Probing nucleon-nucleon correlations in heavy ion transfer reactions

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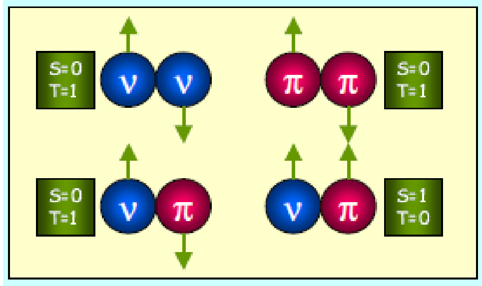
PRISMA collaboration



Catania

Zagreb

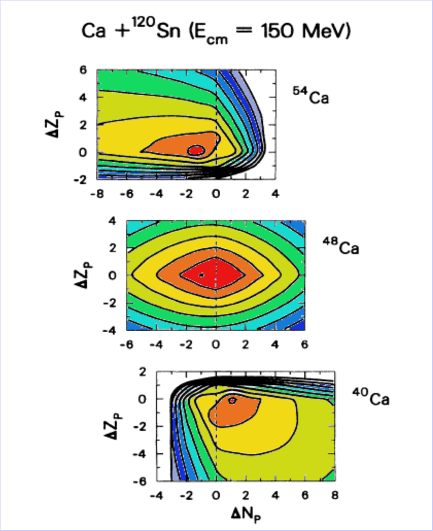
Nucleus Nucleus 2015

21-26 June 2015 *Dipartimento di Fisica ed Astronomia, Università di Catania*

Europe/Rome timezone

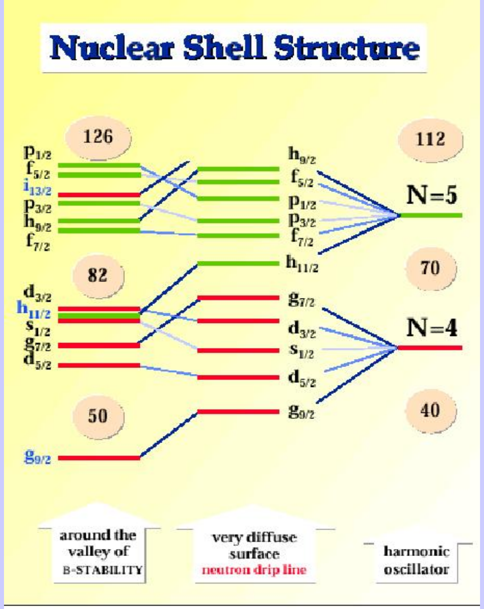
Transfer reactions among heavy ions

✓A study of multiple particle transfers.
✓The transition from quasi elastic to deep inelastic processes.
✓A tool for the population of neutron rich nuclei.

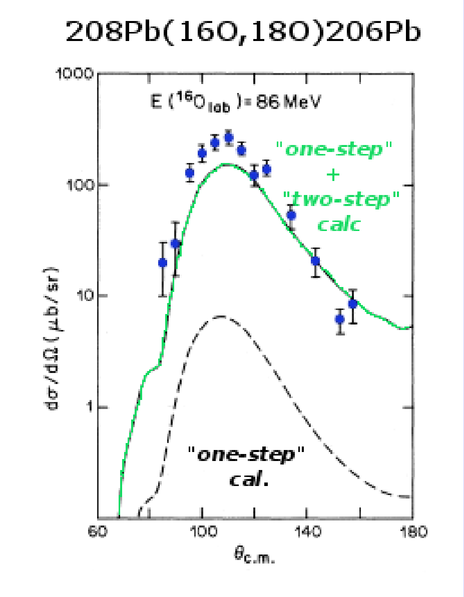


C.H. Dasso et al., PRL 73 (1994) 1907

A study of properties near shell closure:
✓single particle states
✓coupling of the particle/ hole to the collective boson

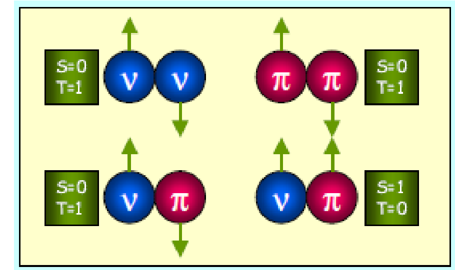


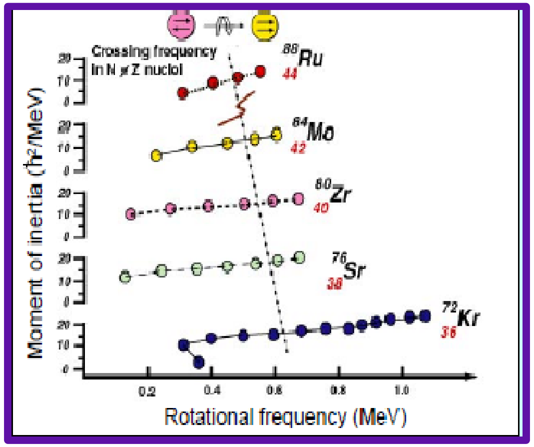
A study of the residual interaction (correlations):
✓two particle transfer (absolute values)
✓population of specific states (pairing vibration/rotation)



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

Probing correlations

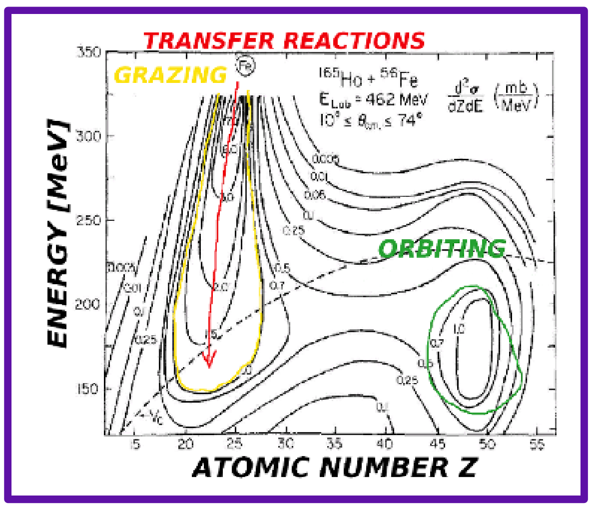




Higher rotational frequency for "pair" break in N=Z

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.



What will be a signature in the heavy ion transfer reactions?

