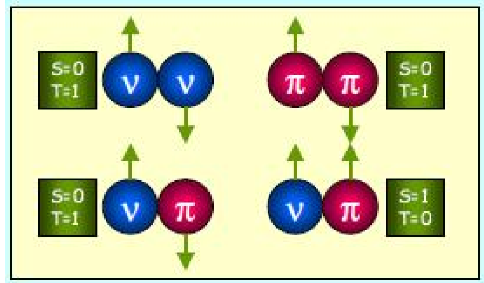
Probing nucleon-nucleon correlations in heavy ion transfer reactions

Suzana Szilner
Ruđer Bošković Institute
Zagreb, Croatia

PRISMA collaboration



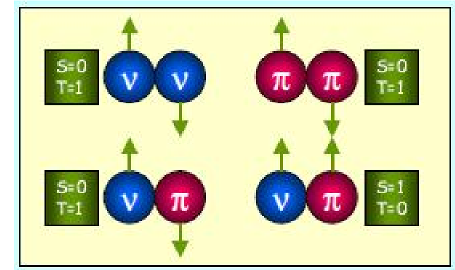
Venezia

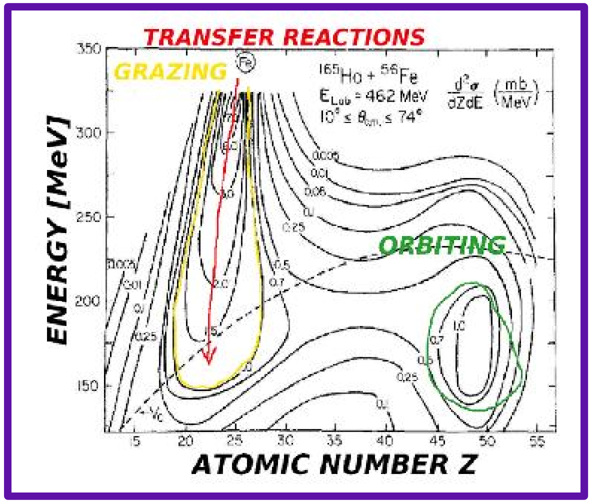
Zagreb

NUSPIN 2016 Workshop of the Nuclear Spectroscopy Instrumentation Network and AGATA Physics Workshop

from 27 June 2016 to 01 July 2016 (Europe/Rome) *San Servolo, Venice*

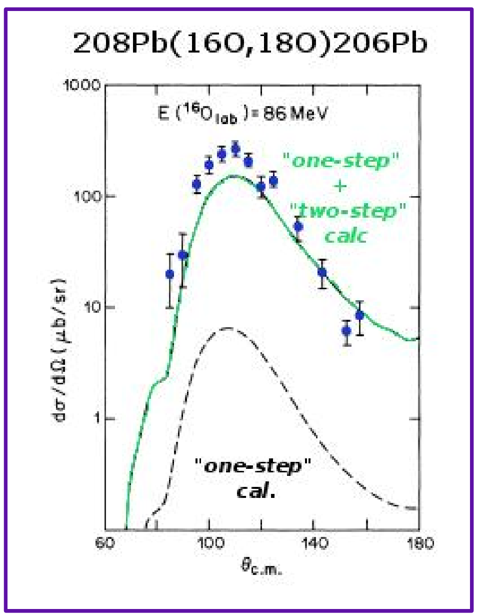
Probing correlations





How the correlations that go beyond a mean field description 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.



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

The 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,
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)

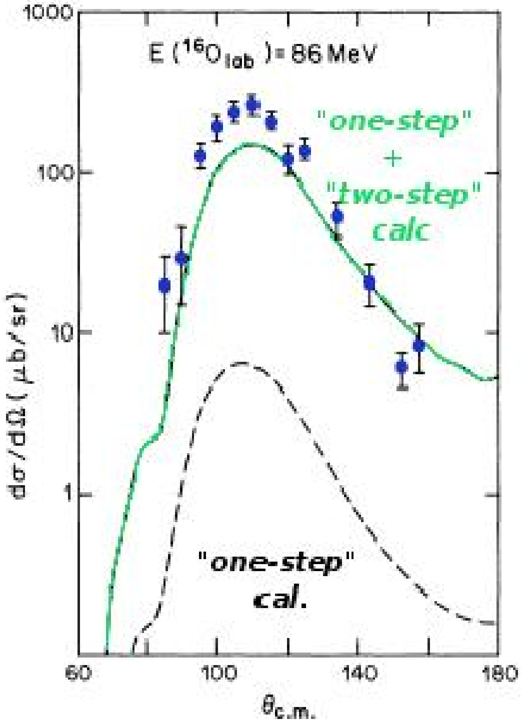
Absolute cross sections for one and two-nucleon transfer reactions

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

______ successive+simultaneous
- - - - - -simultaneous

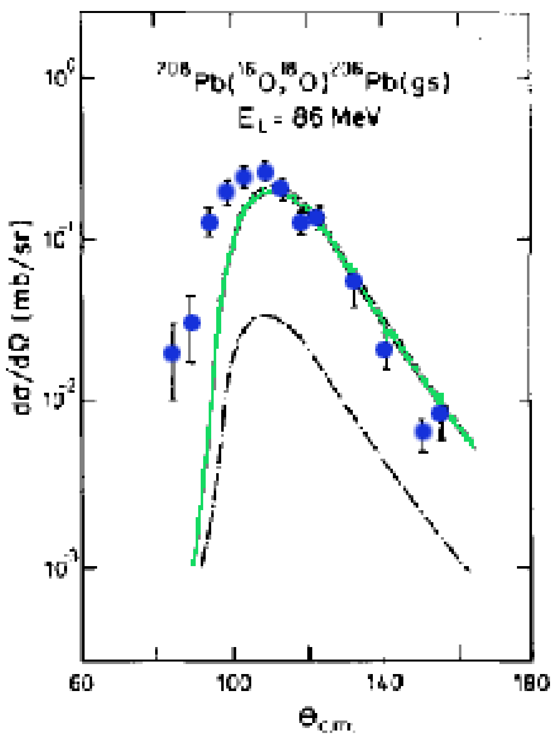
the information about correlations are extracted when experimental absolute cross sections are compared with the microscopic theory which beside correlations includes also the coupling between relative motion (reaction) and intrinsic motion (structure).

