The ^{40}Ca + ^{58,64}Ni fusion reactions : interplay between inelastic and transfer channels

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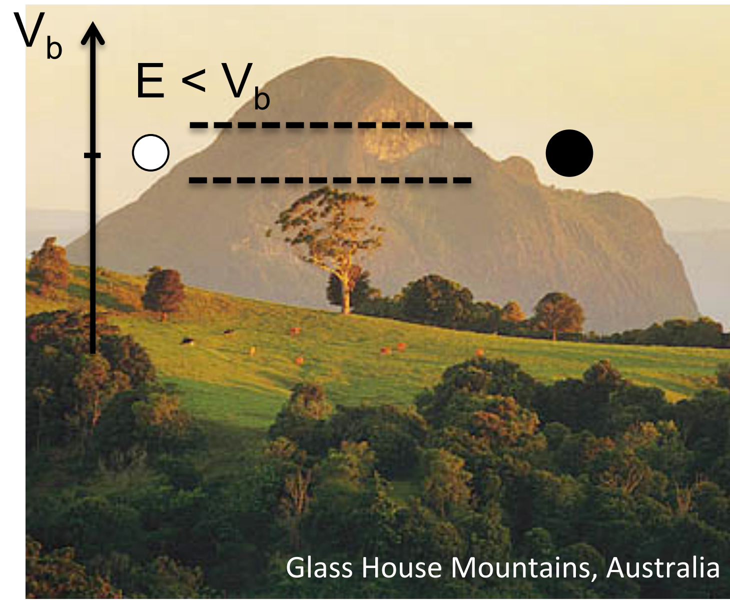
Outline

- Sub-barrier fusion in the Ca + Ni systems. Why ?
- The fusion experiments and results
- Coupled-channels and Hartree-Fock calculations
- The transfer experiment and results
- Conclusions

Sub-barrier fusion : Ca + Ni

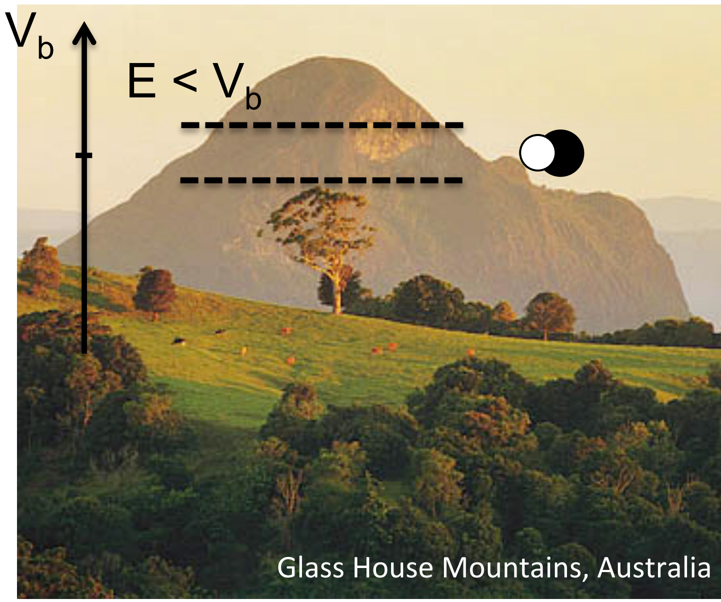
- Fusion: dominant reaction mechanism in heavy-ion collisions at low bombarding energies

- Sub-barrier fusion



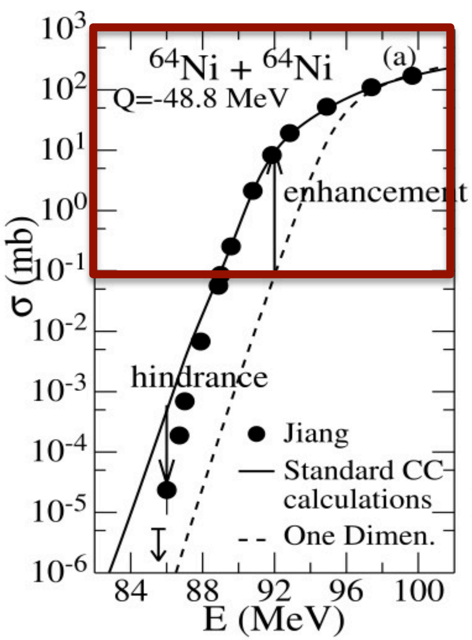
Sub-barrier fusion : Ca + Ni

- Fusion: dominant reaction mechanism in heavy-ion collisions at low bombarding energies
- Sub-barrier fusion
- Nuclear structure vs reaction dynamics in $^{40}Ca+^{58,64}Ni$

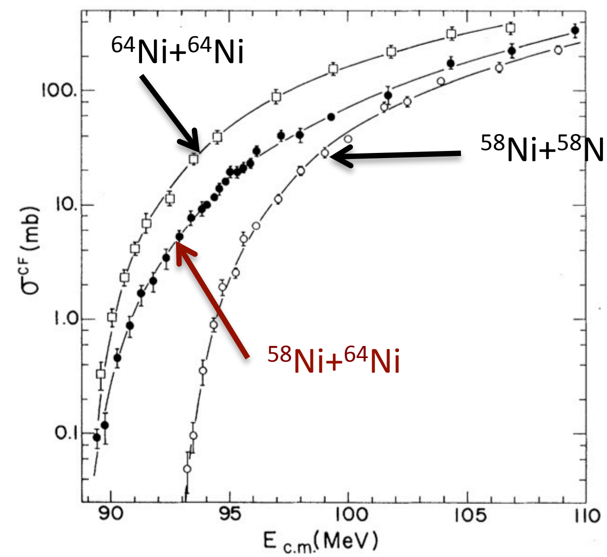


Sub-barrier fusion : Ca + Ni

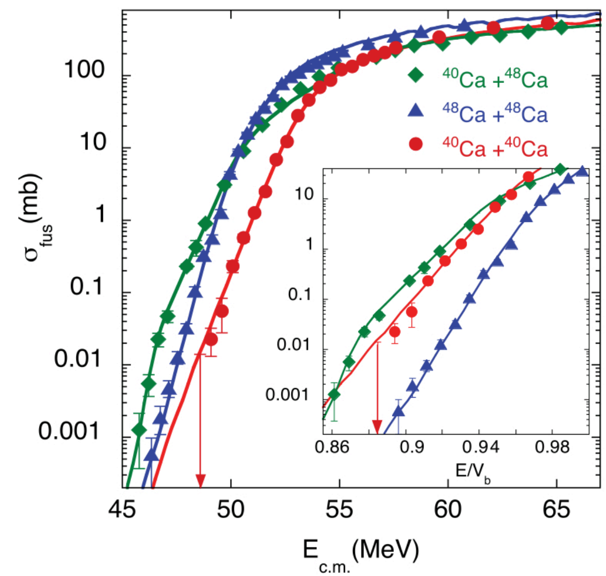
- Ni + Ni and Ca + Ca



C.L. Jiang et al., Nucl.Phys. A834 (2010)



M. Beckerman et al., Phys.Rev.Lett. 45 (1980)



G. Montagnoli et al., Phys.Rev.C85(2012)

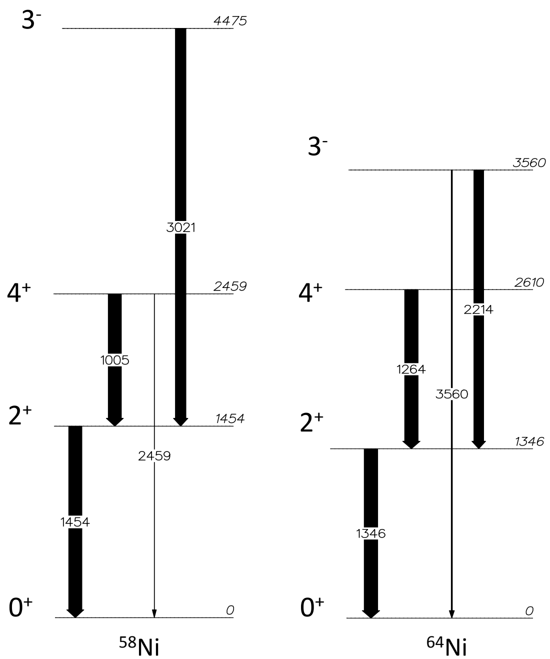
- ^{58,60,64}Ni vibrational, well known 1 and 2 phonon states
- ^{64}Ni+^{64}Ni ‘a textbook example’

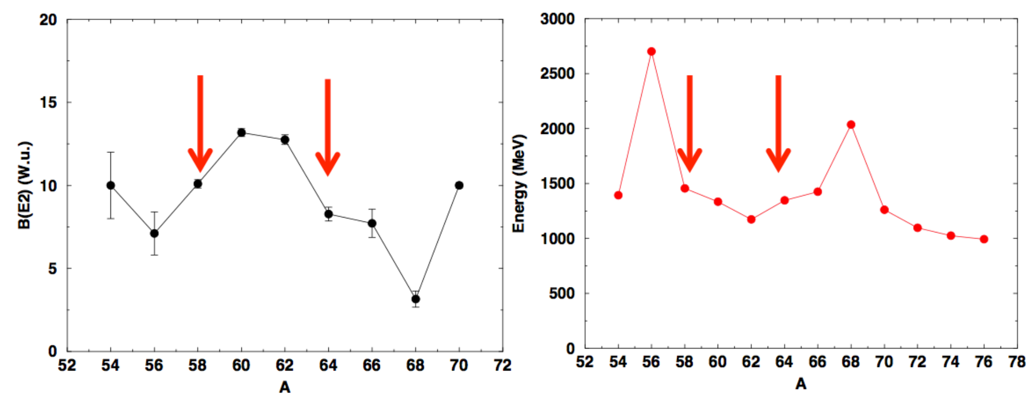
- ^{48}Ca ‘stiff’ / ^{40}Ca ‘soft’ (strong 3$^-$)
- ^{40}Ca+^{48}Ca, hindrance shows up lower
- Qvalue (transfer) >0 for ^{40}Ca+^{48}Ca

