Reazioni tra ioni pesanti: dalle collisioni quasi-elastiche alla fusione completa

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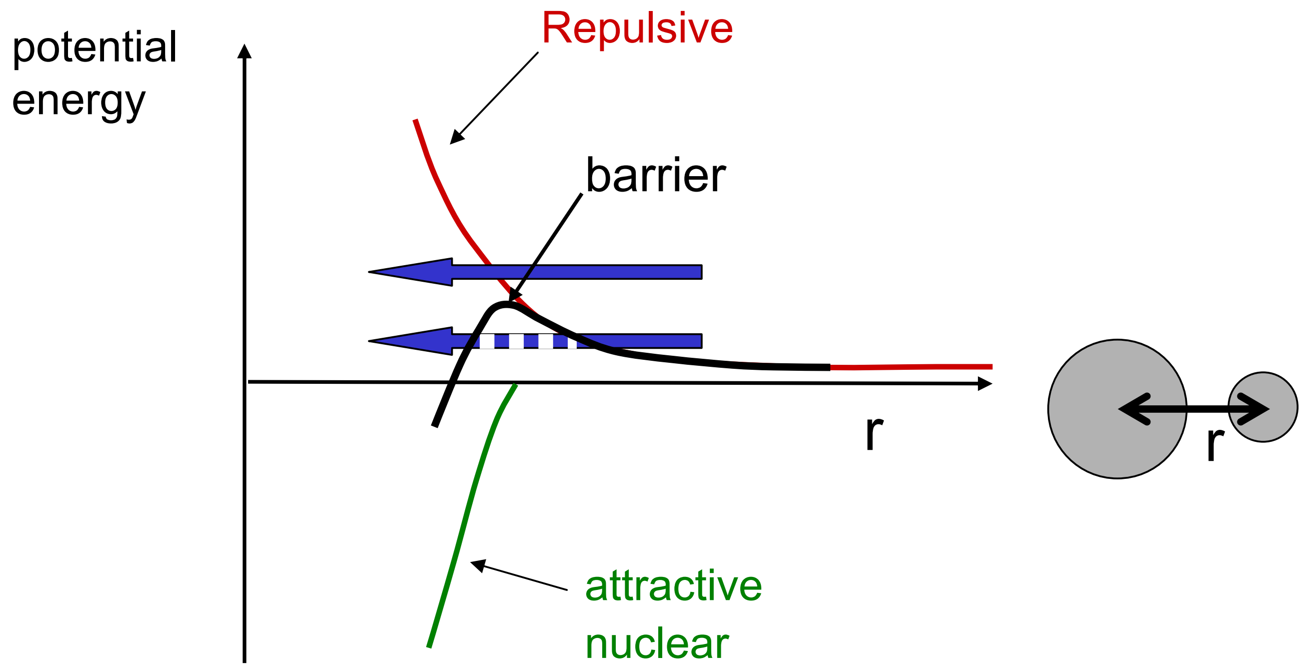
Incontro Nazionale di Fisica Nucleare

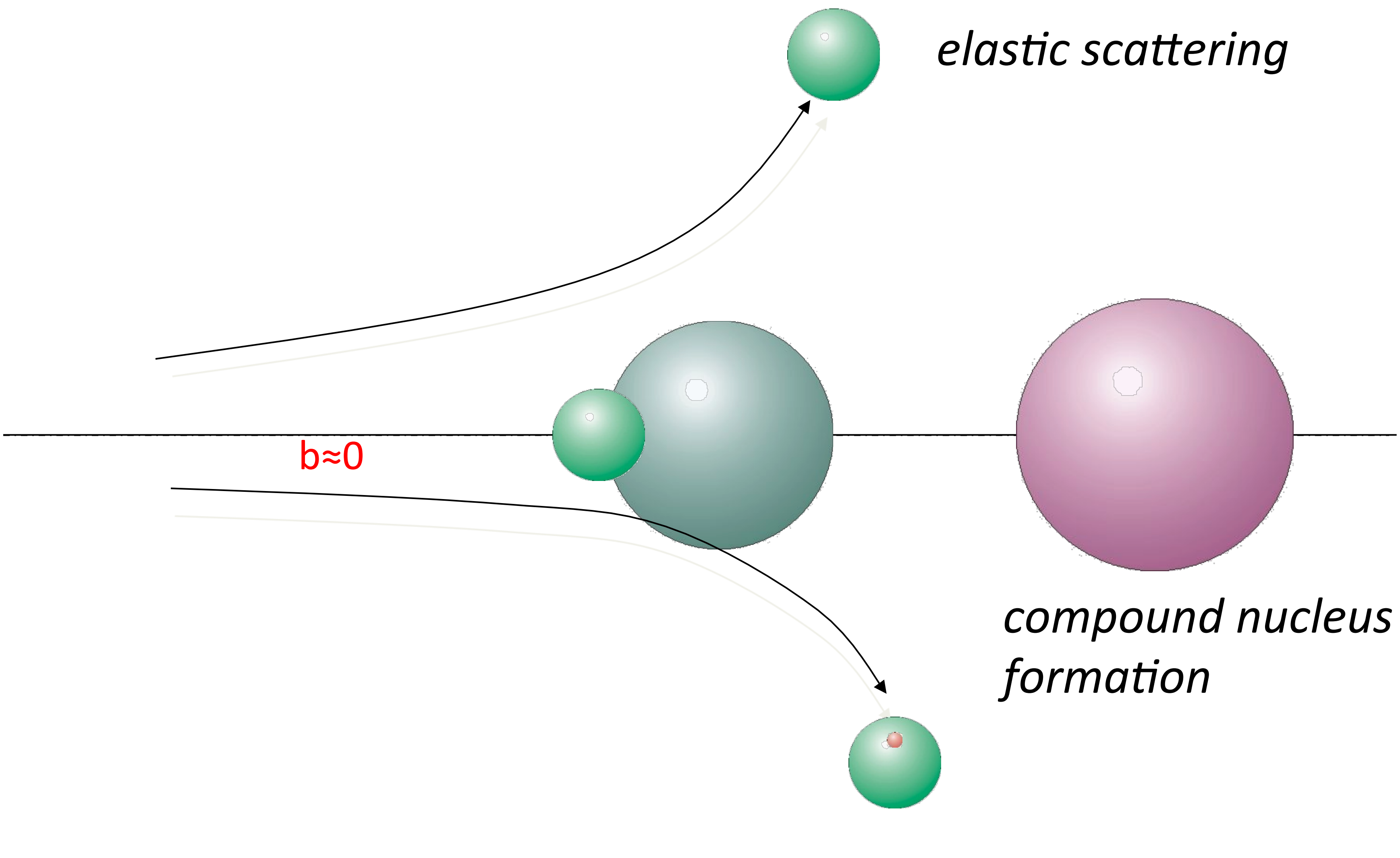
Padova, 25 marzo 2014

Attractive Nuclear Potential vs. Repulsive Electrostatic Potential

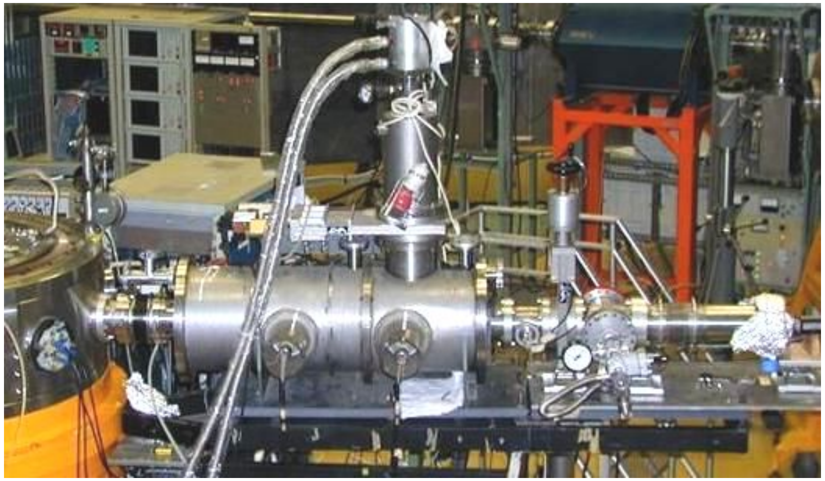


- Nuclear potential – a construct to account for the many body interactions of protons and neutrons
- Barrier passing or tunnelling → capture (fusion)

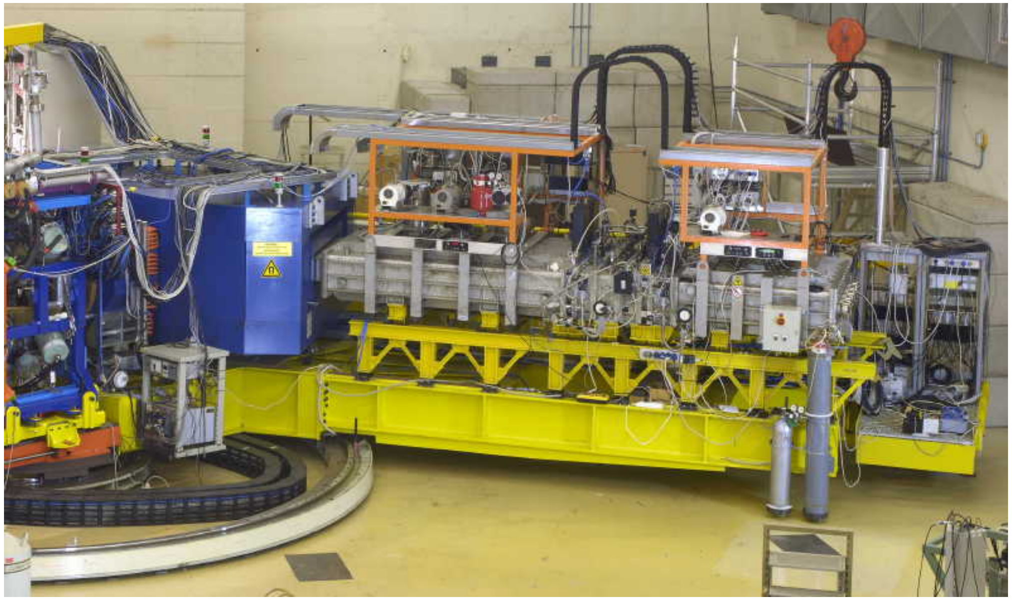
Heavy Ion Reactions @ the Coulomb Barrier



