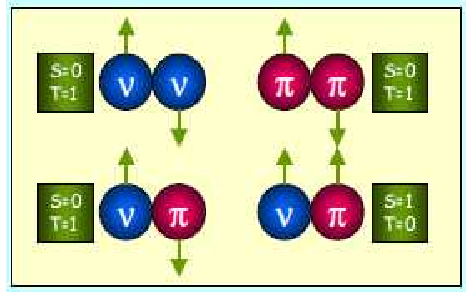
Probing nucleon-nucleon correlations in heavy ion transfer reactions



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IWM-EC 2018

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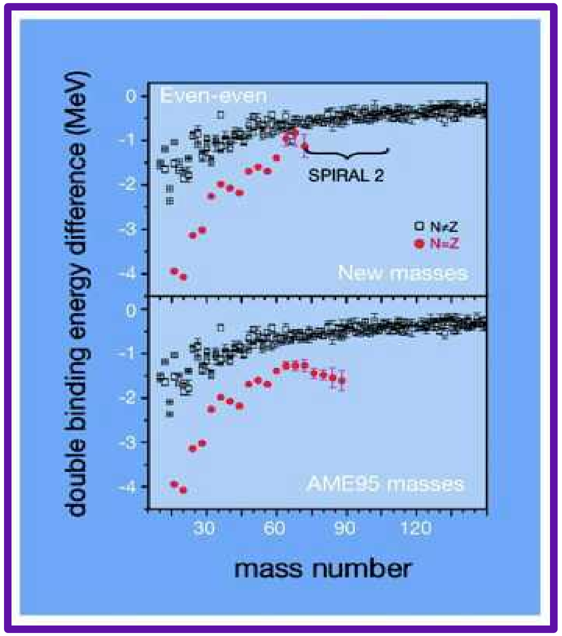
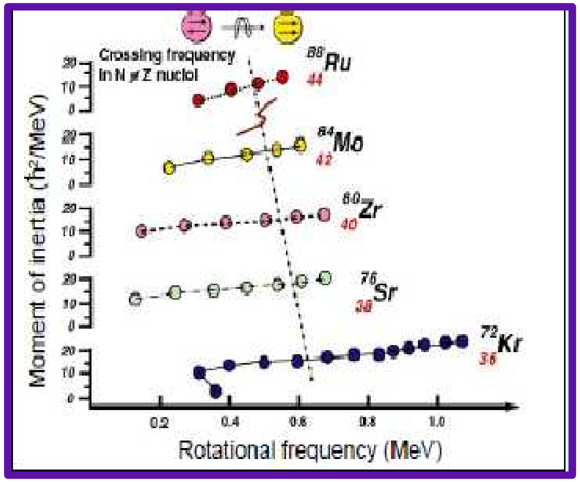
PRISMA collaboration

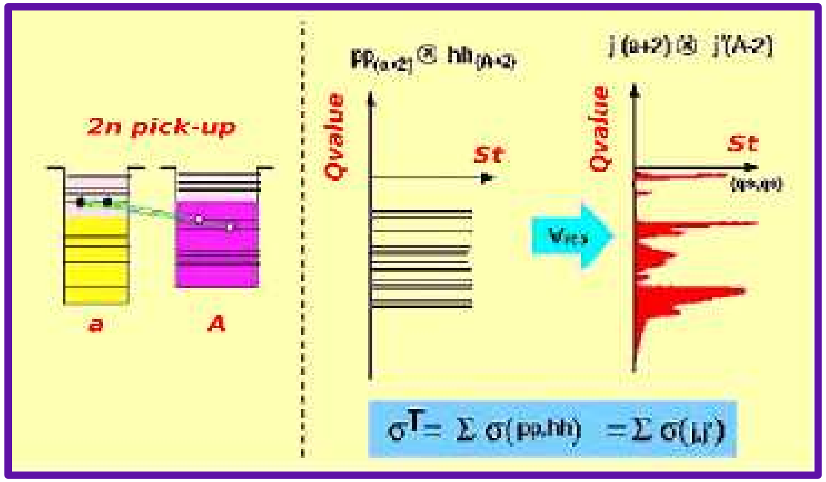
Probing correlations



nuclear binding energies



higher rotational frequency for the "pair" break in N=Z



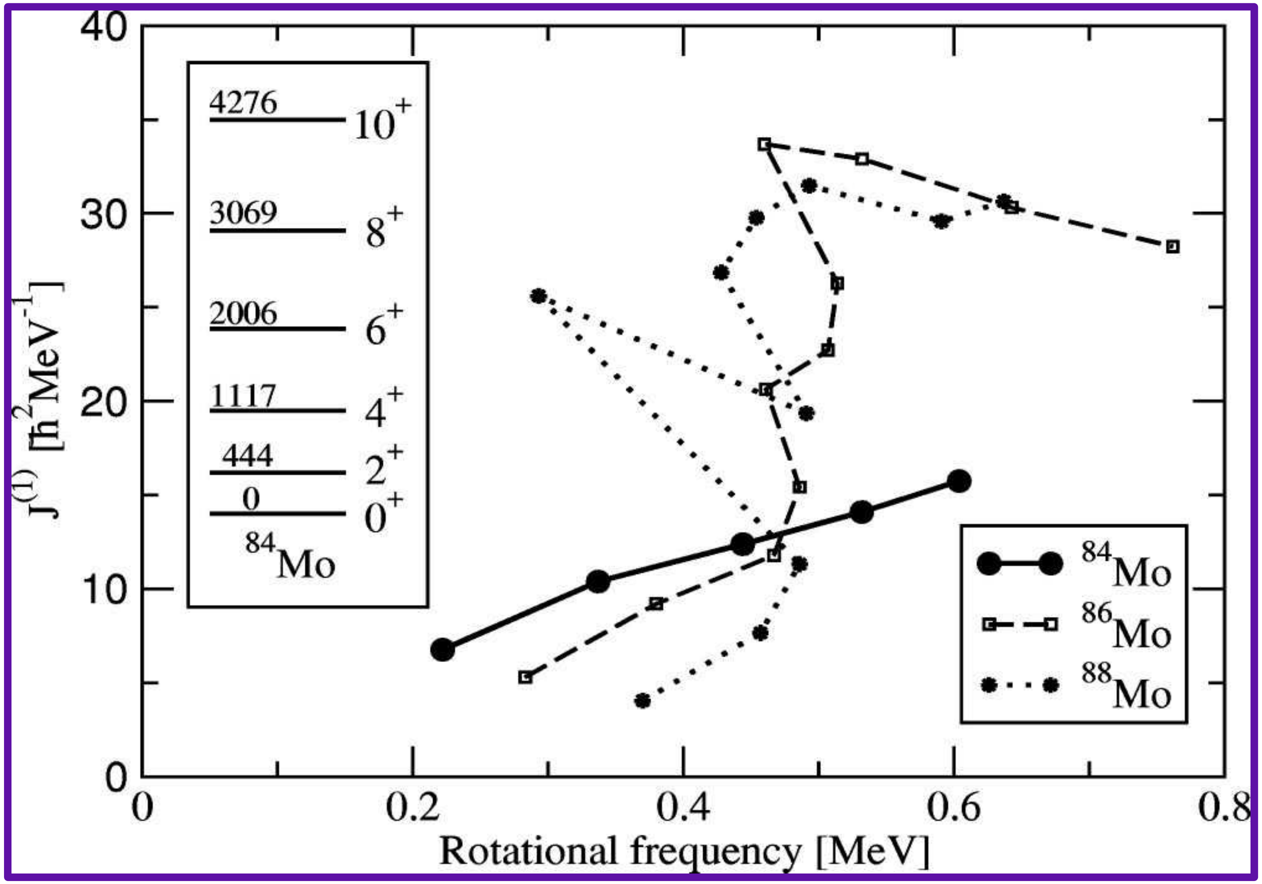
two-nucleon transfer redistribution of the strength around single particle states

How the pairing correlations can be probed (static and dynamics properties and effects)?

- Binding energies: the ground states → description in terms of superfluid condensates, in which the pairs of nucleons form the Cooper pairs
- Significantly different behavior at medium to high spins of rotational bands
- Enhanced probability to add or remove a nucleon-nucleon pair.

Delayed alignments in the N=Z nuclei ^{84}Mo and ^{88}Ru

The np pairing interaction may be the cause of the delayed rotational alignments in the even-even N=Z nuclei (A~80); different pairing fields (nn, pp, and np) respond differently to the Coriolis forces (the enhancement of the np interaction in N=Z nuclei has in general an effect to sustain the pairing field under rotation).



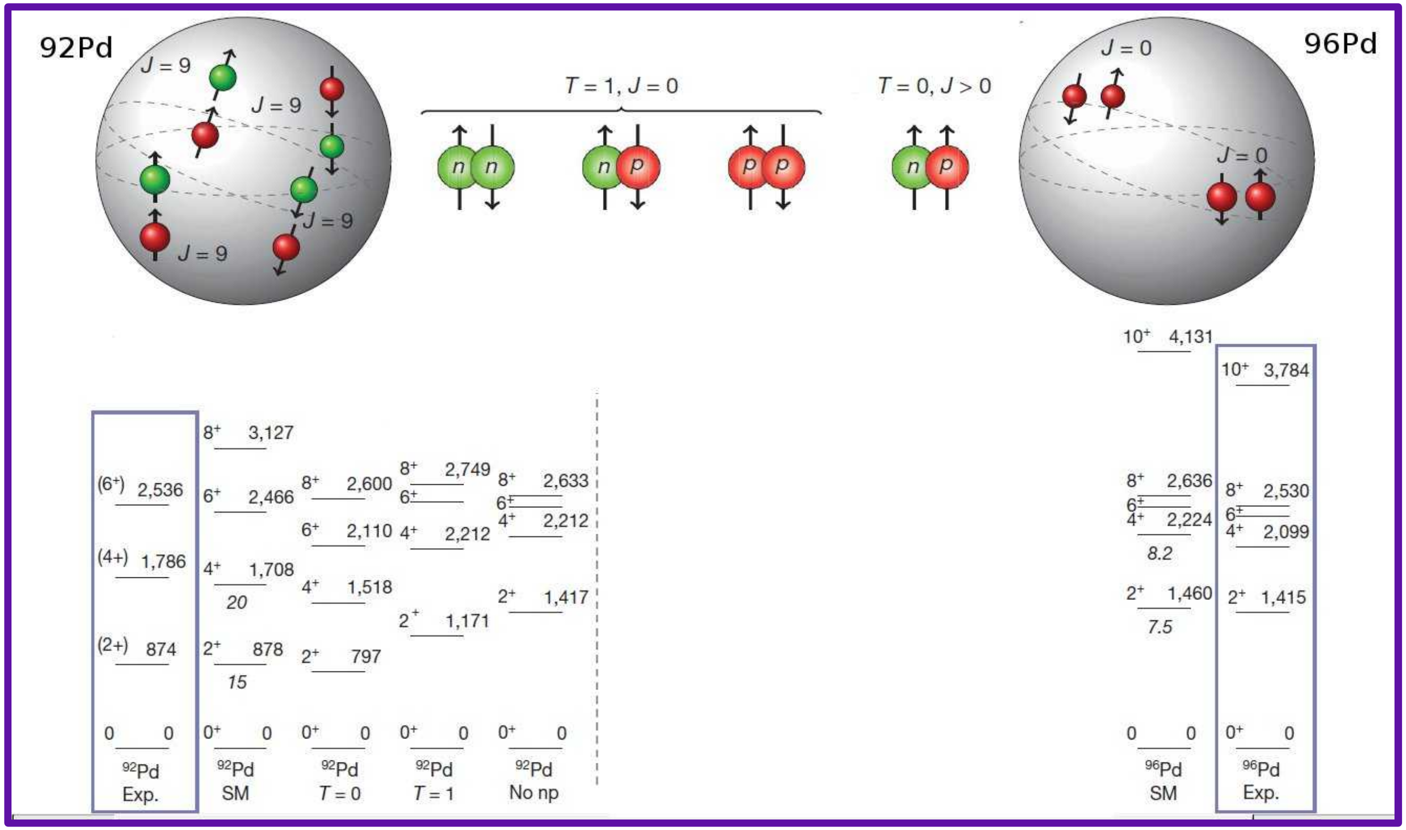
Real sitation is rather complex:

→ the spin alignment may also be influenced by deformation (shapes).

→ different stregths of quadrupole interaction (np QQ) may mimic the experimental bending

N. Marginean et al. Phys. Rev. C 65 (2002) 051303R

Structure: Evidence for a spin-aligned neutron–proton pairs in 92Pd

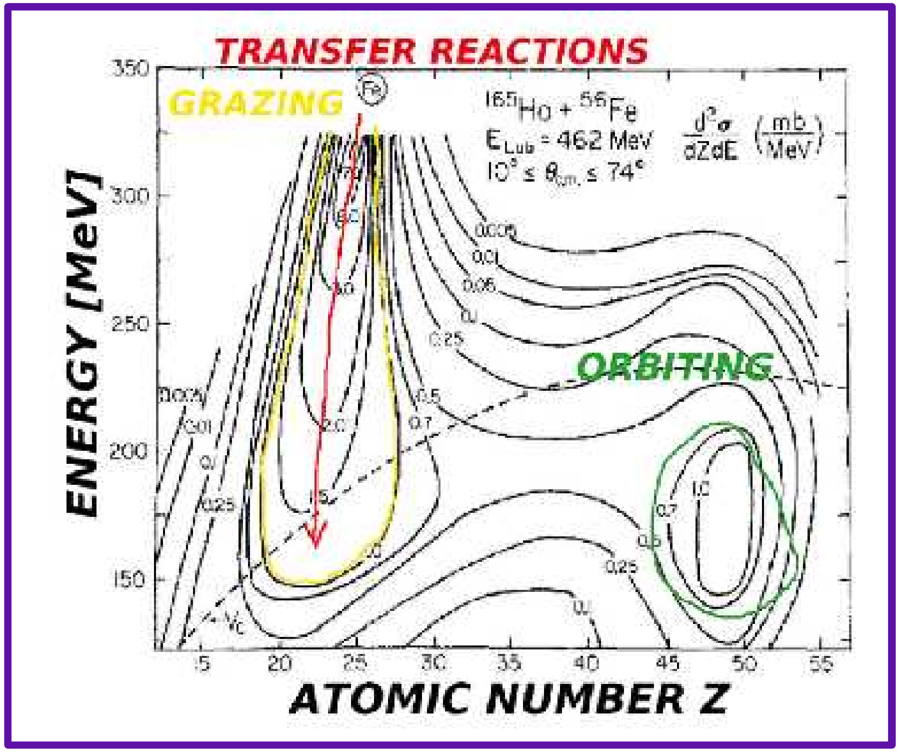


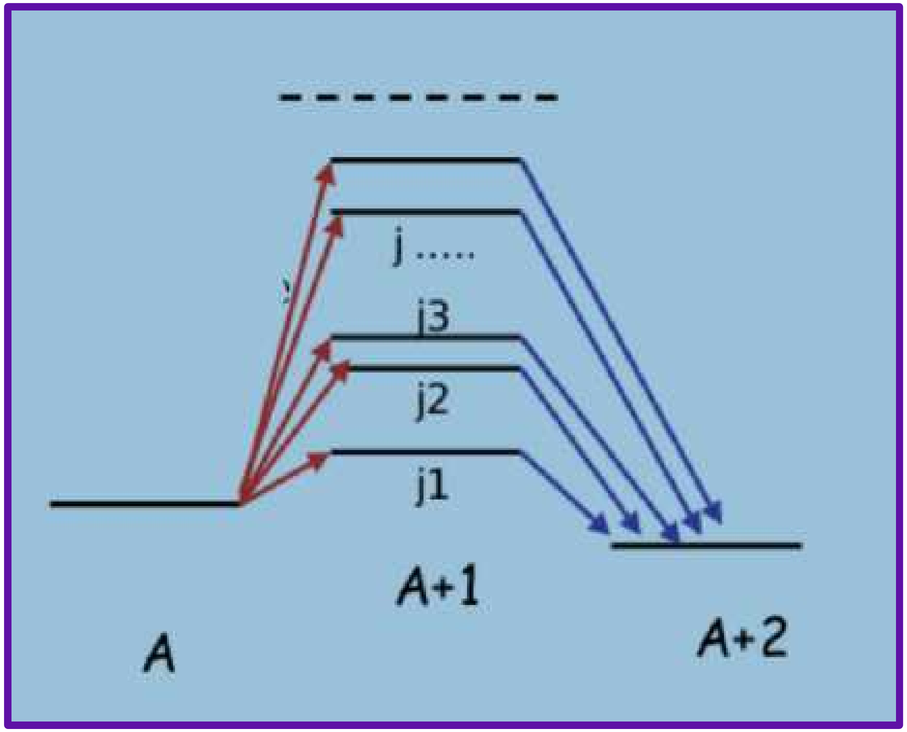
Detailed structure studies and advance calculations where nucleon-nucleon interaction is included (similar structure properties can be due to "other" effects)
→ new data, state-of-art calculations

The structure of the ground-state wave-function of 92Pd in the spin-aligned np paired phase can be viewed as a system of deuteron-like np hole pairs with respect to the 100Sn 'core'.
The SM calculated spectra for 92Pd with "full neutron–proton interactions" (calaculations of the pure T=0 and pure T=1 neutron–proton interaction contributions).

