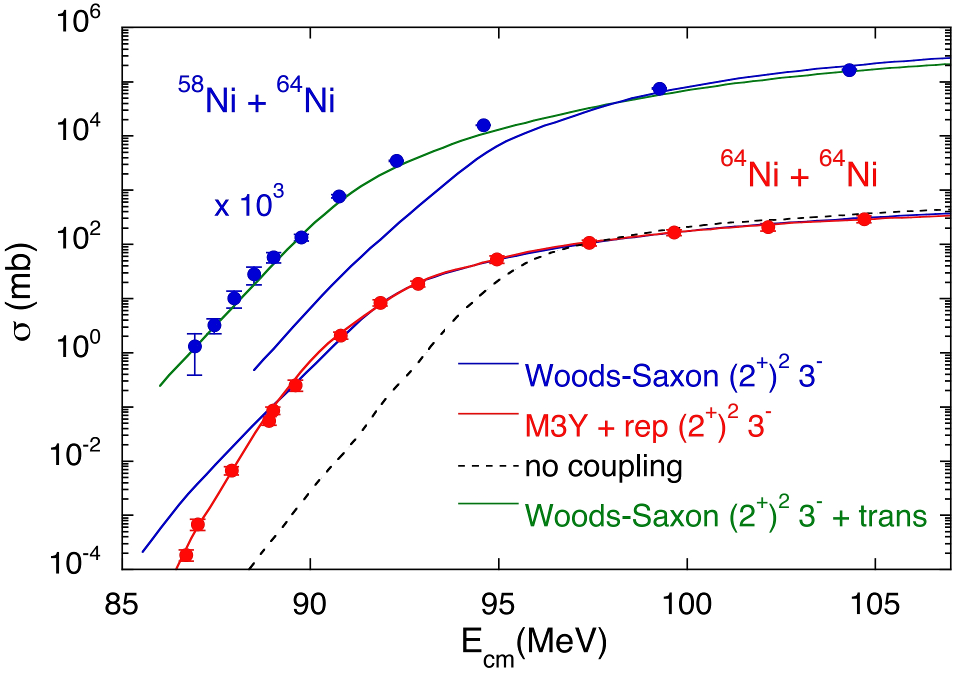
Couplings to transfer channels

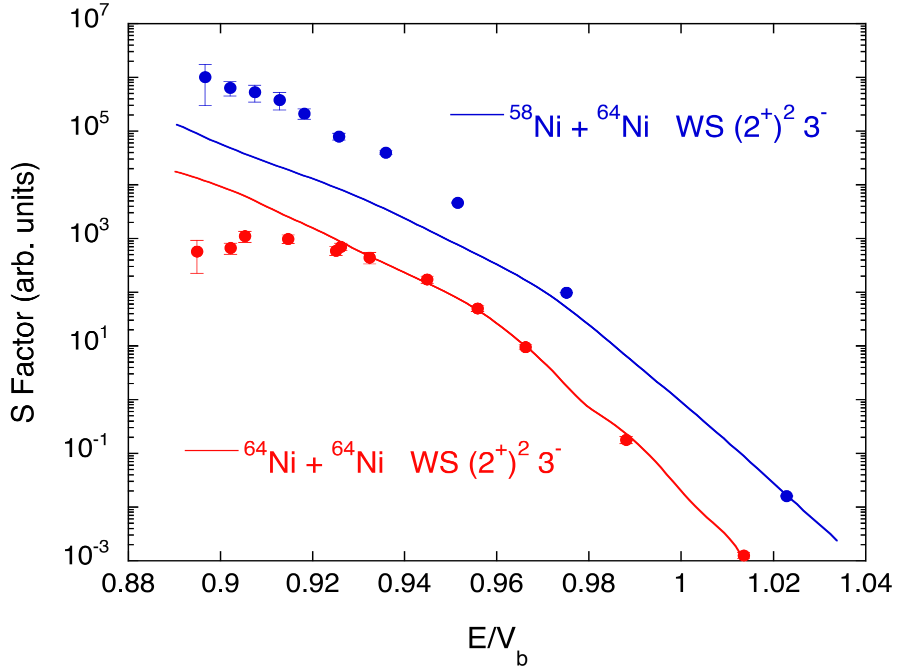


- For ^{40}Ca + ^{96}Zr transfer couplings are dominant, and a smaller derivative d(Eσ)/dE is observed
- the effective one-dimensional barrier is thinner simulating a wider barrier distribution
- the linear plot (right) makes even more clear the difference between the two systems