full quantum-mechanical



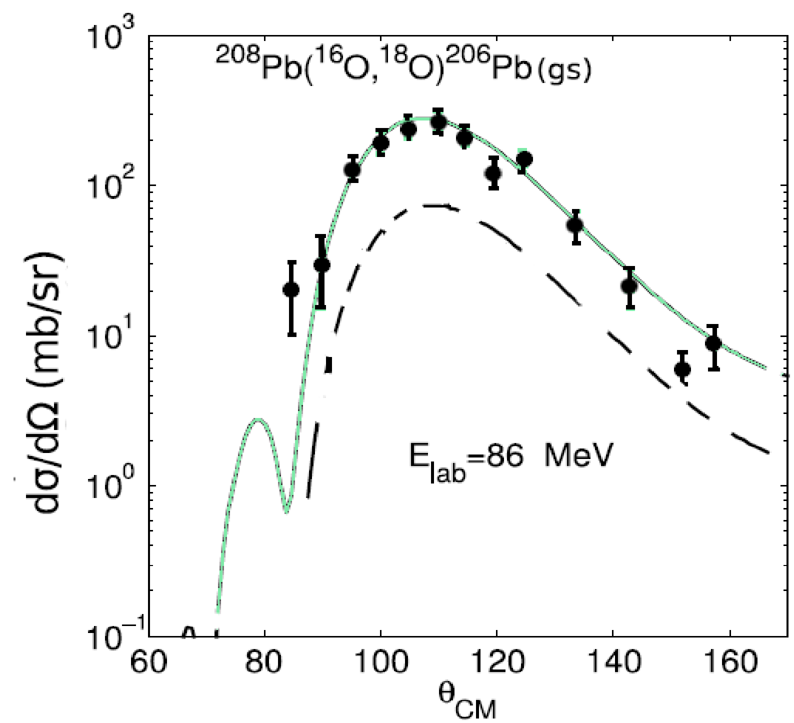
B.F.Bayman and J.Chen, Phys. Rev. C 26 (1982) 1509

semi-classical



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

full quantum-mechanical

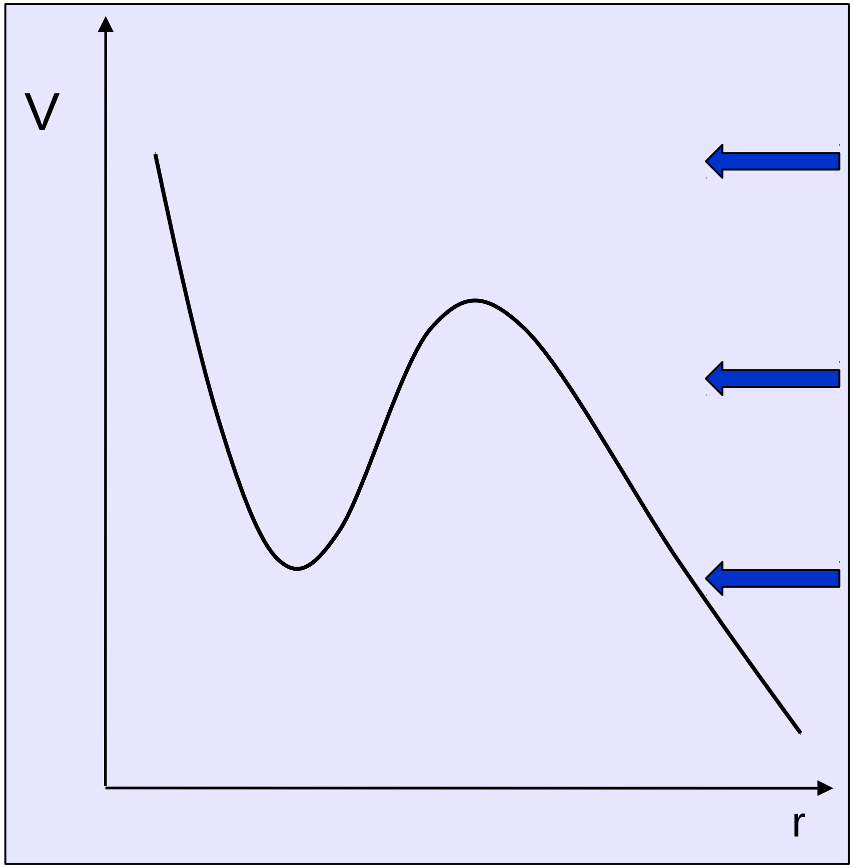


G.Potel, A.Idini, F.Barranco, E.Vigezzi and R.A.Broglia, Rep. Prog. Phys. 76 (2013) 106301;