Sub-barrier fusion : Ca + Ni

- Effects of couplings on fusion well known for Ca and Ni

- Similar structure features for ^{58}Ni and ^{64}Ni / 6 neutrons





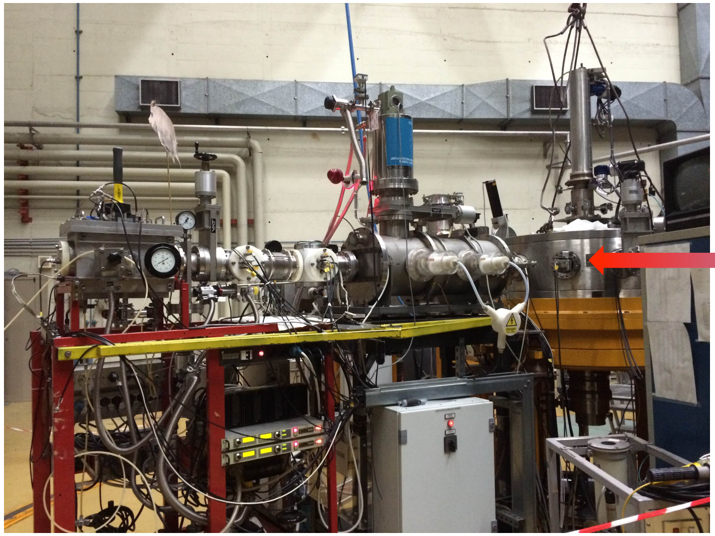
B. Pritychenko et al., Update of B(E2) and E(2$^+$) evaluation near N≈Z≈28, At. Dat. Nucl. Dat. Tables (2012)

- Fusion of Ca+Ni below and around CB almost unknown (except Rochester data for ^{40}Ca +^{58}Ni, Sikora et al. (1979))

- Positive Q value for transfers for ^{40}Ca+^{64}Ni (+2n to +6n and -2p), negative for all transfers in ^{40}Ca+^{58}Ni

The fusion experiment

- Fusion cross section measurements from above to below the Coulomb barrier in at $^{40}Ca + ^{58,64}Ni$ INFN-LNL in Italy
- Electrostatic deflector



^{40}Ca

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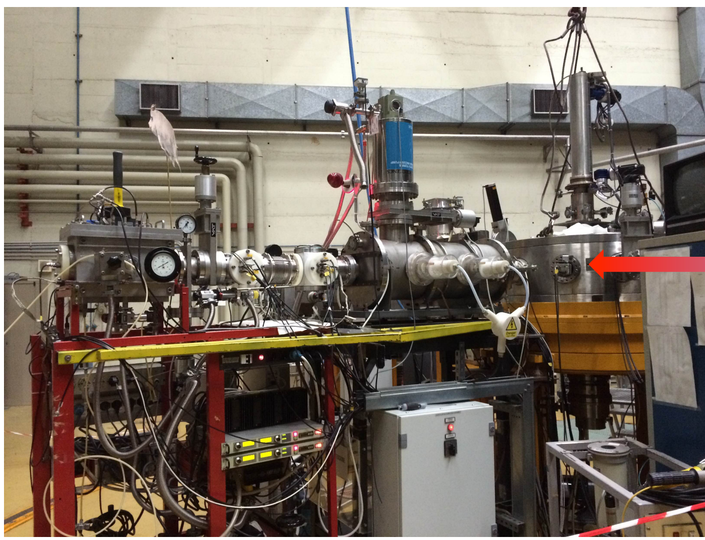

XTU Tandem accelerator

^{40}Ca

high-quality and intense ^{40}Ca beam of ≈ 9 p nA intensity (≈ 6 x 10^{10} p s^{-1})

The fusion experiment

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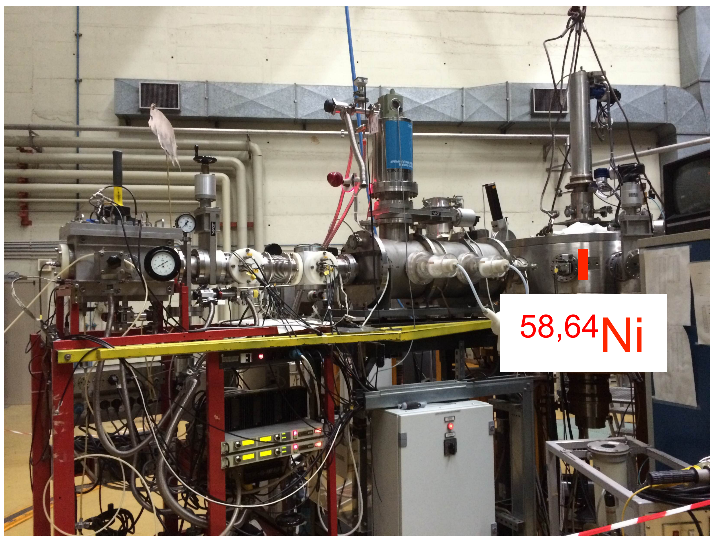

reaction chamber

$^{58,64}Ni$ targets of 50 μg/cm^2 thickness deposited on a 20 μg/cm^2 ^{12}C backing

4 silicon detectors used as monitors

The fusion experiment

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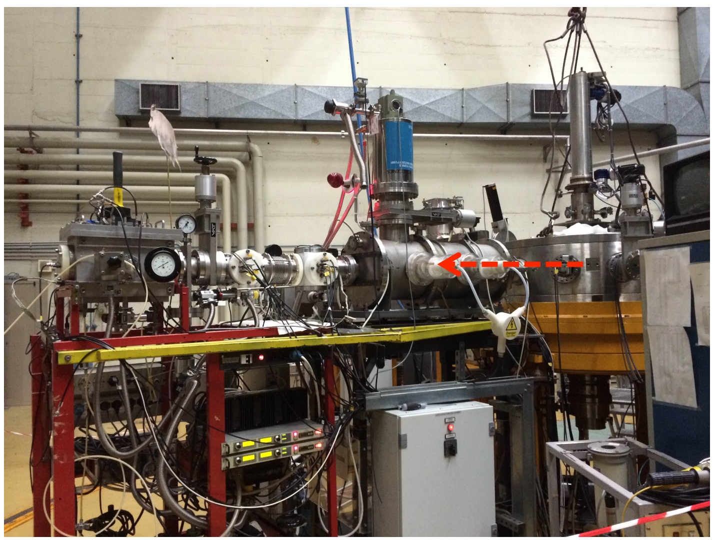

electrostatic deflector

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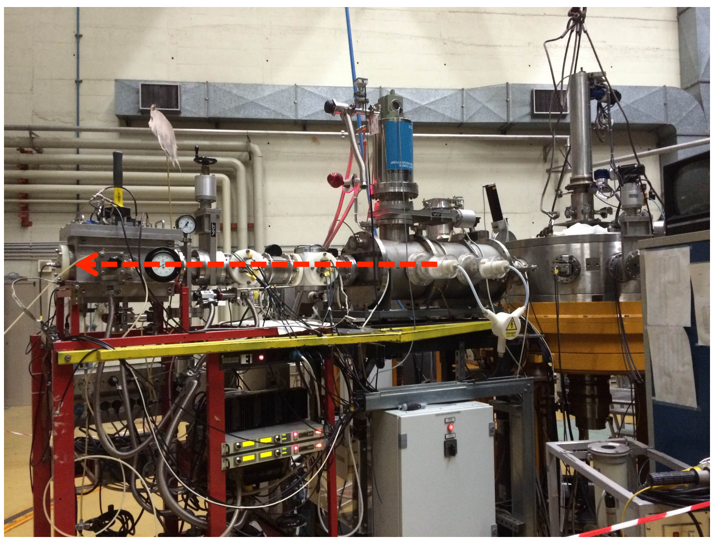


detection system for the evaporation residues

2 MCP detectors $t_{1,2}$

ionisation chamber: ΔE

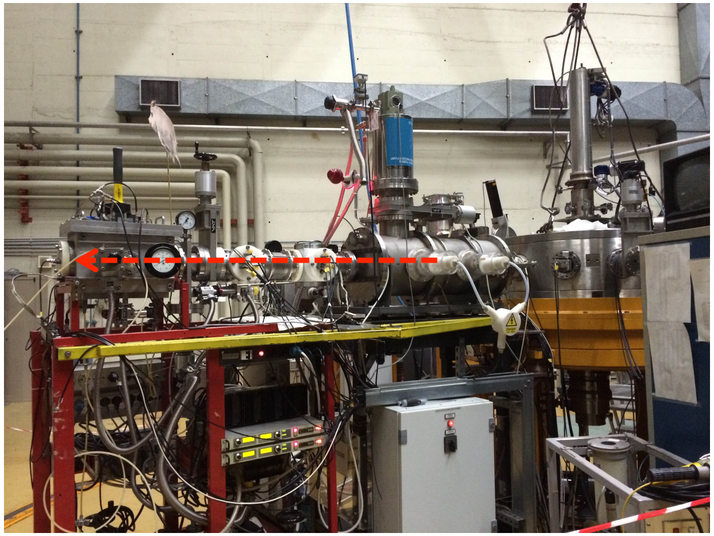
Si detector: E_R, t_3

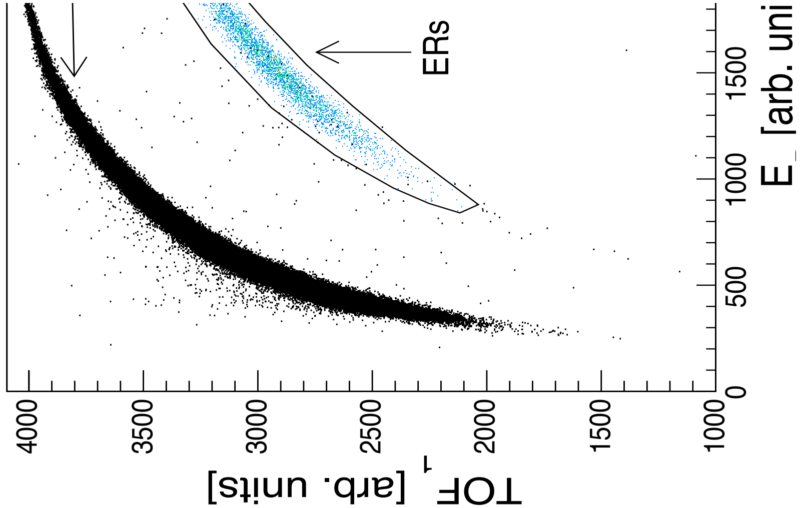
$$TOF_1 = t_3 - t_1$$
$$TOF_2 = t_2 - t_1$$
$$TOF_3 = t_3 - t_2$$

The fusion experiment

- Fusion cross section measurements from above to below the Coulomb barrier in at ^{40}Ca + ^{58,64}Ni INFN-LNL in Italy