A.M. Stefanini et al., PLB 728 (2014) 639
H. Timmers et al., NPA 633 (1998) 421

Fusion cross sections and S-factors of ^{58,64}Ni + ^{64}Ni

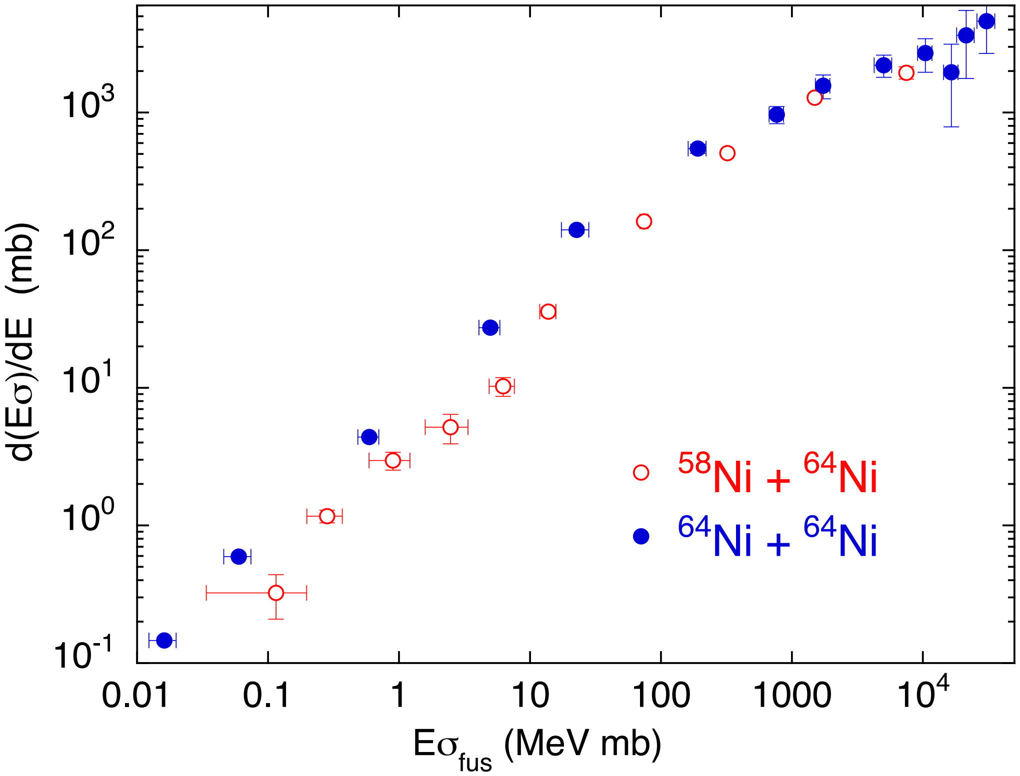


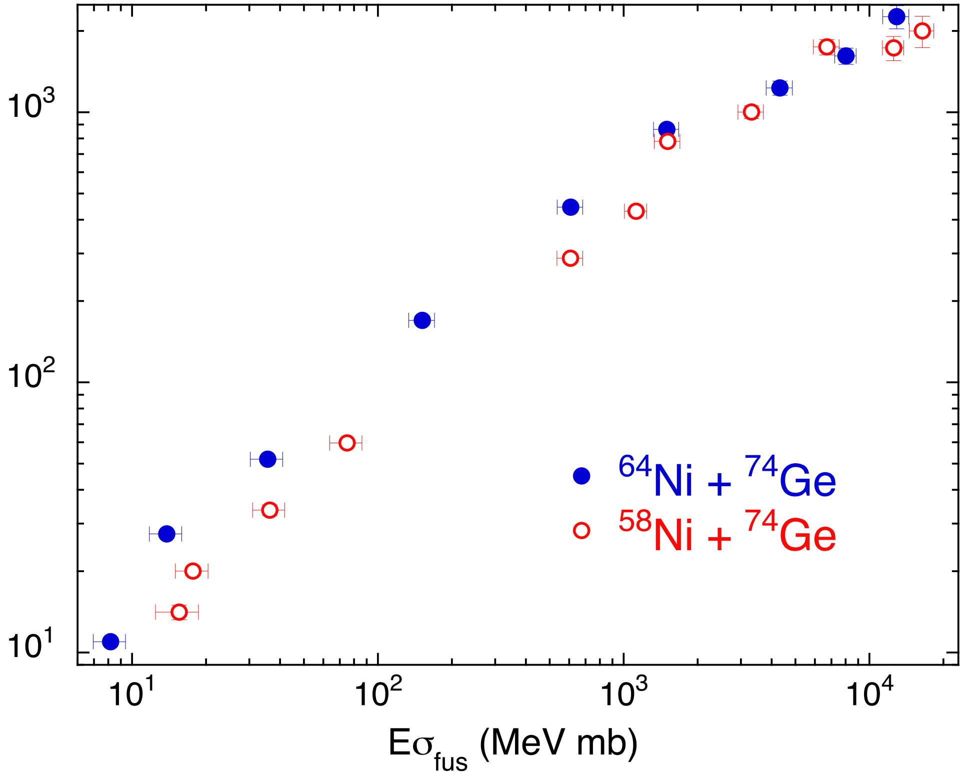


- No fusion hindrance has been observed down to about 1 mb in ^{58}Ni +^{64}Ni
- The behaviour is very different from ^{64}Ni +^{64}Ni
- The difference is due to the existence of Q>0 transfer channels in ^{58}Ni +^{64}Ni, given the similar low-energy vibrational nature of the two nuclei.

A.M.Stefanini, G.Montagnoli et al., PRC100, 044619 (2018)