HI advantages: test of correlation properties in multi-neutron and multi-proton transfer processes via simultaneous comparison of observables for ±nn/±pp/±np pairs

HI drawbacks: difficult experimental conditions (A,Z,Q-value resolutions, total efficiency) and difficult theoretical treatment (complex structure of the two interacting ions, QE and DIC processes, multistep processes, many open channels and CC effects)

Magnetic spectrometers for transfer reaction studies

Q3D, split-pole 1980

✓excited states populated in light ion transfer reactions (en. resolution ~few tenths keV)
✓distribution of atomic charge states
(magnetic elements of different complexity to focus momenta at the focal plane)

TOF spectrometers 1990

✓focus ions of different atomic charge states to a (small) focal plane
✓good A and Z resolution, and detection efficiency, large energy dynamic range of transfer products

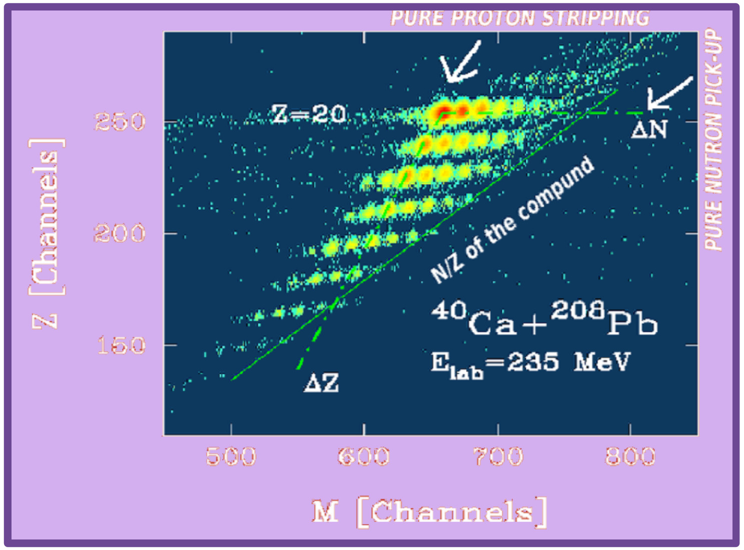
Large solid angle spectrometers 2000

PRISMA, VAMOS, MAGNEX

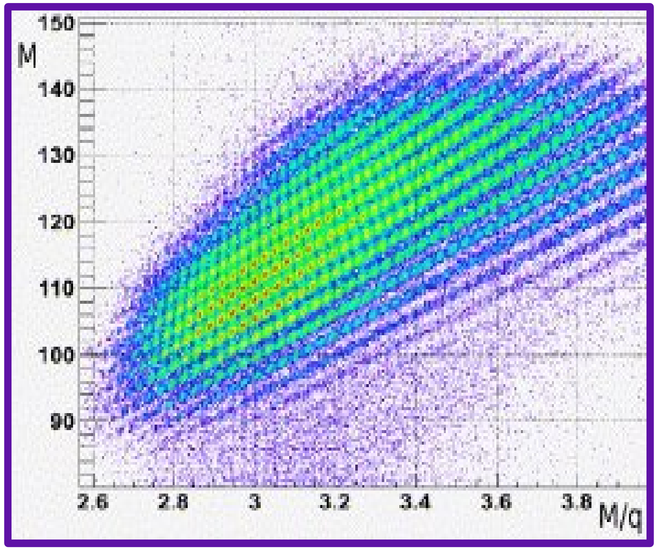
coupling to large γ arrays

CLARA, EXOGAM, AGATA

✓simple magnetic elements and “complex” detector systems
✓good A and Z resolution, detection efficinecy



S.Szilner et al, PRC 71 (2005) 044610



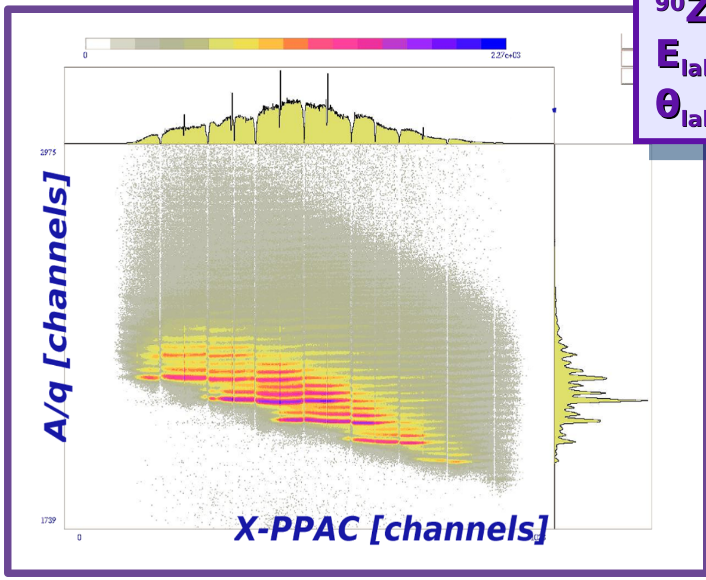
S. Pullanhiotan et al, NIM A 593 (2008) 343

The PRISMA spectrometer

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

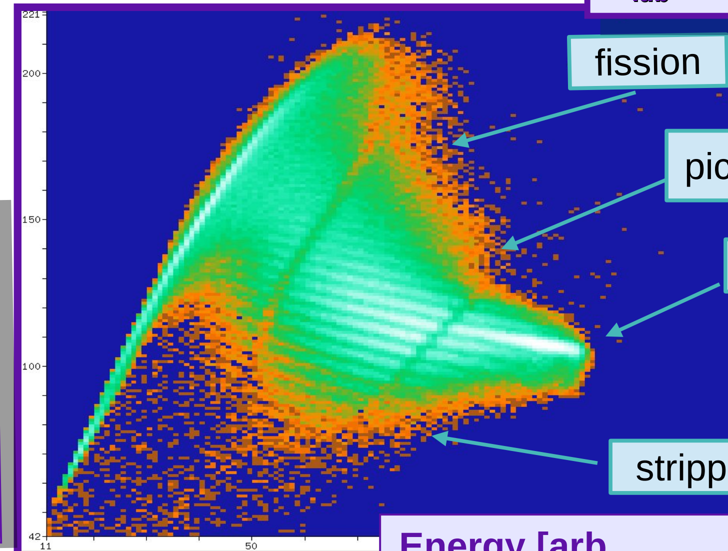
reconstruction of the ion trajectory inside (simple) magnetic elements, ray tracing procedure: position sensitive detectors of large area