Two lines of research

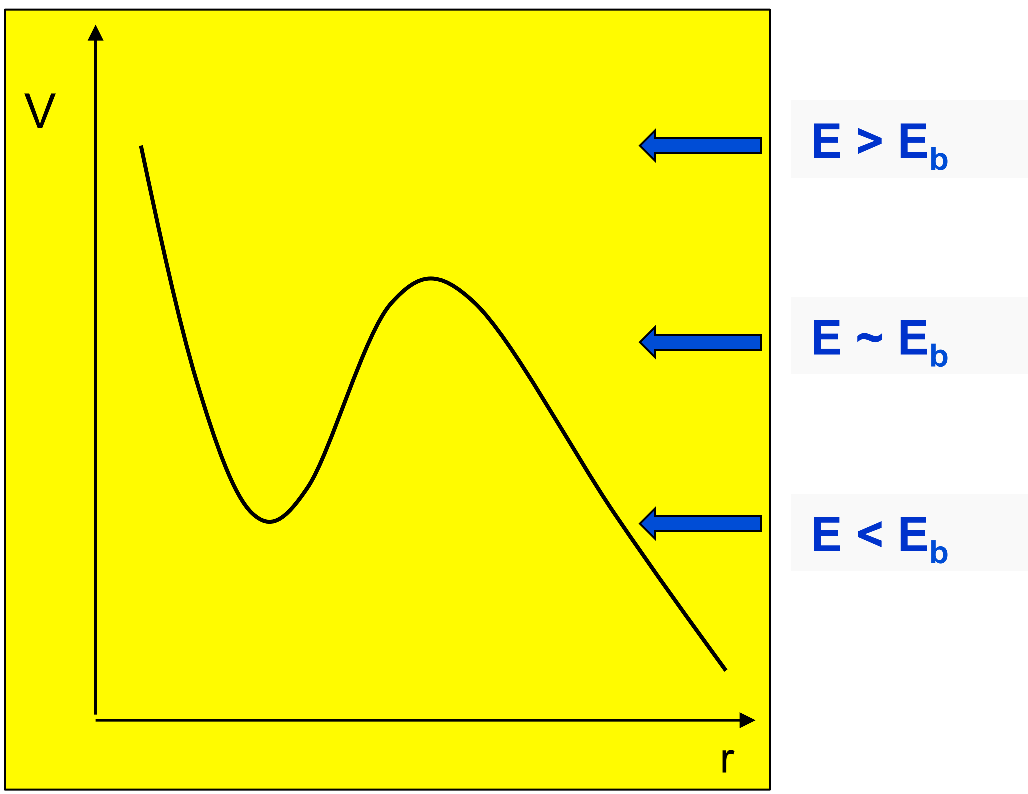


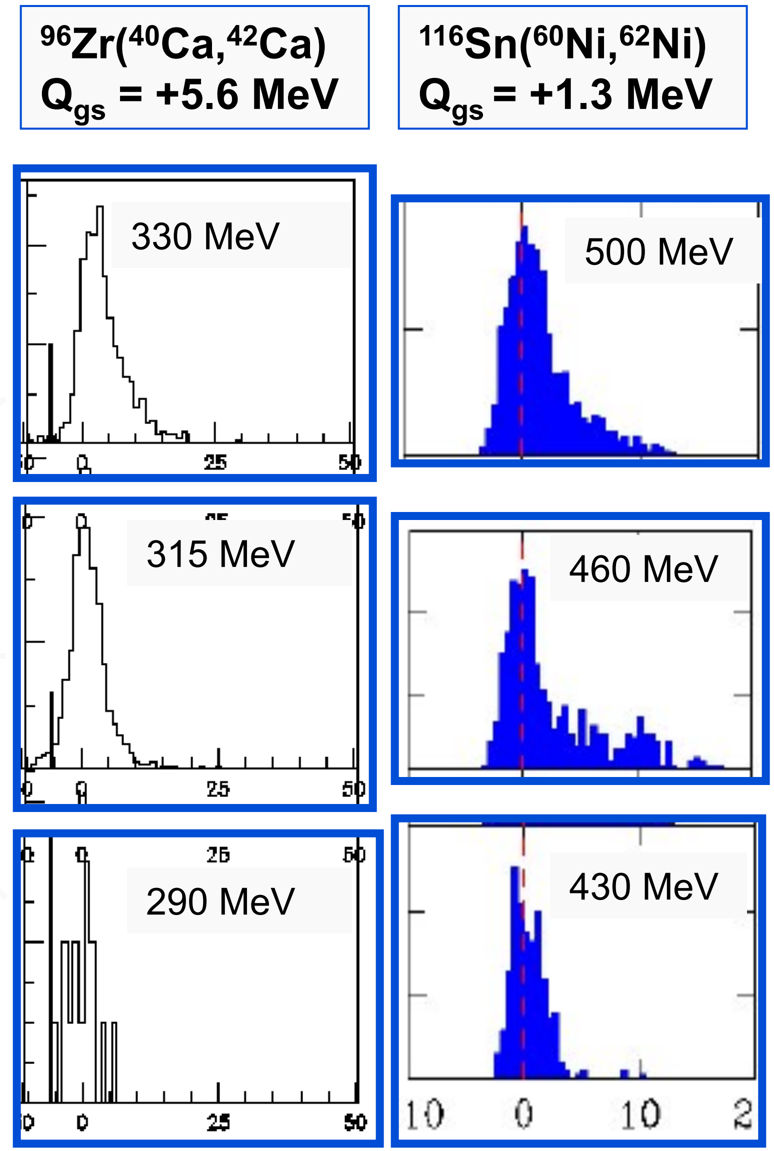
Heavy-ion fusion reactions
electrostatic beam separator
PISOLO



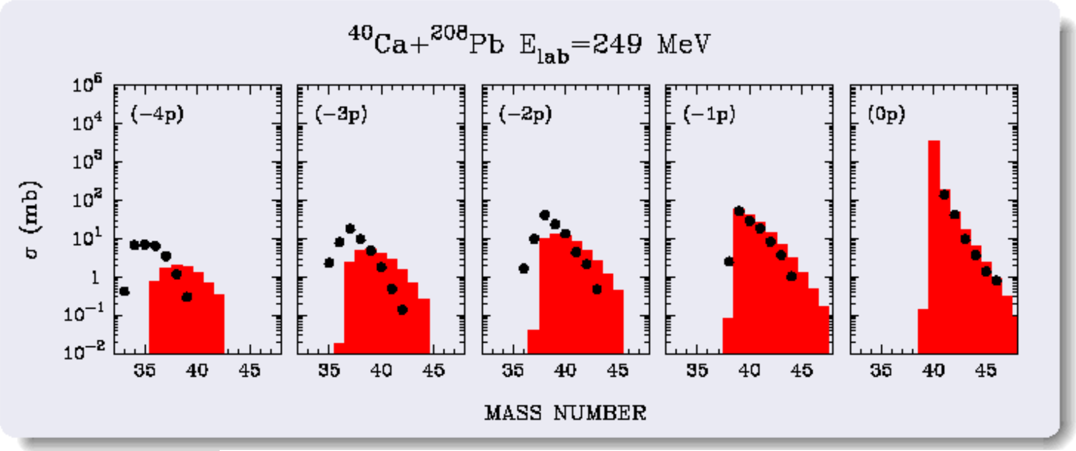
Nucleon transfer reactions
magnetic spectrometer
PRISMA

Nucleon transfer reactions: a smooth transition from deep-inelastic to quasi-elastic processes





Multi-nucleon transfer: experiment vs. theory

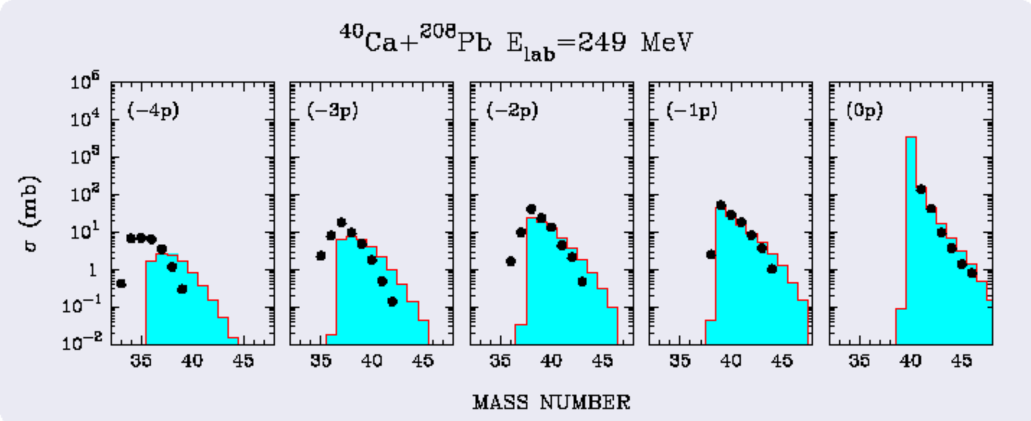


1pt

independent particle transfer

data : LNL

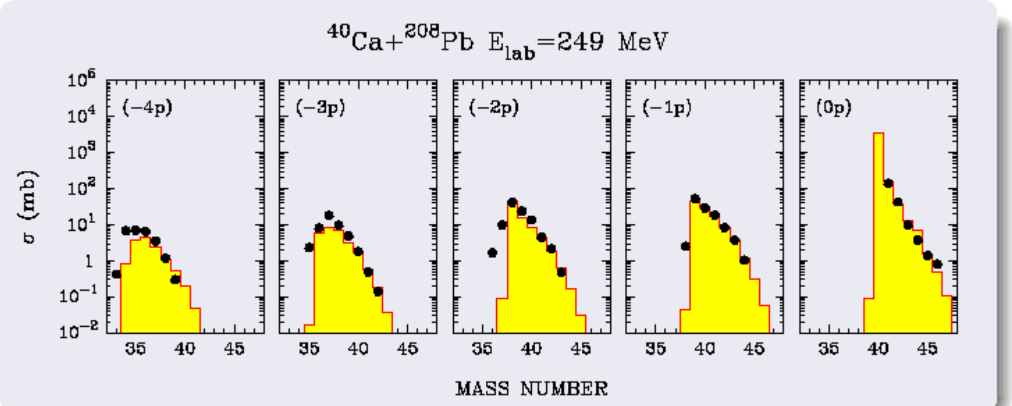
theory : GRAZING code and CWKB



+ pair transfer modes

1pt+2pt

$$F_{fi}^{pair}(r) = \beta_p \frac{\partial V^{opt}(r)}{\partial A}$$



+Evap.

L.Corradi, G.Pollarolo, S.Szilner

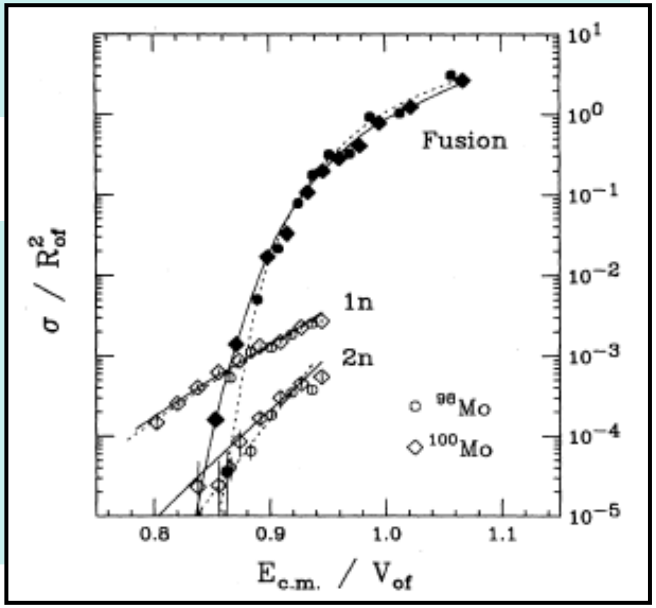
J.Phys. G36(2009)113101 (Topical Review)

Sub-barrier nucleon transfer reactions

Few reaction channels are open → uncertainties related to the nuclear potential are reduced

Q-value distributions are narrow → probe nucleon correlations close to the g.s., interplay between single and multiple particle transfer

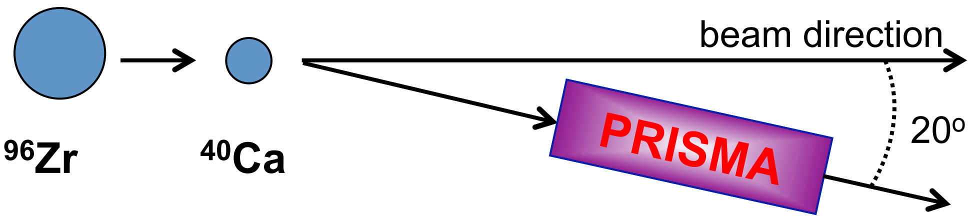
Tunneling between the colliding nuclei → transfer and fusion are measured in an overlapping range of energy and angular momentum

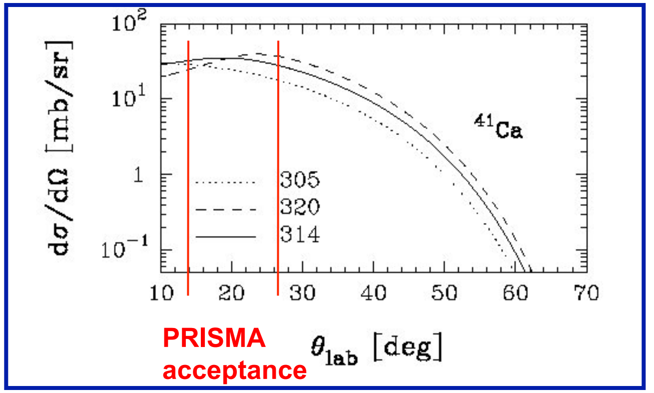


but … experimental difficulties !