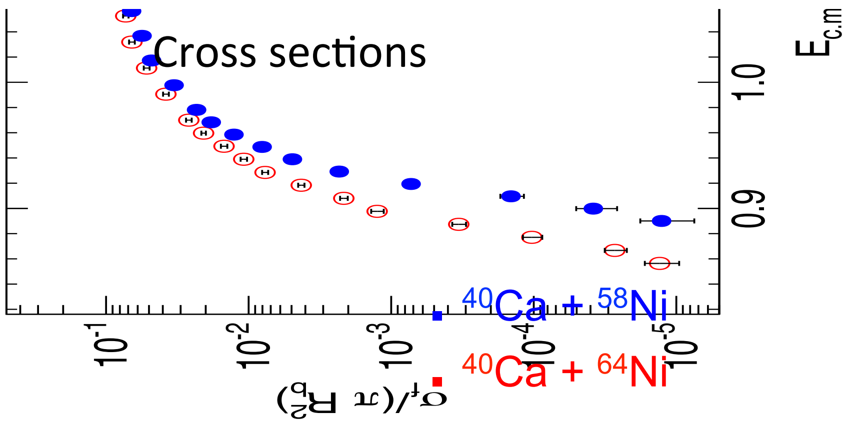
- Electrostatic deflector

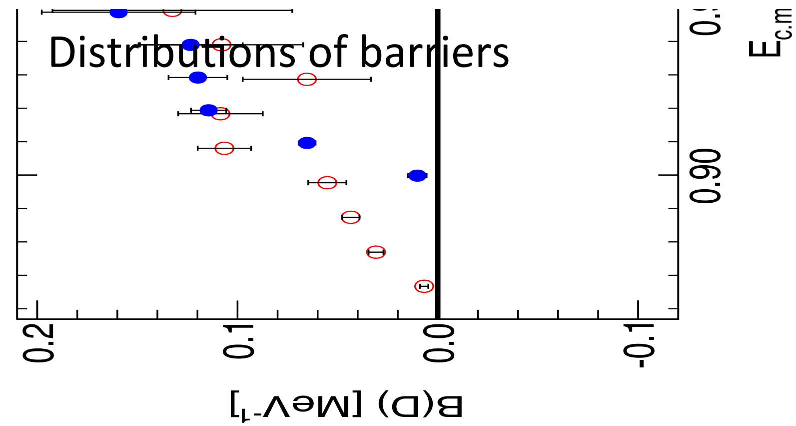




detection system for the evaporation residues

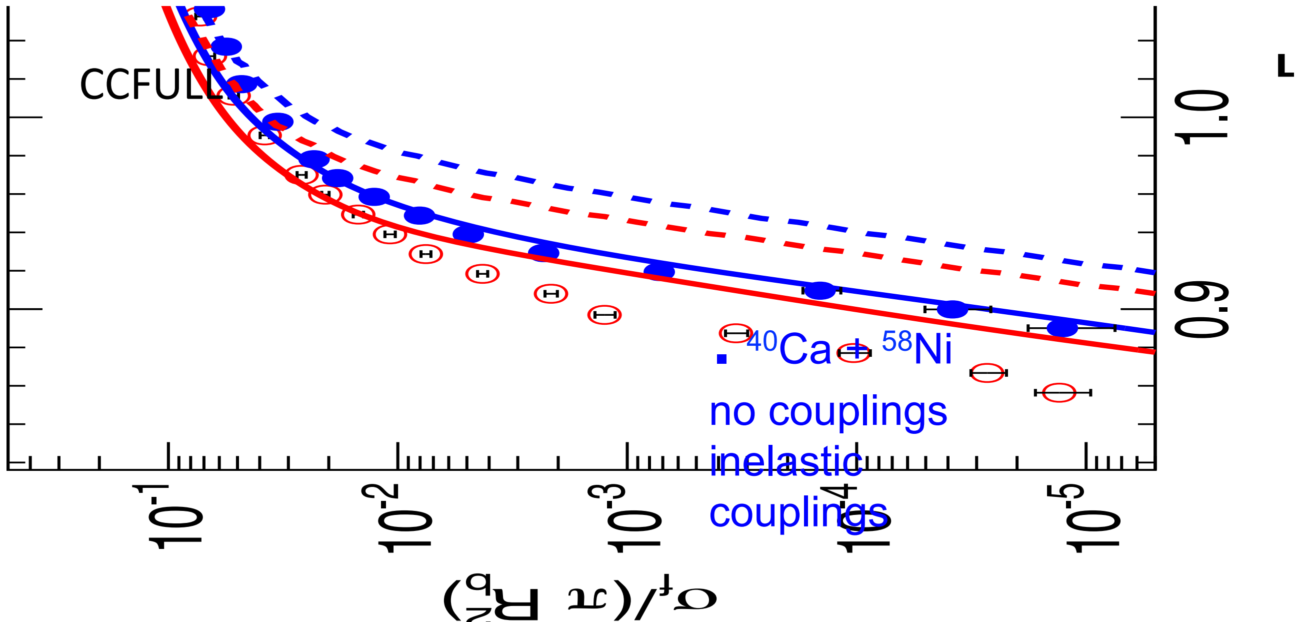
The fusion experiment





PhD : D. Bourgin, University of Strasbourg

The fusion experiment



▪ $^{40}Ca + ^{58}Ni$

no couplings

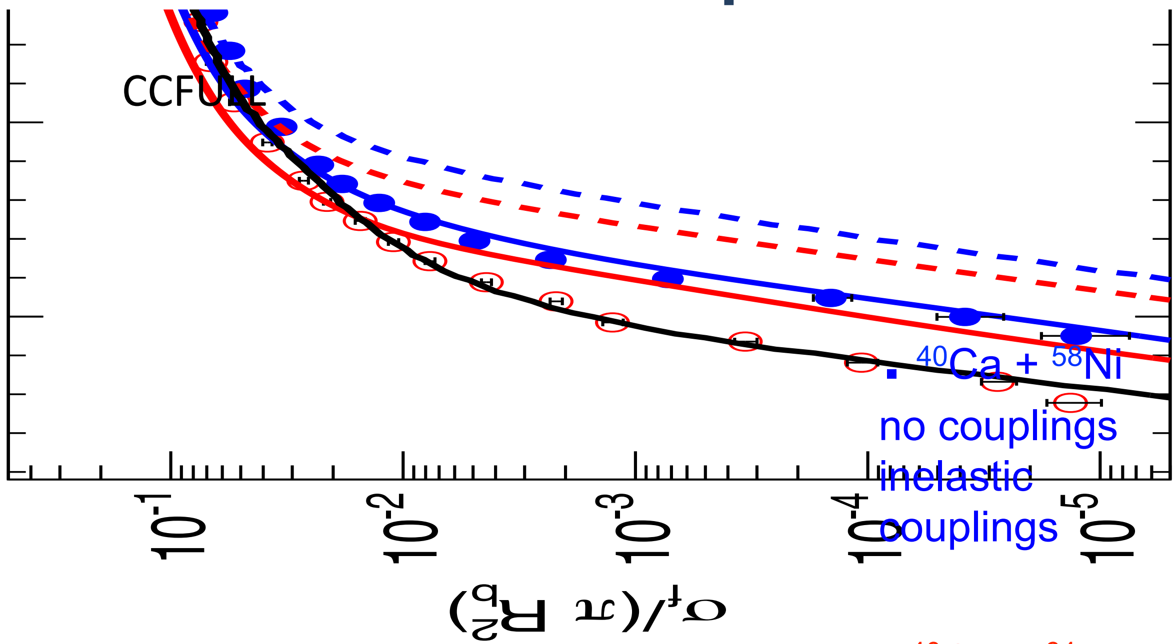
inelastic couplings

▪ $^{40}Ca + ^{64}Ni$

no couplings

inelastic couplings

The fusion experiment

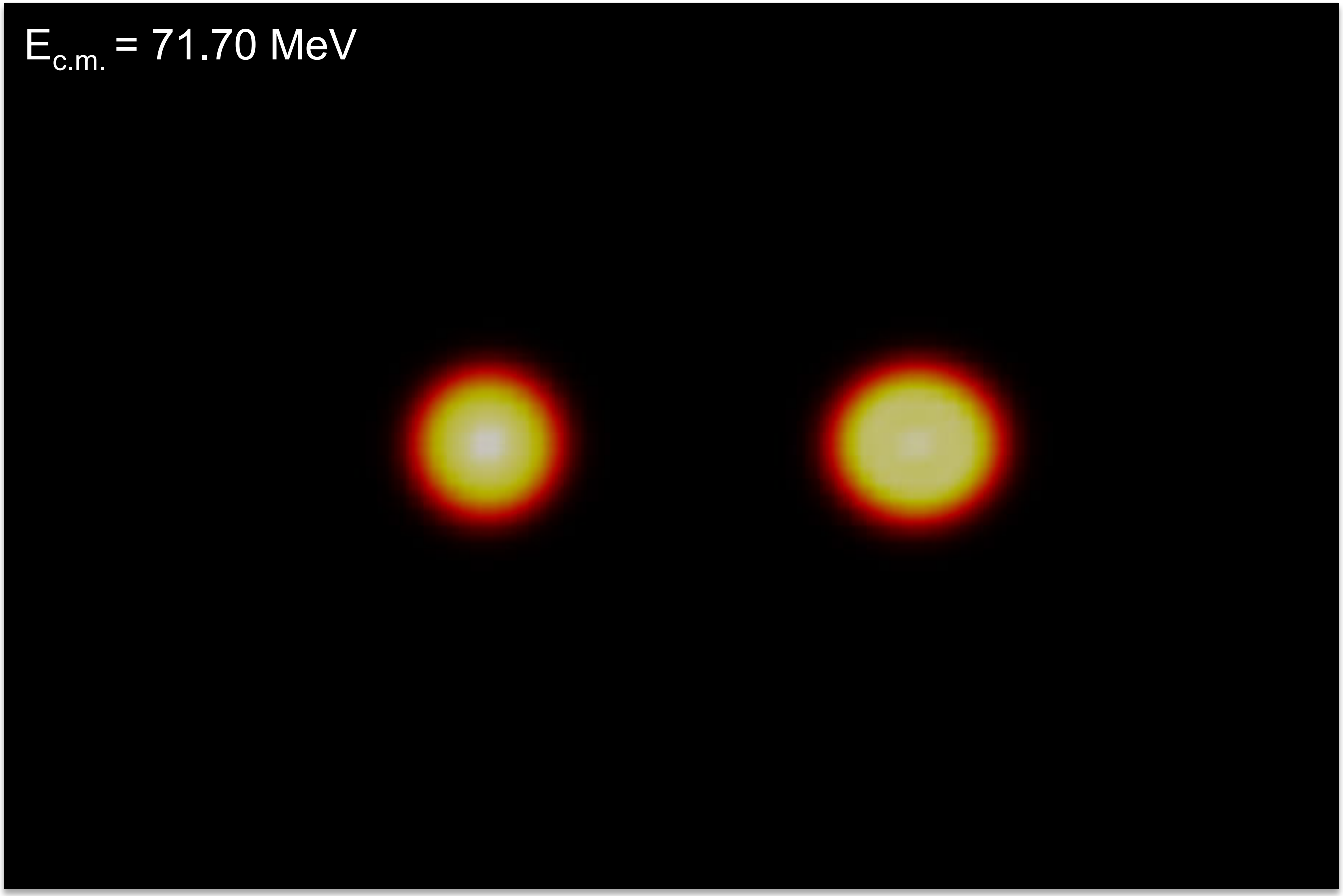


^{40}Ca + ^{58}Ni
no couplings
inelastic couplings

^{40}Ca + ^{64}Ni
no couplings
inelastic couplings
+ transfer
Q_{tr}=1,63 MeV,F_{tr}=0,60 fm