$^{90}Zr+^{208}Pb$
E_{lab} = 560 MeV
θ_{lab} = 61°



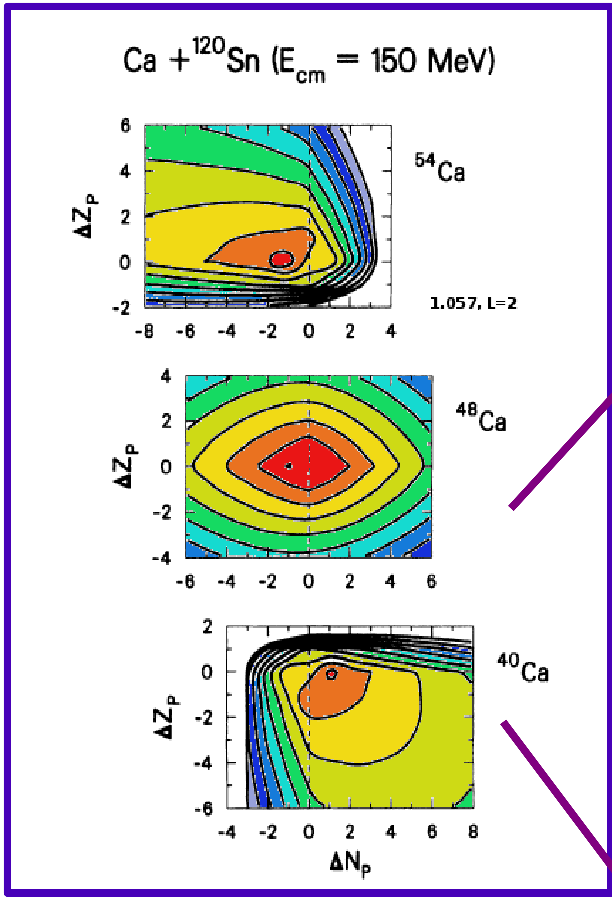
$^{82}Se+^{238}U$
E_{lab} = 505 MeV
θ_{lab} = 64°

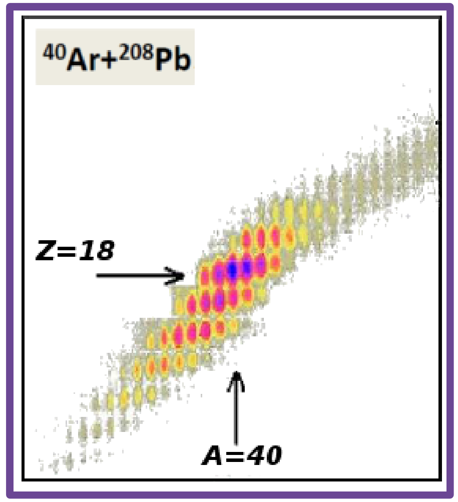
ΔE [arb. units]

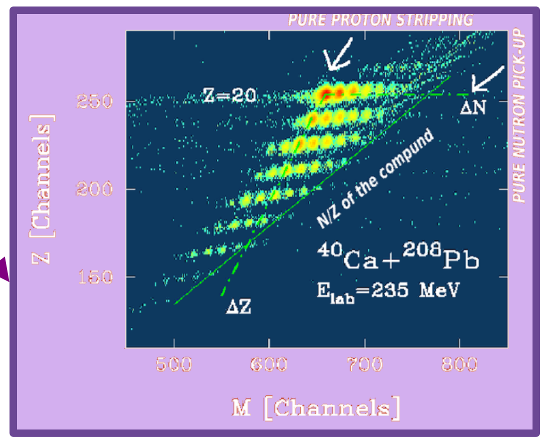


Energy [arb. units]

Properties of transfer reactions at the Coulomb barrier





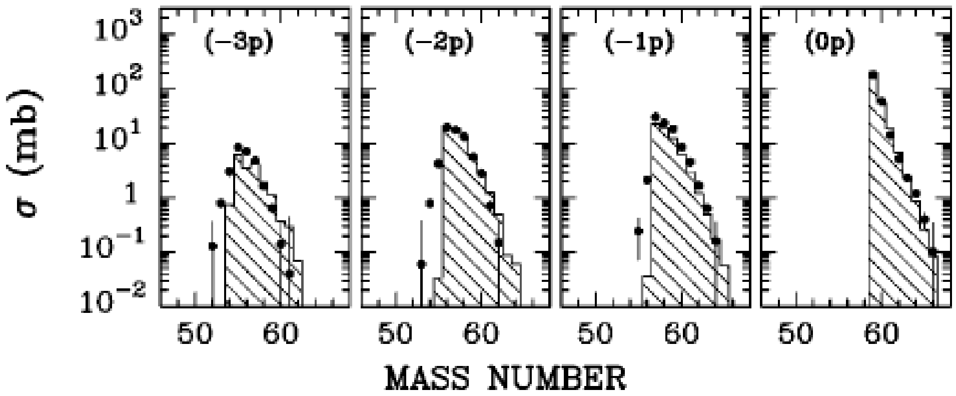


C. H. Dasso, G. Pollarolo, and A. Winther, PRL 73 (1994) 1907
L. Corradi, G. Pollarolo and S. Szilner, J. Phys. G 36 (2009) 113101 (Special Topic)

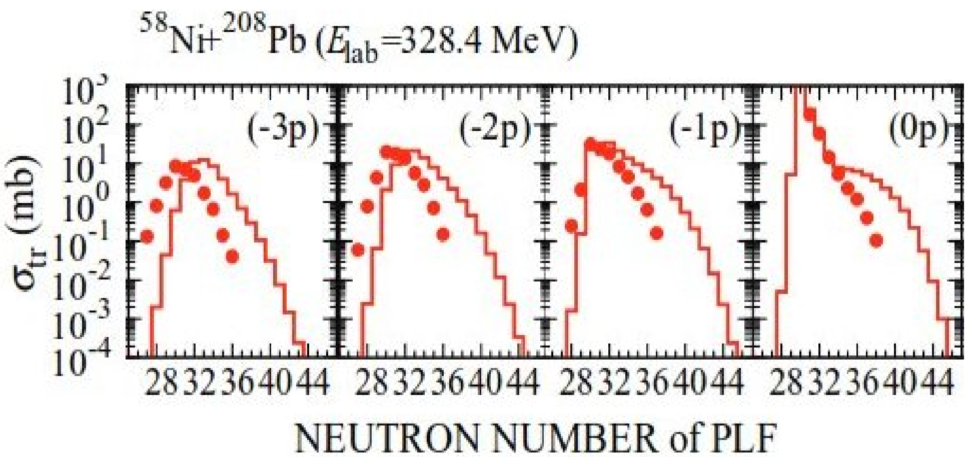
- ✓ The transfer process is governed by optimum Q-value and nuclear structure properties.
- ✓Nuclei are located on the left side of the charge equilibration line --> dominance of a direct mechanism
- ✓ For the massive proton transfer channels → the isotopic distributions drift towards lower masses (neutron evaporation)

- ✓ GRAZING model: calculates the evolution of the reaction by taking into account:
- ✓the relative motion (nuclear + Coulomb field), and
- ✓the intrinsic degrees of freedom of projectile and target (surface vibration and the single-nucleon transfer channels).
- ✓The multinucleon transfers are described via a multistep mechanism.
- ✓The model takes into account the effect of neutron evaporation.