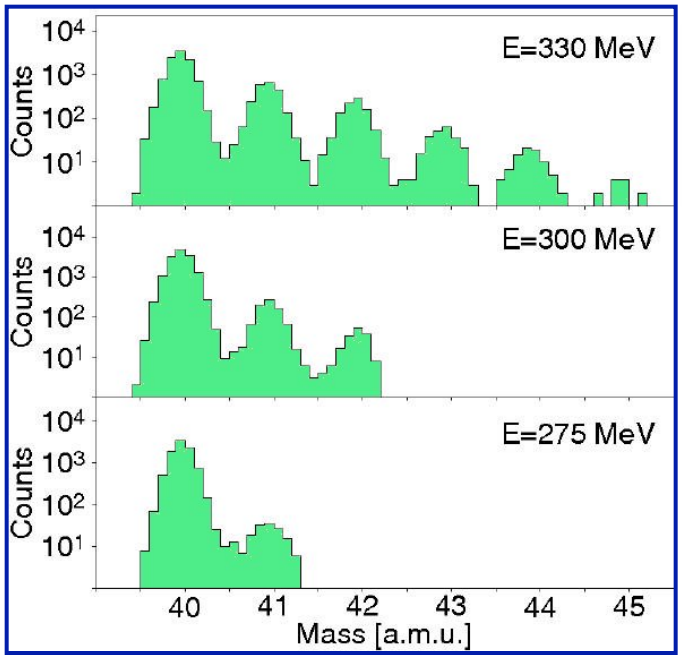
- Angular distributions are backward-peaked and projectile-like particles have low kinetic energies
- Cross sections are very small (hi efficiency needed)
- Complete identification of reaction products in A, Z and Q is difficult

Study of the reaction $^{96}Zr + ^{40}Ca$ using the inverse kinematics





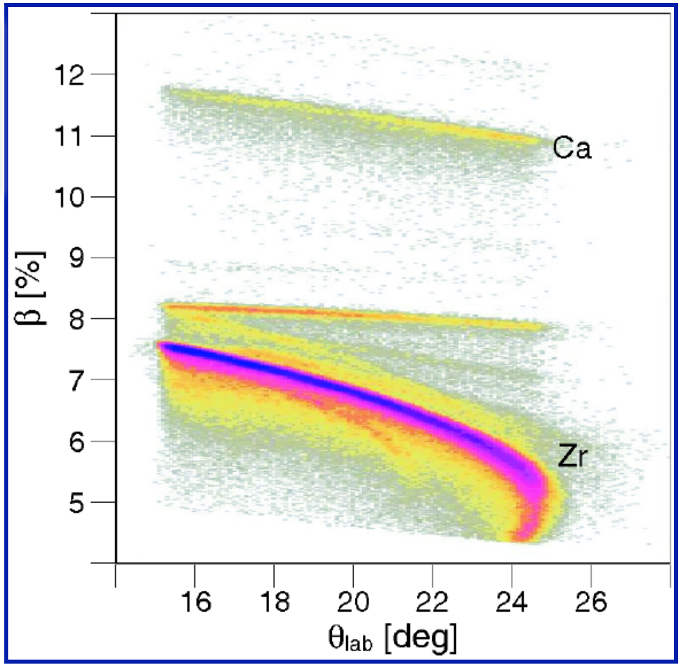
Z=20



Excitation functions

E_{beam} = 330 MeV – 275 MeV

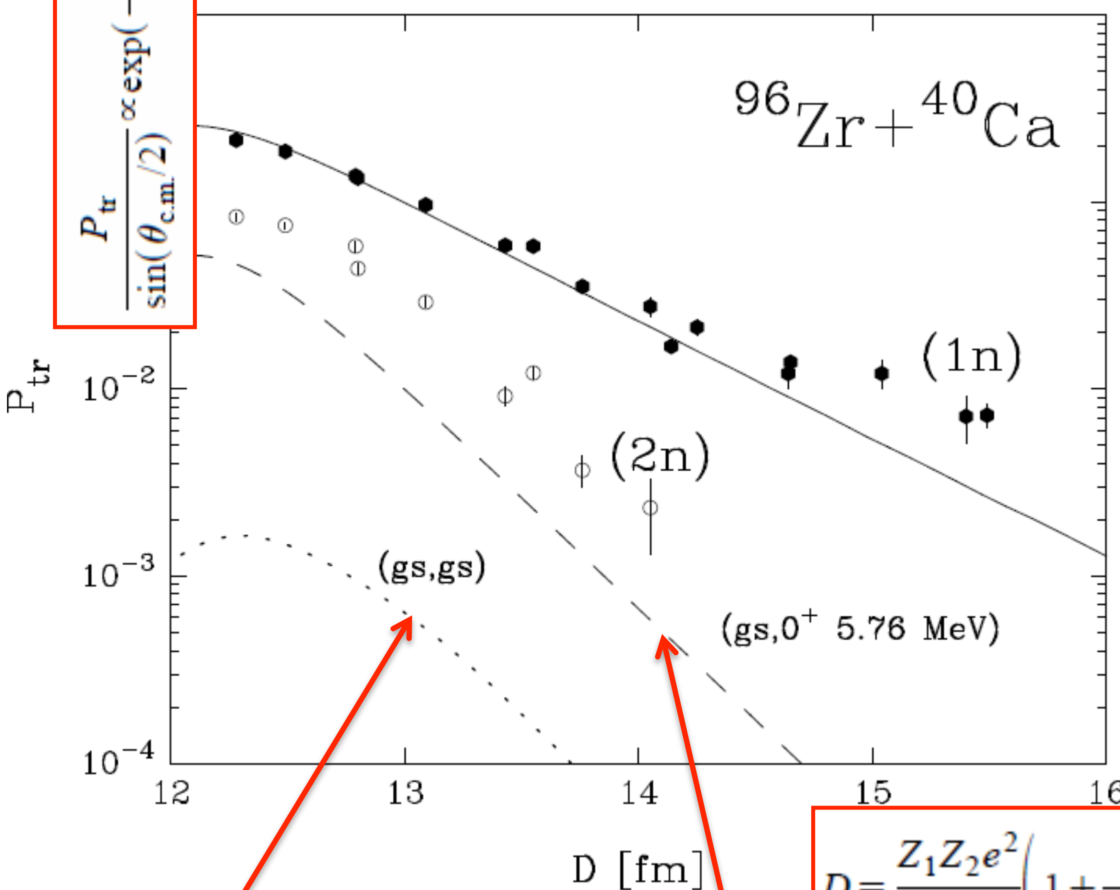
6 MeV step



Nucleon transfer channels have been measured down to 25 % below the Coulomb barrier

Sub-barrier transfer for ^{96}Zr (beam) + ^{40}Ca

$$\frac{P_{tr}}{\sin(\theta_{c.m.}/2)} \propto \exp(-2\alpha D)$$



2n transfer to g.s.

2n transfer to 0⁺ (5.76 MeV)

$$D = \frac{Z_1 Z_2 e^2}{2E_{c.m.}}\left(1 + \frac{1}{\sin(\theta_{c.m.}/2)}\right)$$

+1n well reproduced by theory in slope and absolute value

+2n : theory gives the correct slope, but underestimates the cross section

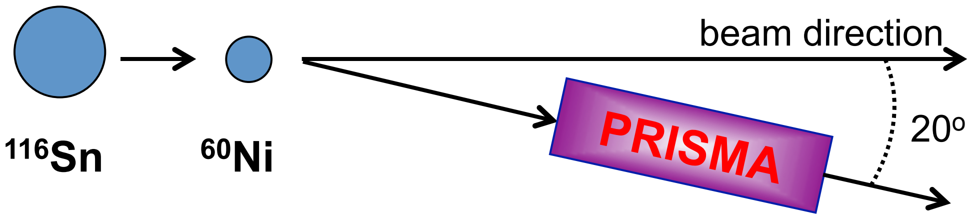
Is this due to the contribution of other excited states ?

(absoption is reproduced by theory)

$$\alpha = \sqrt{\frac{2\mu B}{\hbar^2}}$$

L. Corradi et al., Phys. Rev. C 84, 034603 (2011)

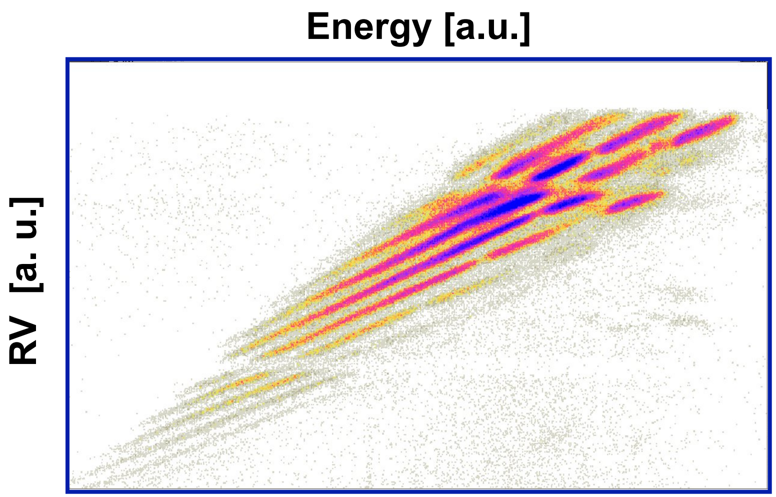
The reaction $^{116}Sn + ^{60}Ni$ using the inverse kinematics

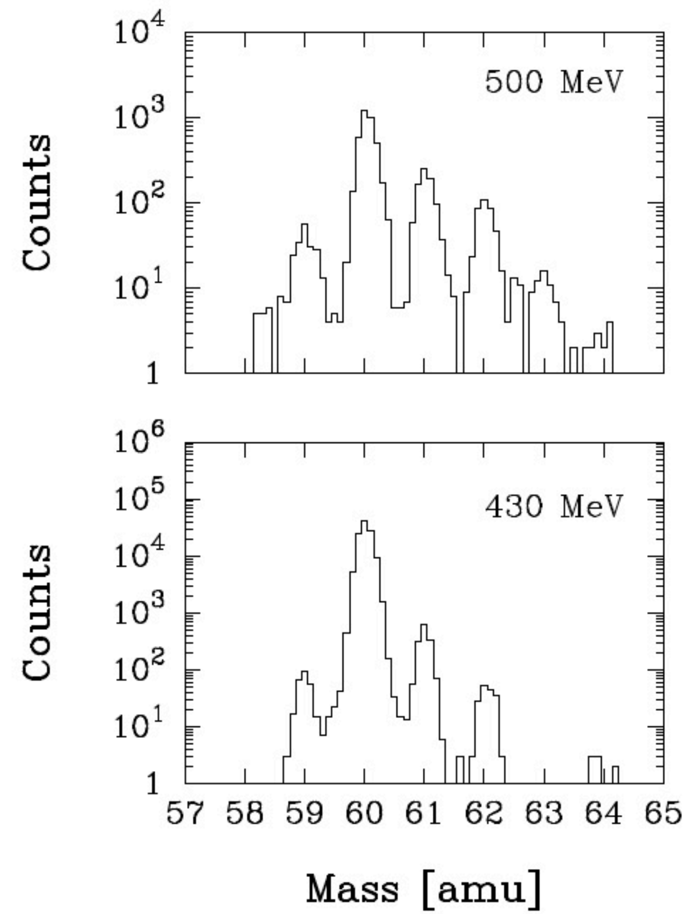


Excitation functions

E_{beam} = 410 MeV – 500 MeV

(D ~ 12.3 to 15.0 fm)