B. Cederwall et al., Nature 469 (2011) 68

Probing correlations in transfer reactions



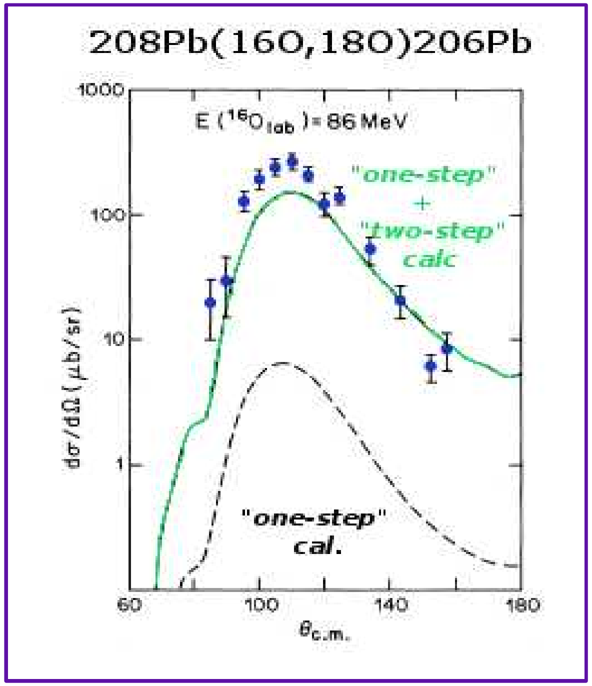


Two-nucleon transfer constitute the specific probe in the study of pairing in nuclei:

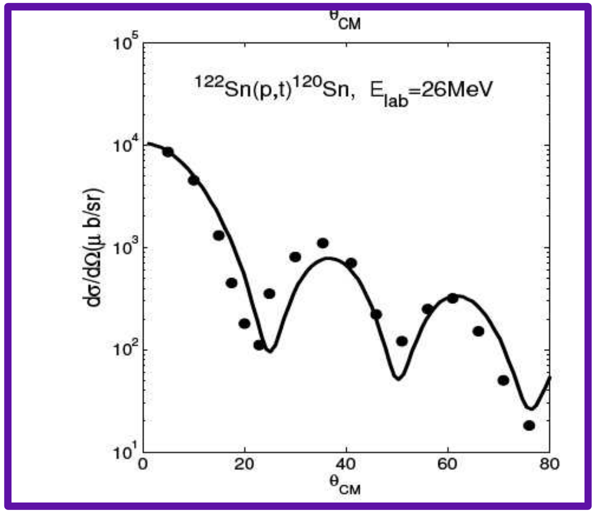
STRUCTURE: The pairing interaction induces particle-particle correlations that are essential in defining the properties of finite quantum many body systems in their ground and neighboring states. These structure properties may influence in a significant way the evolution of the collision of two nuclei.

DYNAMICS: which degrees of freedom describe the evolution of the reaction from the quasielastic to the deep inelastic regimes and to fusion.

Probing correlations in transfer reactions



B.F. Bayman et al., PRC 26 (1982) 1509



G. Potel et al, Reports on Progress in Phy. 76 (2013) 106301

Two-particle transfer processes induced by light and heavy ions are an ideal tool to study the dynamical aspects of pairing correlations.

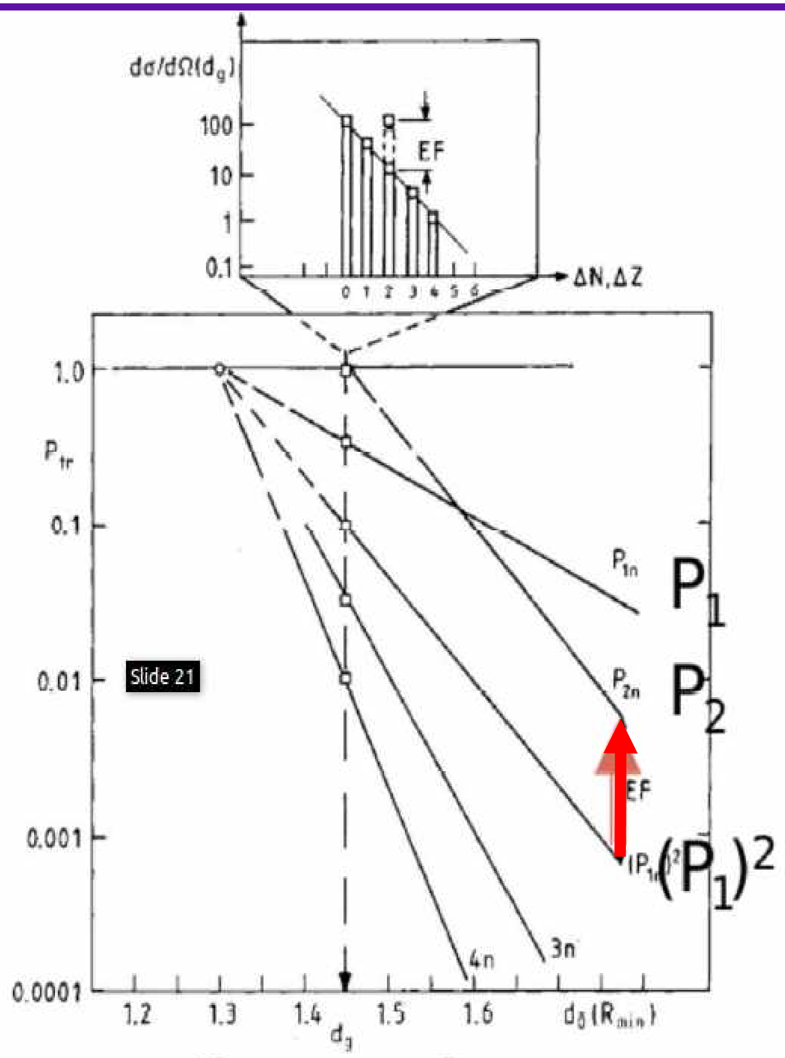
Theoretical treatment: the structure information is entangled with the reaction mechanism (complex structure of the two interacting ions, QE and DIC processes, many open channels).

Light ion induced transfer reactions, (t,p), (p,t), (3He,n), (4He,d):
Advantages: shape defines L transferred, population of the specific final state
Drawbacks: as one uses different probes the reaction mechanism may differ in two-particle transfer reactions involving different reaction participants

Heavy ion transfer reactions:

HI advantages: test of correlation properties in transfer processes via simultaneous comparison of ±n and ±p, and ±nn/±pp/±np pairs; transfer of "many" pairs
HI drawbacks: limited A,Z, energy resolutions.

Enhancement coefficients

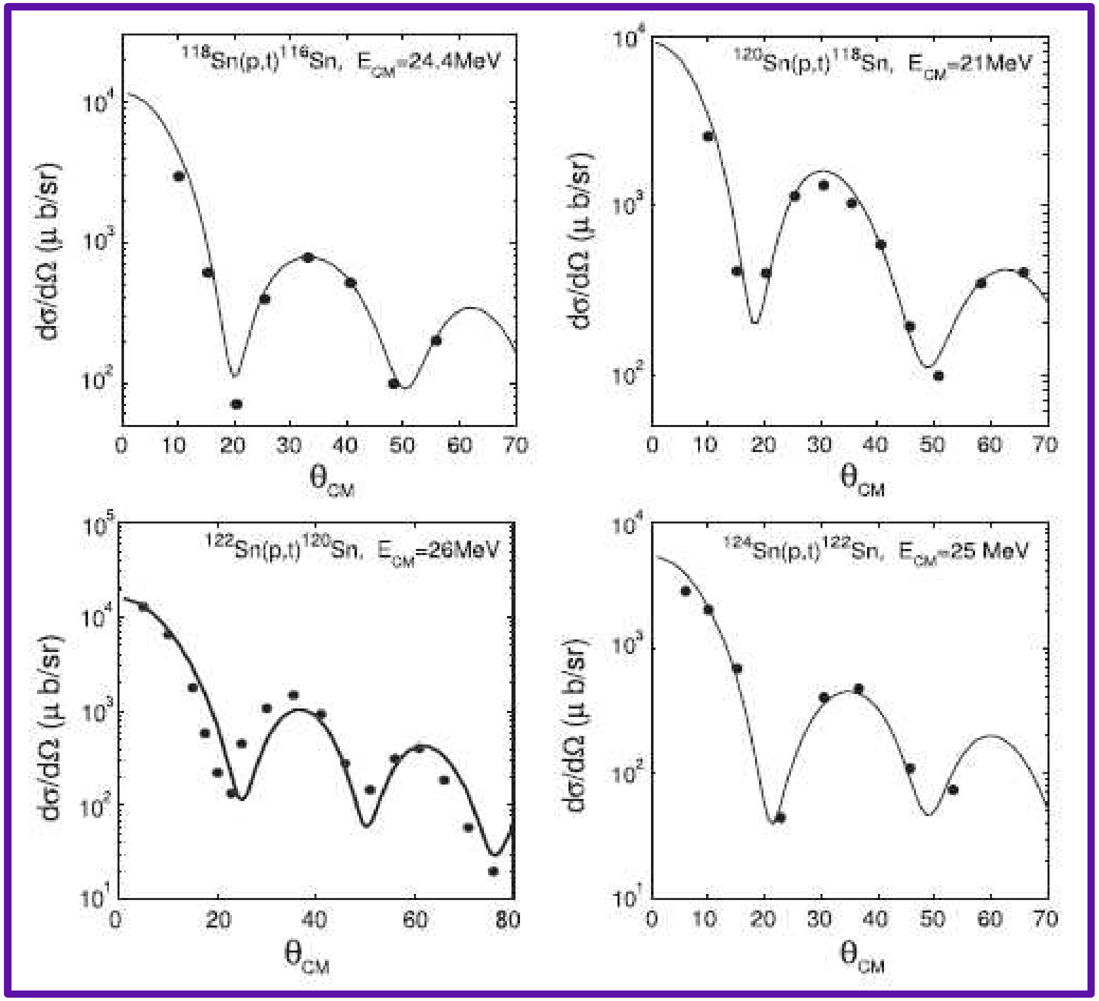


Enhancement coefficients:
the ratio of the actual cross section to the prediction of models using uncorrelated states which provide a direct measurement of the correlation of the populated states.

Experimental extraction by comparison of one- and two-particle transfer probabilities as a function of the distance of closest approach (W. von Oertzen and coworkers)

Drawbacks:
all existing studies involve inclusive cross sections (energy resolution) at energies higher than the Coulomb barrier (many open channels) and at angles forward of the grazing (complex reaction mechanism)

Absolute cross sections for two-nucleon transfer reactions induced by light ions



(p,t) reactions : absolute cross sections

recently performed calculations for two neutron transfer reactions match the experimental data with high accuracy

^{118,120,122,124}Sn(p,t)^{116,118,120,122}Sn

G. Potel et al, Reports on Progress in Phy. 76 (2013) 106301

Absolute cross sections for one and two-nucleon transfer reactions

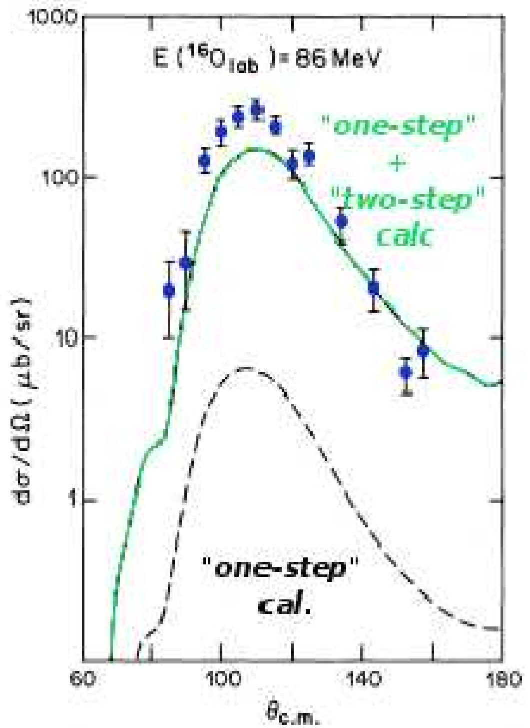
$^{208}Pb(^{16}O,^{18}O_{g.s.})^{206}Pb$

______successive+simultaneous

- - - - - -simultaneous

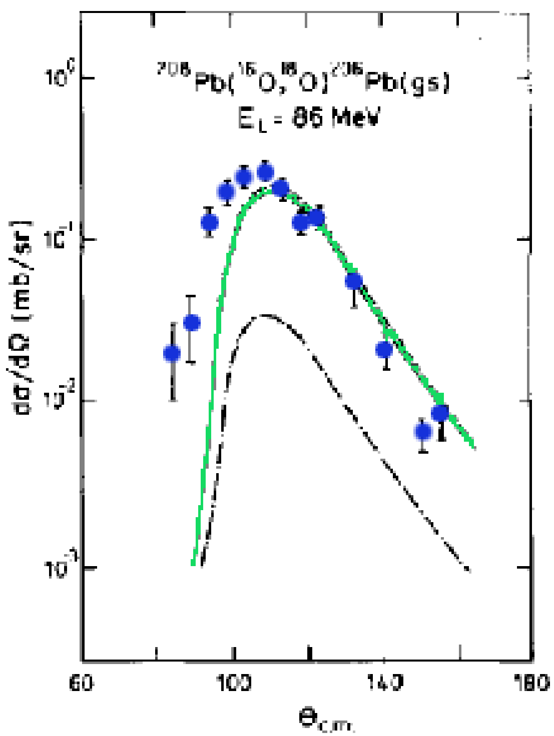
informations about correlations are extracted when experimental absolute cross sections are compared with a microscopic theory which beside correlations includes also the coupling between relative motion (reaction) and intrinsic motion (structure).

full quantum-mechanical



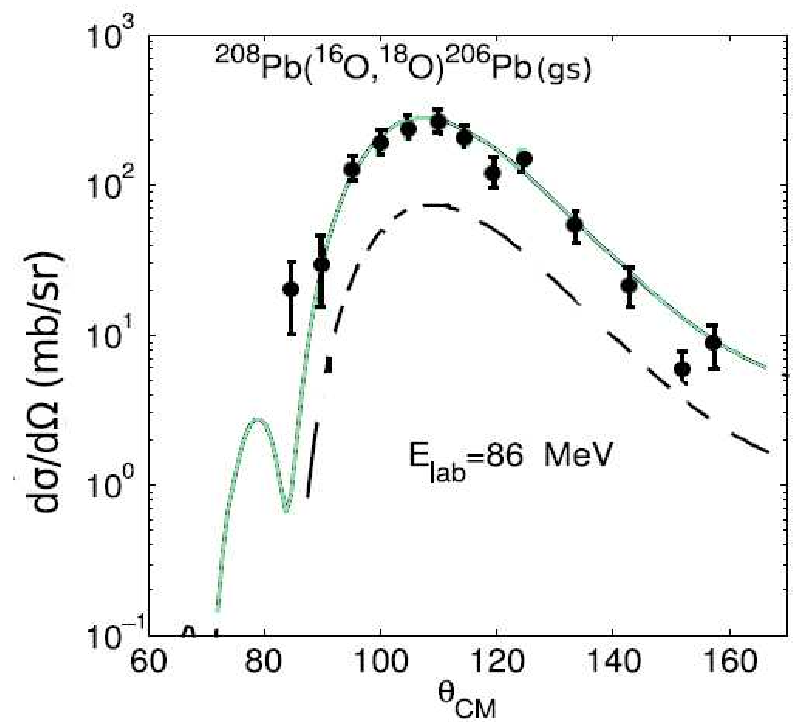
B.F.Bayman and J.Chen, Phys. Rev. C 26 (1982) 1509

semi-classical



E.Maglione, G.Pollarolo, A.Vitturi, R.A.Broglia and A.Winther Phys. Lett. B 162 (1985) 59