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

Measurements below Coulomb barrier

A smooth transition between QE and DIC



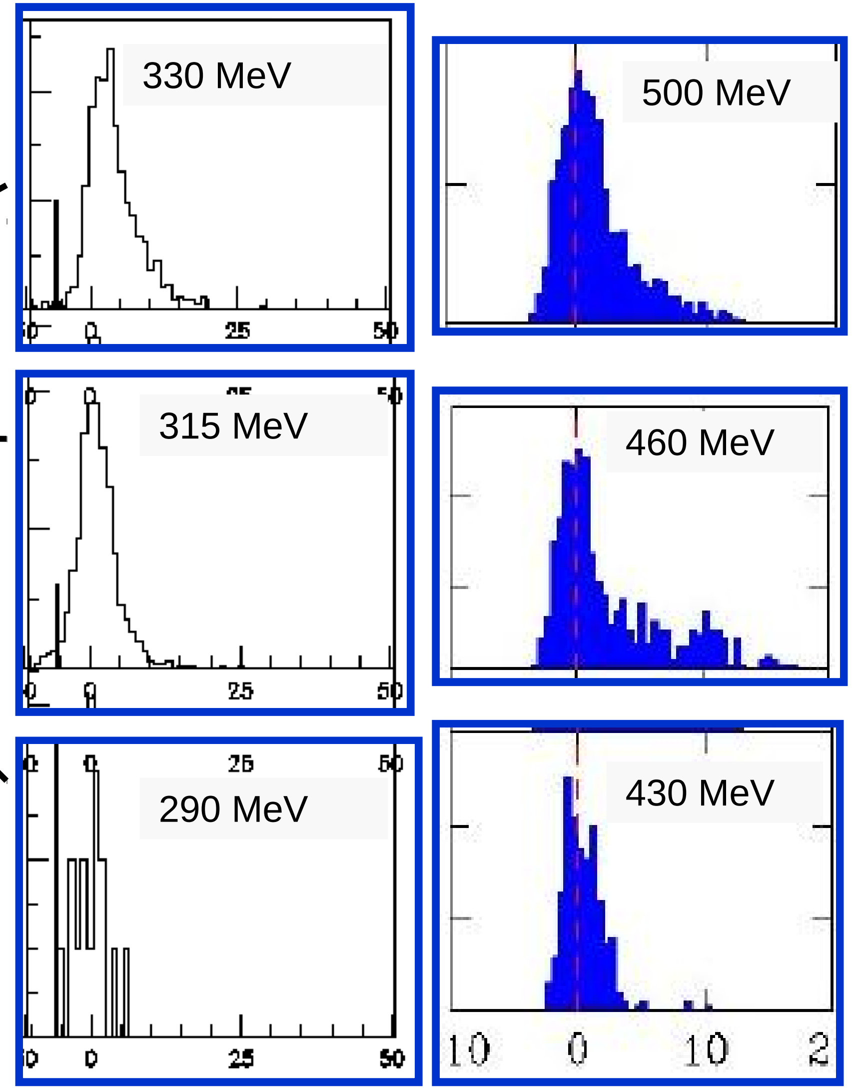
$E > E_b$

$E \sim E_b$

$E < E_b$

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

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



Below the barrier Q-values gets 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

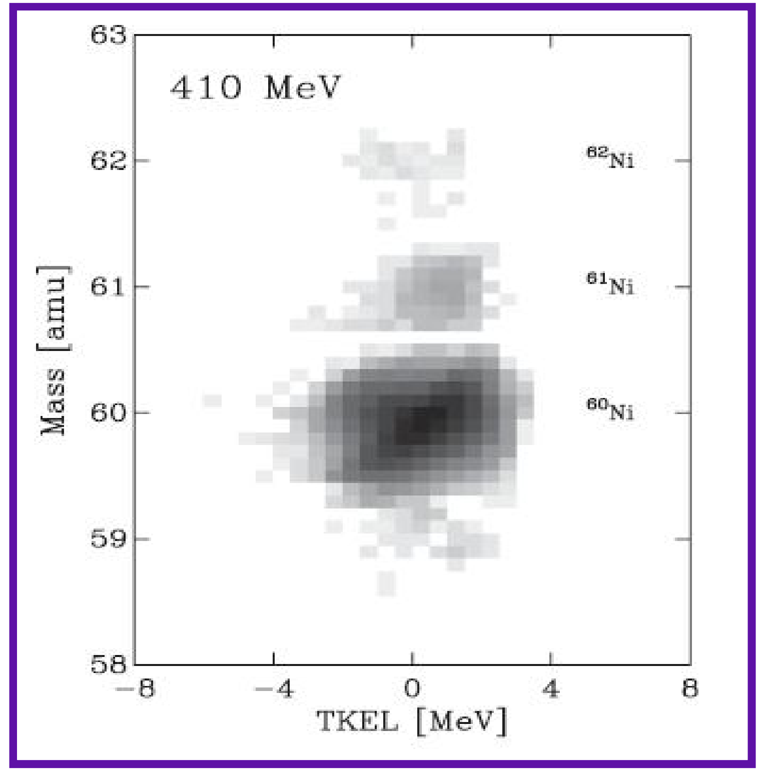
D. Montanari et. al., PRC 93 (2016) 054623

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

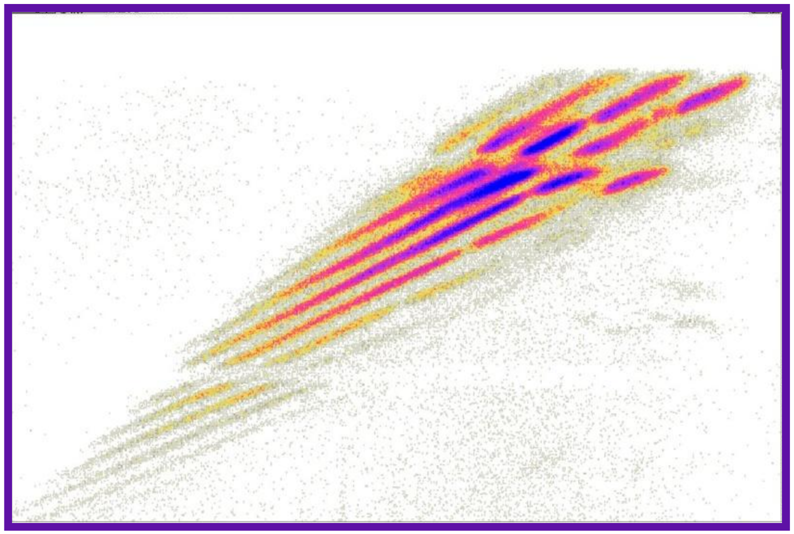
excitation function:

E_{beam} = 410 MeV – 500 MeV

(D ~ 12.3 to 15.0 fm)

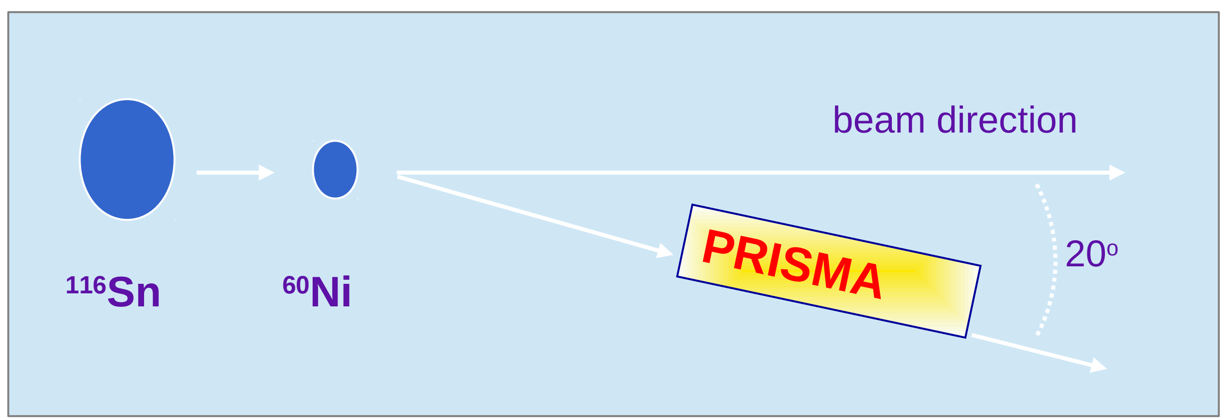


Rv [a.u.]