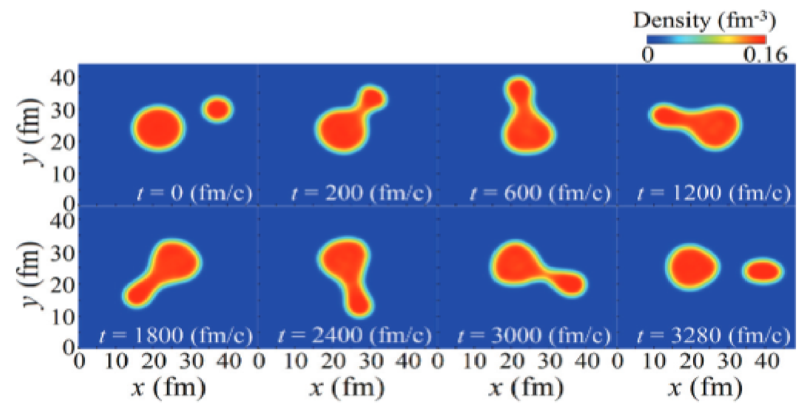
Multinucleon transfer reactions : experiment vs. theory

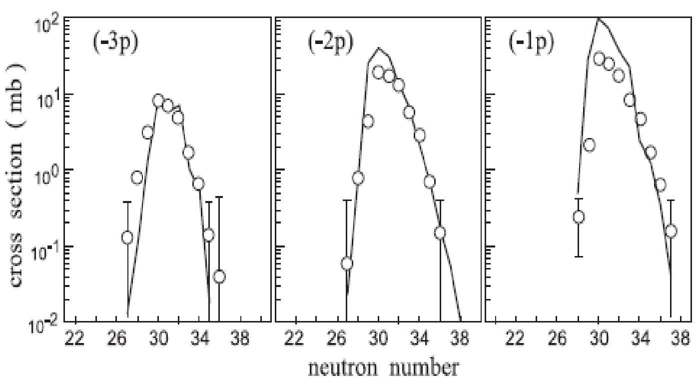


EXP: $^{58}Ni+^{208}Pb$,
L. Corradi et al., PRC 66 (2002) 024606
GRAZING or CWKB, G. Pollarolo



Time Dependent Hartree-Fock theory
K.Sekizawa, K.Yabana, PRC 88 (2013) 014614





Langevin-type dynamical equations of motion
V. Zagrebaev, W. Greiner PRL 101 (2008) 122701

Total cross sections – nucleon-nucleon correlations

$^{40}Ca+^{208}Pb$

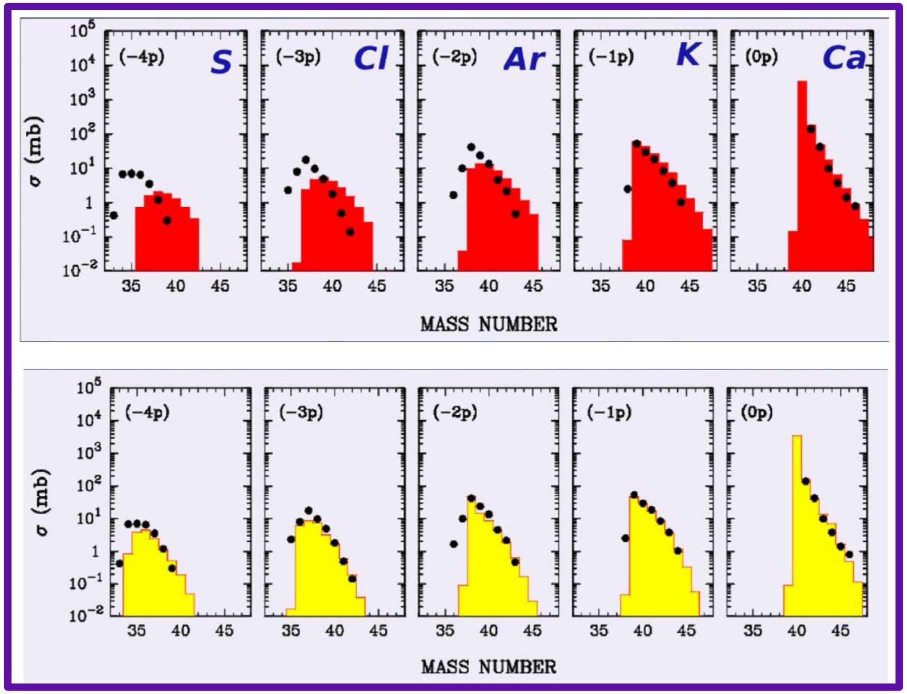
CWKB cal. successive transfer

+

simultaneous transfer (microscopic pair form factor)

+

neutron evaporation



✓The shape of the yield distribution reflects the optimum Q-value
✓The theory describes well (0p) and (−1p) but underestimates (-2p)
✓The contribution of a direct pair mode (“macroscopic”) both for neutrons and protons has been added in the calculations.
✓The same strength of the form factor for neutrons and protons.
✓The pair mode alters little the cross section for neutron transfer but is essential for the proton transfer.

$$F_P(r) = \beta_P \frac{\partial V(r)}{\partial A} \simeq \left(\frac{\beta_P R}{3A}\right)\frac{\partial V(r)}{\partial r},$$

✓The residual interaction: components responsible for the couplings (phonon - single particle), and for nucleon – nucleon correlations

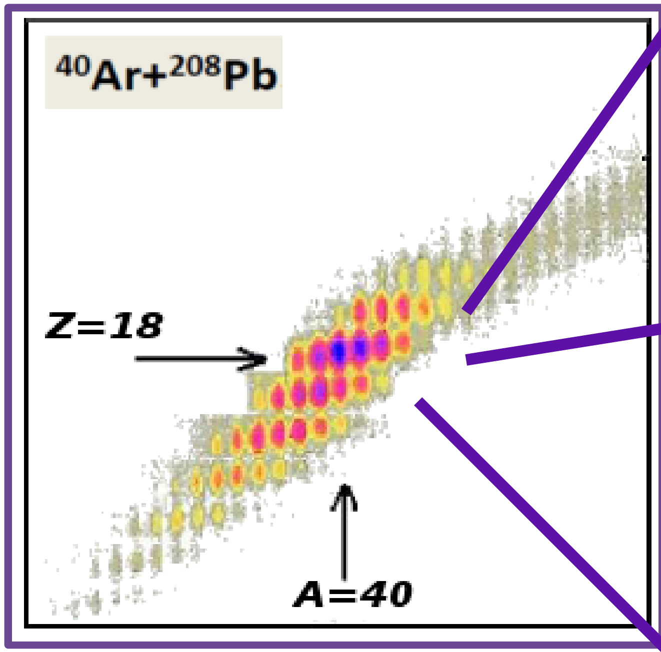
✓Inclusive data - difficult to have a clear signature of pair mode