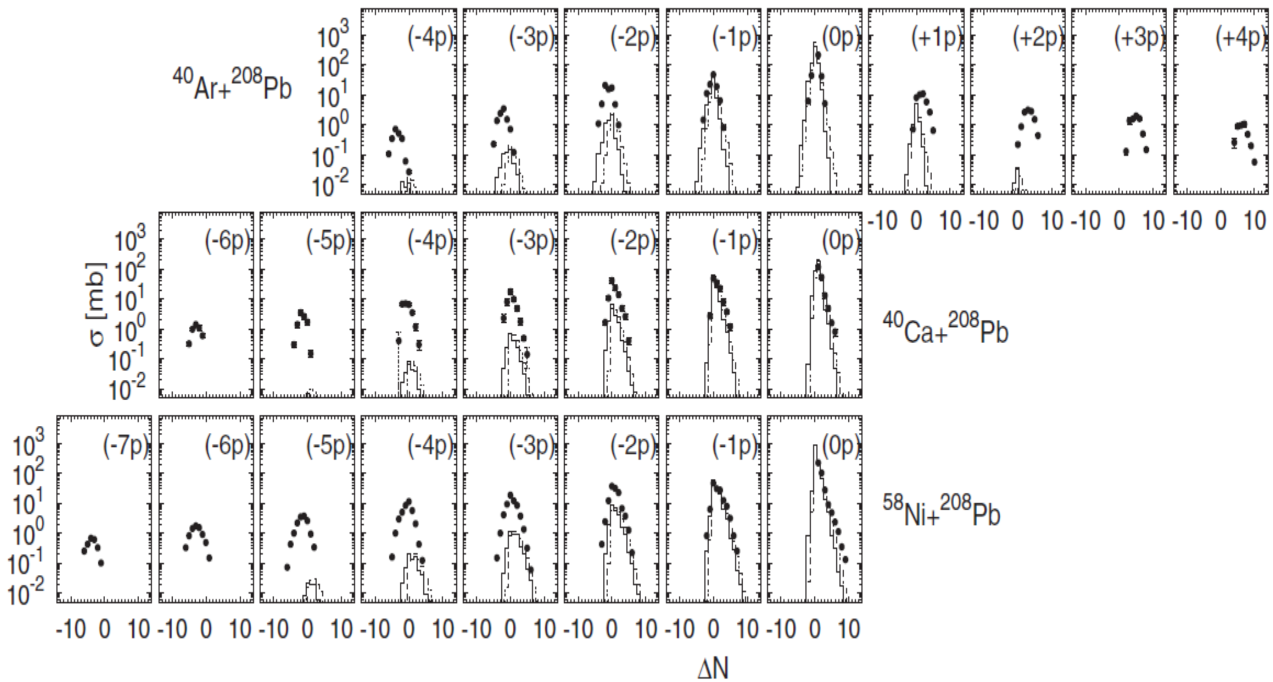
full quantum-mechanical



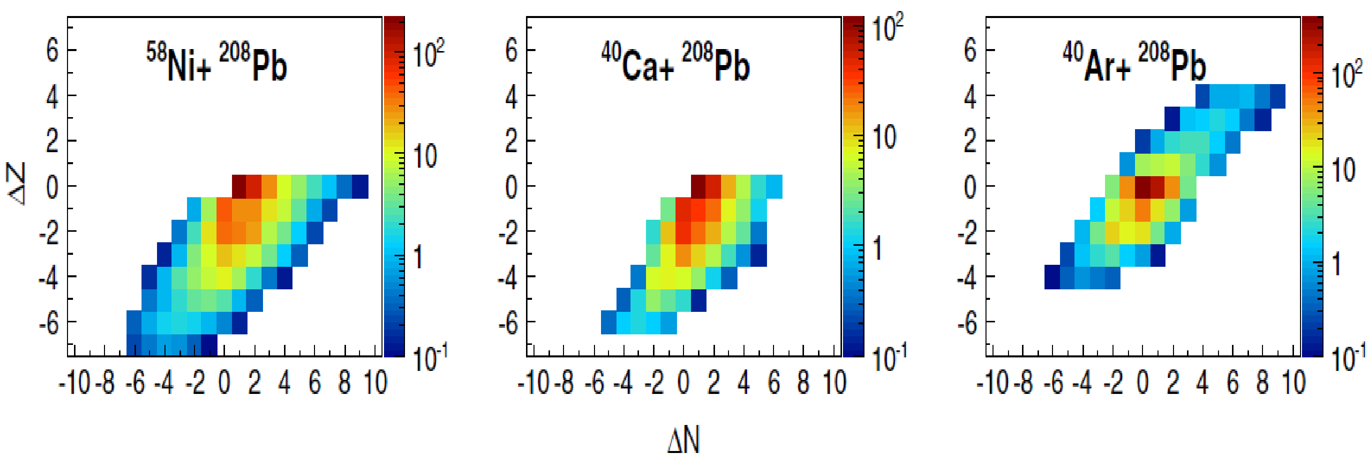
G.Potel, A.Idini, F.Barranco, E.Vigezzi and R.A.Broglia, Rep. Prog. Phys. 76 (2013) 106301;

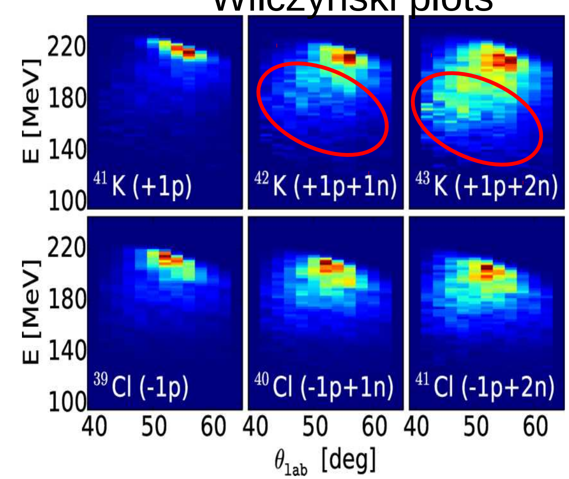
G. Potel et al, PRL 105 (2010) 172502

^{40}Ar+^{208}Pb, ^{40}Ca+^{208}Pb, and ^{58}Ni+^{208}Pb



Above the barrier:
→ many open channels, transfer of 5-10 protons and neutrons governed by optimum Q-value
→ large TKEL, onset of DIC components
→ secondary processes: evaporation, transfer induced fission

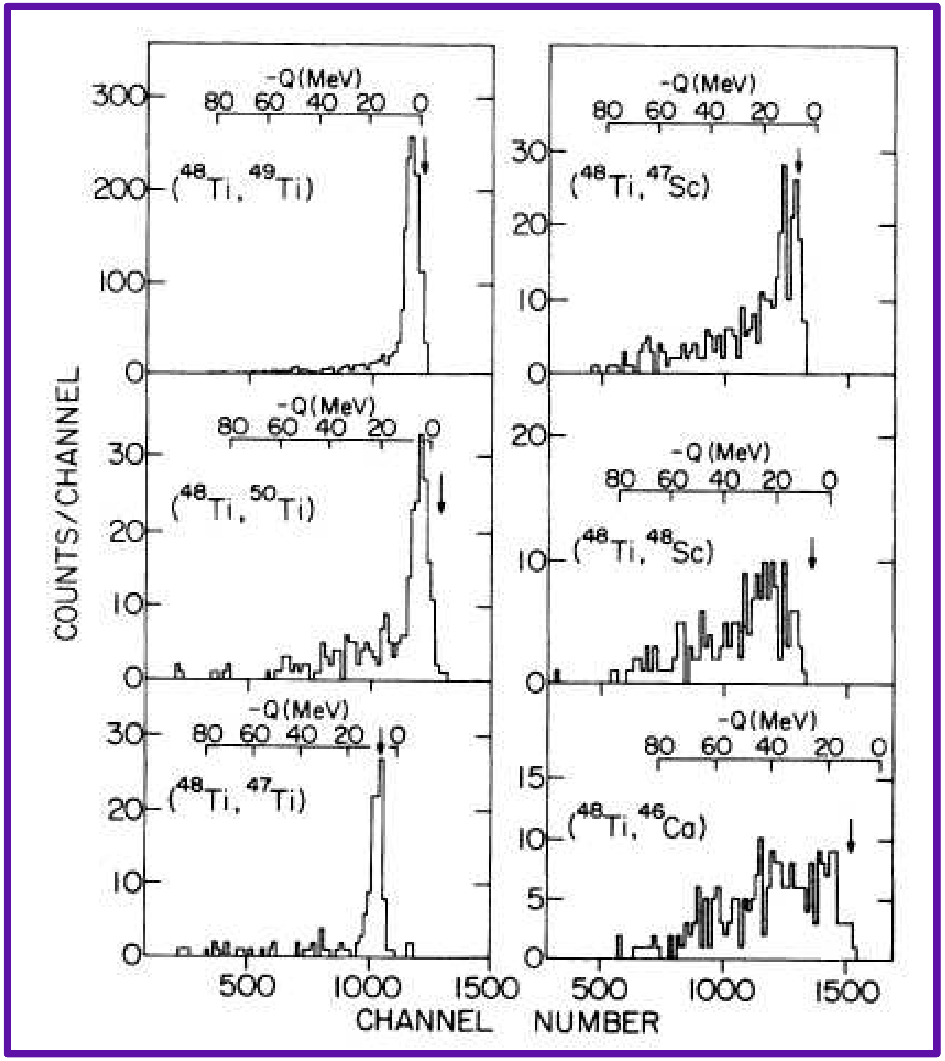


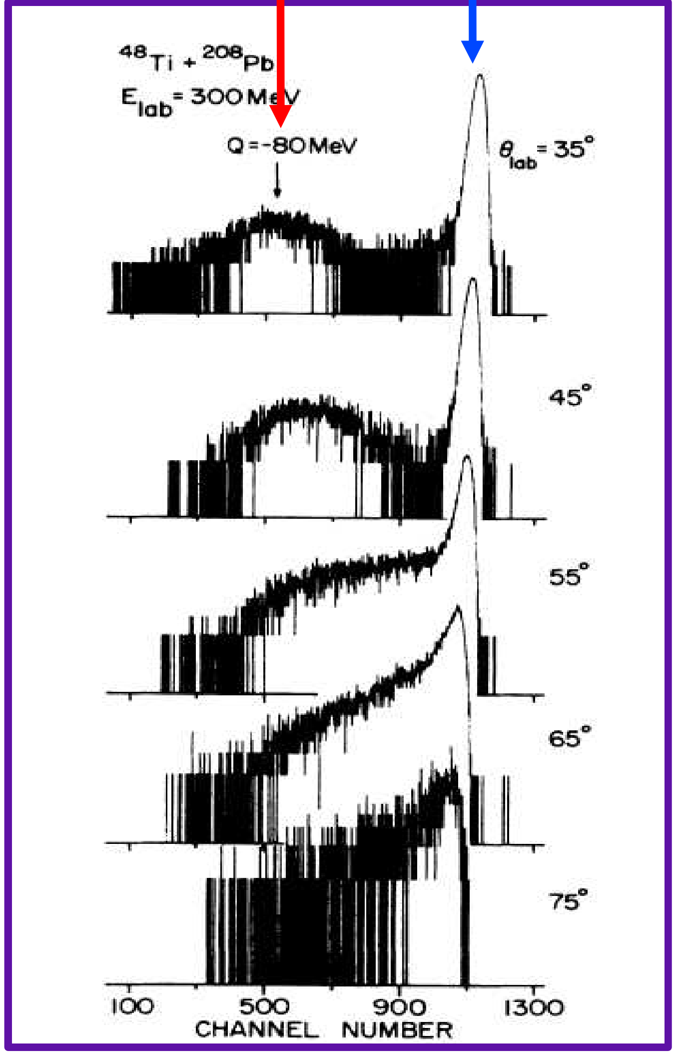


T. Mijatovic et al., Phys. Rev. C 94 (2016) 064616

^{40}Ar+^{208}Pb

$^{48}Ti+^{208}Pb$ – energy distributions





heavy ions: to deal with limited energy resolutions and with the presence of both QE and DIC components

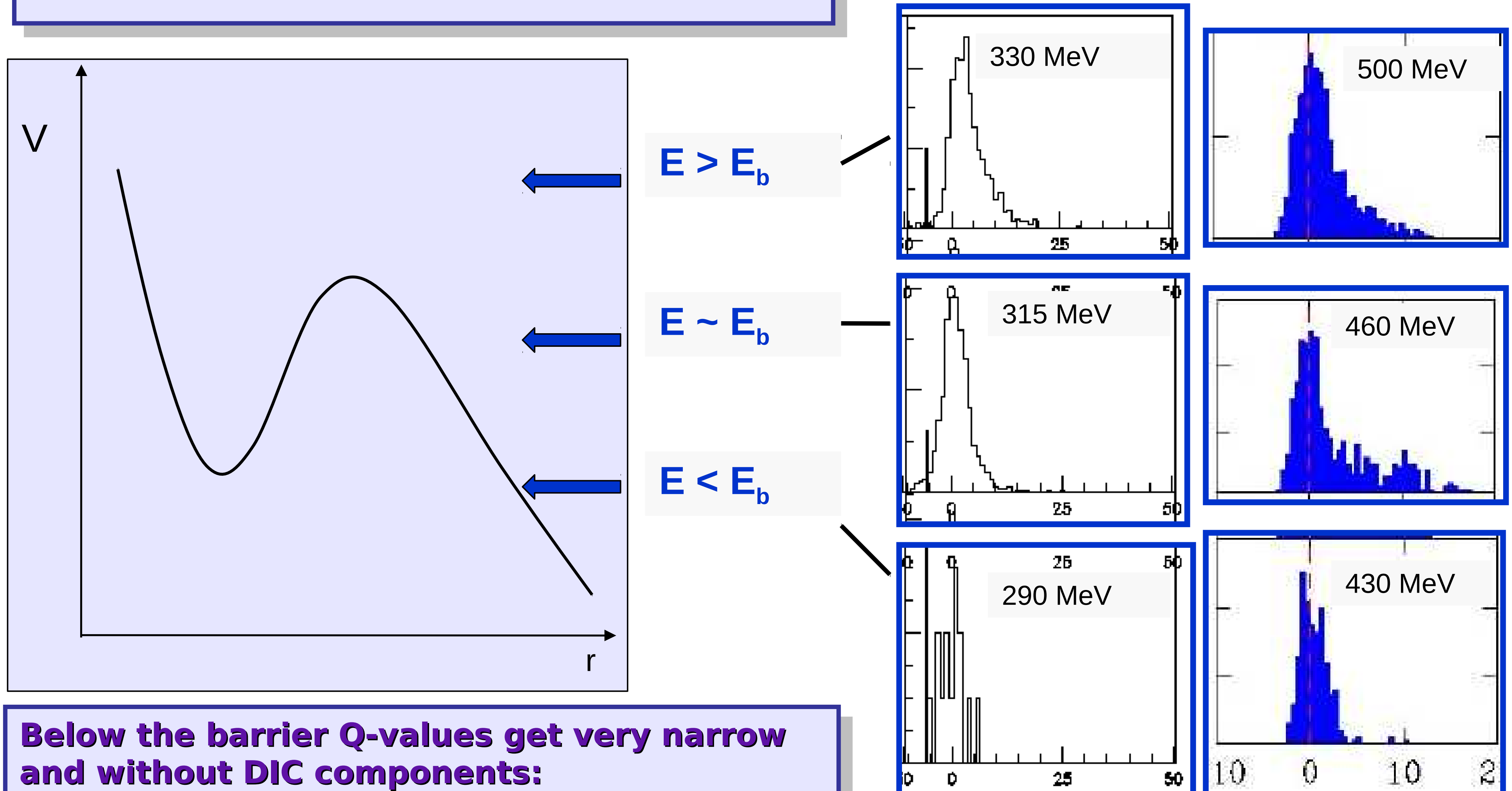
K.E.Rehm et al, PRC37 (1988) 2629

Measurements below Coulomb barrier

A smooth transition between QE and DIC

$^{96}Zr(^{40}Ca,^{42}Ca)$
$Q_{gs} = +5.6$ MeV

$^{116}Sn(^{60}Ni,^{62}Ni)$
$Q_{gs} = +1.3$ MeV



Below the barrier Q-values get very narrow and without DIC components:
1) $E > E_b$ large number of open channels, DIC components / evaporation effects
2) $E < E_b$ narrow Q-value distributions (concentrated at “one state”)

L. Corradi et. al., PRC 84 (2011) 034603

D. Montanari et. al., PRL 113 (2014) 052501

D. Montanari et. al., PRC 93 (2016) 054623

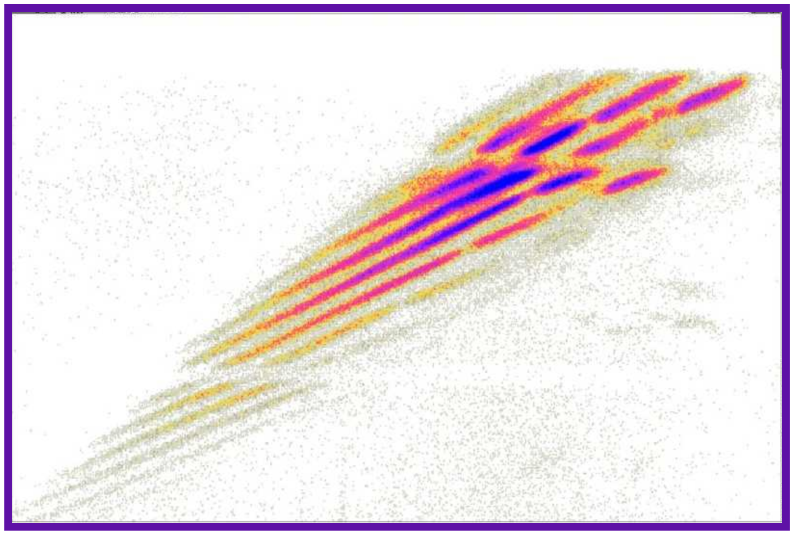
^{116}Sn+^{60}Ni: detection of (light) target-like ions in inverse kinematics with PRISMA

excitation function:

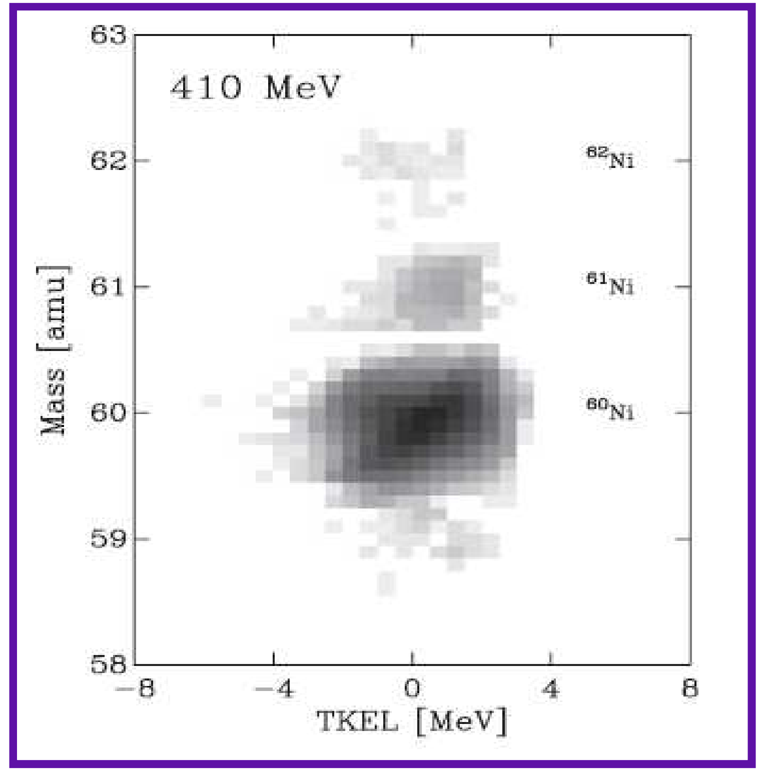
E_{beam} = 410 MeV – 500 MeV

(D ~ 12.3 to 15.0 fm)

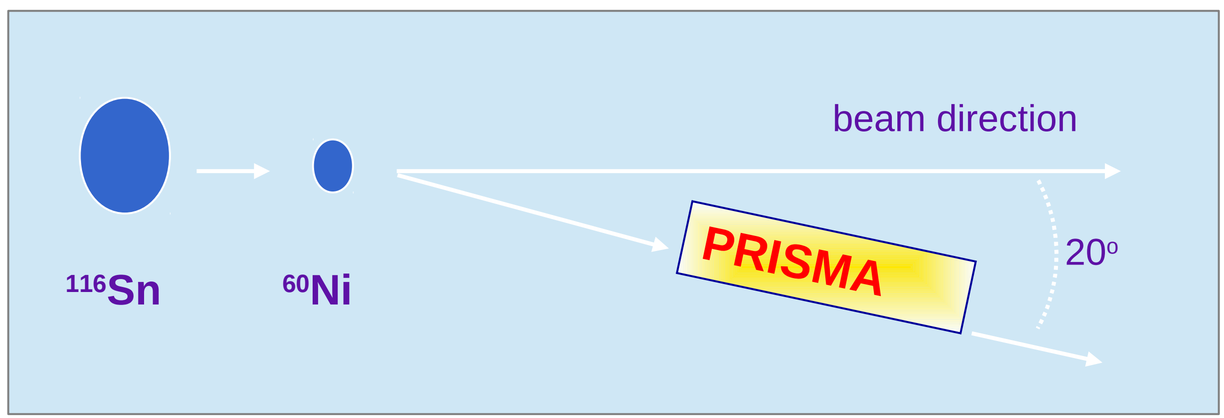
Rv [a.u.]