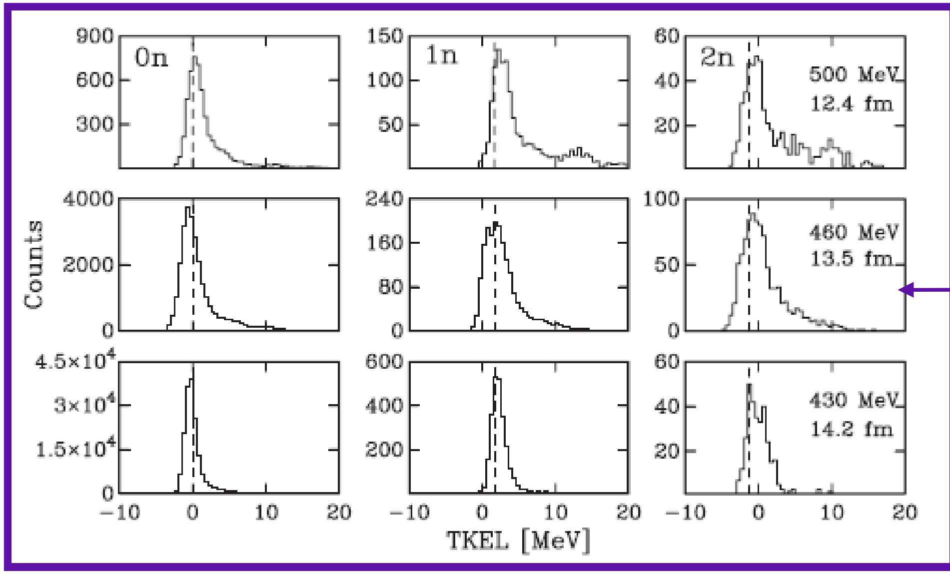
Energy [a.u.]

excellent channel separation at D ~ 15 fm

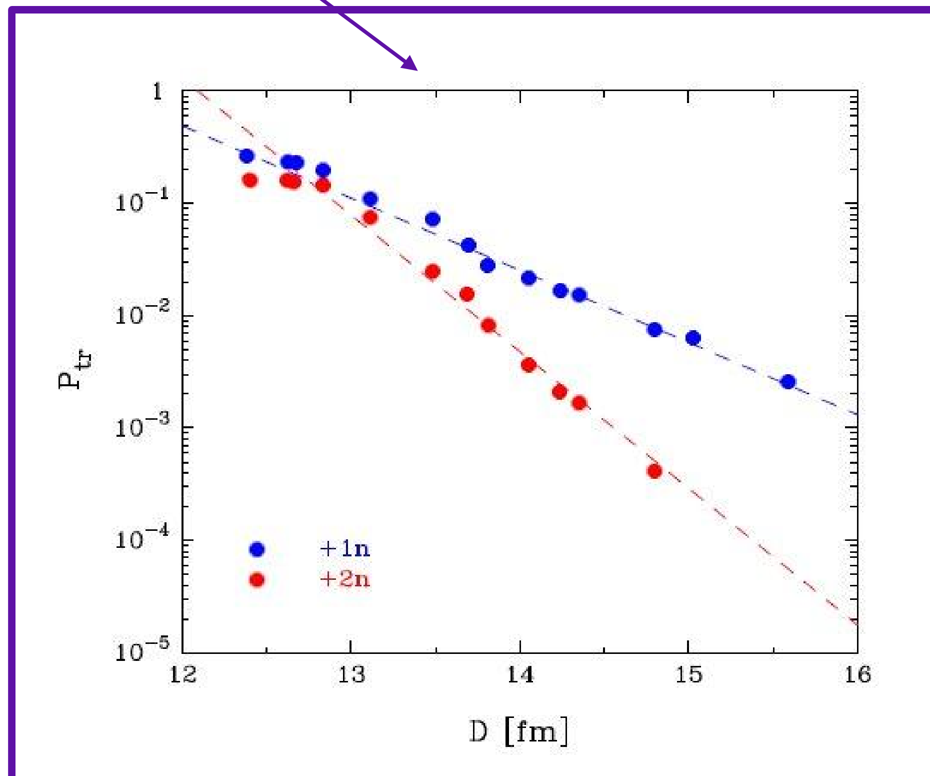


$^{116}Sn+^{60}Ni$: neutron pair transfer far below the Coulomb barrier

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



Coulomb barrier



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

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

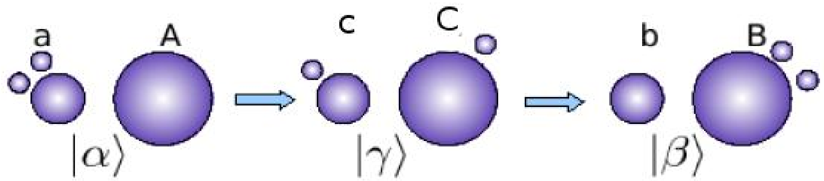
$$D = \frac{Z_a Z_A e^2}{2E_{\mathrm{c.m.}}}\left(1 + \frac{1}{\sin(\theta_{\mathrm{c.m.}}/2)}\right)$$

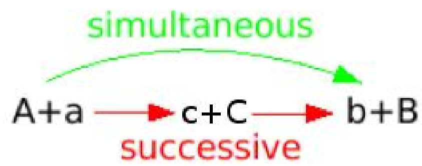
P_{tr} slope

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

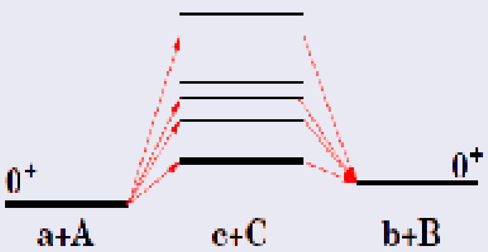
B $\rightarrow$ binding energy

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





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



	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

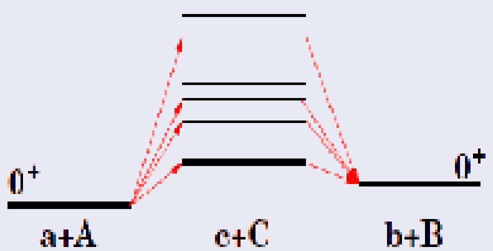
only the successive term contributes to the transfer amplitude (simultaneous component is canceled out by the nonorthogonality correction)

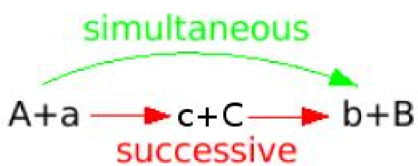
Only 0+ to 0+ transitions are included (BCS).