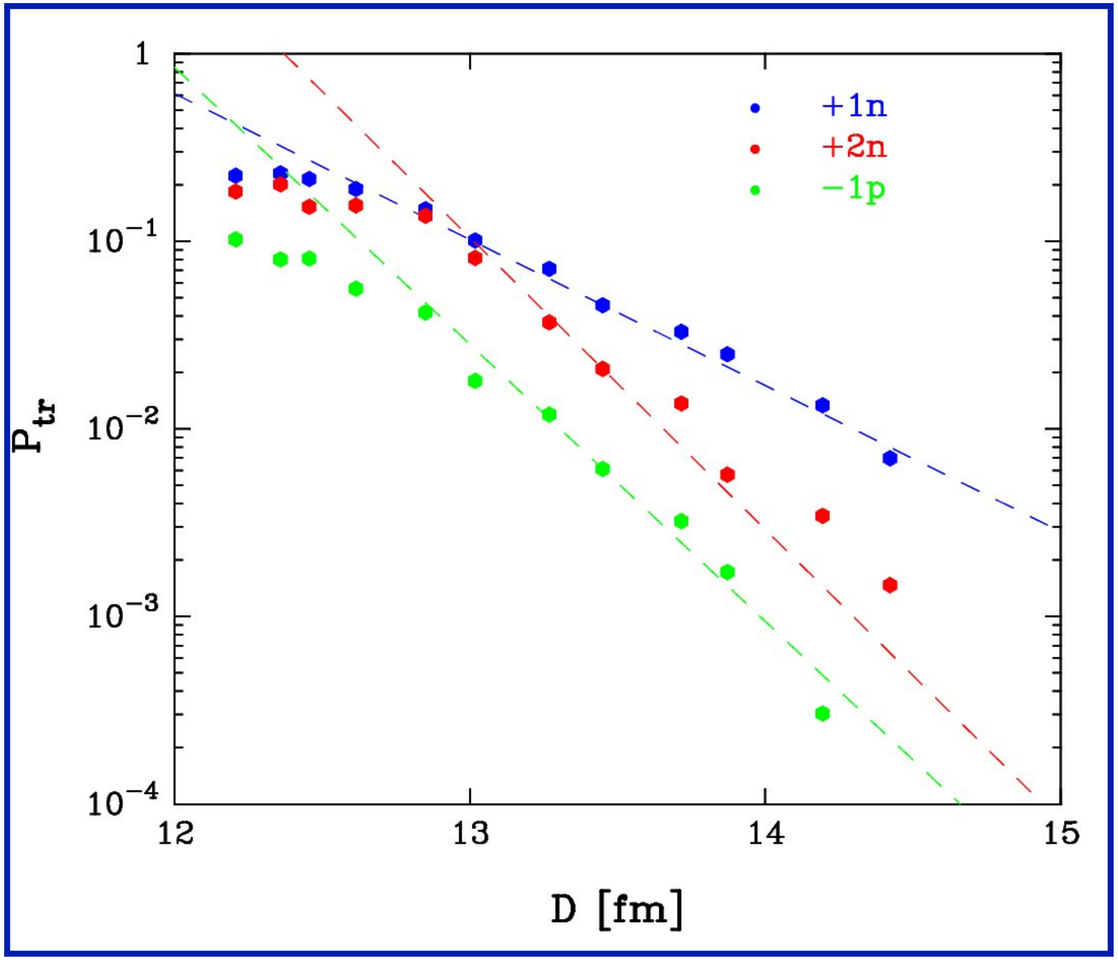


Ground state Q-values

	+1n	+2n	+3n	+4n
$^{96}Zr + ^{40}Ca$	+ 0.51	+ 5.53	+ 5.24	+ 9.64
$^{116}Sn + ^{60}Ni$	- 1.74	+ 1.31	- 2.15	- 0.24

➔ Most recent measurement for the case of $^{92}Mo + ^{54}Fe$: study of pair correlations populating ±(nn), ±(pp) and ±(np) transfer channels

Transfer probabilities for $^{116}Sn + ^{60}Ni$



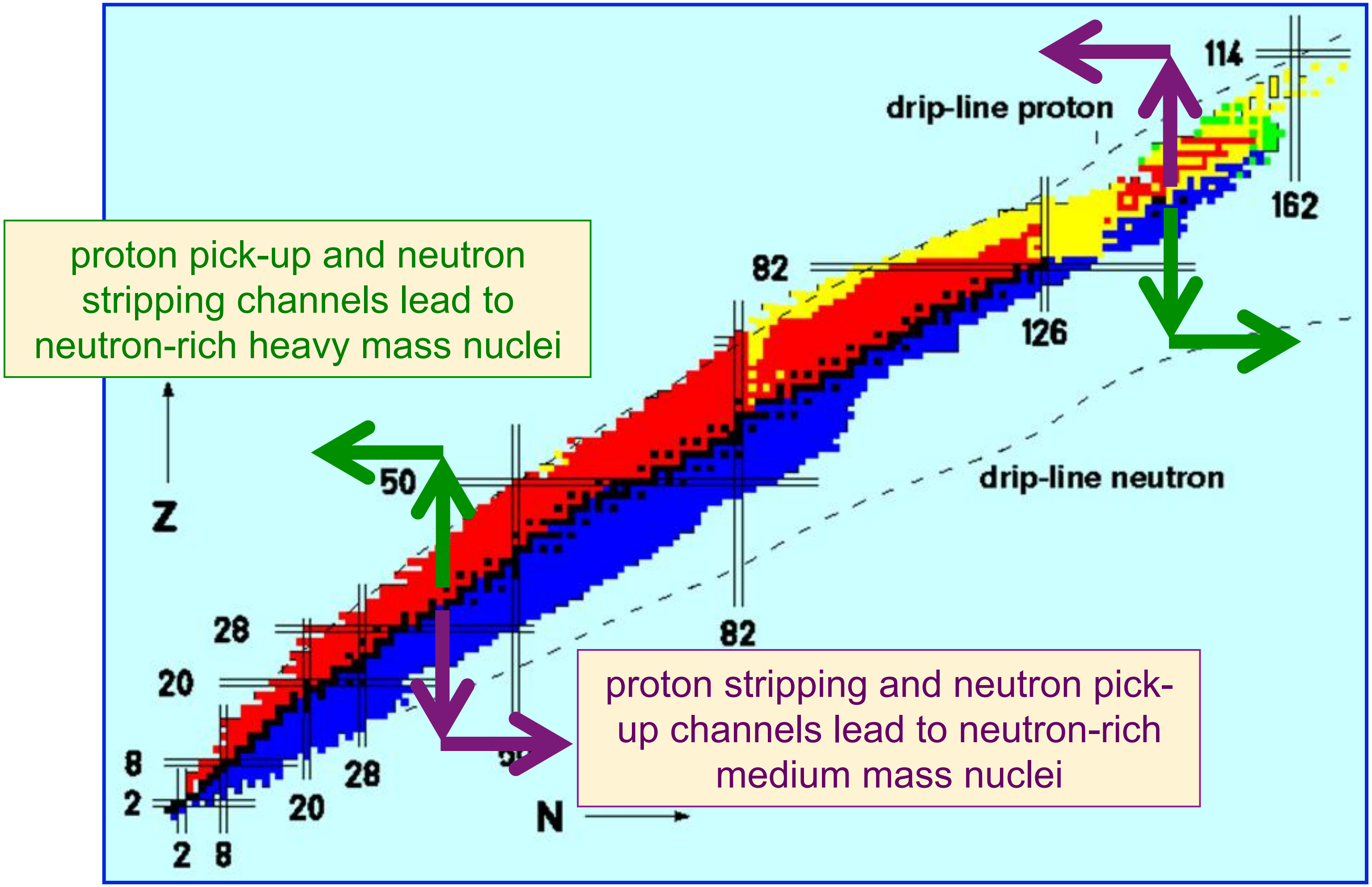
+1n and +2n slopes are in agreement with those expected from binding energies

An enhancement factor is needed for the +2n channel also in this system

Microscopic calculations in progress

D. Montanari et al., EPJ Web of Conf. 66, 03063 (2014)

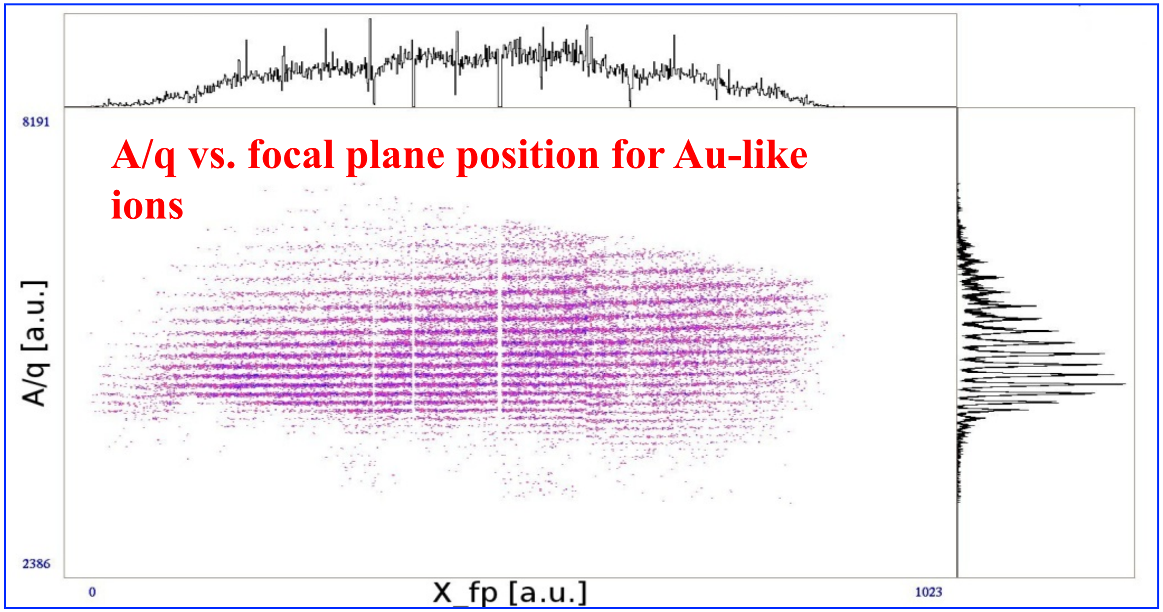
What about the heavy partner in multi-nucleon transfer reactions ?

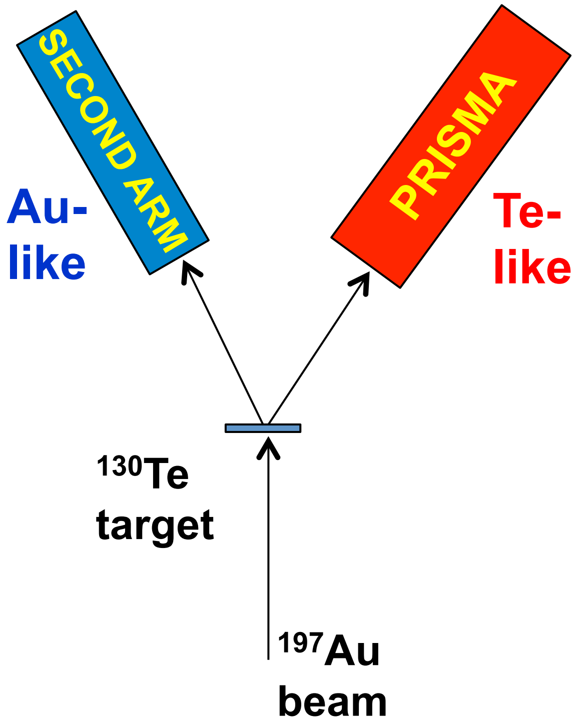


Certain regions of the nuclear chart, like that below ^{208}Pb or in the actinides, can be hardly accessed by fragmentation or fission reactions, and multi-nucleon transfer represents a suitable mechanism to approach those neutron rich areas.