The cases of ^{58,64}Ni + ^{64}Ni, ^{74}Ge



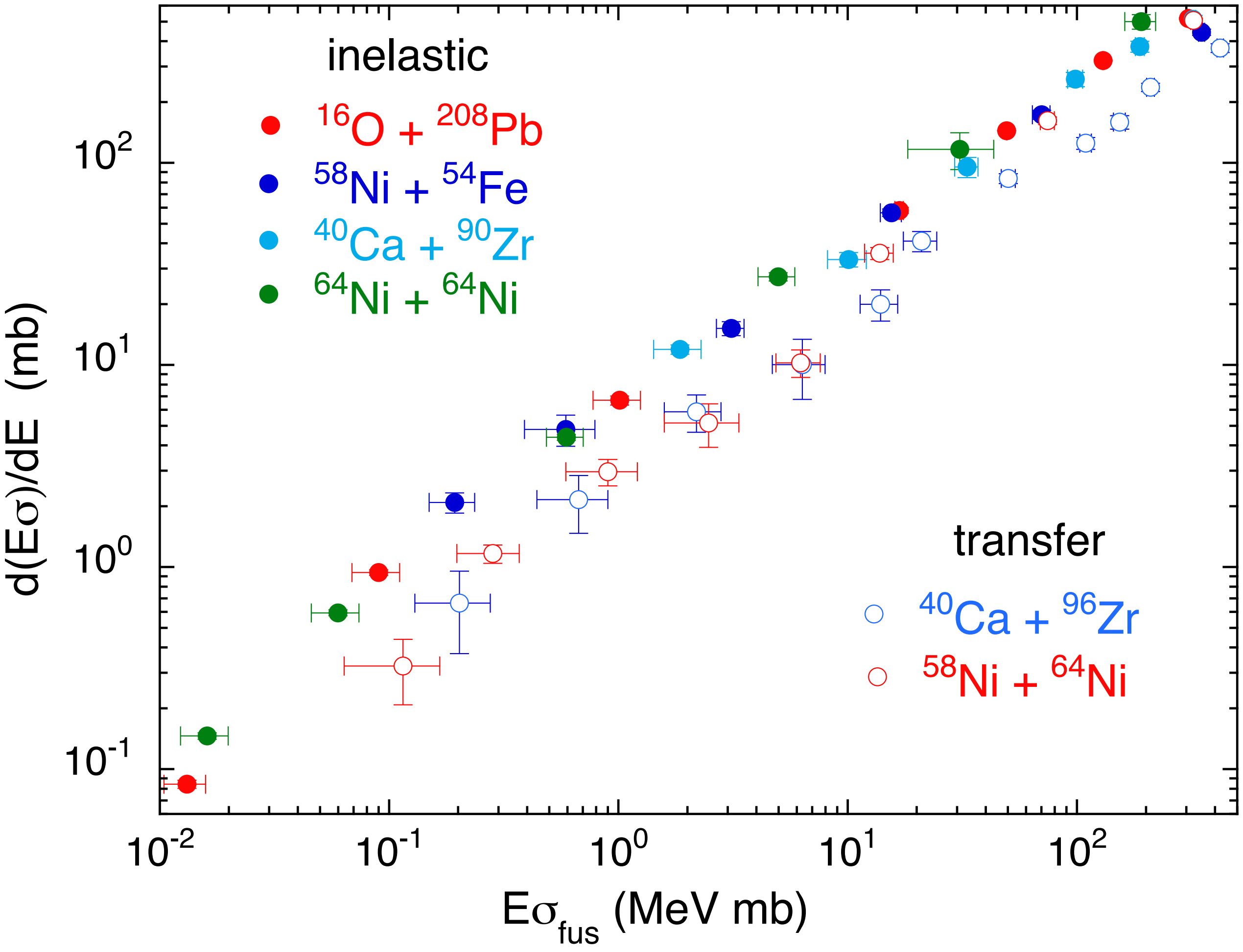


- Nucleon transfer couplings with Q > 0 produce large cross section enhancements in ^{58}Ni + ^{64}Ni ⟶ a smaller derivative below Eσ ≈ 50 MeV mb

- ^{74}Ge is vibrational, however the influence of strong