Energy [a.u.]

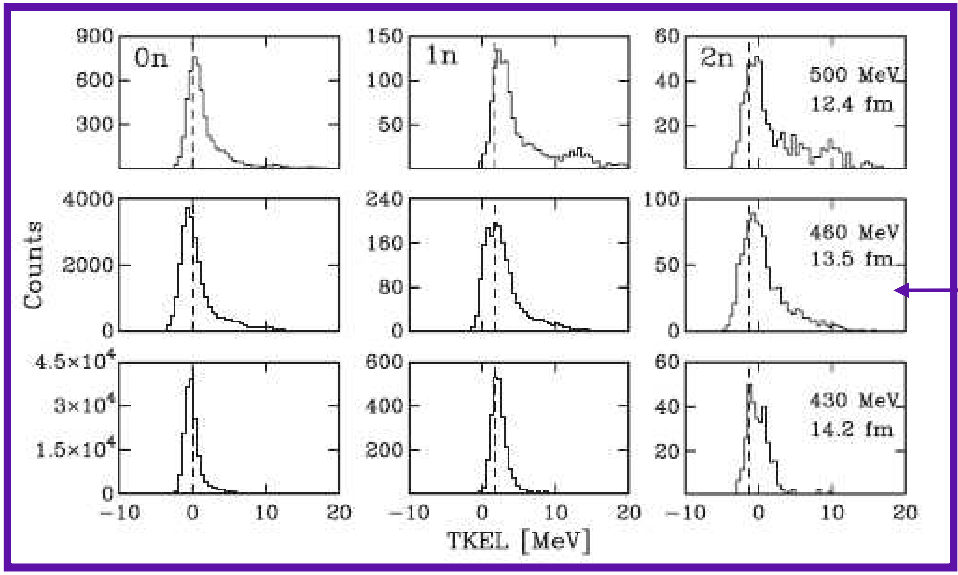


excellent channel separation at D ~ 15 fm



$^{116}Sn+^{60}Ni$: neutron pair transfer far below the Coulomb barrier

Transfer strength very close to the g.s. to g.s. transitions



D. Montanari, L. Corradi, S. Szilner, G. Pollarolo et. al., Phys. Rev. Lett. 113 (2014) 052501

$$P_{tr} = \frac{d\sigma_{tr}}{d\sigma_{\mathrm{Ruth}}}$$

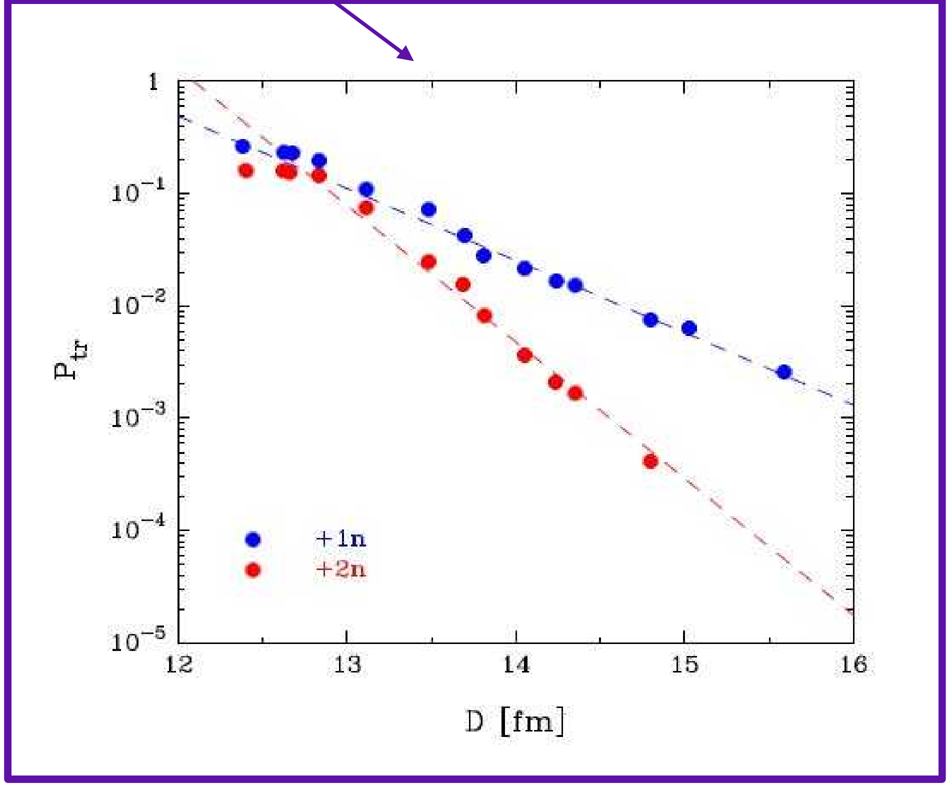
$$D = \frac{Z_a Z_A e^2}{2E_{\mathrm{c.m.}}}\left(1 + \frac{1}{\sin(\theta_{\mathrm{c.m.}}/2)}\right)$$

P_{tr} slope

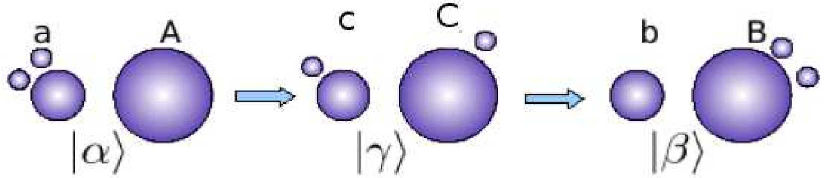
$$P_{tr} \propto e^{-2\alpha D} \qquad \alpha = \sqrt{\frac{2mB}{\hbar^2}}$$

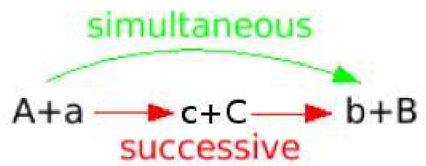
B → binding energy

Coulomb barrier

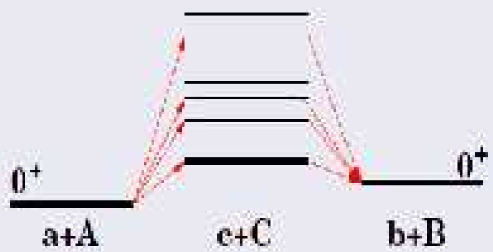


^{116}Sn+^{60}Ni: two particle transfer (semiclassical theory, microscopic calculations, 2nd order Born app.)





$$c_\beta(t) = c_\beta^{(1)} + c_\beta^{ort} + c_\beta^{succ}$$



	nlj
^{116}Sn	$1g_{9/2}$
	$2d_{5/2}$
	$1g_{7/2}$
	$3s_{1/2}$
	$2d_{3/2}$
	$1h_{11/2}$
	$2f_{7/2}$
	$3p_{3/2}$
^{60}Ni	$2p_{3/2}$
	$2p_{1/2}$
	$1f_{5/2}$
	$1g_{9/2}$

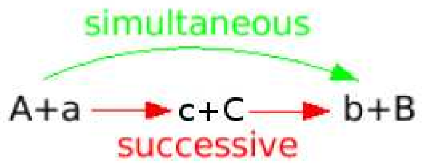
3 terms : simultaneous, orthogonal and successive

only the successive term contributes to the transfer amplitude (simultaneous component is canceled out by the nonorthogonality correction)

Only 0+ to 0+ transitions are included (BCS).

$$(c_\beta)_{\rm succ} = \frac{1}{\hbar^2}\sum_{a_1,a_1'} B^{(A)}(a_1a_1;0)B^{(a)}(a_1'a_1';0)2\frac{(-1)^{j_1+j_1'}}{\sqrt{(2j_1+1)}\sqrt{(2j_1'+1)}}\sum_{m_1m_1'}(-1)^{m_1+m_1'}$$
$$\times\int_{-\infty}^{+\infty} dt\, f_{m_1m_1'}(\mathcal{R})e^{i[(E_\beta-E_\gamma)t+\delta_{\beta\gamma}(t)+\hbar(m_1'-m_1)\Phi(t)]/\hbar}$$
$$\times\int_{-\infty}^{t} dt\, f_{-m_1-m_1'}(\mathcal{R})e^{i[(E_\gamma-E_\alpha)t+\delta_{\gamma\alpha}(t)-\hbar(m_1'-m_1)\Phi(t)]/\hbar}.$$

$^{116}Sn+^{60}Ni$: two particle transfer (simultaneous vs. successive transfer)



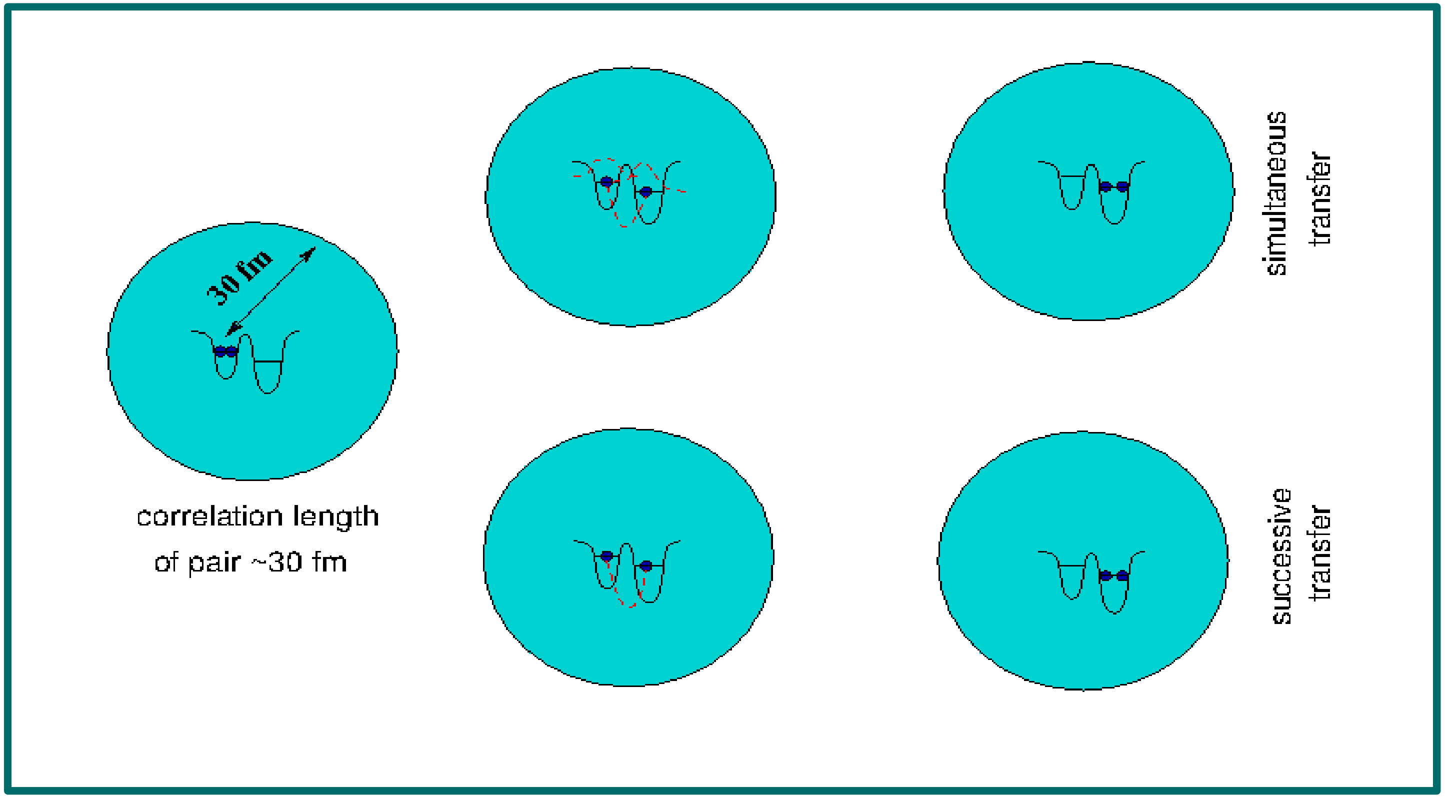
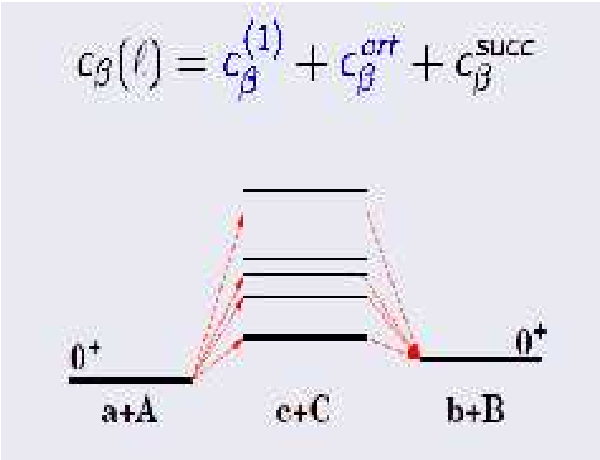


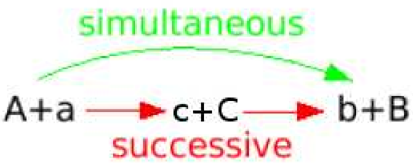
Fig. courtesy of G. Potel

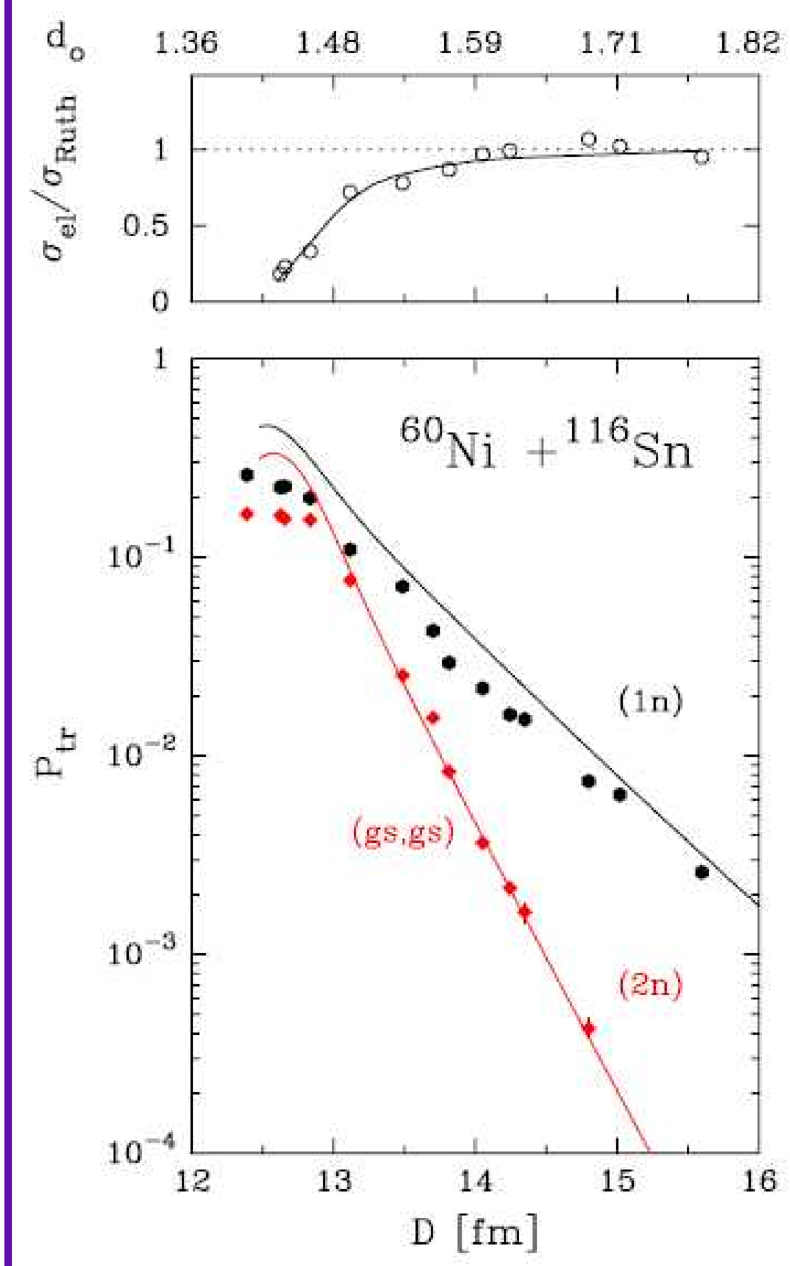
A measure of the sensitivity of two-nucleon transfer reactions to pairing correlations is provided by the "enhancement" of the calculated cross sections with respect to pure configurations.