Neutron rich nuclei populated via multinucleon transfer reactions: preliminary results on the $^{197}Au+^{130}Te$ system

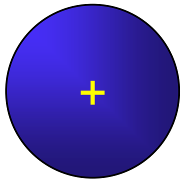
E_L =1070 MeV, θ_L =37° and E_L =1300 MeV, θ_L =27°
Detected both Te- and Au-like transfer products



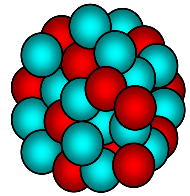


We obtained excellent A/q resolution.
The present problem is to get atomic charge states discrimination to uniquely identify final A

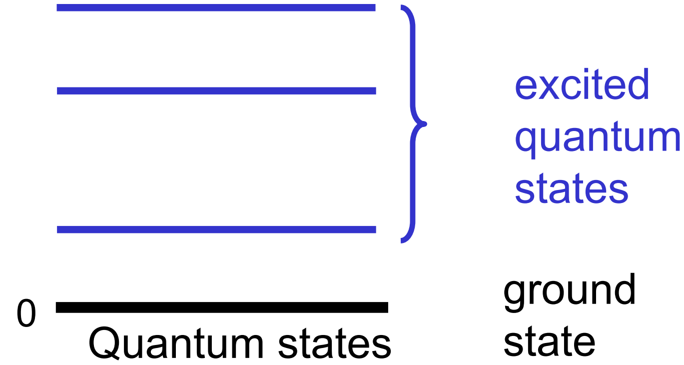
Sometimes the colliding nuclei may decide to proceed to fusion, even at sub-barrier energies …



Not an elementary particle

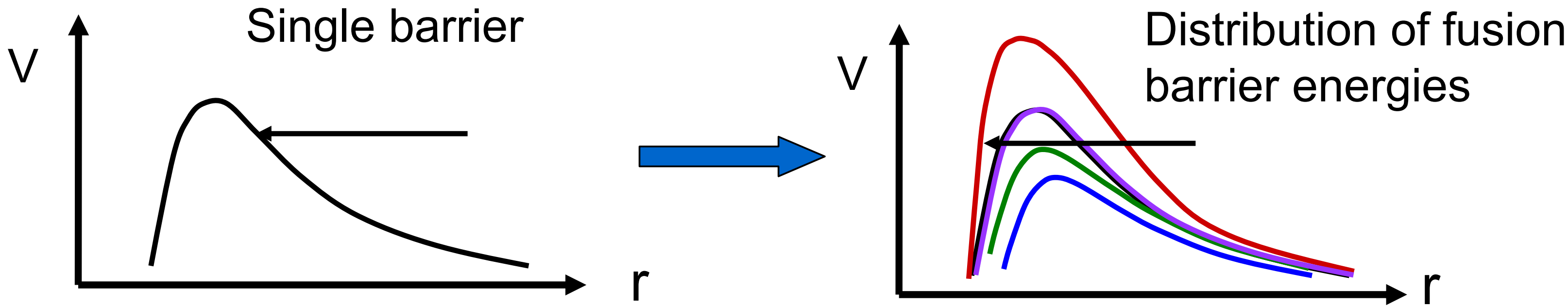


Many body quantum system



- Colliding nuclei in a superposition of quantum states

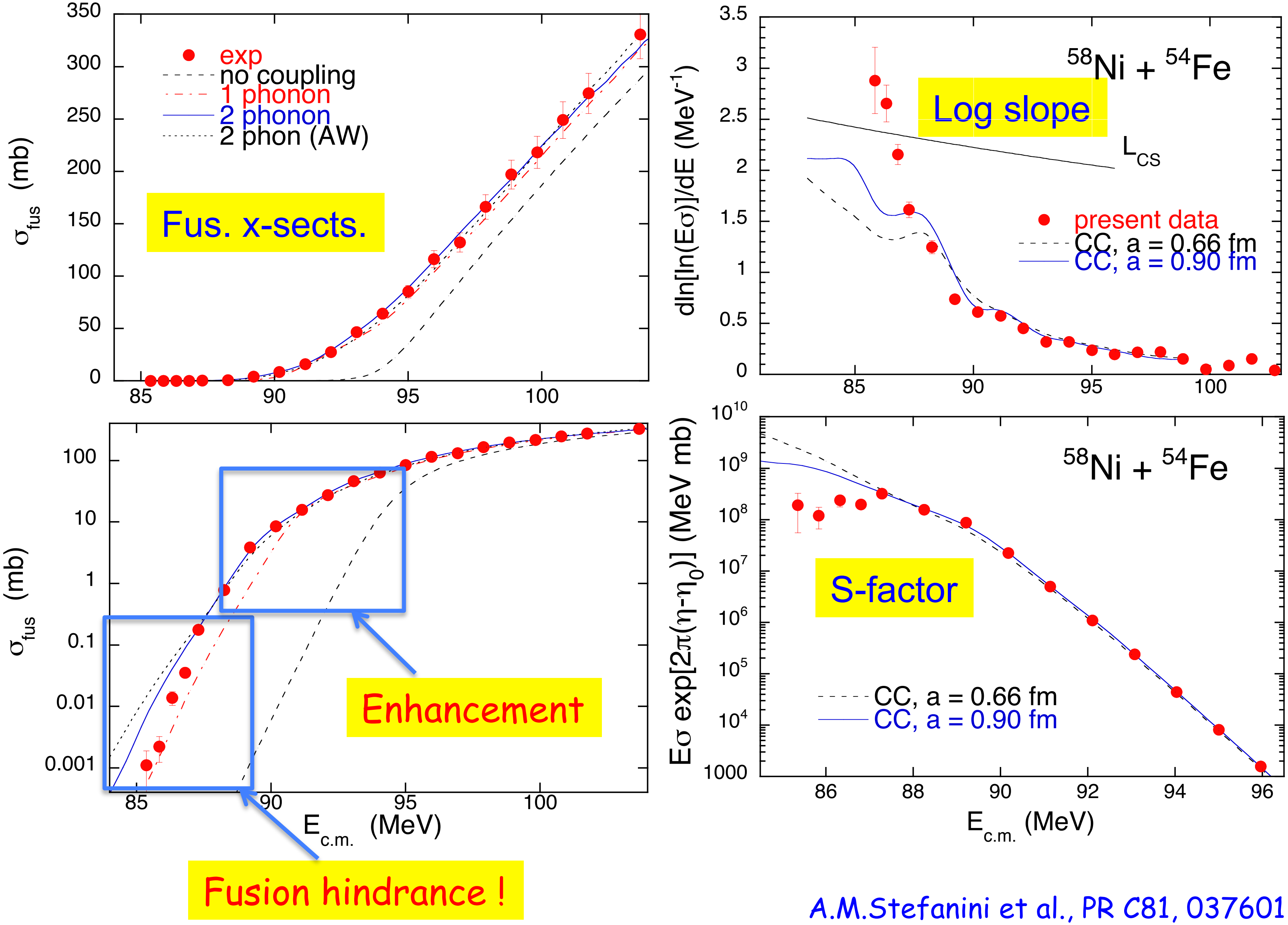
Dasso et al., NPA 405 (1983) 221



- Experimental barrier distribution $d^2(\sigma E)/dE^2$

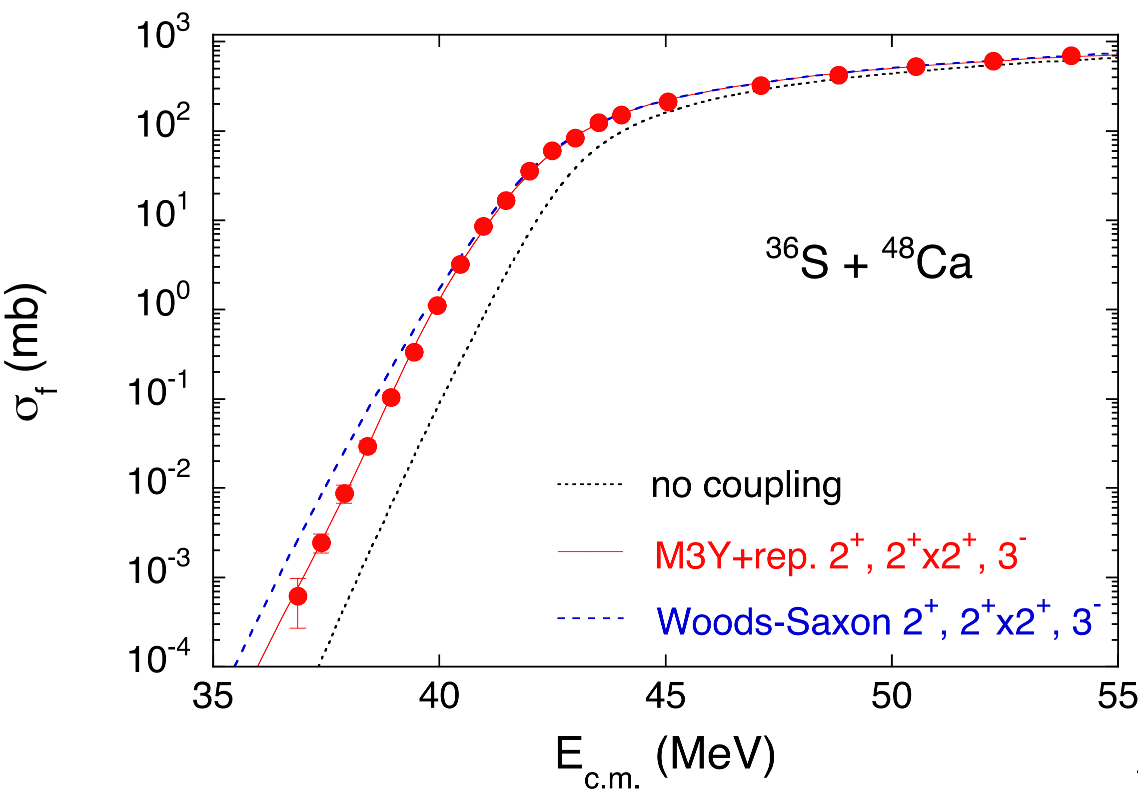
Rowley et al., PLB 254(1991)25

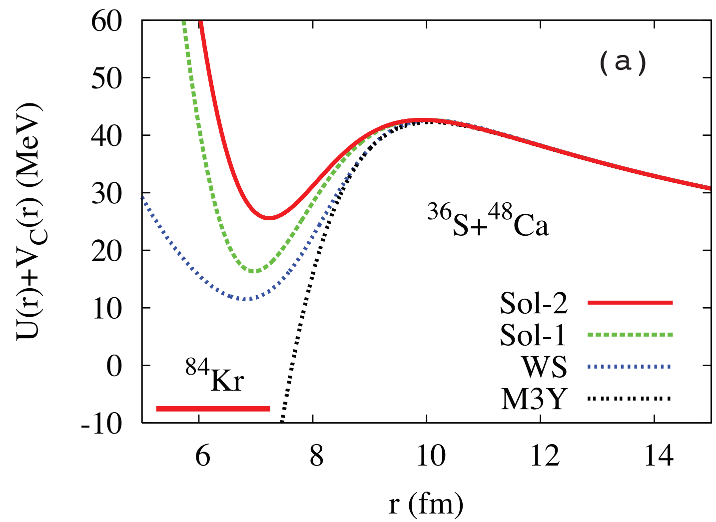
Fusion of stiff nuclei: the case of ^{58}Ni + ^{54}Fe