L. Corradi et al., PRC 66 (2002) 024606
S. Szilner et al., PRC 71 (2005) 044610
L. Corradi, G. Pollarolo and S. Szilner, J. Phys. G 36 (2009) 113101 (Special Topic)

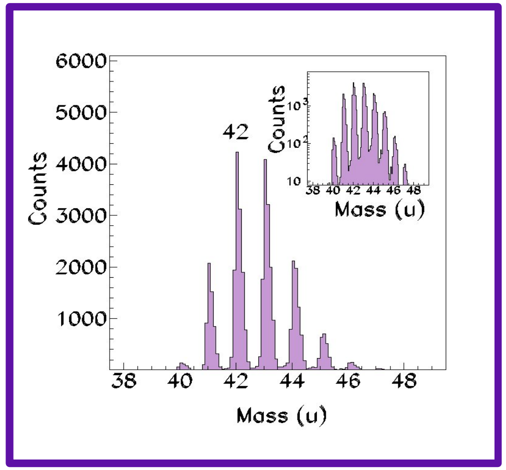
“coupling to large γ arrays”

exp: $^{40}Ar+^{208}Pb$

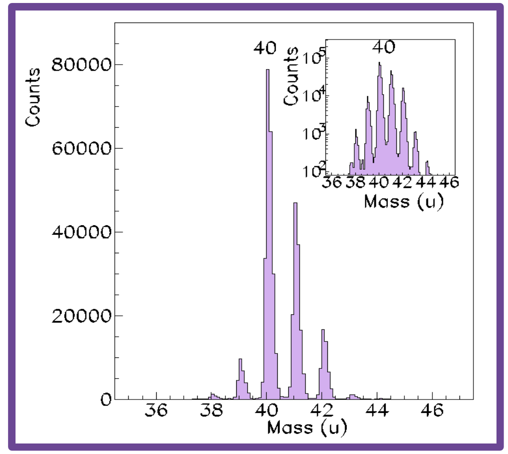
θ_{lab} = 46°
54° (grazing)
59°



T. Mijatović, Ph.D. Thesis, 2015
Diff. and total cross sections

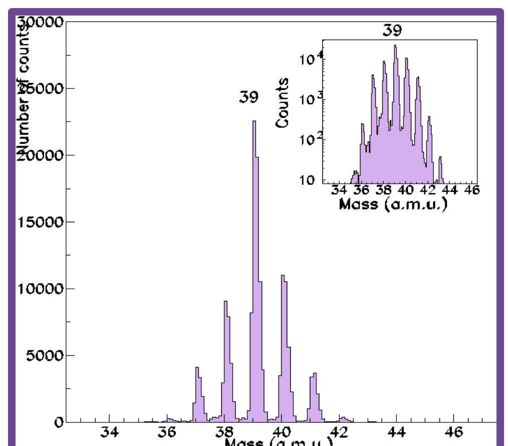


Z=19: K isotopes
A=40-46
(+1p±xn) transfer channels



Z=18: Ar isotopes
A=38-43
Neutron transfer channels

S. Szilner et al,
PRC 84 (2011) 014325

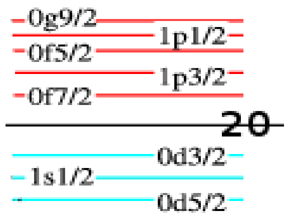


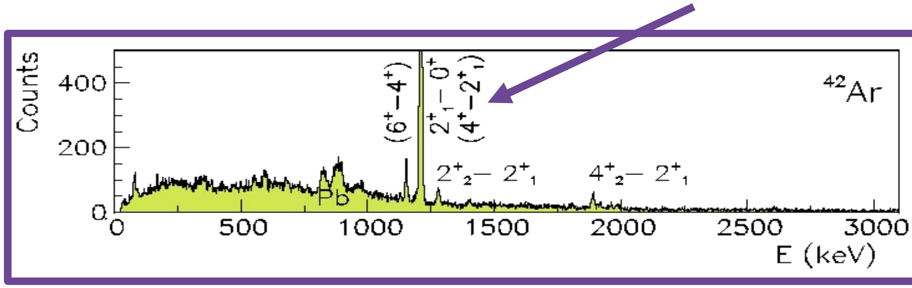
Z=17: Cl isotopes
A=37-42
(-1p±xn) transfer channels