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

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

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

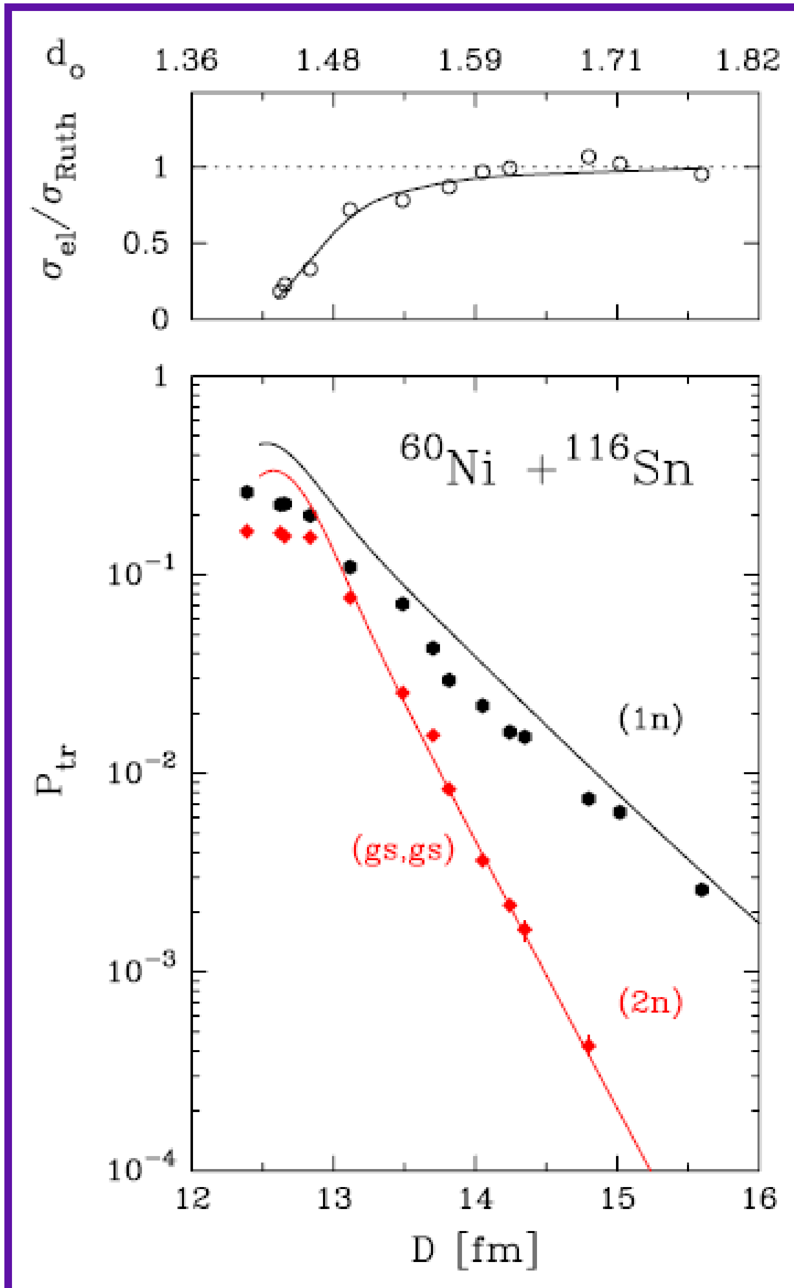




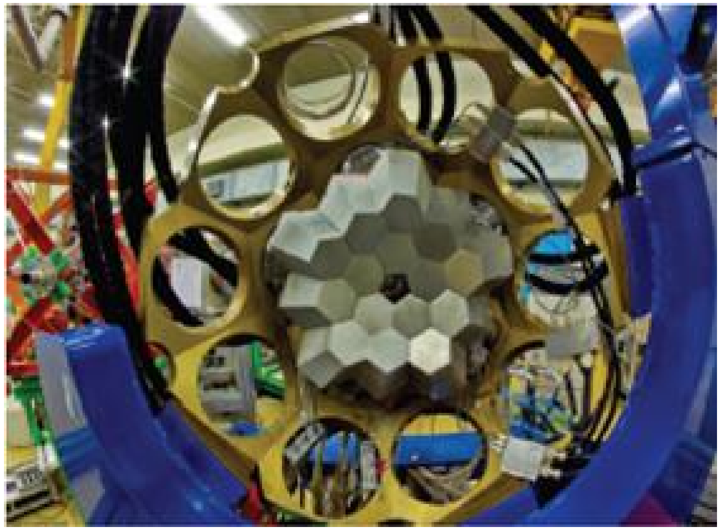
The experimental transfer probabilities are well reproduced, for the first time with heavy ion reactions, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon correlations:

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

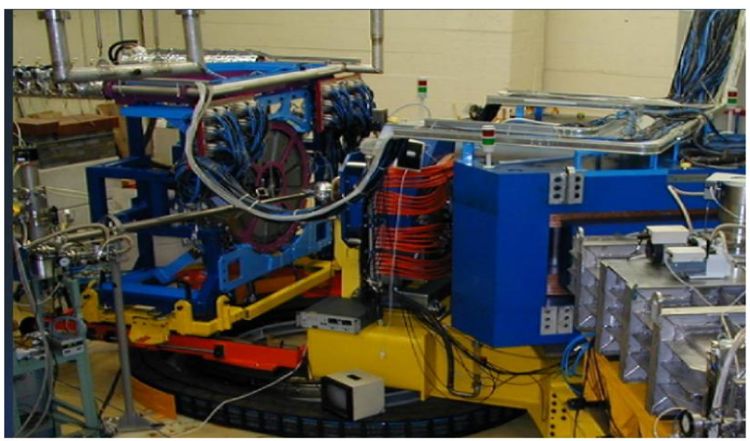
✓ the formalism for (2n) incorporates the contribution from both the simultaneous and successive terms (only the ground-to-ground-state transition has been calculated)