character of pairing correlations manifests itself equally well in simultaneous and in successive transfers due to the correlation length

$^{60}Ni+^{116}Sn$: neutron pair transfer far below the Coulomb barrier





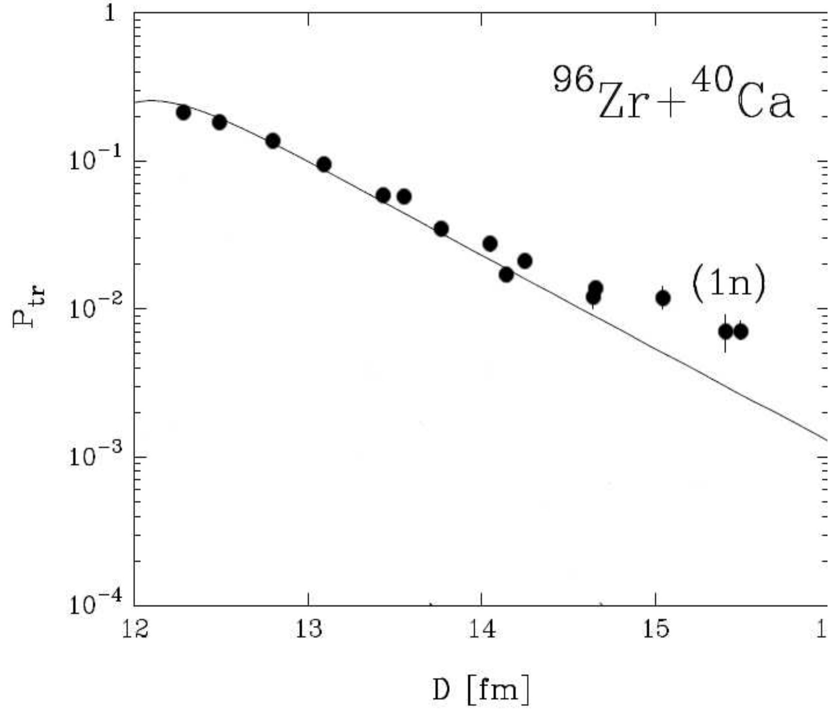


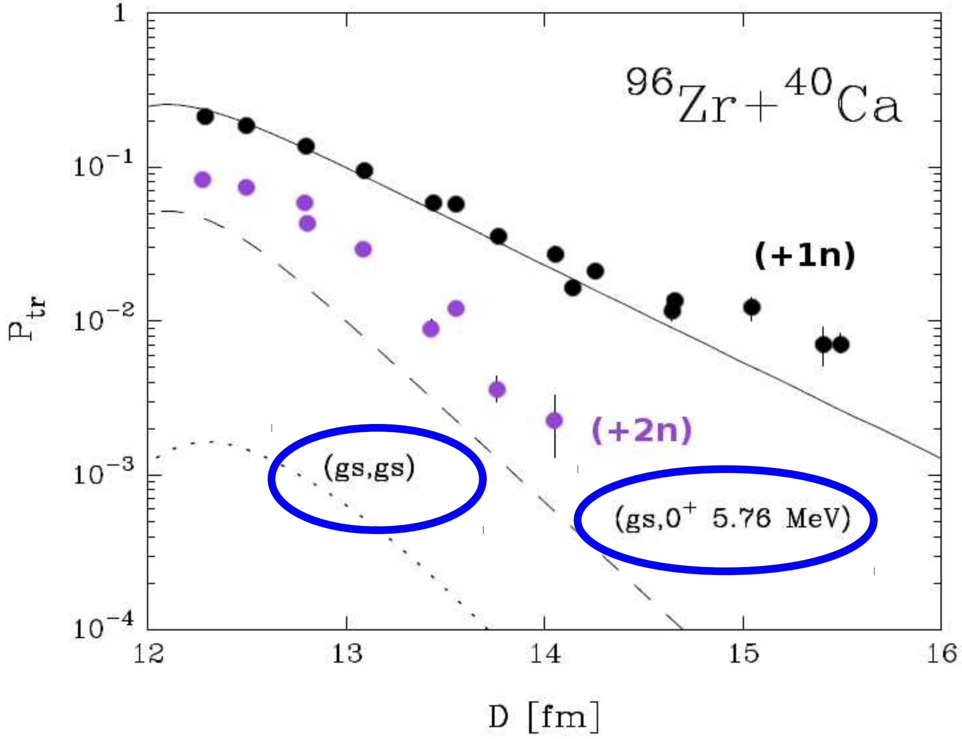
The experimental transfer probabilities are well reproduced, in **absolute values** and in **slope** by **microscopic** calculations which incorporate nucleon-nucleon **correlations:**

✓ a consistent description of (1n) and (2n) channels

✓ the formalism for (2n) incorporates the contribution from both the **simultaneous** and **successive** terms (only the **ground-to-ground-state** transition has been calculated)

$^{40}Ca+^{96}Zr$: neutron pair transfer far below the Coulomb barrier



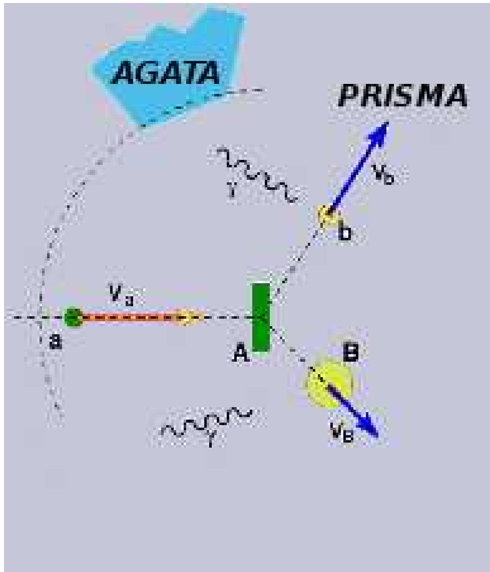


-to obtain P_{tr} : summed over all possible transitions that can be constructed from the single particle states in projectile and target
- the set of single particle states covers a full shell below the Fermi level for ^{96}Zr and a full shell above for ^{40}Ca

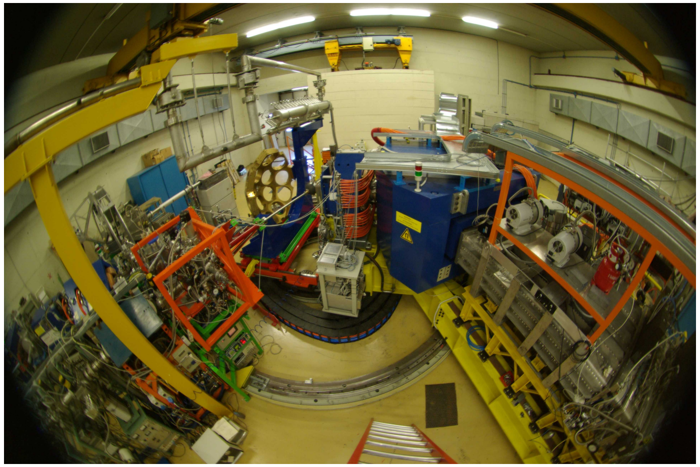
Two particle transfer (semiclassical theory, microscopic calc.)
3 terms : simultaneous, orthogonal and successive (only the successive term contributes to the transfer amplitude)

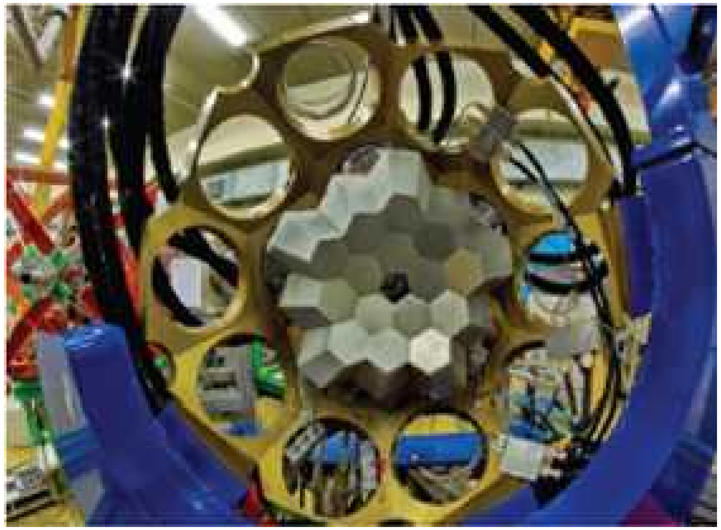
L. Corradi et. al., PRC 84 (2011) 034603

$^{60}Ni+^{116}Sn$: PRISMA+AGATA measurement
$^{40}Ca+^{96}Zr$: PRISMA + CLARA measurement



$^{60}Ni+^{116}Sn$, $^{40}Ca+^{96}Zr$: detection of beam-like ions (direct kinematics) with PRISMA, coincident gamma with CLARA/AGATA





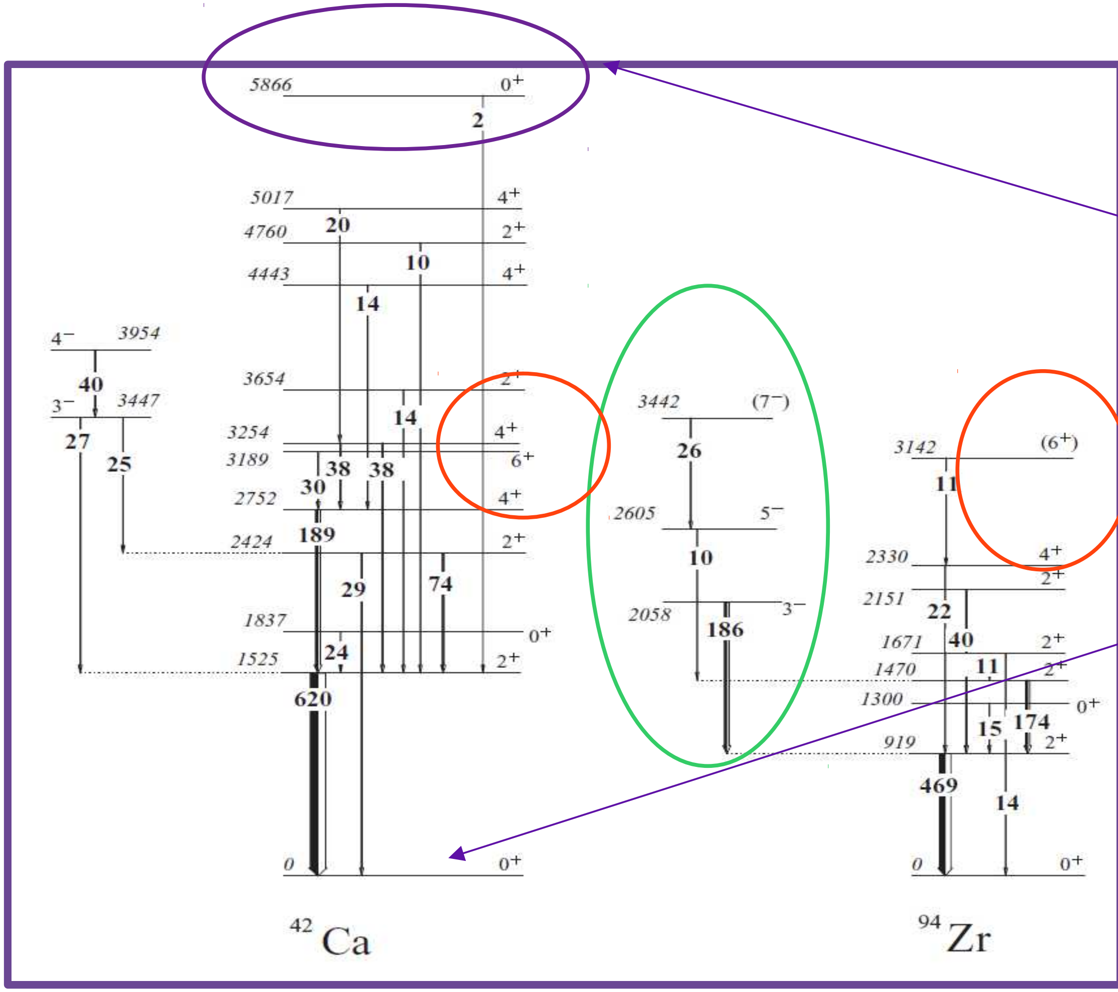
$^{60}Ni+^{116}Sn$: angular distributions measurement:

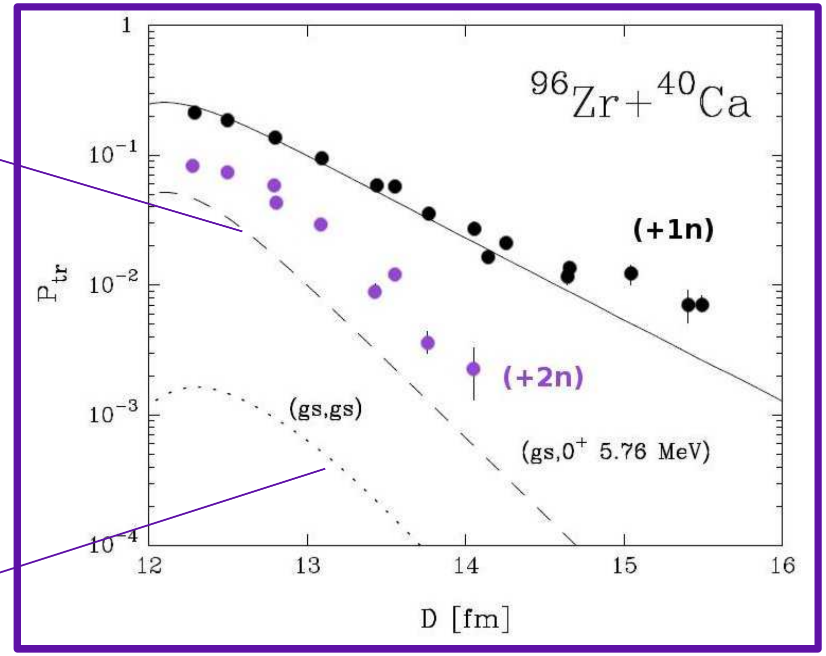
E_{beam} = 245 MeV at 70^0

(D ~ 14.5 fm)

AGATA demonstrator (four triple cluster modules): at 16.5 cm from the target covering angular range : 130^0 - 170^0
simulated full-absorption efficiency: 2.64% for 1.3 MeV

Coincident gamma spectra for ^{42}Ca (+2n) channel

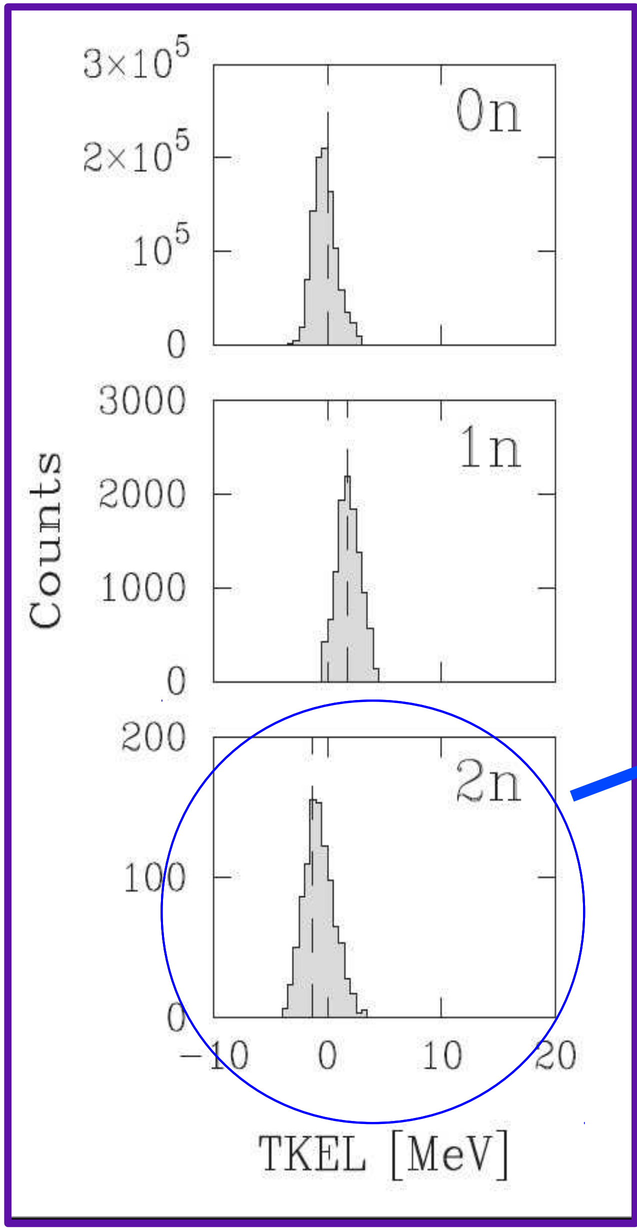


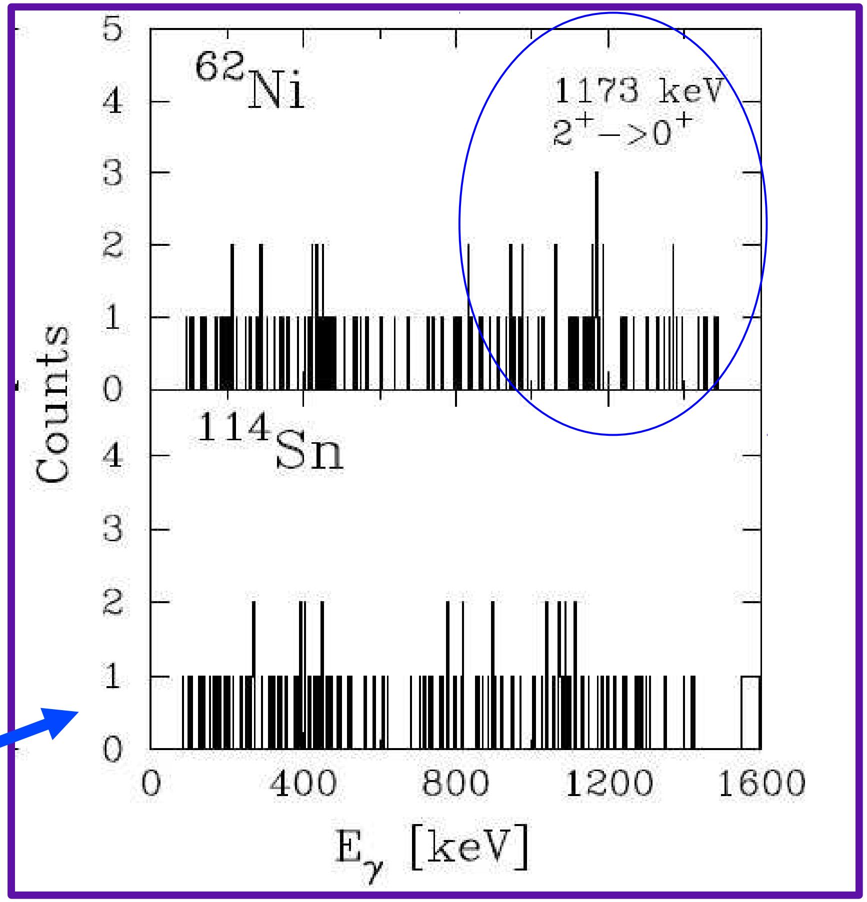


- ✓states with relatively high angular momentum
- ✓states with non-natural parity
- ✓comparison between experimental and theoretical transfer probabilities: the two-nucleon transfer reaction does not populate only 0+ states; more complicated two-particle correlations have to be taken into account.