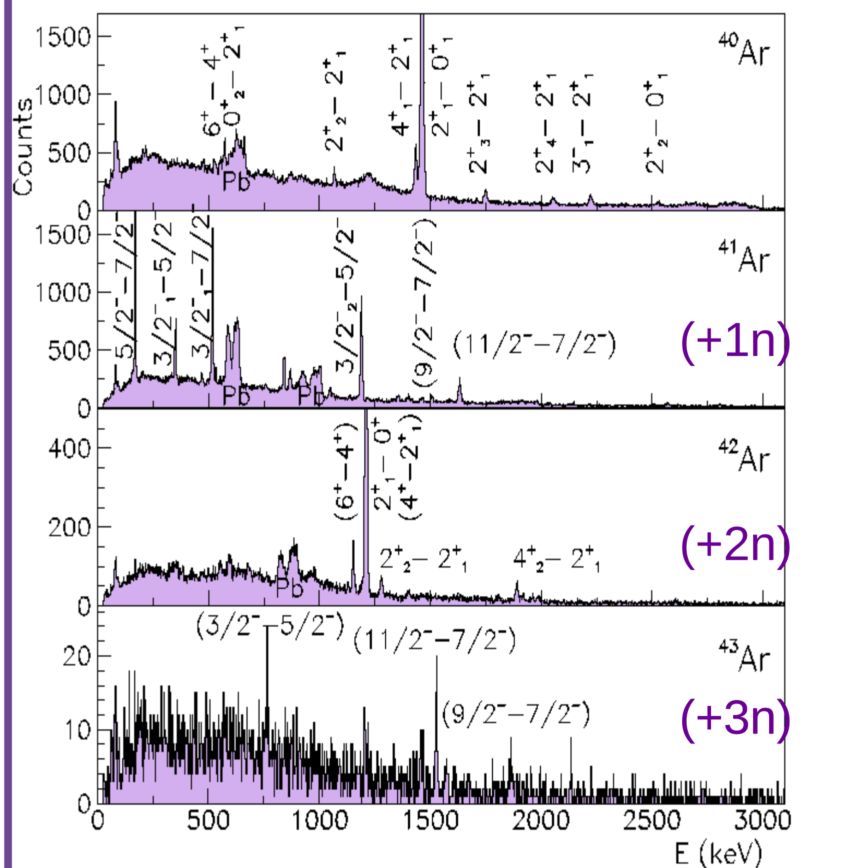
S. Szilner et al,
PRC 87 (2013) 054322

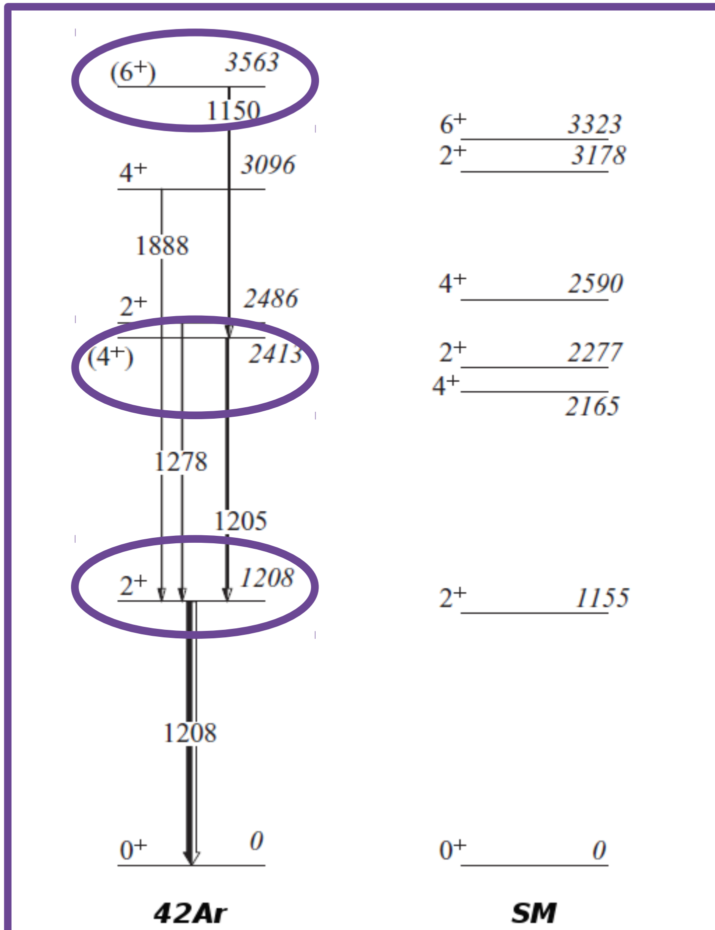
The character of states populated in transfer reactions