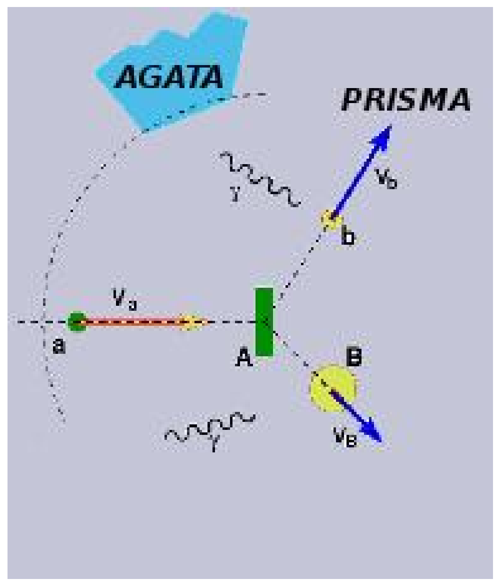


$^{60}Ni+^{116}Sn$: PRISMA+AGATA measurement



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





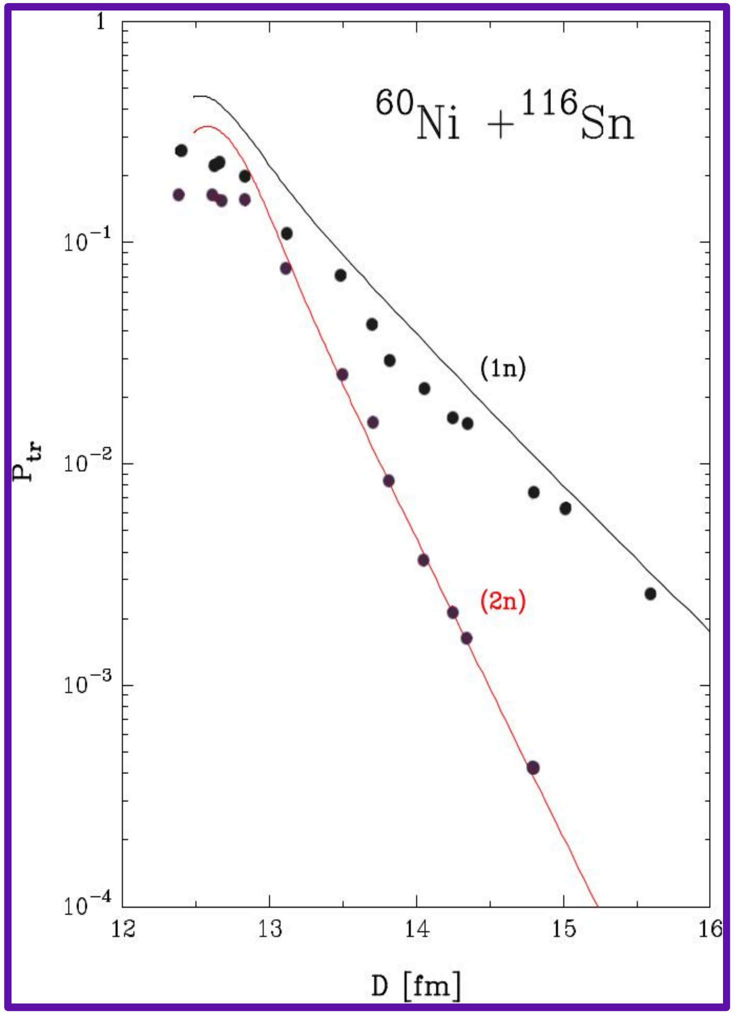
$^{60}Ni+^{116}Sn$: detection of beam-like ions (direct kinematics) with PRISMA, coincident gamma with AGATA

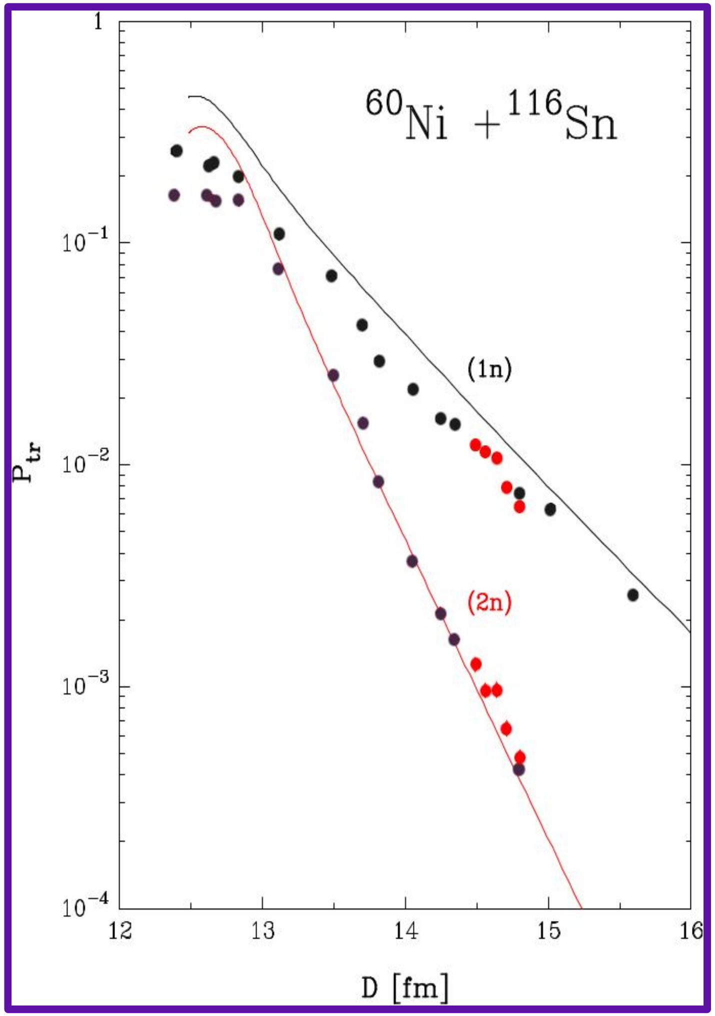
Angular distributions:

E_{beam} = 245 MeV at 70^0

(D ~ 14.5 fm)

Transfer probabilities





A consistent matching of the two experiments:

PRISMA (exc. function)

PRISMA+AGATA (angular dis.)