L. Corradi et al., PRC 84 (2011) 034603

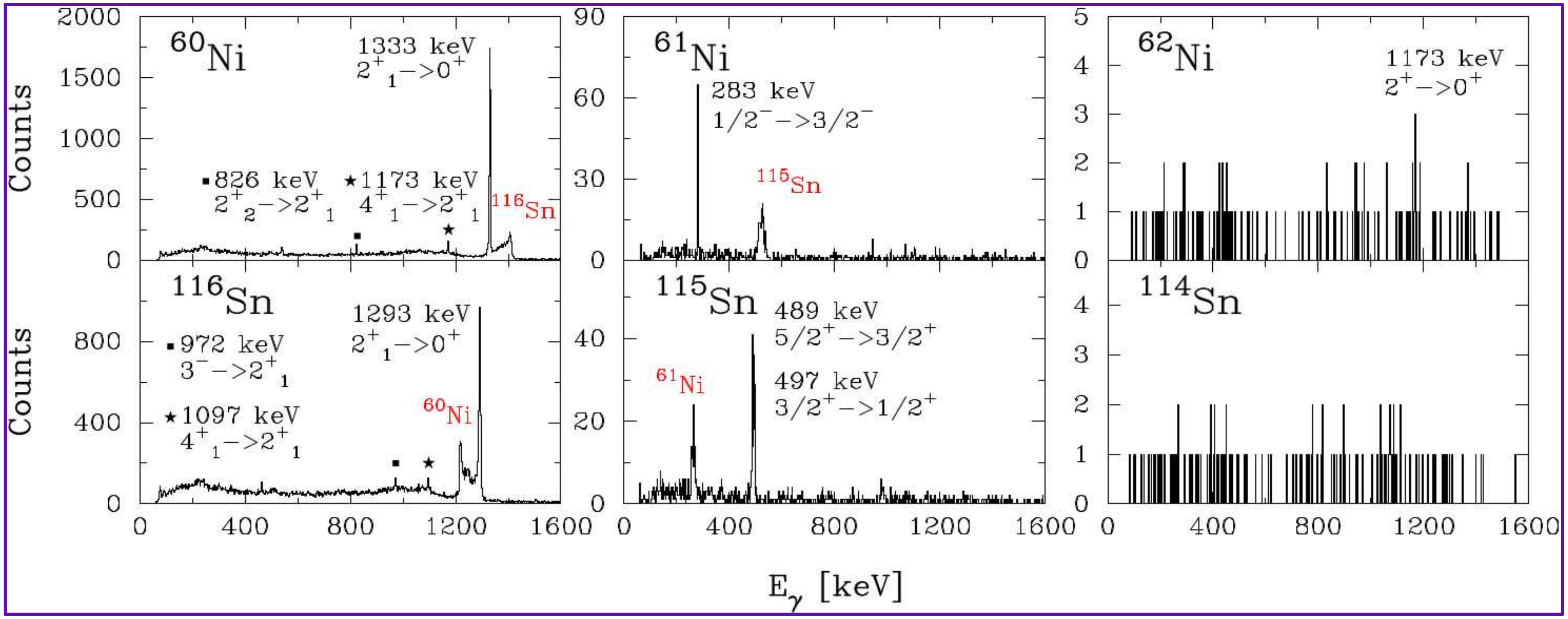
$^{60}Ni + ^{116}Sn \rightarrow ^{62}Ni + ^{114}Sn$ (2n channel)

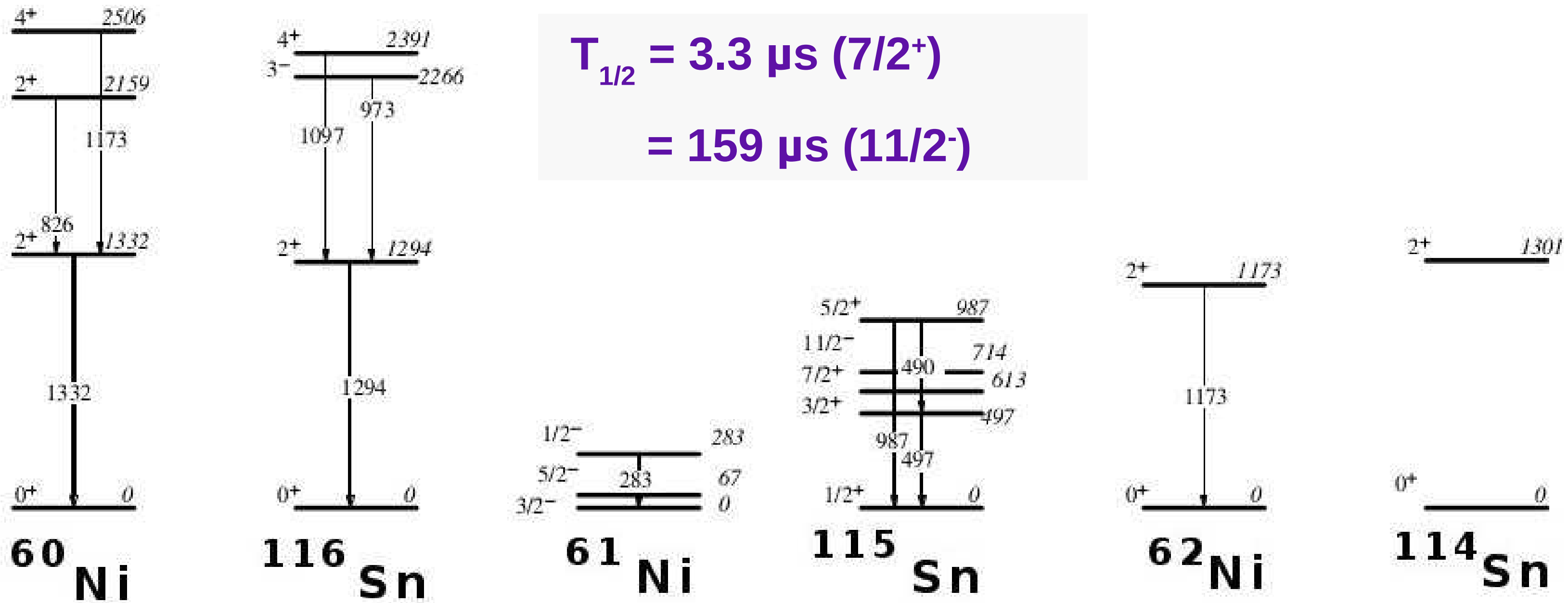




✓no gamma in ^{114}Sn, few gamma in ^{62}Ni compatibile with $2^+ \rightarrow 0^+$ transitions

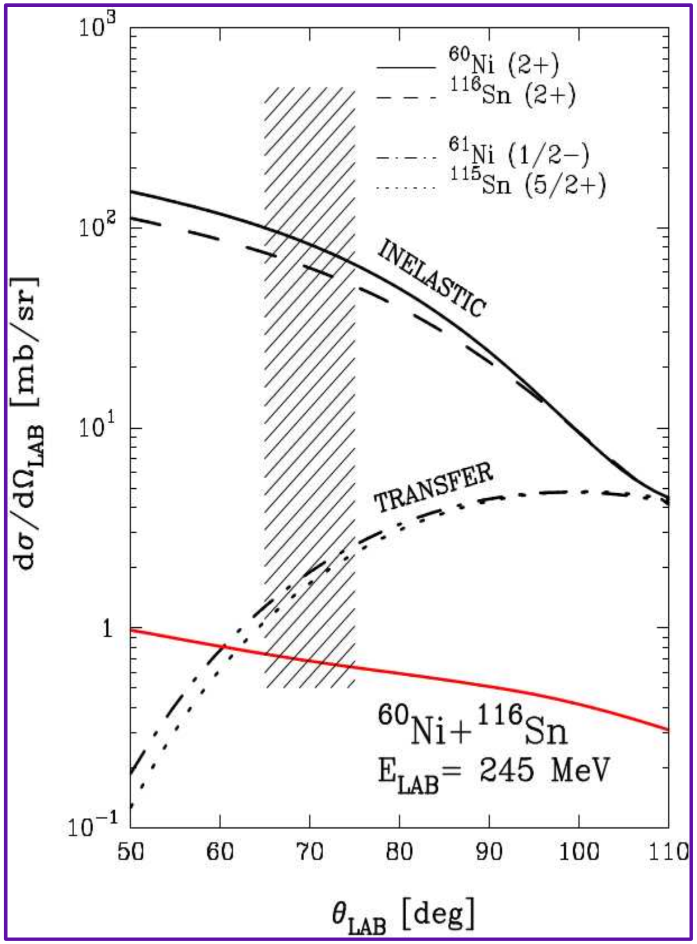
$^{60}Ni+^{116}Sn$: PRISMA+AGATA measurement





$T_{1/2}$ = 3.3 μs ($7/2^+$)

= 159 μs ($11/2^-$)



The strengths (normalized to $2^+ \rightarrow 0^+$ in ^{60}Ni) of the most important transitions, corrected for the contributions of the feeding and for their relative detection efficiency in AGATA.

	Experiment	Theory
$^{116}Sn(2^+)$	0.792 ± 0.160	0.720
$^{116}Sn(4_1^+)$	0.042 ± 0.011	0.056
$^{60}Ni(4_1^+)$	0.060 ± 0.013	0.11
$^{115}Sn(5/2^+)$	0.018 ± 0.003	0.037
$^{61}Ni(1/2^-)$	0.014 ± 0.003	0.033
$^{62}Ni(2^+)$	< 0.00145	-

- ✓the direct population of states can be compared with any reaction code
- ✓DWBA, coupled channels, tabulated deformations, spectroscopic factors
- ✓a direct check on the one-particle form factors (+1n), and of potential

INELASTIC:

^{60}Ni (2^+)

^{116}Sn (2^+)

TRANSFER:

^{61}Ni ($1/2^-$)

^{115}Sn ($5/2^+$)

Next step: to estimate the fraction of total cross section of the (2n) channel, ^{62}Ni, going into 2^+

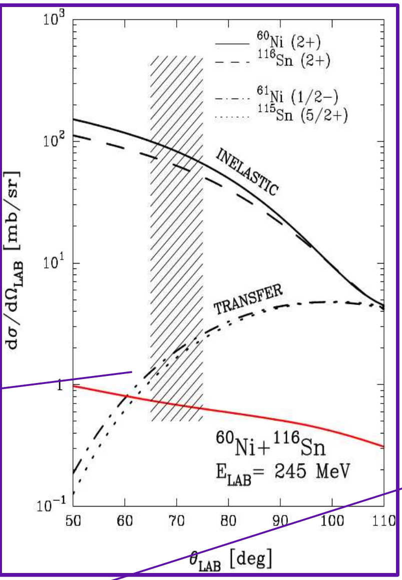
$$\sigma_R - \sigma_{el} = \sigma(2^+, {}^{60}\mathrm{Ni}) + \sigma(2^+, {}^{116}\mathrm{Sn})$$

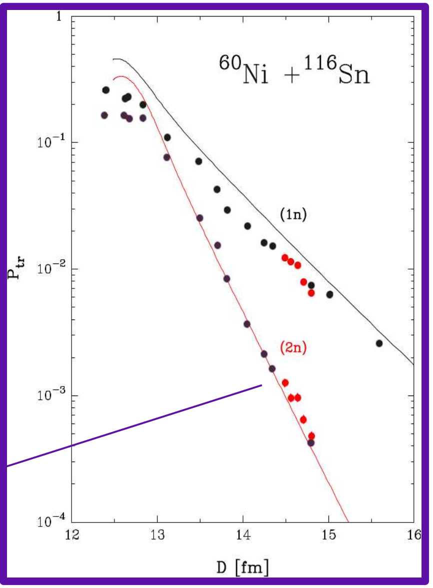
$$\sigma_R\left(1 - \frac{\sigma_{el}}{\sigma_R}\right) = \sigma(2^+, {}^{60}\mathrm{Ni})\left(1 + \frac{\sigma(2^+, {}^{116}\mathrm{Sn})}{\sigma(2^+, {}^{60}\mathrm{Ni})}\right)$$

$$\sigma_{el}/\sigma_R = 0.64$$

$$\sigma_{2n} = \sigma_R \; P_{2n} \qquad P_{2n} = 0.0012$$

$$\frac{\sigma_{2n}}{\sigma(2^+, {}^{60}\mathrm{Ni})} = 0.006$$

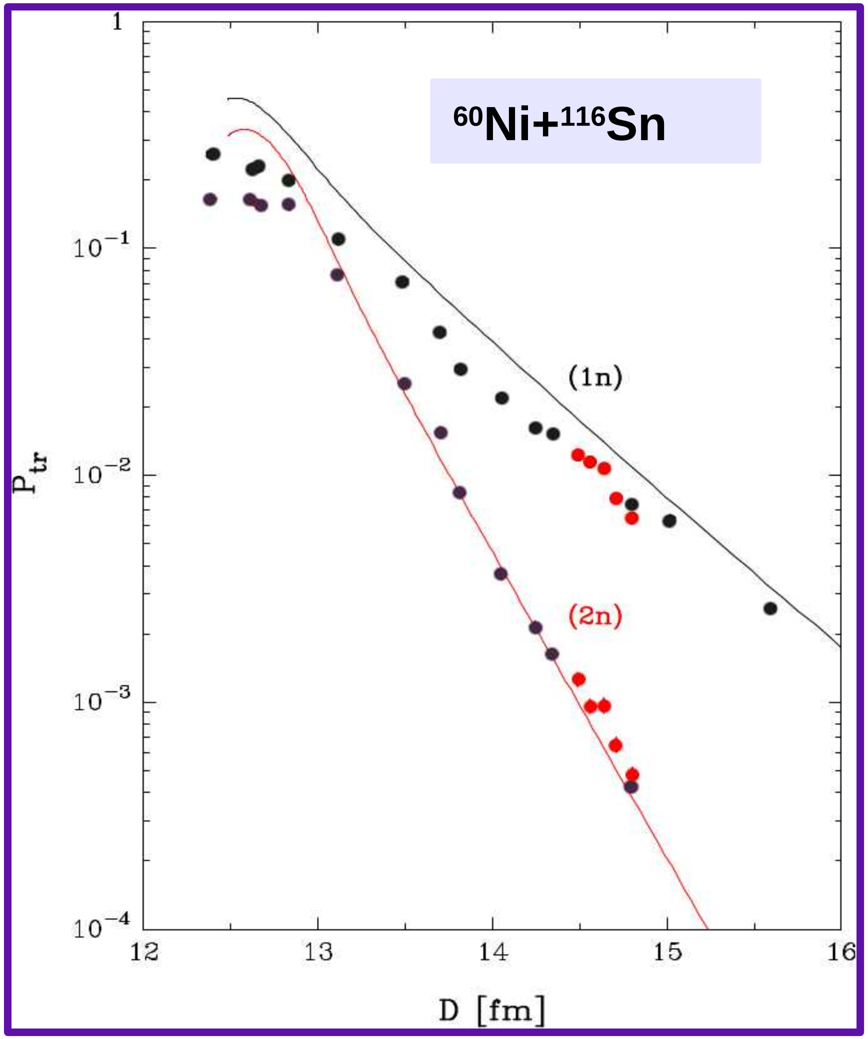




	Experiment	Theory
^{116}Sn(2^+)	0.792 ± 0.160	0.720
^{116}Sn(4_1^+)	0.042 ± 0.011	0.056
^{60}Ni(4_1^+)	0.060 ± 0.013	0.11
^{115}Sn($5/2^+$)	0.018 ± 0.003	0.037
^{61}Ni($1/2^-$)	0.014 ± 0.003	0.033
^{62}Ni(2^+)	< 0.00145	-