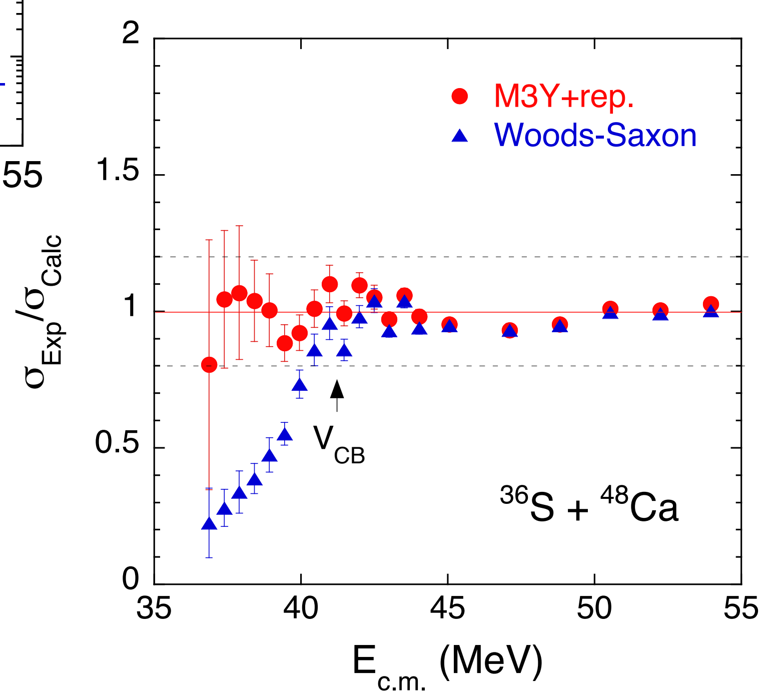


A.M.Stefanini et al., PR C81, 037601 (2010)

Fusion excitation function of $^{36}S + ^{48}Ca$



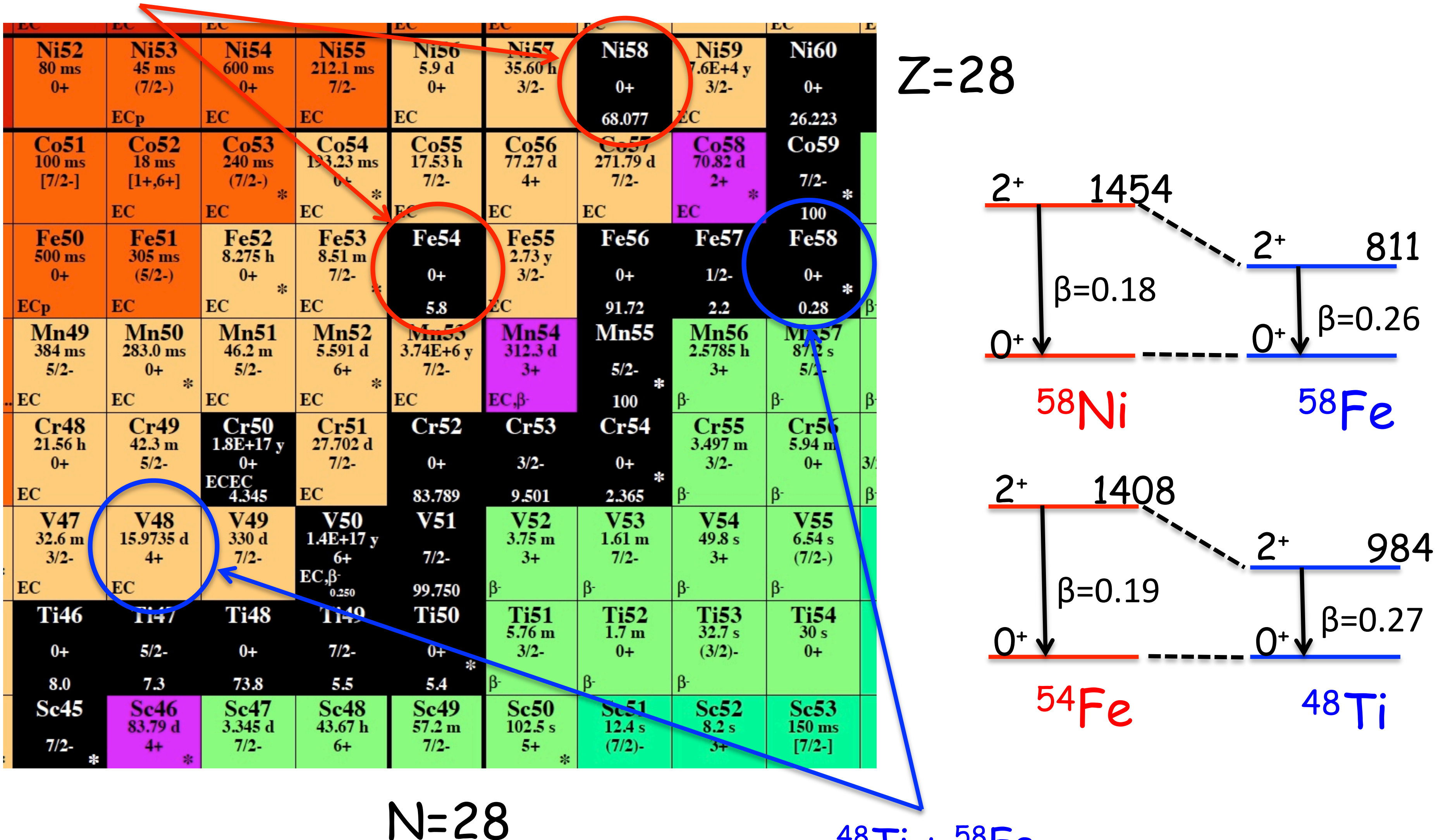




G.Montagnoli et al., PRC87, 014611 (2013)

Influence of low-energy nuclear structure on hindrance

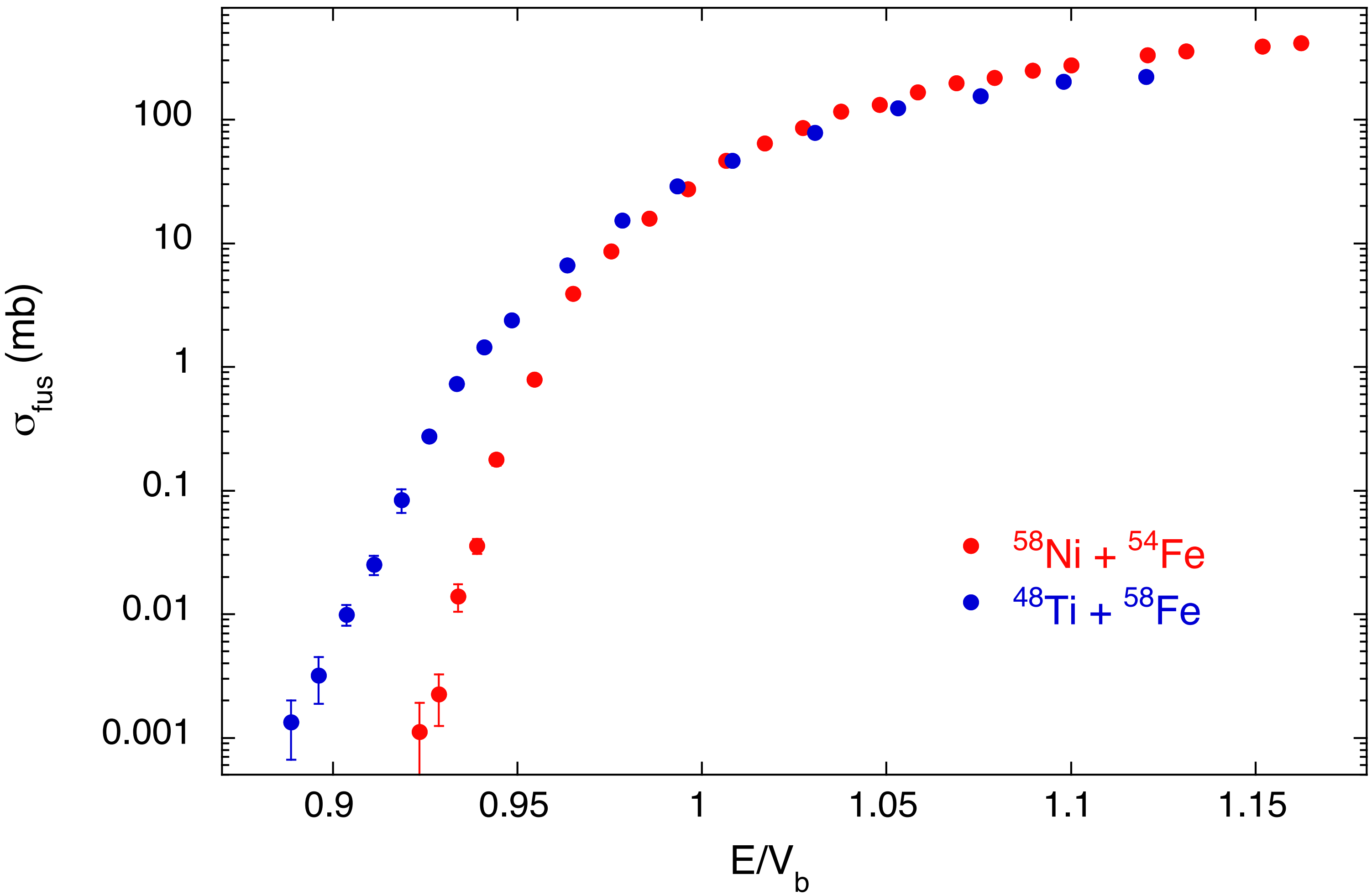
stiff nuclei-less fusion-hindrance near the barrier
$^{58}Ni+^{54}Fe$



$^{48}Ti + ^{58}Fe$

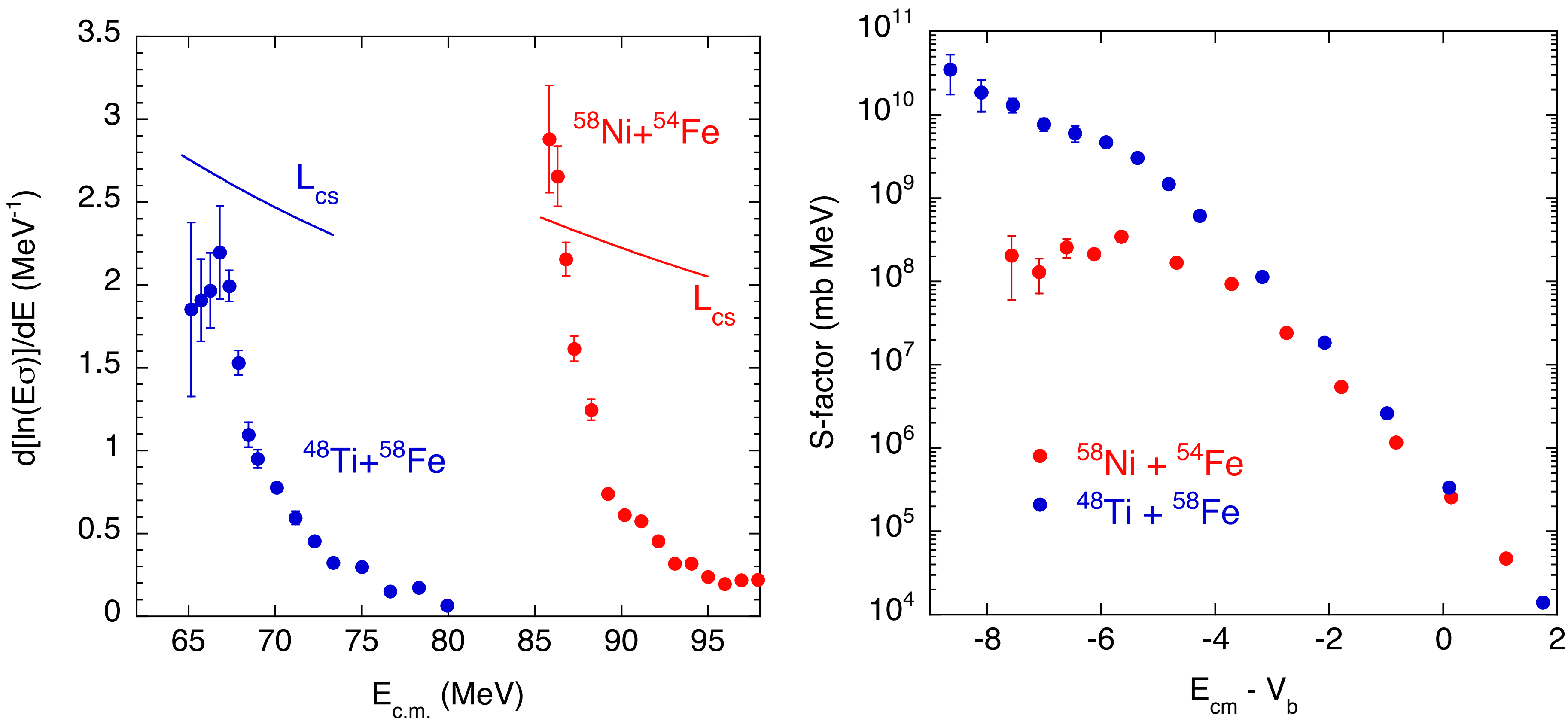
soft nuclei-more fusion-hindrance far below the barrier

Fusion excitation functions of $^{48}Ti + ^{58}Fe$ and $^{58}Ni + ^{54}Fe$, plotted vs. the energy relative to the nominal barrier. V_b is the barrier height produced by the Akyüz-Winther potential.