TDHF calculations

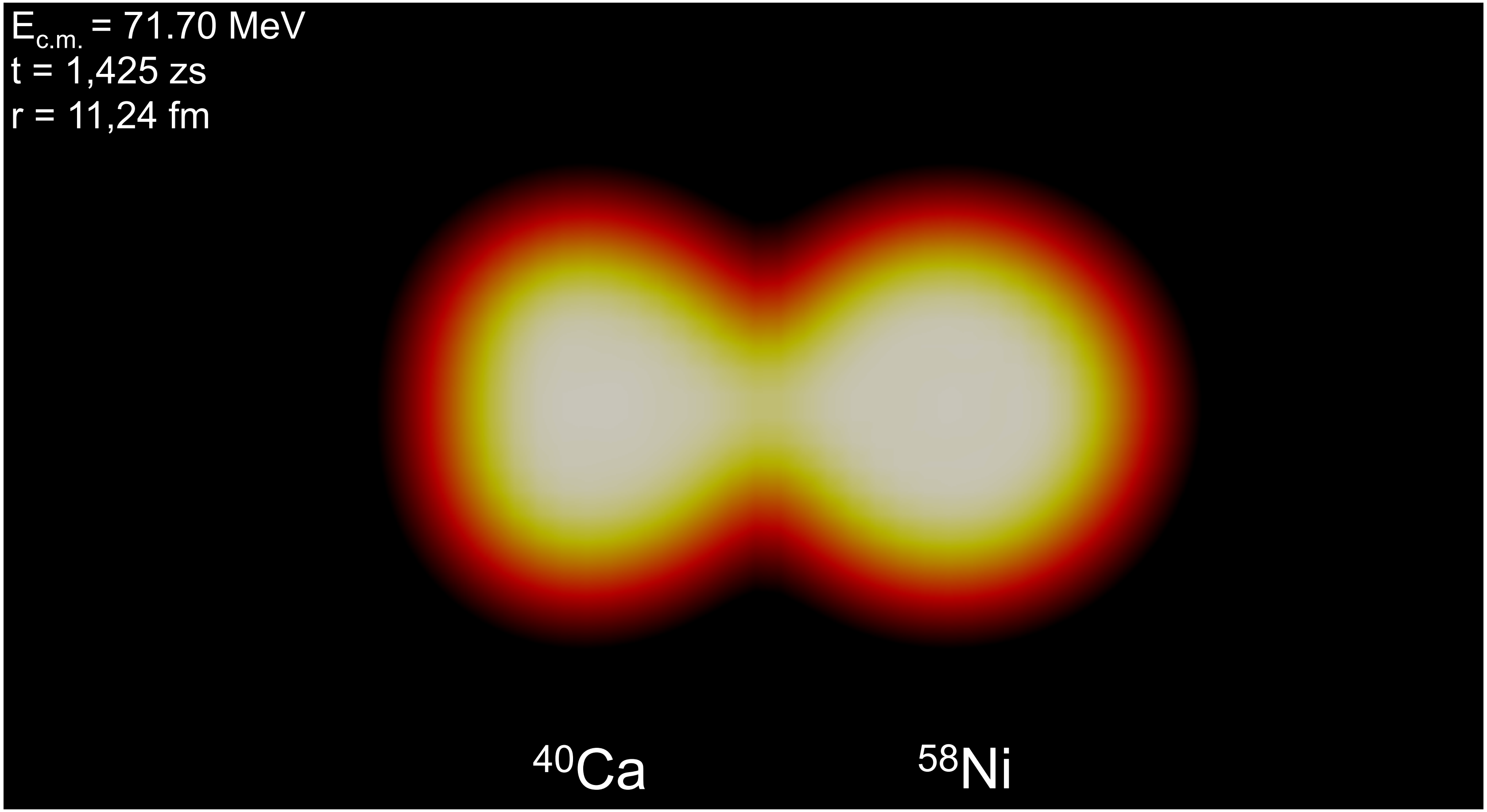
TDHF + BCS calculations / 1 parameter (Skyrme) / dynamical effects at the mean-field level



In collaboration with C. Simenel, Australian National University, Australia

TDHF calculations

TDHF + BCS



TDHF calculations

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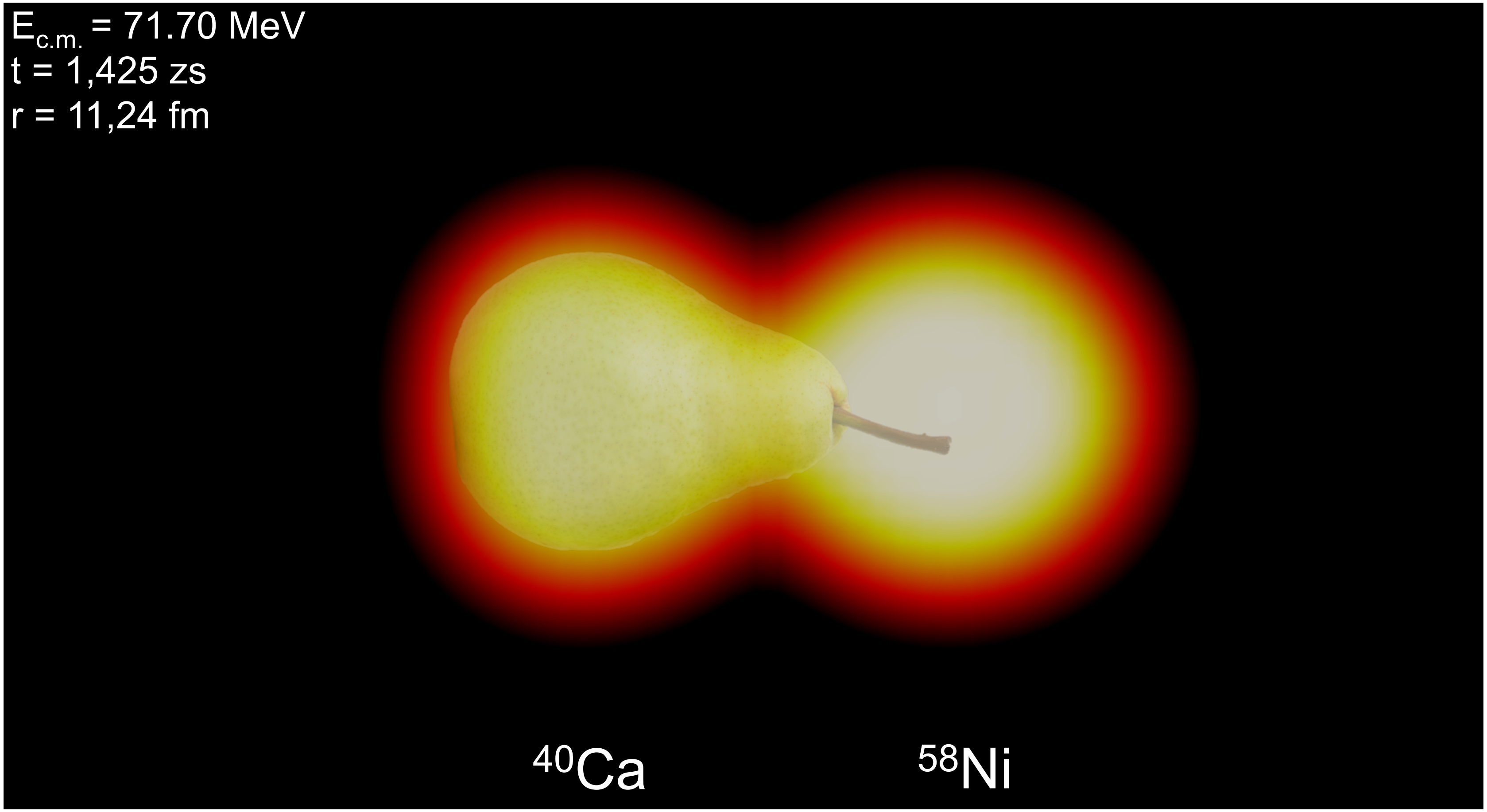