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

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

excitation function:

E_{beam} = 410 MeV – 500 MeV

(D ~ 12.3 to 15.0 fm)

angular distributions:

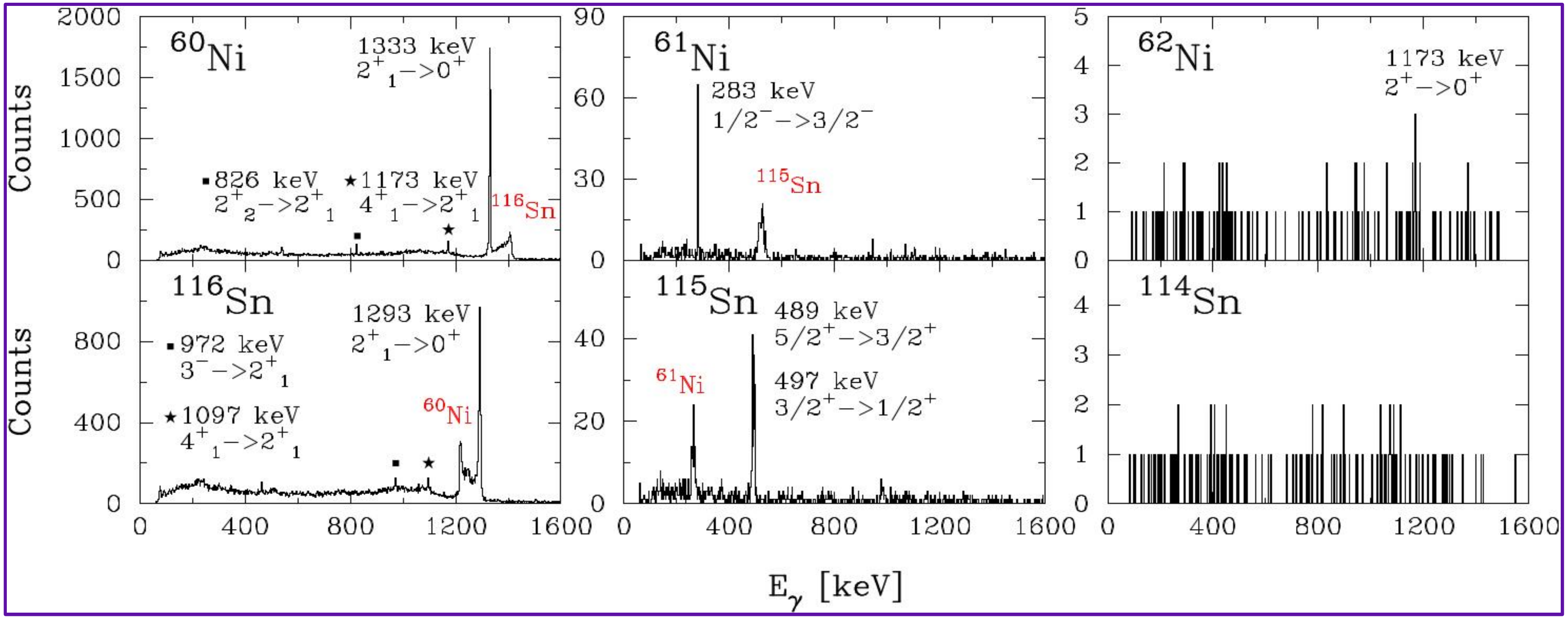
E_{beam} = 245 MeV at 70^0

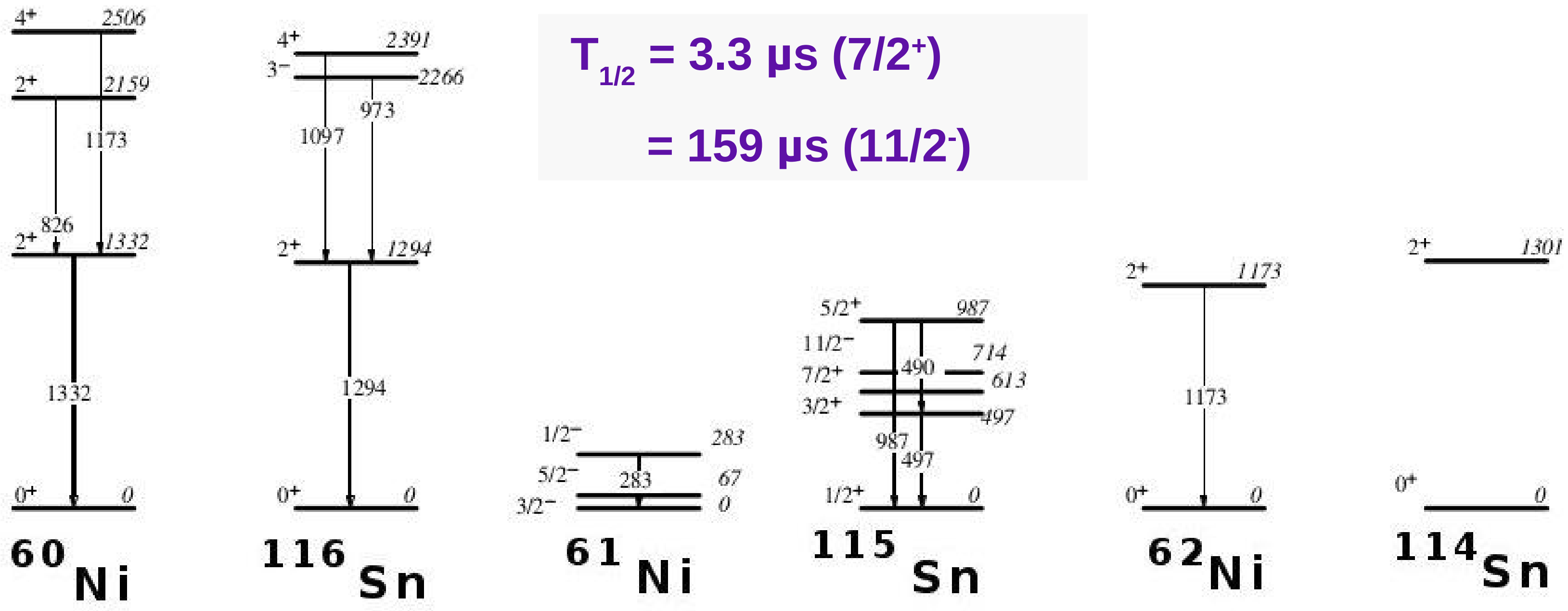
(D ~ 14.5 fm)