Q > 0 neutron pick-up couplings in ^{58}Ni + ^{74}Ge, produces a less steep slope, even if ^{58}Ni is more rigid than ^{64}Ni

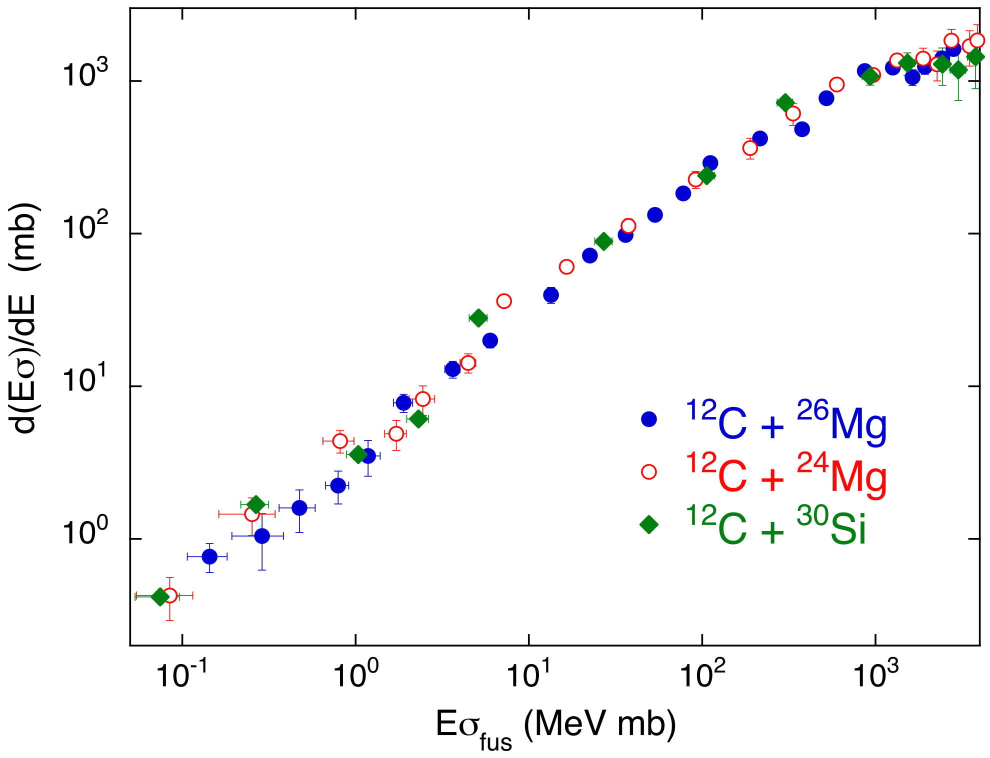
A.M. Stefanini, et al., PRC 100 044619 (2019)
C.L.Jiang, et al., PRL 93, 012701 (2004)
M. Beckerman et al., PRC 25, 837 (1982)