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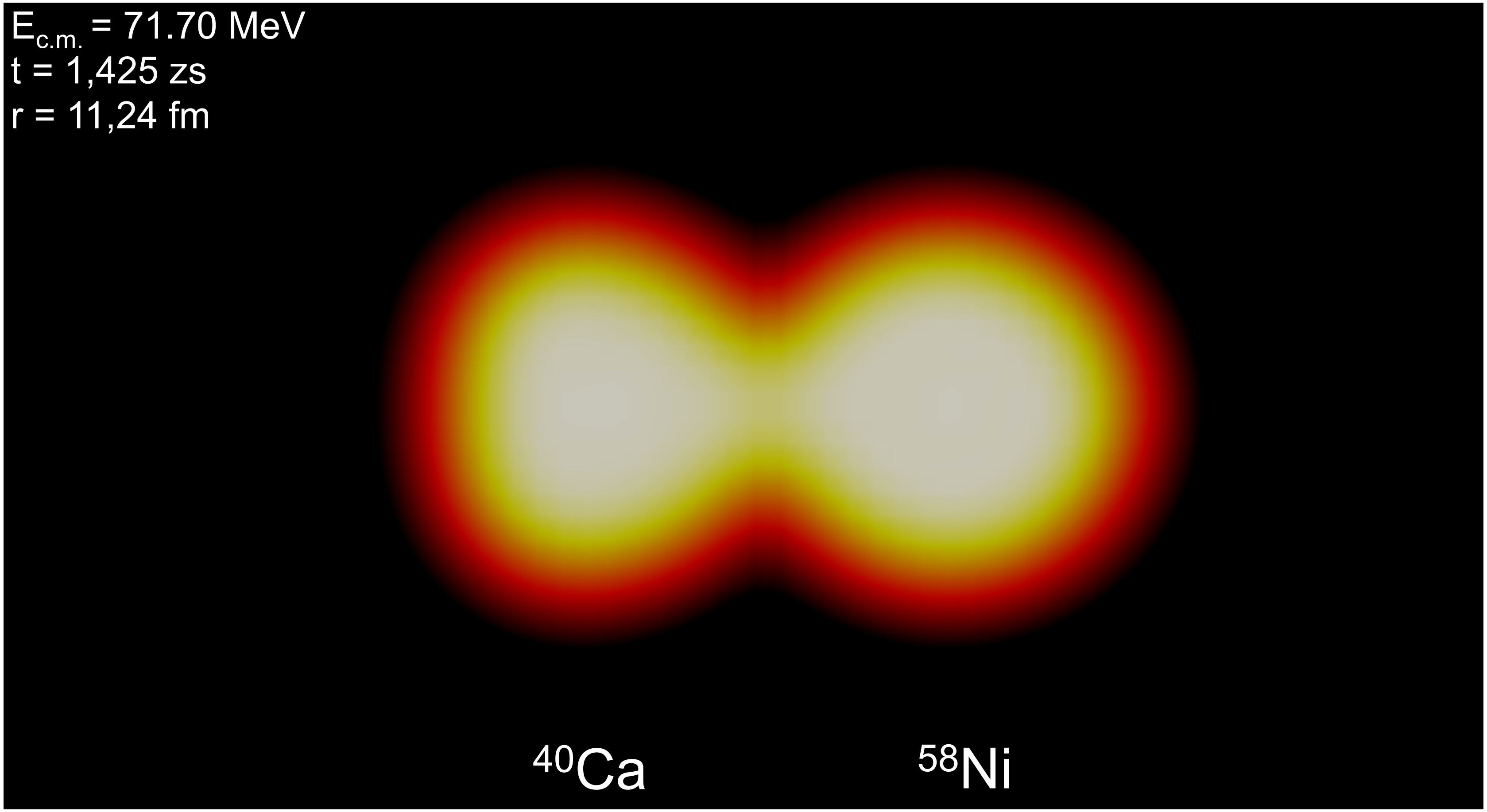
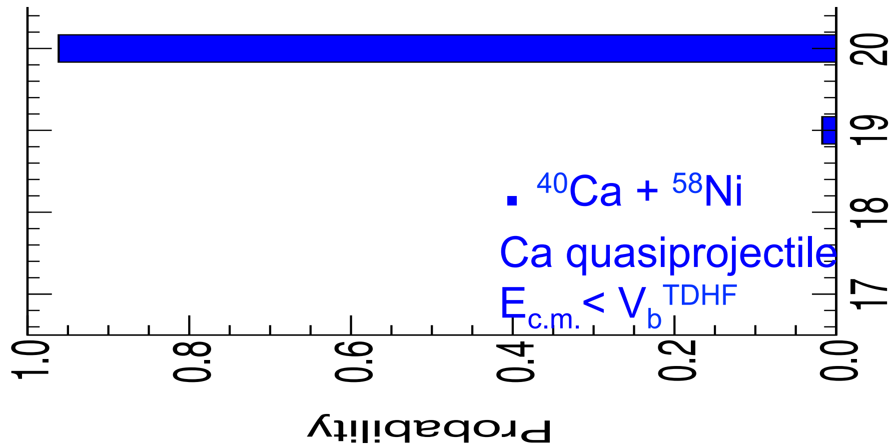


TDHF calculations

Particle number projection technique

Time-Dependent Hartree-Fock + BCS calculations with the EV8 and TDHF3D codes



➔ sum of the transfer probabilities < 0.04

TDHF calculations

Particle number projection technique

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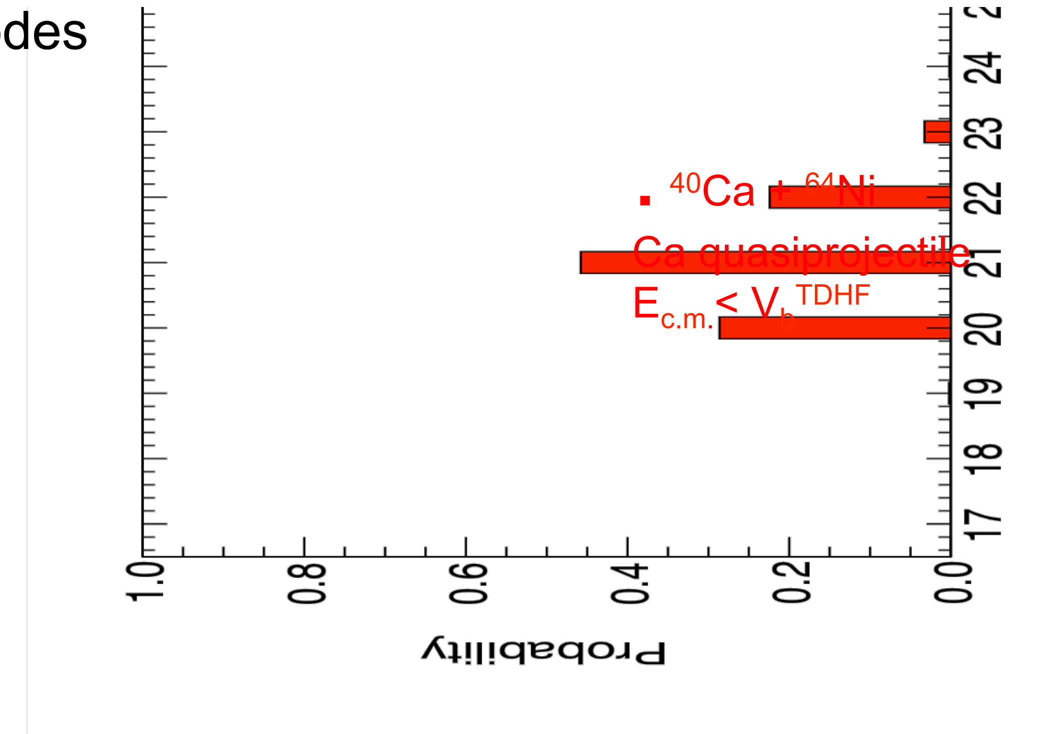
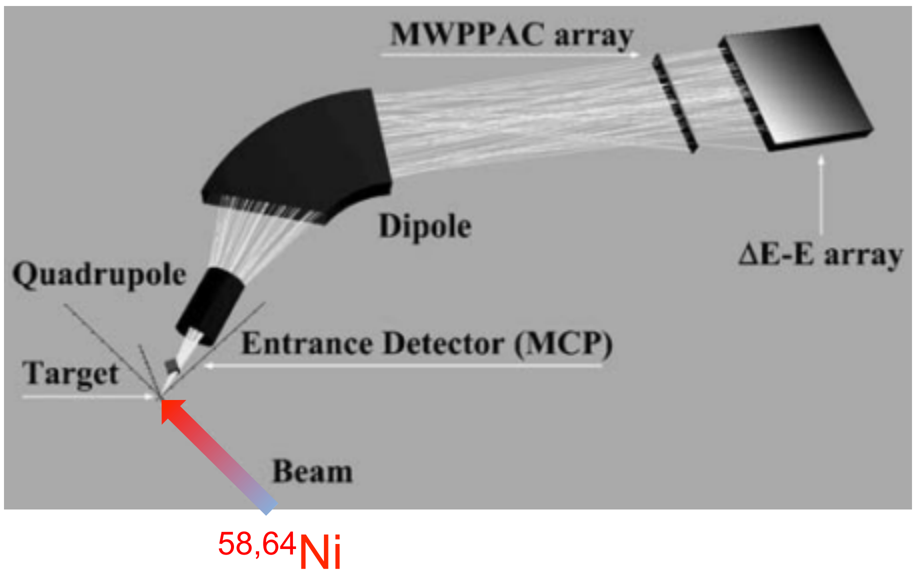


➔ sum of the transfer probabilities ~ 0.7

The transfer experiment

Nucleon transfer channels in $^{40}Ca + ^{58,64}Ni$

Transfer probability measurements from above to below the Coulomb barrier at INFN-LNL (Italy)



XTU Tandem accelerator

^{58,64}Ni beams / 3 p nA intensity (≈ 2 x 10^{10} p s^{-1})

PRISMA magnetic spectrometer

The transfer experiment

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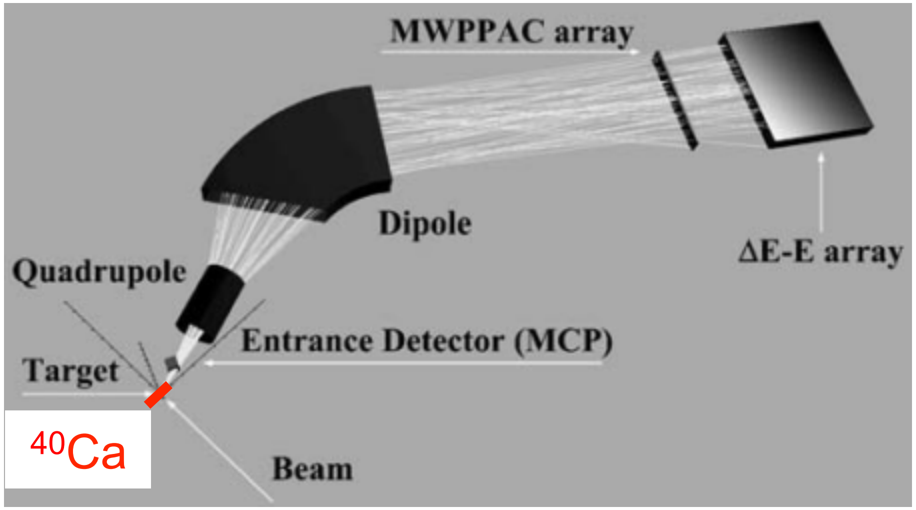