Ar isotopes: neutron transfer channels

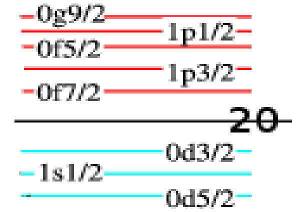


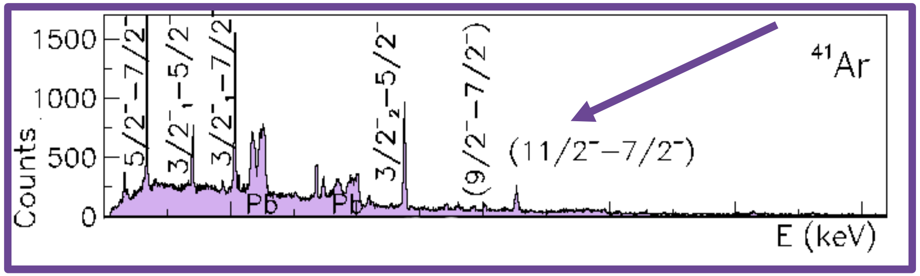


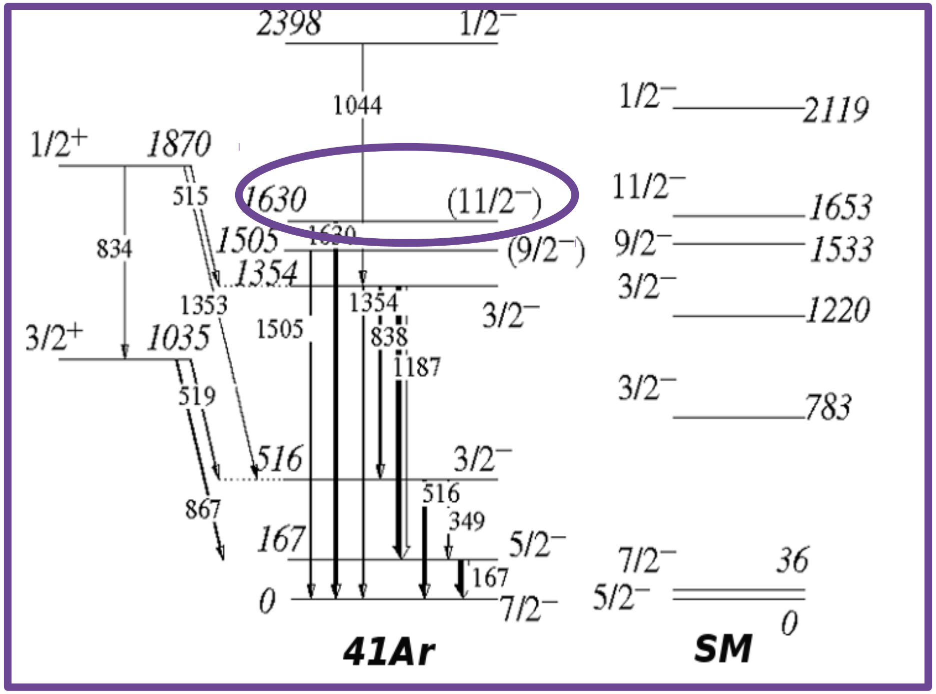




The character of states populated in transfer reactions



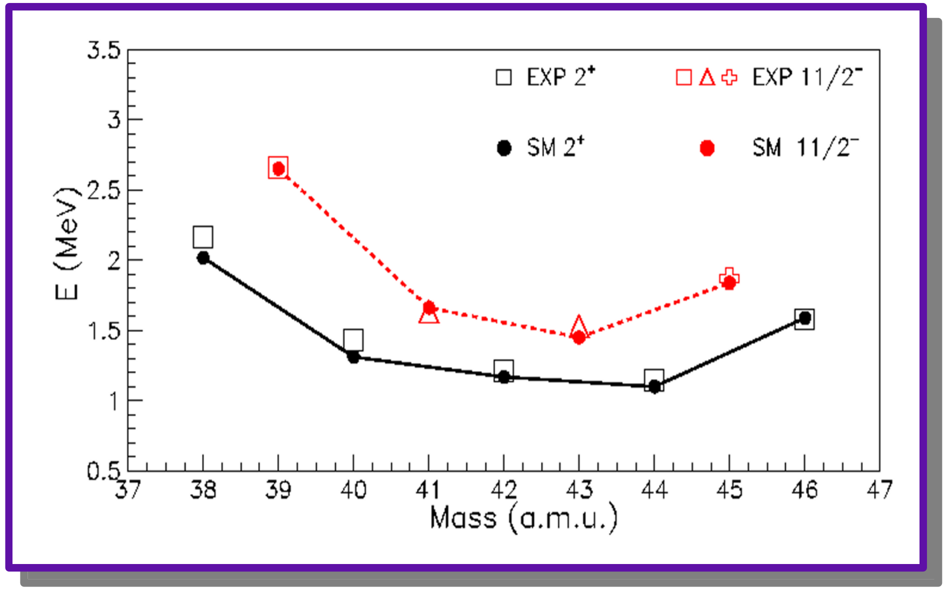




Ar isotopes

$$\nu p_{1/2}, \nu p_{3/2}, \nu f_{7/2}, \nu f_{5/2} \rightarrow 1/2^-,\ 3/2^-,\ 5/2^-,\ 7/2^-$$

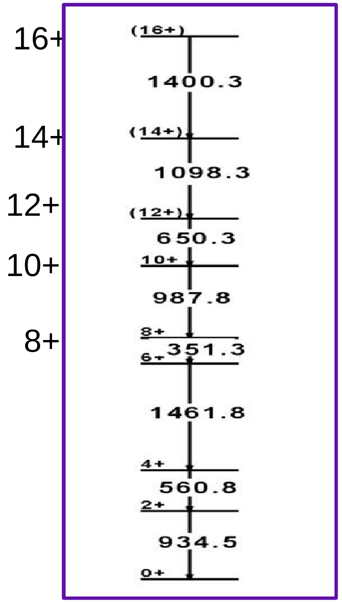
$$2^+ \otimes \nu f_{7/2} \rightarrow 11/2^-,\ 9/2^-, ..., 3/2^-$$



- odd: excitation of states of single-particle character
- a significant population of a stretched configuration of the valence neutron coupled to the vibration quanta
- SDPF-U SM calculations

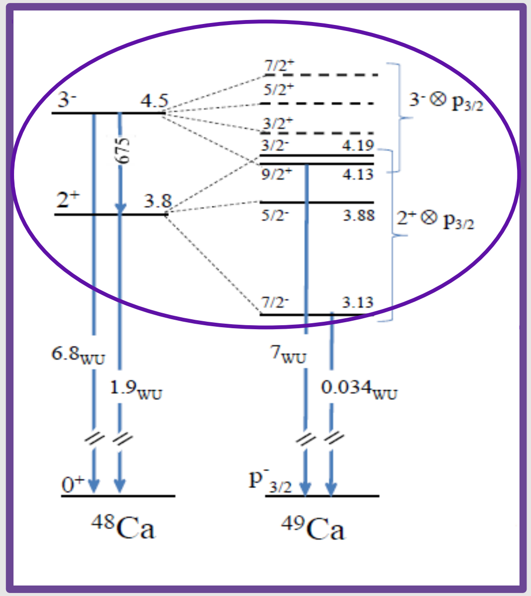
A strong interplay between single-particle and collective degrees of freedom and the reaction dynamics

"yrast" states; "fermion-boson" coupling



90Zr+208Pb reaction:
92Zr: a strong population of the "yrast" states (up to 16+ at 7.4 MeV

M. Varga Pajtler, Ph.D. Thesis, University of Zagreb, 2014.

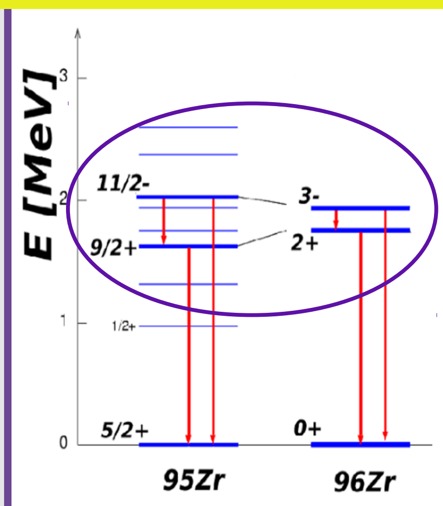


48Ca+64Ni reaction:
49Ca: a strong population of "boson-fermion" multiplets

D. Montanari et al., PLB 697, 288 (2011); PRC 85 (2012) 044301

$(d_{5/2})^{-}$ x 3^{-} --> $1/2^{-}, 3/2^{-}, \ldots, 11/2^{-}$

$(d_{5/2})^{-}$ x 2^{+} --> $1/2^{+}, 3/2^{+}, \ldots, 9/2^{+}$



40Ca+96Zr reaction:
95Zr: a strong population of the 9/2+ and 11/2- states ("boson-fermion" couplings)

S. Szilner et al, PRC 76 (2007) 024604

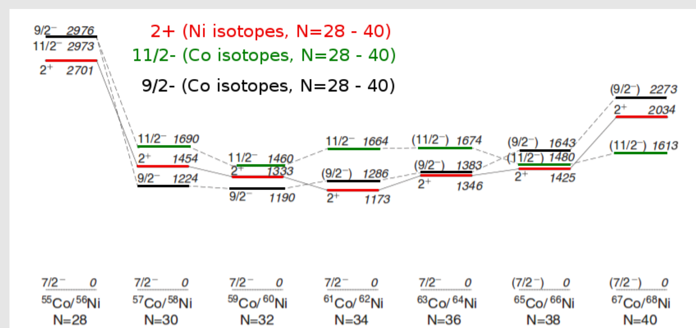


FIG. 8. Systematics of the first excited 9/2⁻ and 11/2⁻ states in the odd-even Co isotopes compared with the 2⁺ levels in their respective nickel isotope.