G.Montagnoli, Fusion14, New Delhi

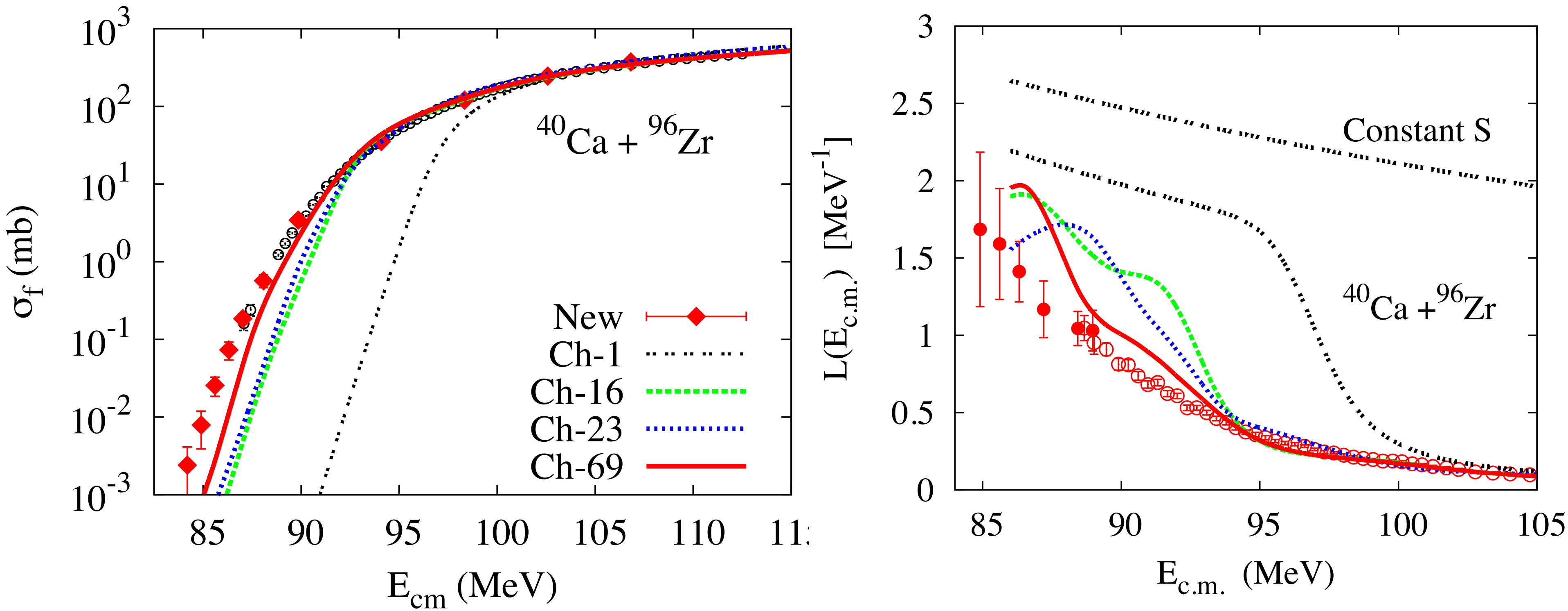
Logarithmic derivative of the fusion excitation function of $^{48}Ti+^{58}Fe$ and $^{58}Ni+^{54}Fe$, and comparison of the S-factors for the two systems



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 $^{48}Ti+^{58}Fe$

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

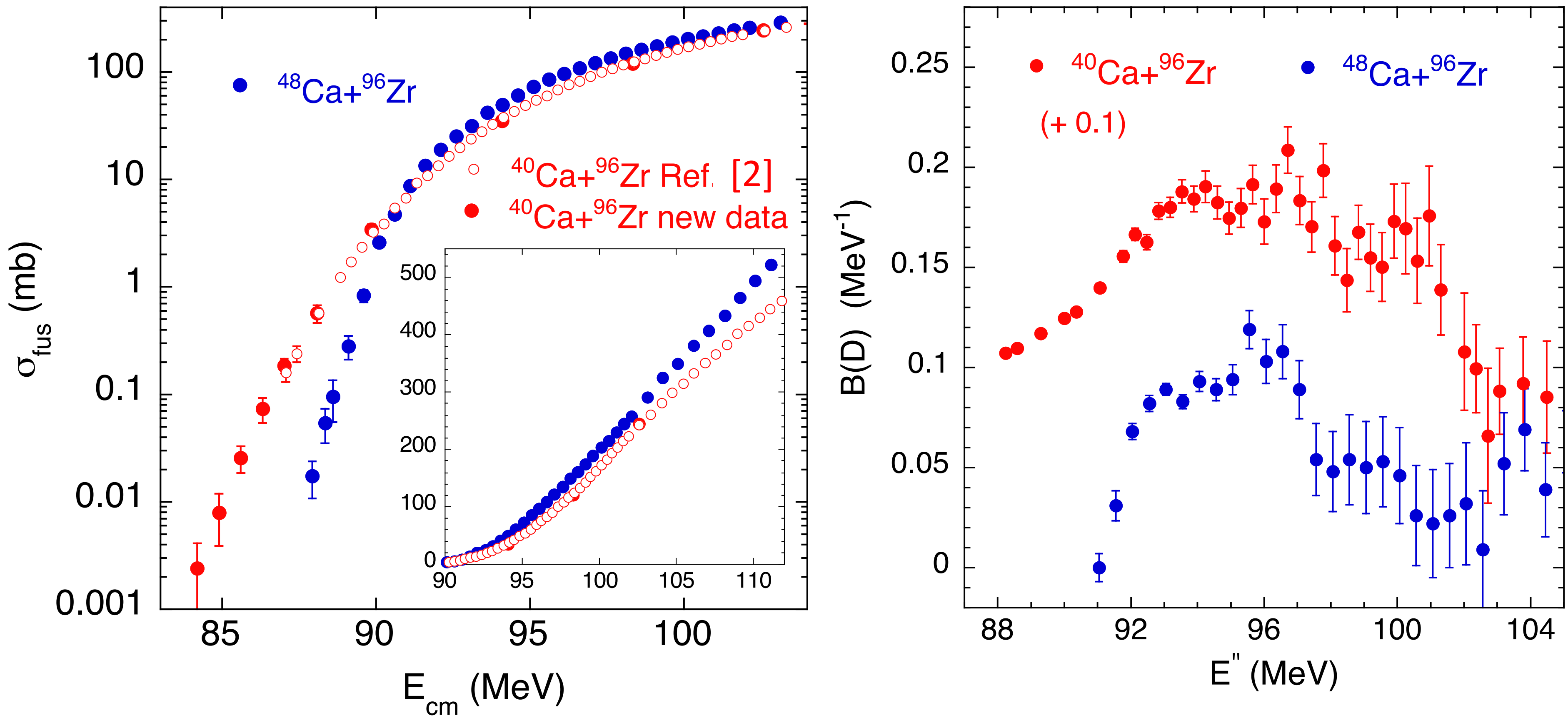


The cross sections are strongly underestimated below a few mb.
The low-lying 2+ and 3– states (Ch-23) produce strong effects.
Couplings to Q >0 one- and two-nucleon transfer channels (Ch-69)
bring further significant enhancements, even at the level of a few μb,
but no indication of hindrance appears yet.

A.M.Stefanini et al., Phys. Lett. B728 (2014) 639

Comparing the two cases of $^{40,48}Ca + ^{96}Zr$

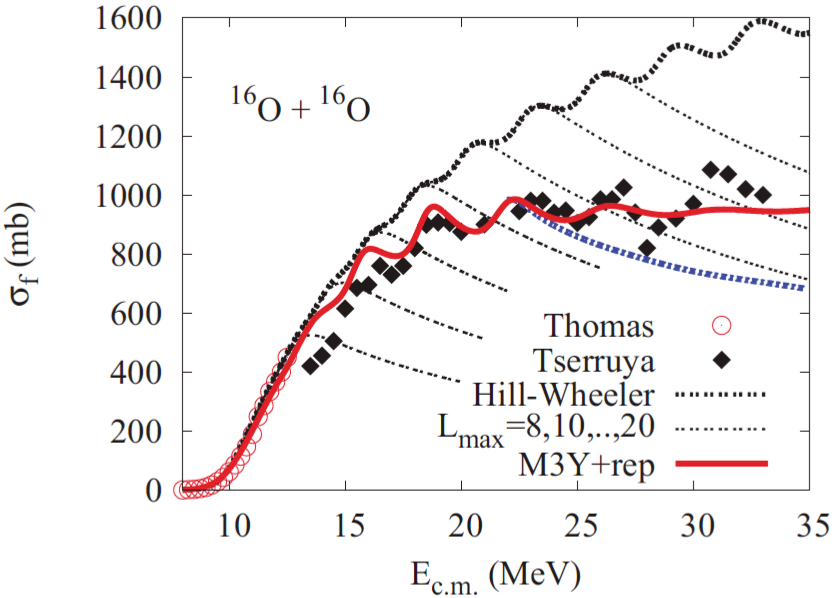
sub-barrier slopes ⟷ barrier distributions

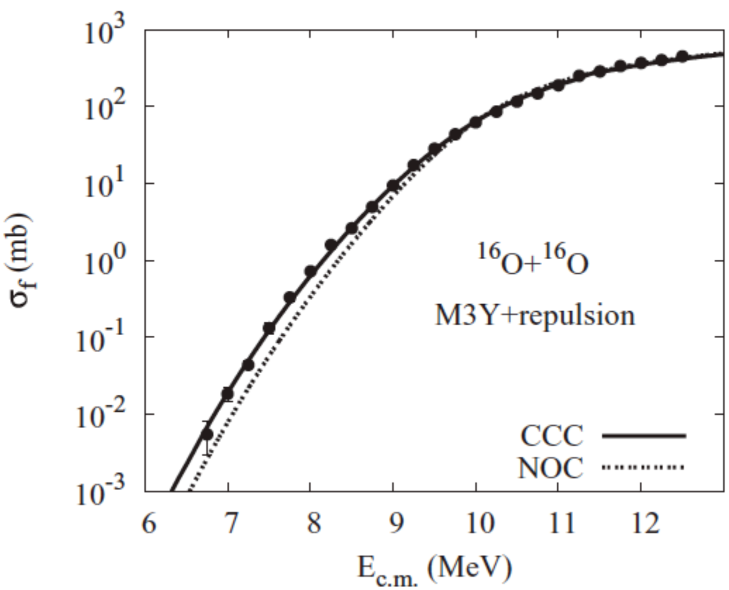


The cross section for $^{48}Ca + ^{96}Zr$ decreases very sharply below the barrier and, indeed, this system shows hindrance. The decrease of the excitation function for $^{40}Ca+^{96}Zr$ is by far slower.