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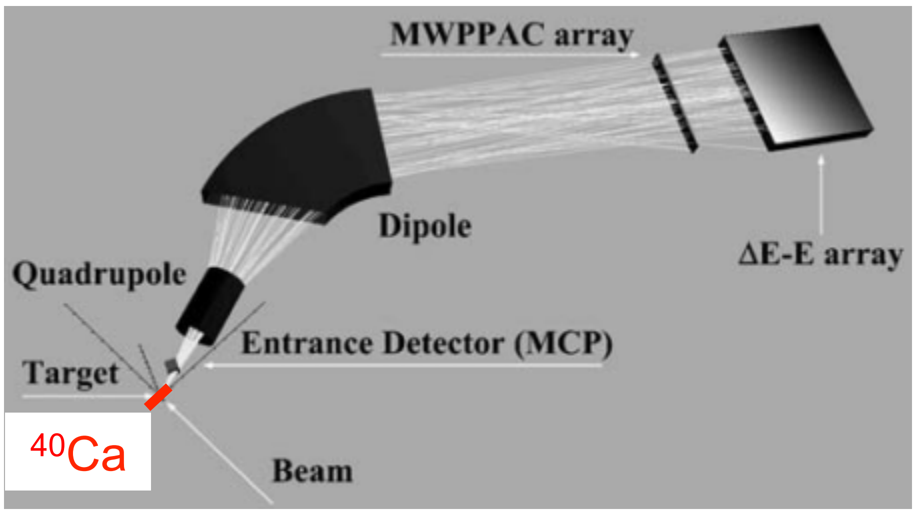

reaction chamber

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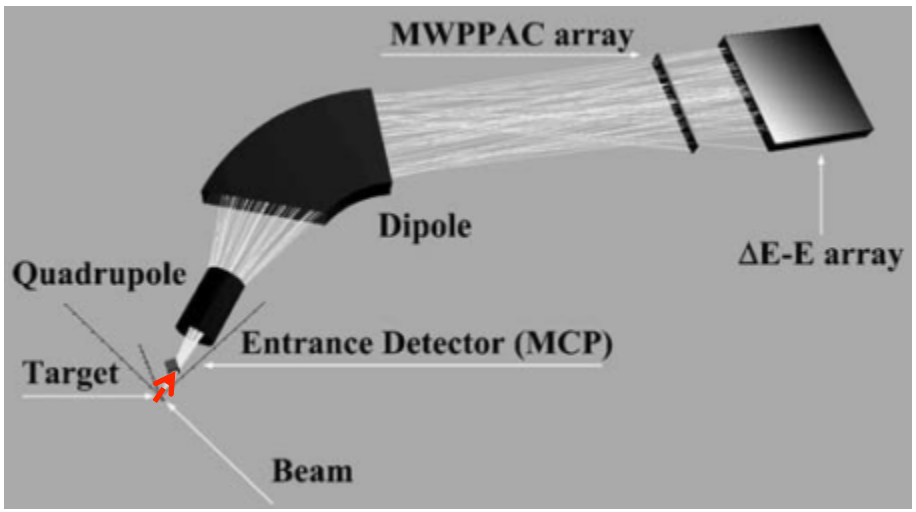

MCP: t_i

PRISMA magnetic spectrometer

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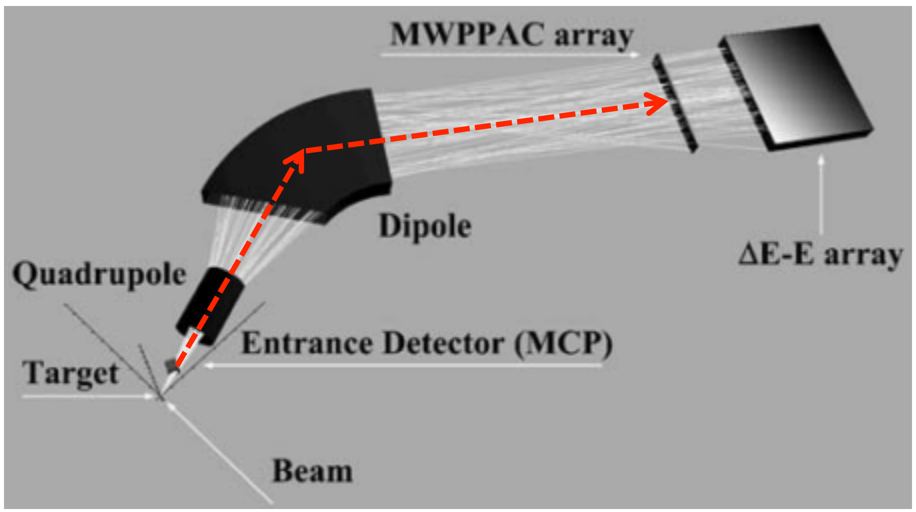

MWPPAC : t_f

TOF = $t_f - t_i$

PRISMA magnetic spectrometer

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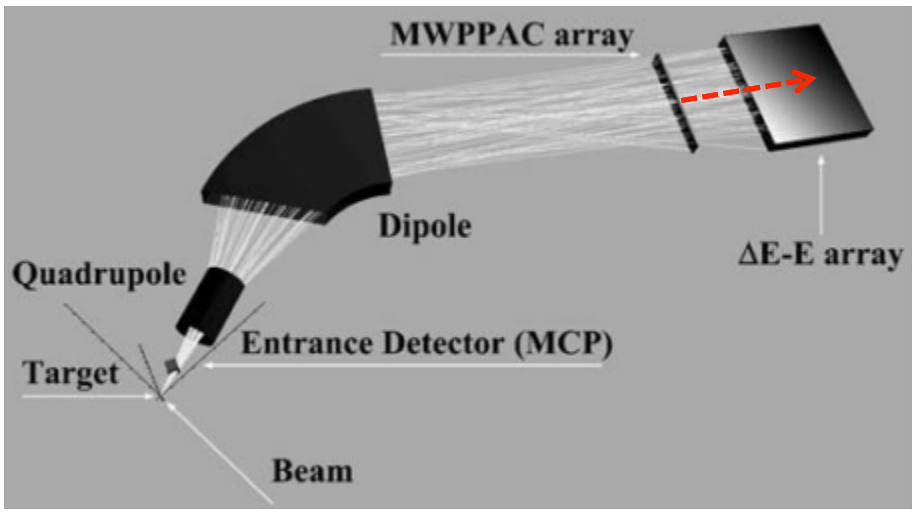
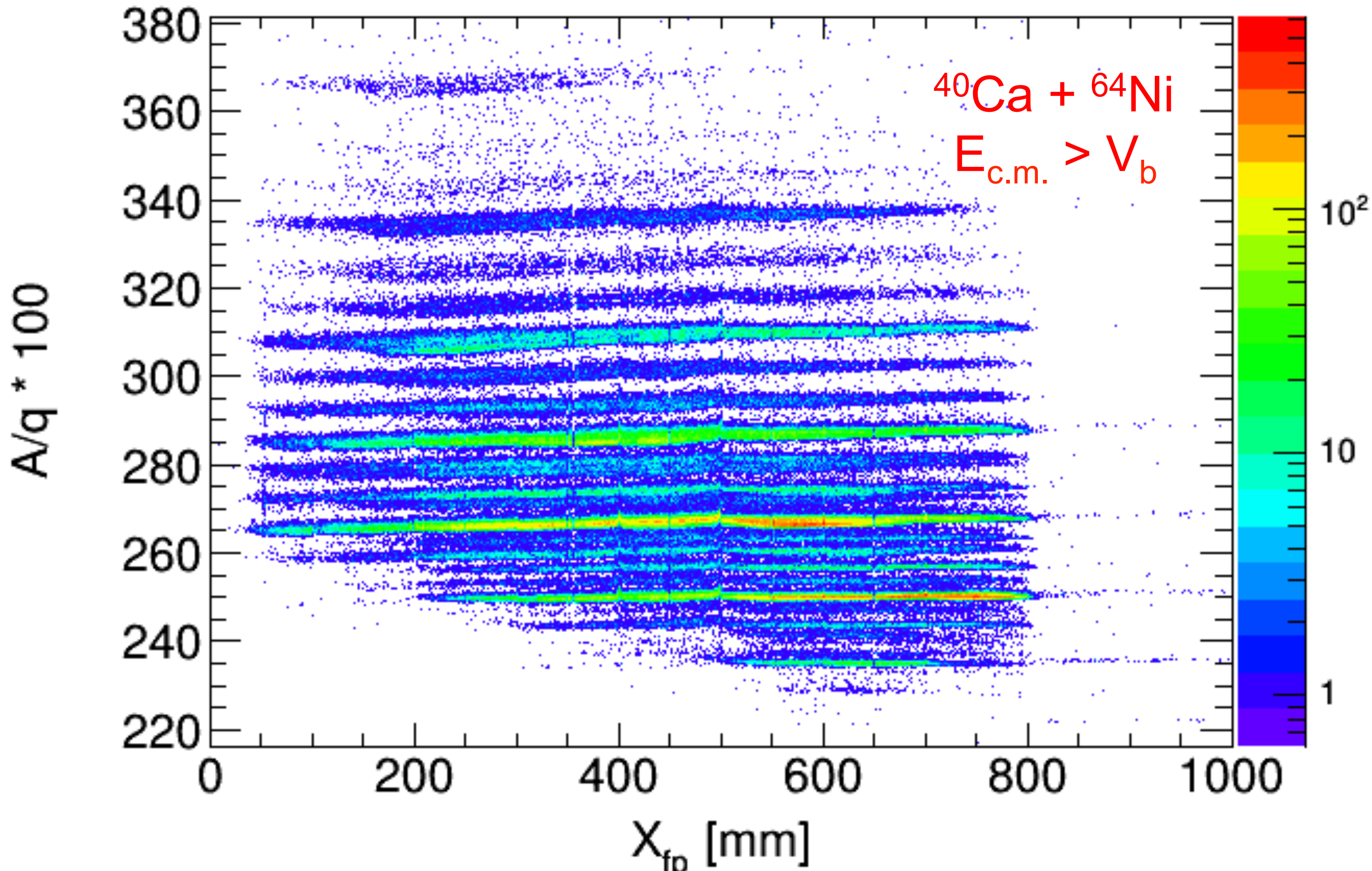