PRISMA

PRISMA+AGATA

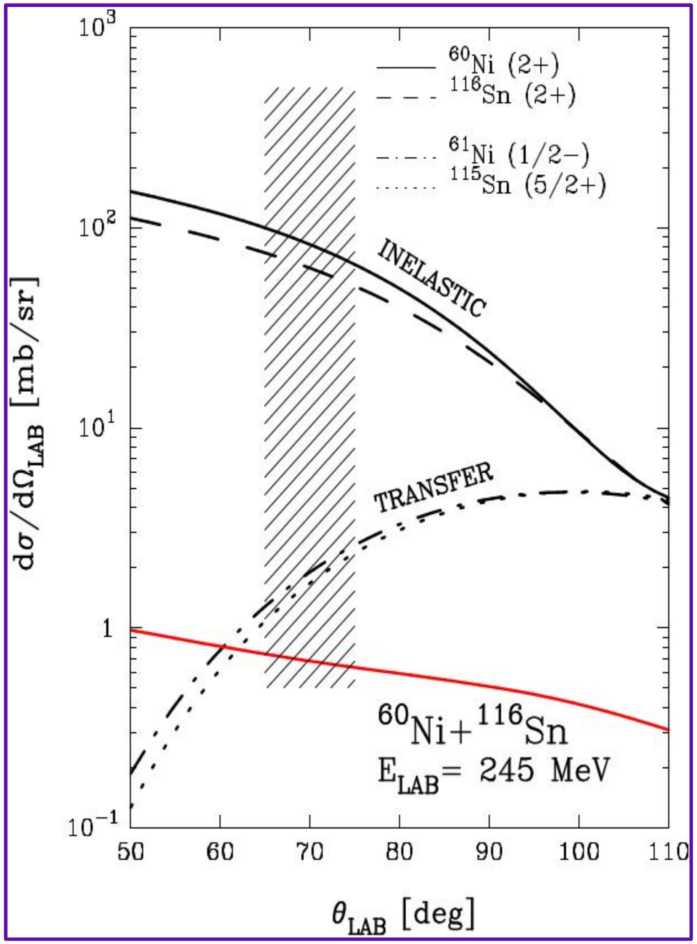
^{60}Ni+^{116}Sn: PRISMA+AGATA measurement





$T_{1/2}$ = 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:

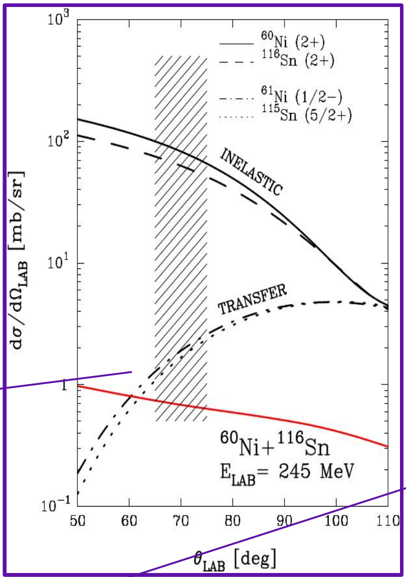
^{61}Ni ($1/2^-$)

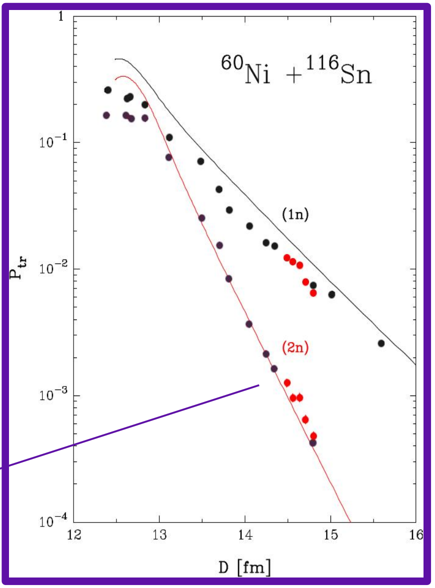
^{115}Sn ($5/2^+$)

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%

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 the microscopic theory which beside correlations includes also the coupling between relative motion (reaction) and intrinsic motion (structure).

OUTLOOK:

➔very heavy systems ($^{206}Pb(^{118}Sn,^{118+X}Sn)^{206-X}Pb$ transfer reaction at far sub-barrier en.)

➔proton transfer channels at large D

➔(np) correlations (Probing nucleon-nucleon correlations at sub-barrier energies in ^{92}Mo+^{54}Fe)

D. Montanari, L. Corradi, G. Pollarolo, T. Mijatović, A. Goasduff,
E. Fioretto, G. Montagnoli, F. Scarlassara, A.M. Stefanini, C.A. Ur, J.J. Valiente-Dobon,
D. Bazzacco, A. Gadea, C. Michelagnoli, O. Stezowski, P. Čolović, D. Jelavić Malenica, N. Soić, M. Varga Pajtler and AGATA collaboration

D. Montanari,[1,*] L. Corradi,[2] S. Szilner,[3] G. Pollarolo,[4] A. Goasduff,[2] T. Mijatović,[3] D. Bazzacco,[1] B. Birkenbach,[5] A. Bracco,[6] L. Charles,[7] S. Courtin,[7] P. Désesquelles,[8] E. Fioretto,[2] A. Gadea,[9] A. Görgen,[10,11] A. Gottardo,[2] J. Grebosz,[12] F. Haas,[7] H. Hess,[5] D. Jelavić Malenica,[3] A. Jungclaus,[13] M. Karolak,[10] S. Leoni,[6] A. Maj,[12] R. Menegazzo,[2] D. Mengoni,[1,14] C. Michelagnoli,[2,15] G. Montagnoli,[1] D. R. Napoli,[2] A. Pullia,[6] F. Recchia,[1] P. Reiter,[5] D. Rosso,[2] M. D. Salsac,[10] F. Scarlassara,[1] P.-A. Söderström,[16,17] N. Soić,[3] A. M. Stefanini,[2] O. Stezowski,[18] Ch. Theisen,[10] C. A. Ur,[1,19] J. J. Valiente-Dobón,[2] and M. Varga Pajtler[20]

Ruđer Bošković Institute, Zagreb, Croatia
INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
IPHC, CNRS/IN2P3 and Universit´e de Strasbourg, Strasbourg, France
INFN and Universit`a di Torino, Italy
INFN and Universit`a di Padova, Padova, Italy
IFIC, CSIC-Universidad de Valencia, Valencia, Spain
H.H. National Institute of Physics and Nuclear Engineering, Bucharest, Romania

Kokopelli: links distant and diverse communities together.

This work was partly supported by the Croatian Science Foundation under the project 7194.