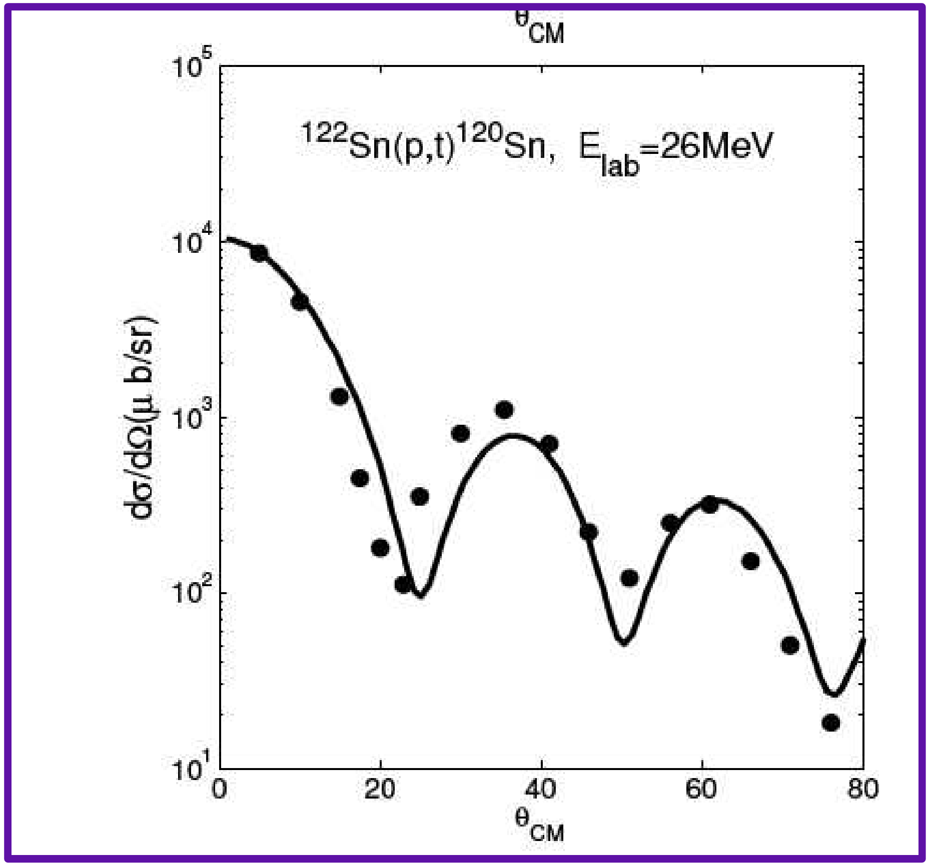
The transitions to the excited states in (2n) channels contribute to the total strength: <24%

Heavy ion transfer reactions



Transfer reactions with light nuclei

^{122}Sn(p,t)^{120}Sn



D. Montanari et. al., PRL 113 (2014) 052501

D. Montanari et. al., PRC 93 (2016) 054623

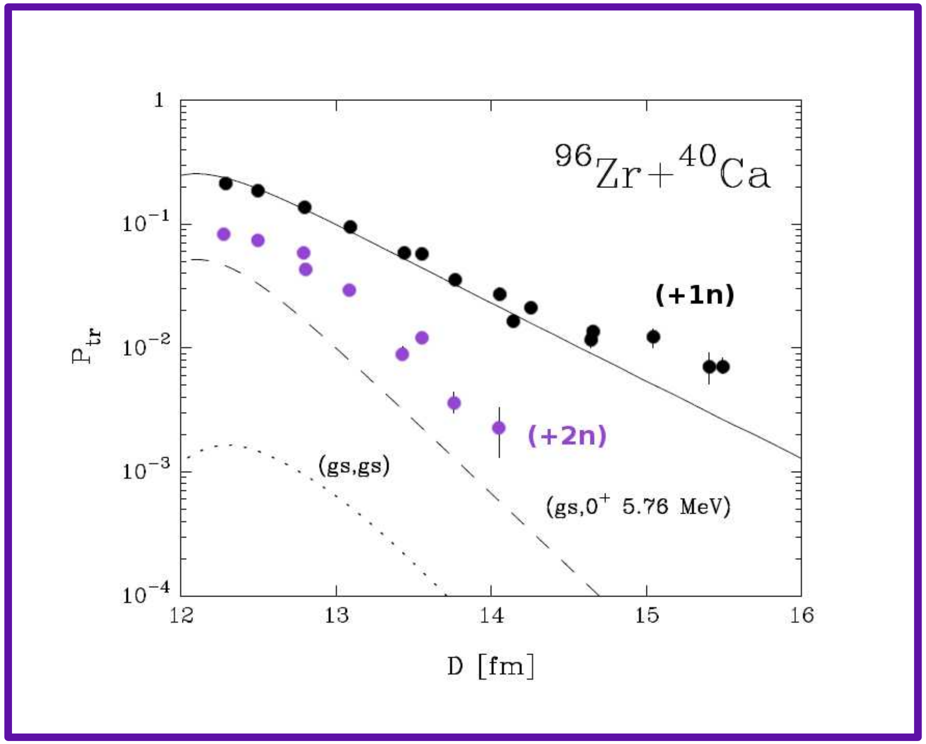
G. Potel et al, Reports on Progress in Phy. 76 (2013) 106301

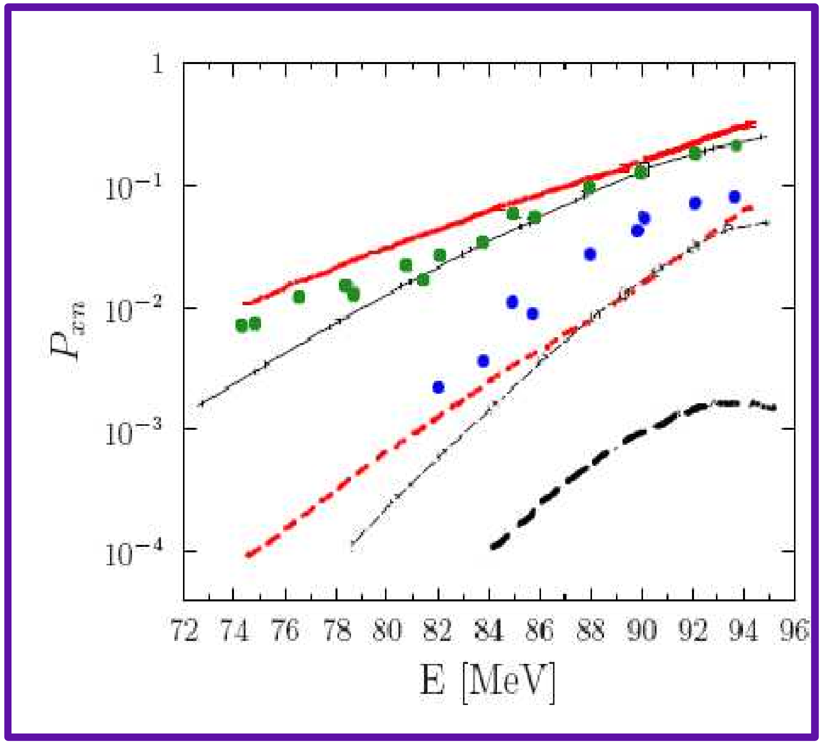
$$D = \frac{Z_a Z_A e^2}{2E_{c.m.}}\left(1 + \frac{1}{\sin(\theta_{c.m.}/2)}\right)$$

Sub-barrier transfer : TDHF or TDHF+BCS

$^{40}Ca+^{96}Zr$

______(2n) TDHF+BCS
- - - - - -(1n) TDHF+BCS





EXP (1n) and (2n);
(1n) c.c.; (2n) (g.s. →g.s.)
(g.s. → 0+ at ~6MeV)

L. Corradi et. al., PRC 84 (2011) 034603

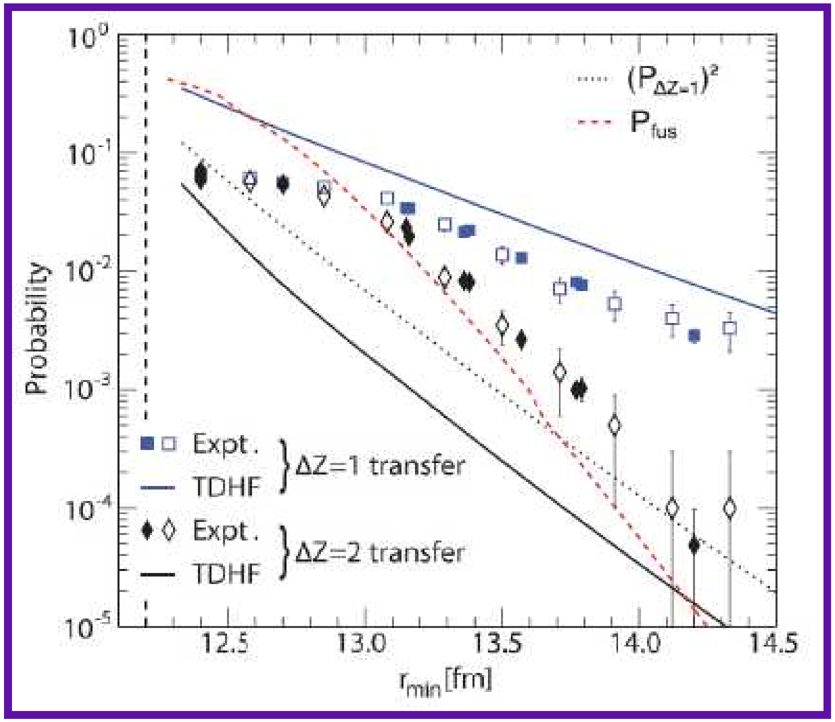
G.Scamps et al., EPJ Web Conf. 86 (2015) 00042

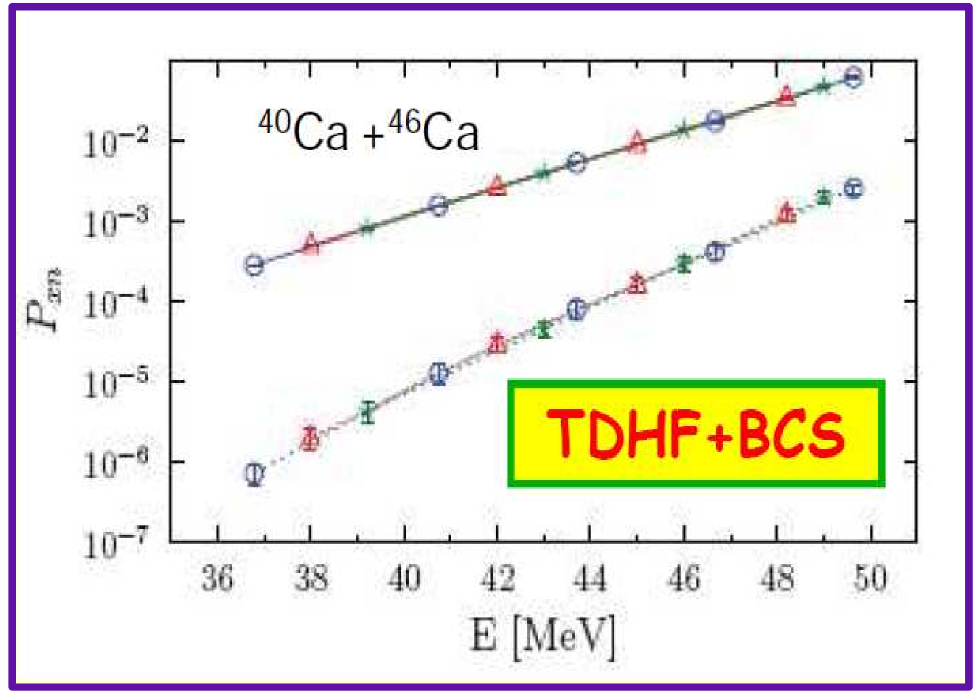
Sub-barrier transfer : TDHF or TDHF+BCS

$^{16}O+^{208}Pb$

______(2n) TDHF
- - - - - -(1n) TDHF

$^{40}Ca+^{46}Ca$





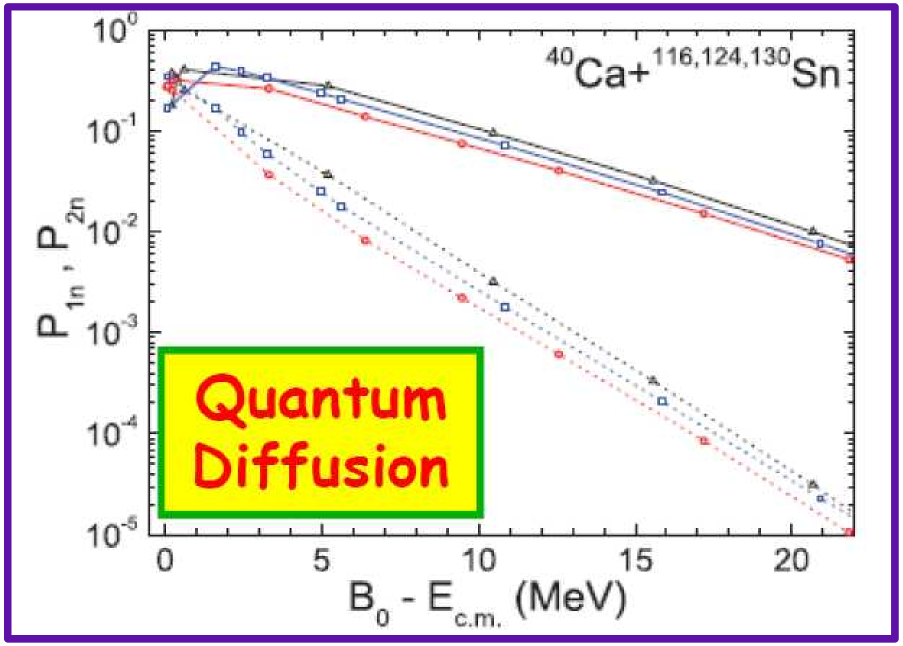
C.Simenel, PRL105(2010)192701

M.Evers et al, PRC84(2011)054614

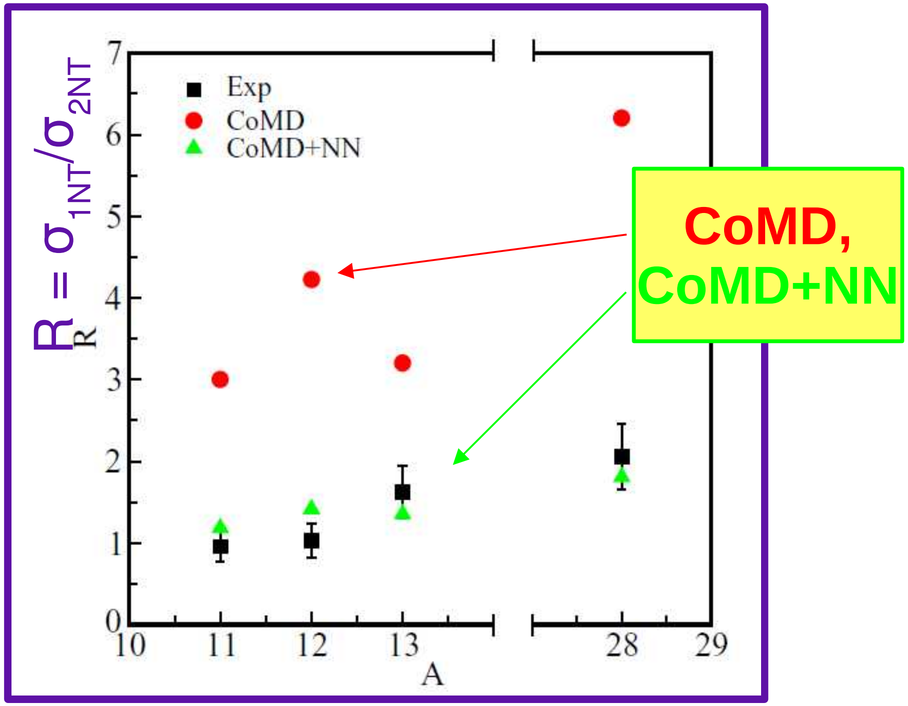
G.Scamps and D.Lacroix, PRC87(2013)014605

One- and two-neutron transfer

$^{40}Ca+^{116,124,130}Sn$



$^{18}O+^{28}Si$, $^{18}O+^{11}B$, $^{18}O+^{12,13}C$



calculations: constrained molecular dynamics
exp: MAGNEX

V.V.Sargsyan et al., Phy. Rev. C 88 (2013) 064601

C. Agodi et al., Phys. Rev. C 97, 034616 (2018)

Summary

✓The comparison between data and theory: elementary modes of the complex mechanism can be probed.

✓"large" spectrometers coupled to "large" gamma arrays are powerful tools to study the correlations.