ionisation chamber: ΔE, E

PRISMA magnetic spectrometer

The transfer experiment

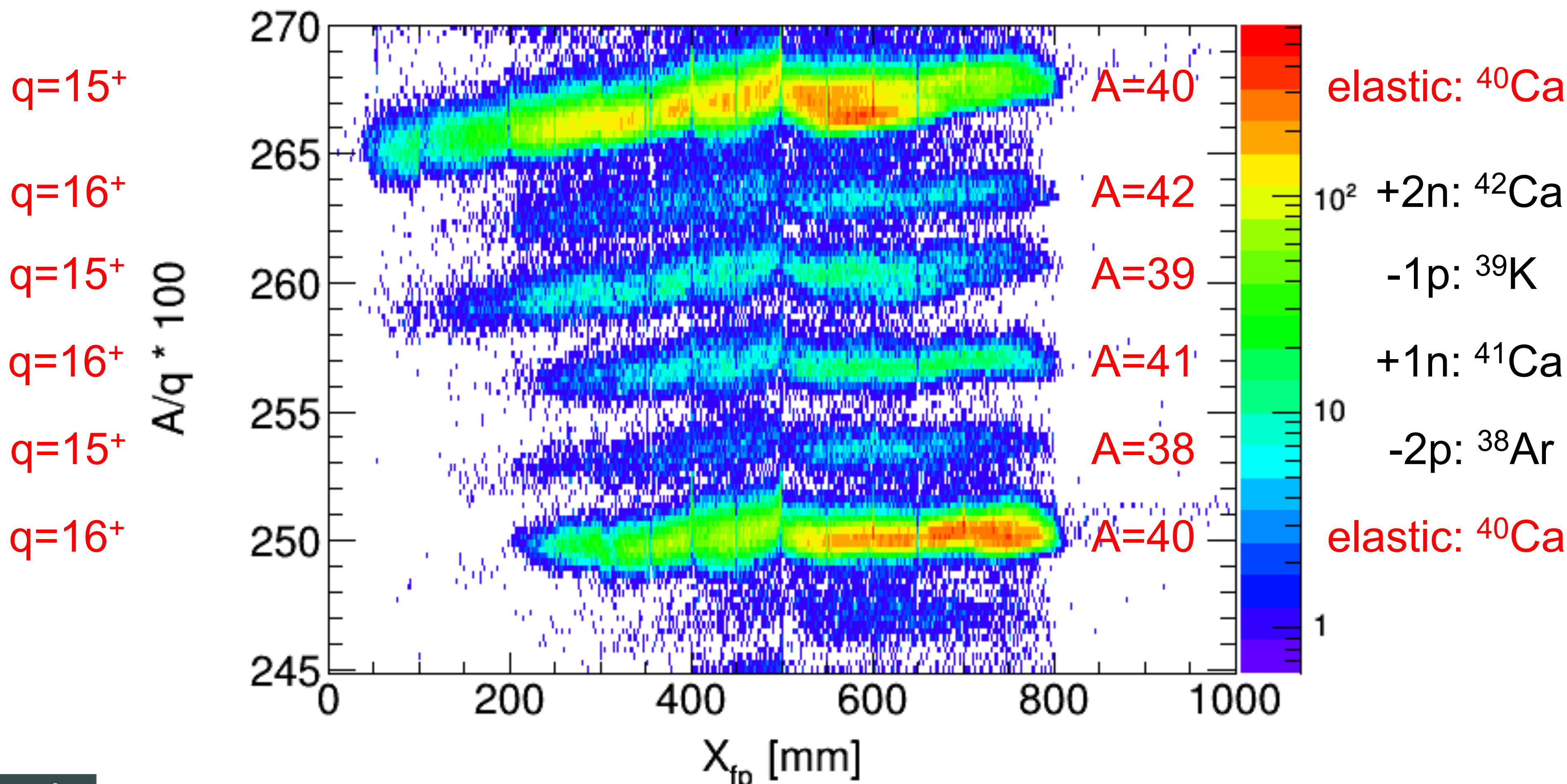
Spectrum of A/q vs X_{fp}



The transfer experiment

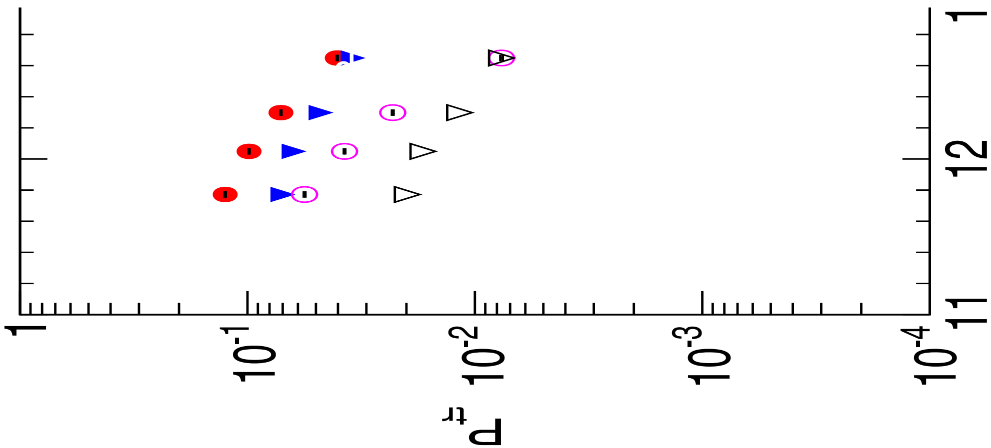
Spectrum of A/q vs X_{fp}

TDHF + BCS



The transfer experiment

Nucleon transfer probabilities $P_{tr} = N_{tr} / N_{el+inel}$ vs distance of closest approach D for $^{64}Ni + {}^{40}Ca$



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

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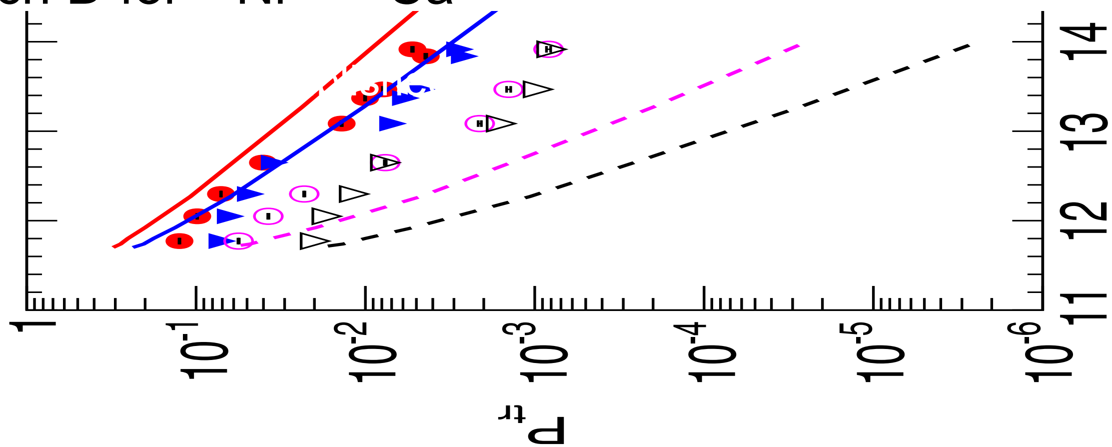

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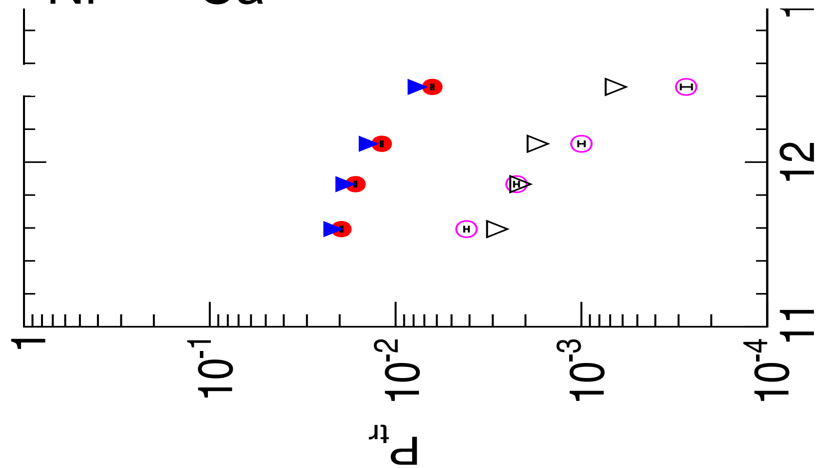

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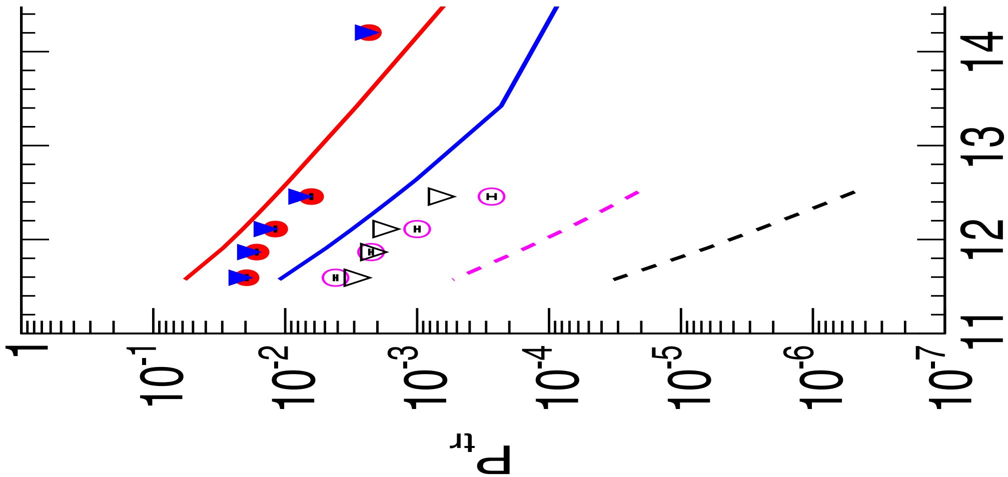


$$D = \frac{Z_p Z_t e^2}{2E_{c.m.}} \left(1 + \frac{1}{\sin\left(\theta_{c.m.}/2\right)} \right)$$

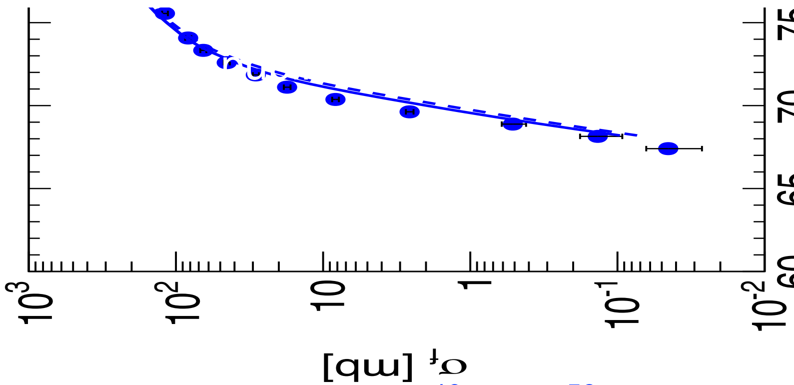
Back to coupled channels

→ the parameters for the transfer coupling form factors are extracted from the measured transfer probabilities

→ then these parameters are used in the coupled-channels calculations of fusion cross sections