Medium-light systems and oscillations

Structures in fusion excitation function of light systems





- Oscillatory structures were recently interpreted due to the penetration of successive centrifugal barriers

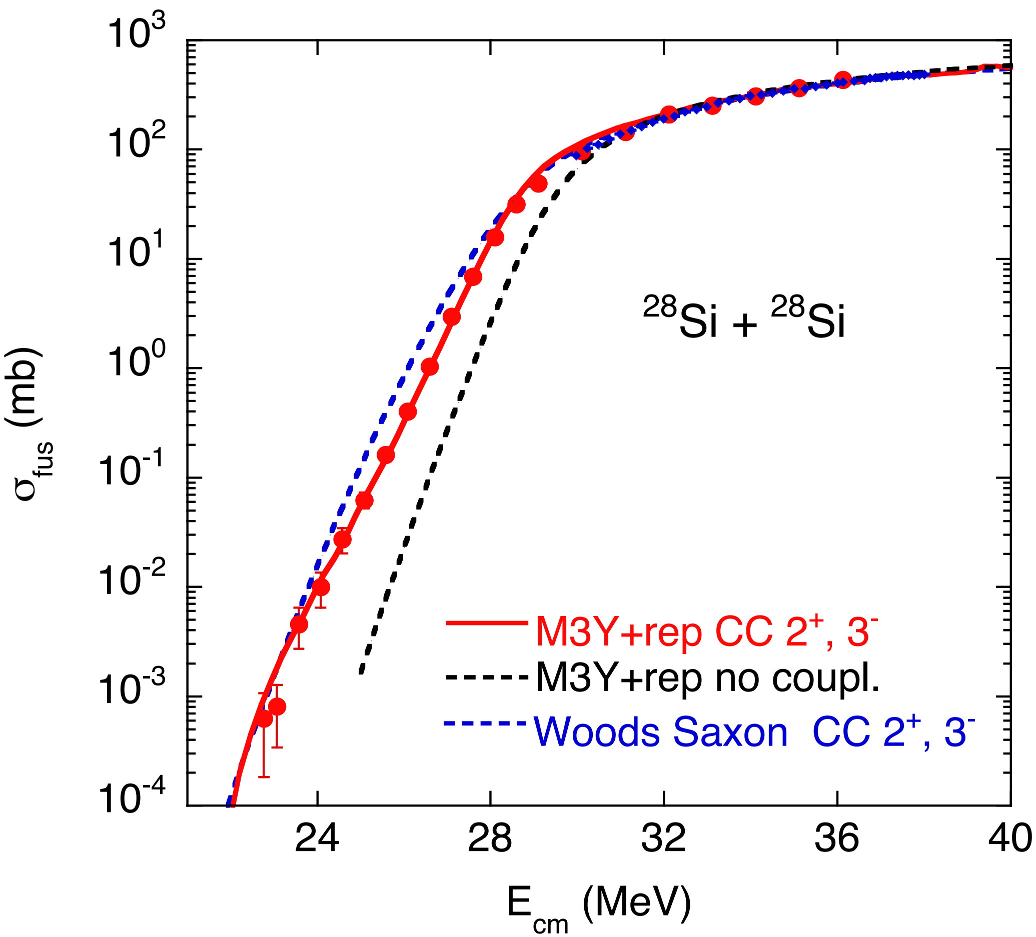
$$V_B(L) = V_{CB} + \frac{\hbar^2 L(L+1)}{2\mu R_{CB}^2}$$

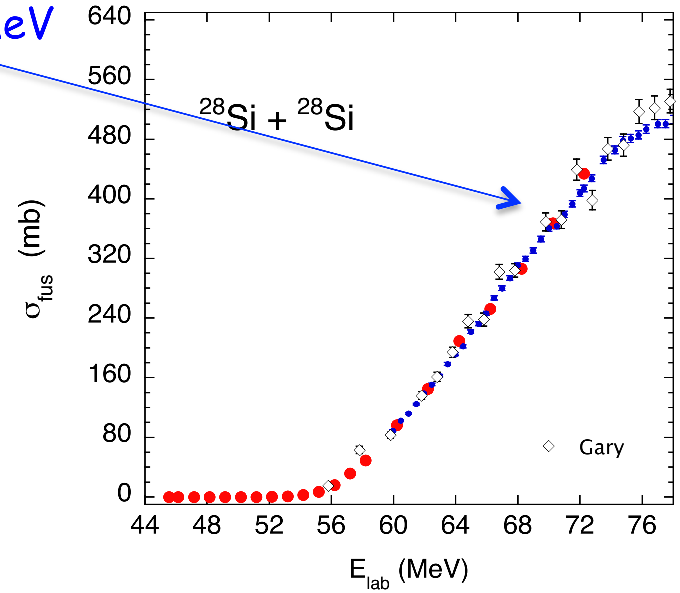
- A shallow ion-ion potential (M3Y+rep) is needed to fit the data above (and below) the barrier.
- ➔➔ Look for above-barrier oscillations in heavier systems, where sub-barrier hindrance is stronger and better established.
- Clearly observing such oscillations would put strong constraints on the ion-ion potential in a wide energy range.

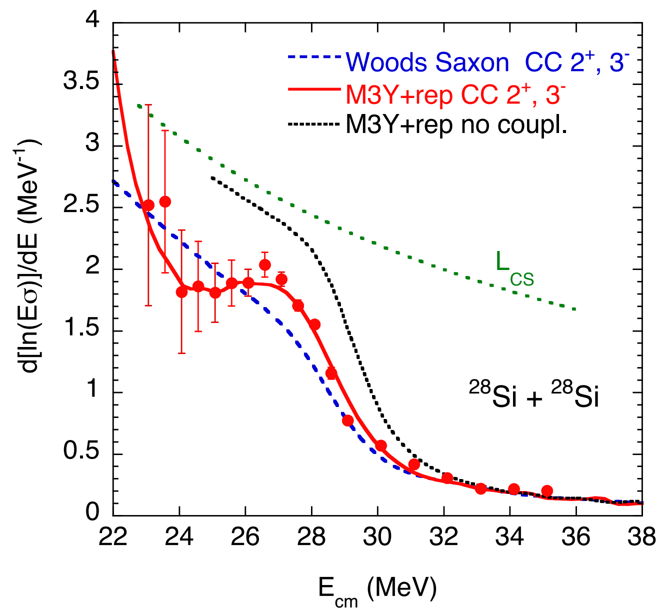
H.Esbensen, PRC77, 054608 (2008); PRC85, 064611 (2012)
C.Y.Wong, PRC86, 064603 (2012)

The case of ^{28}Si + ^{28}Si: new measurement of the fusion excitation function

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

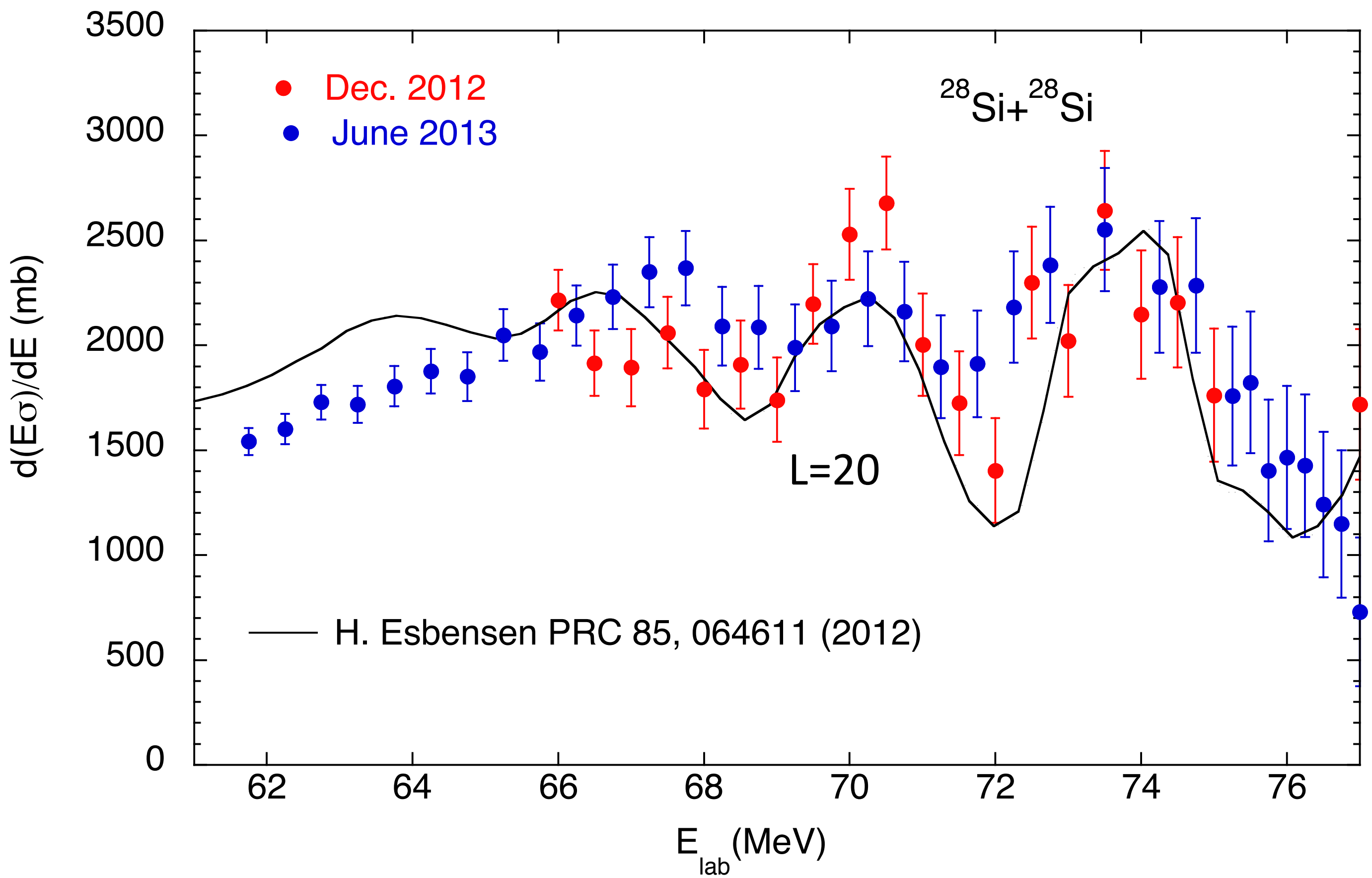






A.M.Stefanini et al., EPJ Web of Conf. 66, 03082 (2014)

We take the energ-wighted derivative of the exc. function, and we compare with the result of a recent CC calculation



The energy difference between successive barriers:

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

(twice as that for a symmetric system like $^{28}Si + ^{28}Si$, i.e. $\Delta V_{B\,(c.m.)} \approx 1.52$ MeV)

Summary

- Few- and multi-nucleon transfer reactions are a suitable tool for studies both of nuclear structure and reaction dynamics
- Suitable conditions for investigating pair correlations in heavy ion collisions are offered by sub-barrier transfer reactions
- Interesting results have been obtained for the systems $^{96}Zr + ^{40}Ca$ and $^{116}Sn + ^{60}Ni$ using the inverse kinematics and the PRISMA spectrometer
- Heavy-ion fusion below the barrier continues displaying interesting, and sometimes unexpected, features, such as the hindrance phenomenon
- The low-lying collective structure of the colliding nuclei strongly influences the threshold of hindrance, through CC effects
- A shallow potential (M3Y+Rep) allows reproducing the x-sects. far below the barrier; oscillations have been observed above the barrier for $^{28}Si + ^{28}Si$, that are described in the same theoretical frame

Our collaboration in recent experiments

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