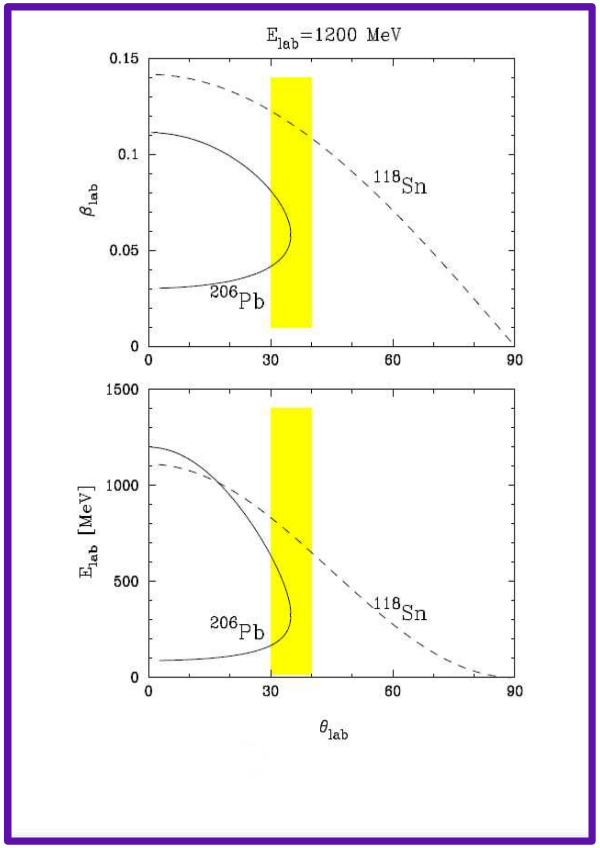
✓Sub-barrier transfer reaction measurement (nuclei interact at large distances): good probe for pair correlations

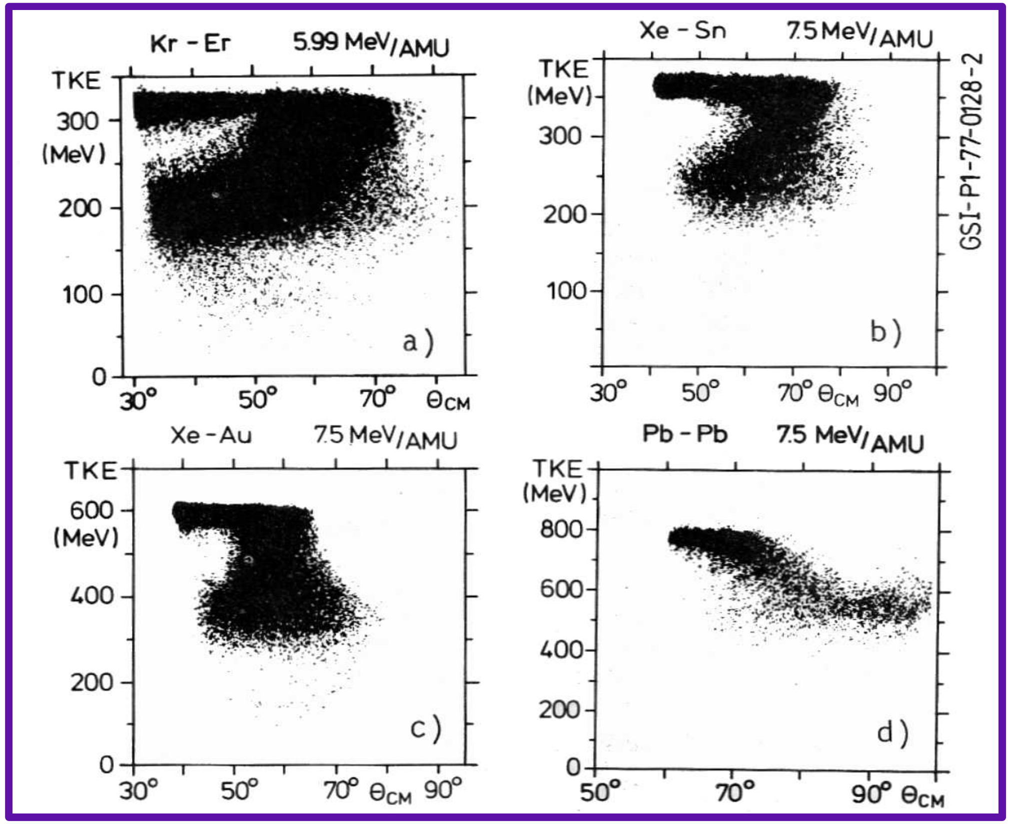
✓The information about correlations are extracted when experimental **absolute** cross sections are compared with a microscopic theory which beside correlations includes also the coupling between relative motion (reaction) and intrinsic motion (structure).

Outlook

➔very heavy systems
➔proton transfer channels at large D
➔(np) correlations

Nucleon-nucleon pairing correlations probed in the $^{206}Pb+^{118}Sn$



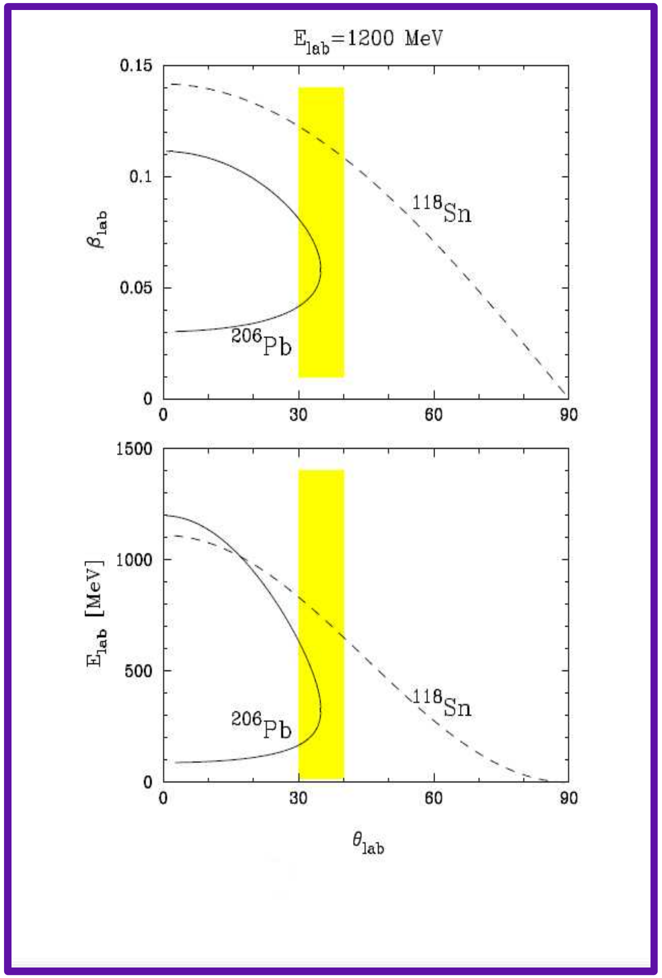


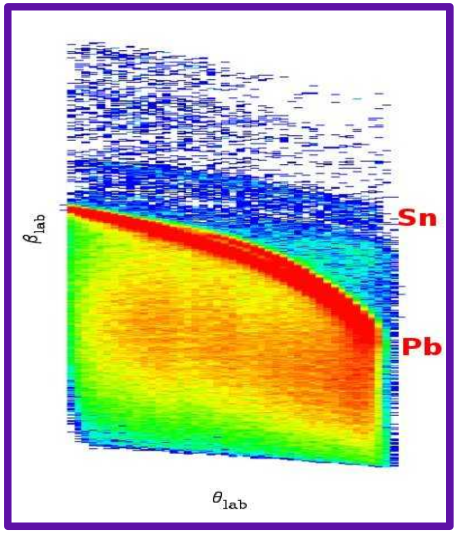
in the collision between **very heavy ions,** population of final states with high excitation and angular momenta may significantly change the transfer strength for the g.s. to g.s. transitions.

“**Q-value matching**”: the heavy semi-magic combination with closed proton shells and open neutron shells and the g.s. to g.s. Q-values close to Q-optimum

whether and to what extent **the effect of neutron-neutron correlations** in the evolution of the reaction is modified in the presence of **high Coulomb fields.**

Kinematics of ^{206}Pb+ ^{118}Sn



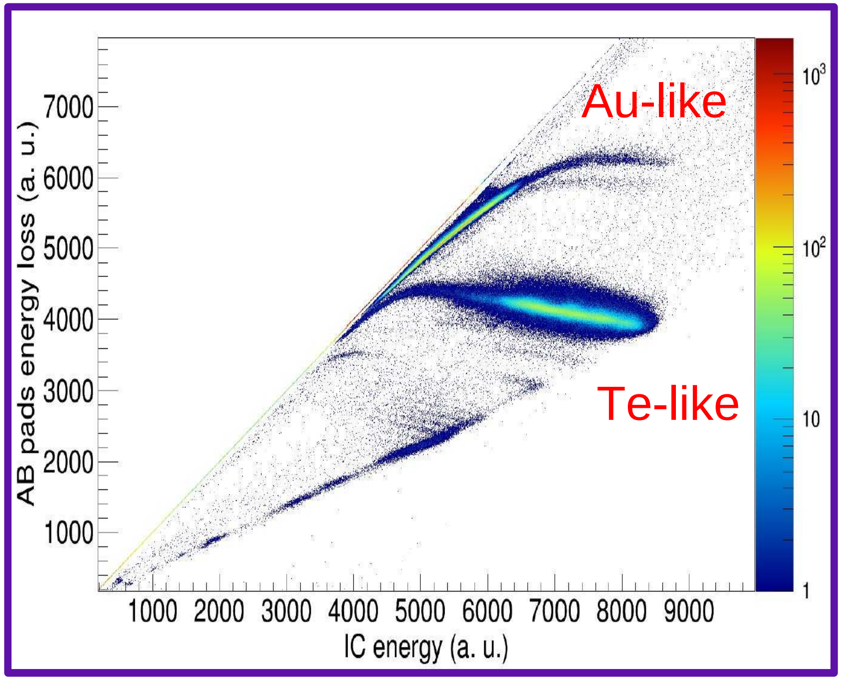


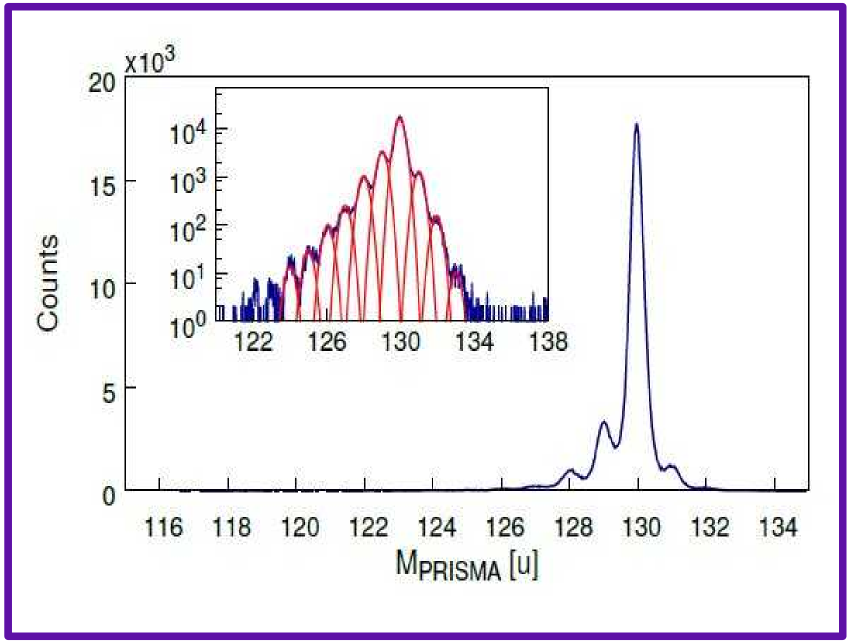
$\theta_{lab}=35^o$ is close to the limiting angle for Pb-like ions, so one can safely control the correct geometry of the experiment

With PRISMA at $\theta_{lab}=35^o$ Sn-like ions have kinetic energies ~ 750 MeV at E_{lab}=1200 MeV, so one expects good A,Z resolutions

INFN – LNL, PRISMA spectrometer, February, 2018, L. Corradi, S. Szilner: Nucleon-nucleon pairing correlations probed in the 206Pb+118Sn transfer reaction at far sub-barrier energies

The $^{197}Au+^{130}Te$ multinucleon transfer reaction: Te-like in PRISMA



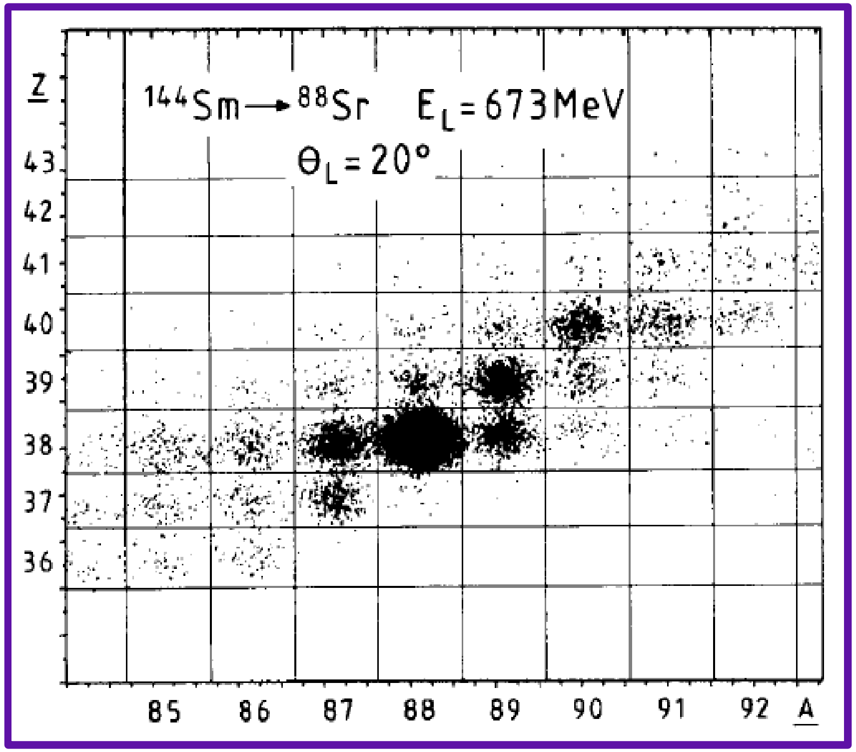


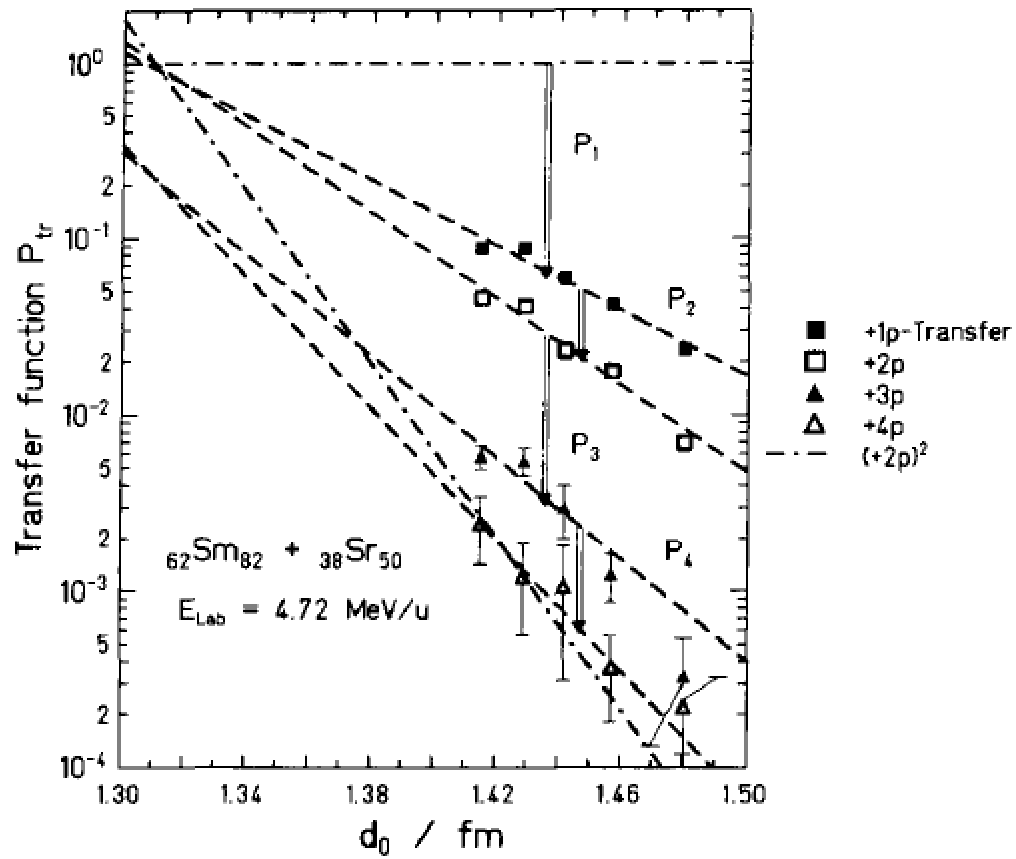
$^{197}Au+^{130}Te$ at $E(^{197}Au)=1097$ MeV, $\theta_{PRISMA}=37^{O}$

Mass distribution for the Te isotopes obtained after ion trajectory reconstruction in PRISMA.

The mass-mass correlations in multinucleon transfer reaction
F. Galtarossa et al., Phys. Rev. C 97 (2018) 054606
A gas detection system for fragment identication in low-energy heavy-ion collisions
E. Fioretto et al. NIM A, in press

Sub-barrier transfer : proton channels





Few data are available, but for small D's, where absorption plays an important role, the analysis done via the interpretation of the enhancement factors at the phenomenological level

R.Kunkel et al., PLB 208 (1988) 355

The proton transfer processes in a heavy-ion collisions are much less understood (large modification in the trajectories of entrance and exit channels are involved due to the modification of the Coulomb field).
The single-particle level density for protons is less studied and the corresponding single-particle form factors are less known (even the one-proton transfer cross sections are not very well described in the DWBA).

L. Corradi, G. Pollarolo, D. Montanari, F. Galtarossa, T. Mijatović, A. Goasduff, E. Fioretto, D. Mengoni, M. Milin, G. Montagnoli, F. Scarlassara, A.M. Stefanini, C.A. Ur, J.J. Valiente-Dobon, P. Čolović, D. Jelavić Malenica, N. Soić and CLARA-AGATA collaboration

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Kokopelli: links distant and diverse communities together.