In collaboration with G. Scamps, Tohoku University, Japan

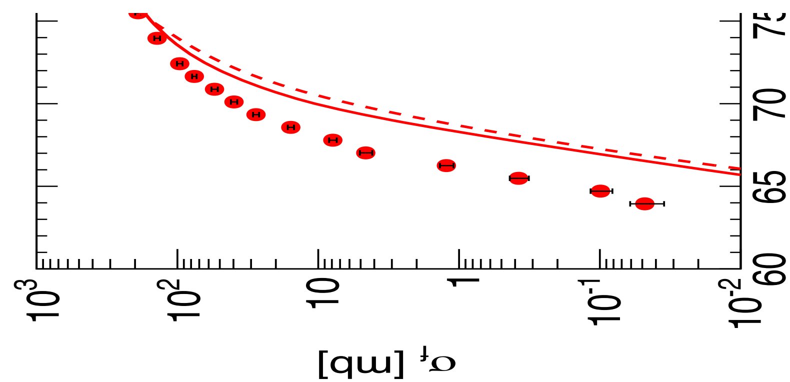
Back to coupled channels



■ ^{40}Ca + ^{58}Ni

- - inelastic couplings

--- inelastic and transfer couplings



■ ^{40}Ca + ^{64}Ni

- - inelastic couplings

--- inelastic and transfer couplings

- the direct two-neutron transfer scheme does not seem to explain the importance of nucleon transfer channels for ^{40}Ca + ^{64}Ni with $Q_{tr} > 0$
- underestimation of the sub-barrier fusion cross sections also observed for ^{40}Ca + ^{96}Zr with $Q_{tr} > 0$ [G. Scamps *and K. Hagino*, Phys. Rev. C **92**, 054614 (2015)]

Conclusions

- Study of $^{40}Ca+^{58}Ni$ and $^{40}Ca+^{64}Ni$ fusion reactions at energies above and below CB Nickel target nuclei : same structure features but different neutron numbers

- Influence of couplings to 2^+, 3^- (^{40}Ca)

- Large influence of transfer channels in the $^{40}Ca+^{64}Ni$ system

- Transfer probabilities measured with the PRISMA spectrometer

… underestimated by CC calculations using form factors adjusted to transfer probabilities

- Challenges for the future

- Calculation including different parameters for the transfer channels
- complementary transfer probability measurements for ^{40}Ca + ^{58}Ni with Qtr < 0 around the Coulomb barrier
- New experimental setup for transfer measurements ?

… pave the way to exotic n-rich nuclei.

Collaboration

D. Bourgin, Florent Haas, G. Fruet, D. Montanari
IPHC and University of Strasbourg, France

A. Stefanini, G. Montagnoli, E. Fioretto, F. Galtarossa[3], A. Goasduff, L. Corradi, F. Galtarossa, A. Goasduff, T. Mijatovic[4], F. Scarlassara, G. Zhang
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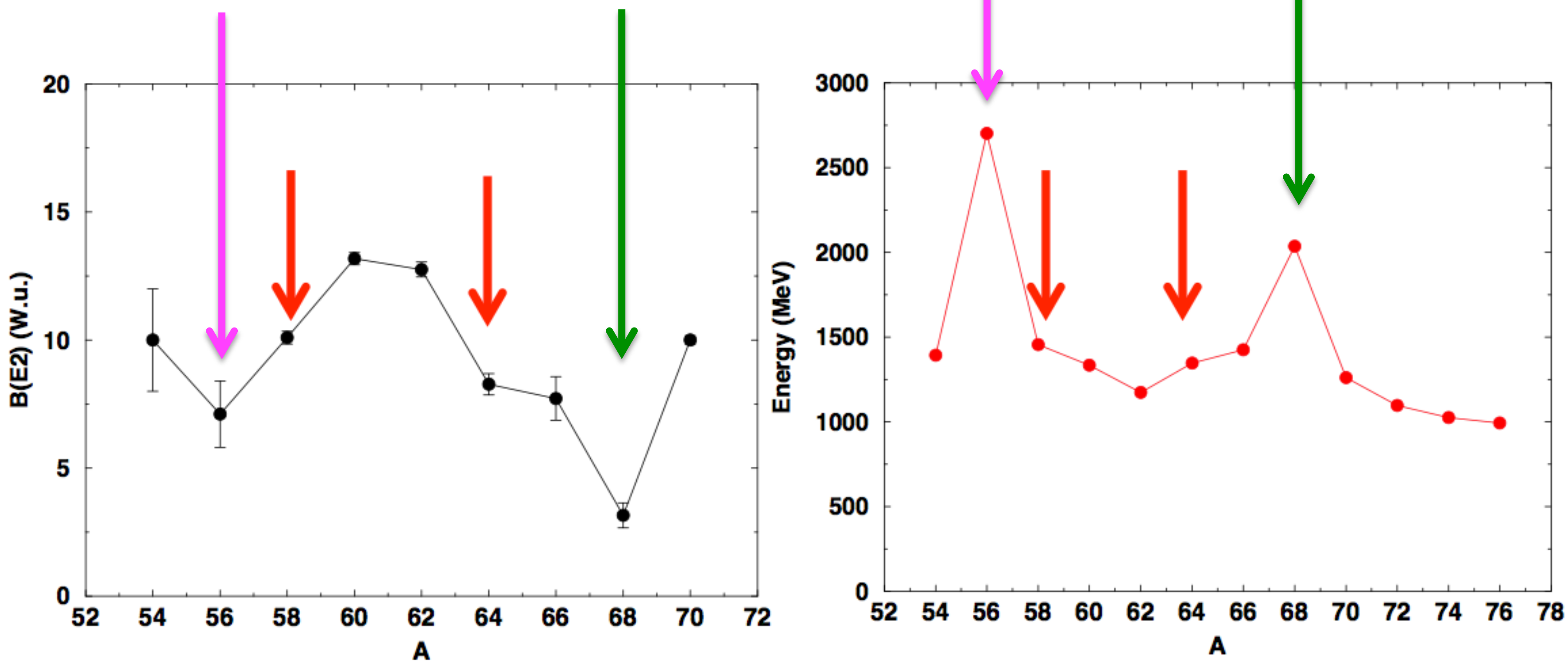
G. Montagnoli, F. Scarlassara, E. Strano,
University of Padova, Italy

D. Ackermann
GSI, Darmstadt Germany and GANIL, Caen, France

S. Szilner, T. Mijatovic, M. Varga Pajtler
RBI, Zagreb, Croatia

Ni + ^{40}Ca fusion reactions

neutron-rich Ni isotope : ^{68}Ni
neutron-poor Ni isotope : ^{56}Ni



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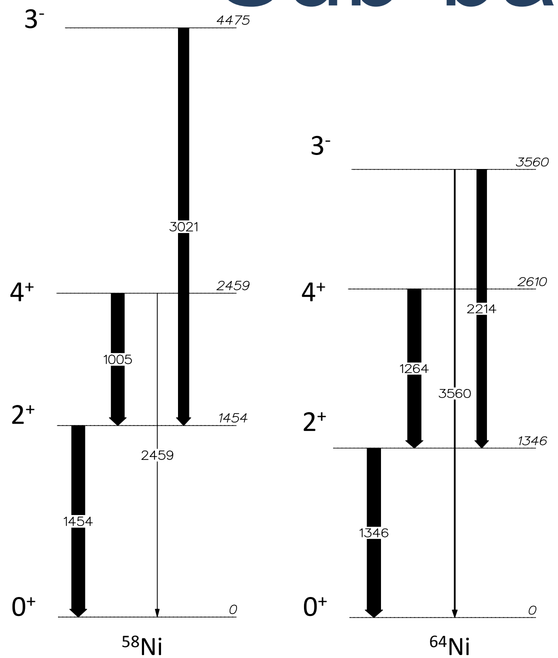
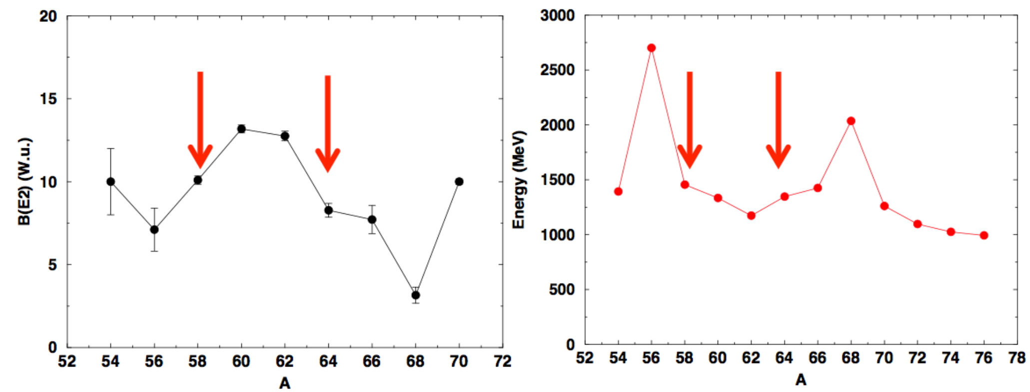
Sub-barrier fusion : Ca + Ni





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- Positive Q value for transfers for ^{40}Ca+^{64}Ni (+2n to +6n and -2p), negative for all transfers in ^{40}Ca+^{58}Ni (corrected for Coulomb, $Q_{corr}=Q_{transfer}+V^{c}_{b\text{-}in}-V^{c}_{b\text{-}out}$)

System	+1n	+2n	+3n	+4n	-1p	-2p	-3p	-4p
^{40}Ca+^{58}Ni	-3.80	-2.52	-11.19	-14.21	-3.75	-3.60	-11.95	-15.97
^{40}Ca+^{64}Ni	-1.23	3.47	0.86	4.22	0.26	4.19	0.88	1.81

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Transfer coupling form factors

C. H. Dasso and A. Vitturi, Phys. Lett. B **179**, 337 (1986)

→ Q_{tr} and F_{tr} are adjusted to fit the measured fusion

$$F(r) = F_{tr} \frac{dV_N}{dr} \sim \frac{F_{tr} V_0}{a} e^{\frac{-(r-R_0)}{a}}$$

$$[F_{tr}] = fm, [V_0] = MeV, [a] = fm$$

G. Scamps and K. Hagino, Phys. Rev. C **92**, 054614 (2015)

$\beta_{nn'}$ and $\alpha_{nn'}$ are adjusted to fit the measured transfer probabilities to be used in the coupled-channels calculations of fusion cross sections

$$V_{nn'}(r) \sim \frac{\beta_{nn'}}{\sqrt{4\pi\alpha_{nn'}}} e^{\frac{-(r-r_p)}{\alpha_{nn'}}}$$

$$[\beta_{nn'}] = MeV.fm, [\alpha_{nn'}] = fm$$