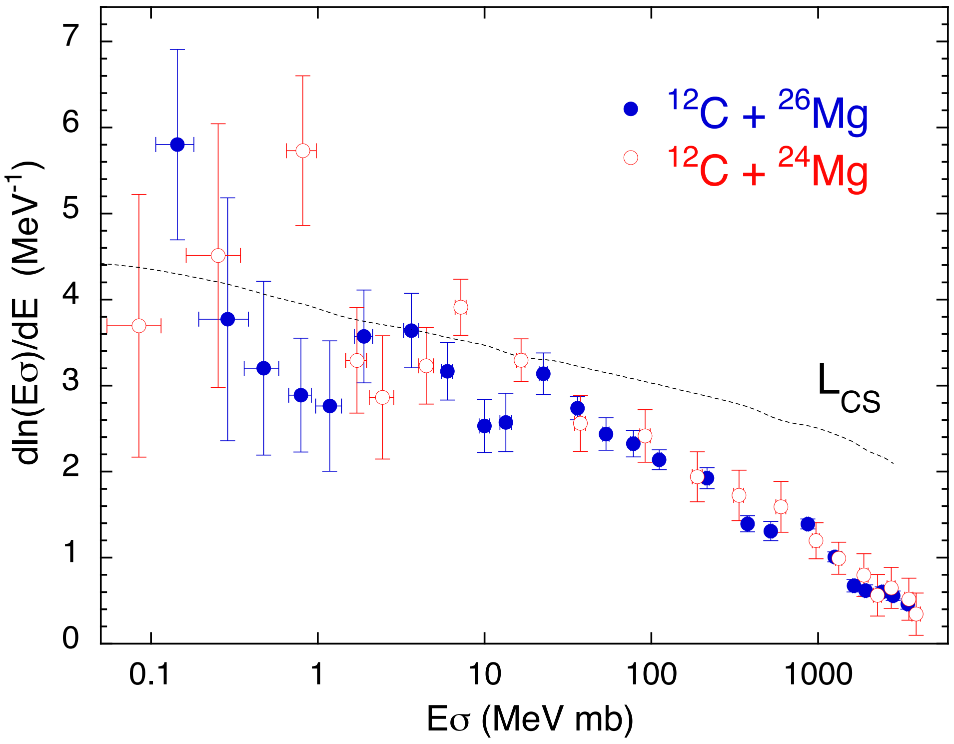
All together now !



- Two well separated groups of systems are evident, matching the nature of the dominant couplings

What about medium-light systems ?





- The behaviour of the three systems (left) is similar
- ^{30}Si is spherical, while ^{26,24}Mg have a permanent prolate deformation
- one observes various oscillations in the logarithmic derivatives (right), even if the experimental errors are large for ^{24}Mg + ^{12}C
- (identifying the hindrance threshold is not straightforward)

A.M.Stefanini et al., PRC 108, 014602 (2023)
G. Montagnoli et al., PRC 101, 044608 (2020); PRC 97, 024610 (2018)

Summary and Conclusions

- the Wong's formula, in relation to basic concepts of the CC model
- the representation of $d(E\sigma)/dE$ vs σE removes the difference due to the Coulomb barrier height of different systems
- it is sensitive to the barrier width
- $d(E\sigma)/dE$ vs σE does not essentially change when comparing systems where couplings to inelastic excitations are dominant
- strong transfer couplings with $Q > 0$ change that slope, as predicted by the CC model
- for medium-light systems this analysis may be complicated by the presence of cross section oscillations

Collaboration

A.M.S.[1], G. Montagnoli[2], M. Del Fabbro[2], L. Corradi[1], E. Fioretto[1], S. Szilner[3] … and many others

1 INFN, Laboratori Nazionali di Legnaro, Italy
2 Dipartimento di Fisica e Astronomia Universita' di Padova and INFN, Padova, Italy
3 Ruder Boskovic Institute, Zagreb, Croatia

Thank you for your attention