F. Recchia et al, PRC 85 (2012) 064305
Co isotopes

Fe: S. Lunardi et al, PRC 76 (2007) 034303
Ar: D. Mengoni et al, PRC 82 (2010) 024308
S. Bhattacharyya et al, PRL 101 (2008) 03501 …

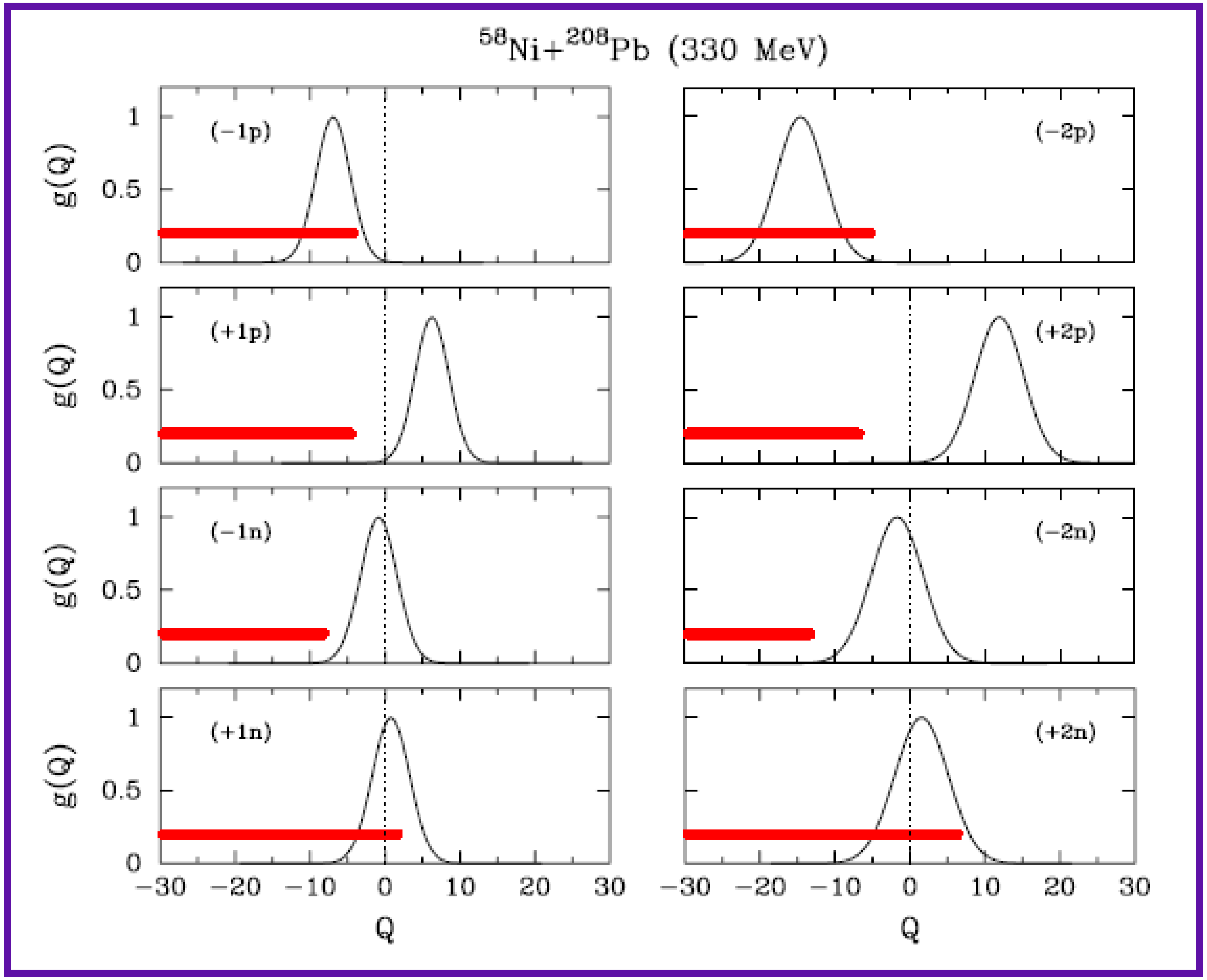
Properties of transfer reactions at the Coulomb barrier: optimum Q-value

cut-off function

$$g(Q) = \exp\left(-\frac{(Q - Q_{opt})^2}{\hbar^2 \ddot{r}_0 \kappa_{a'_1}}\right)$$

transfer probability

$$P_{\beta\alpha} = \sqrt{\frac{1}{16\pi\hbar^2 |\ddot{r}_0| \kappa_{a'_1}}} |f_{\beta\alpha}(0, r_0)|^2 g(Q_{\beta\alpha})$$

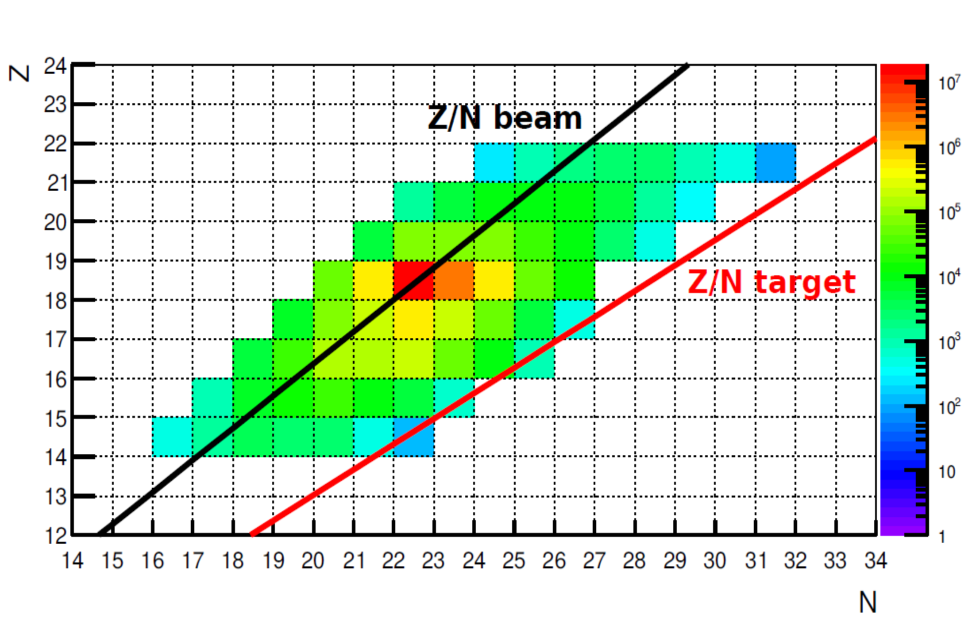


open reaction channels are those compatible with the optimum Q-value window (kinematical condition).

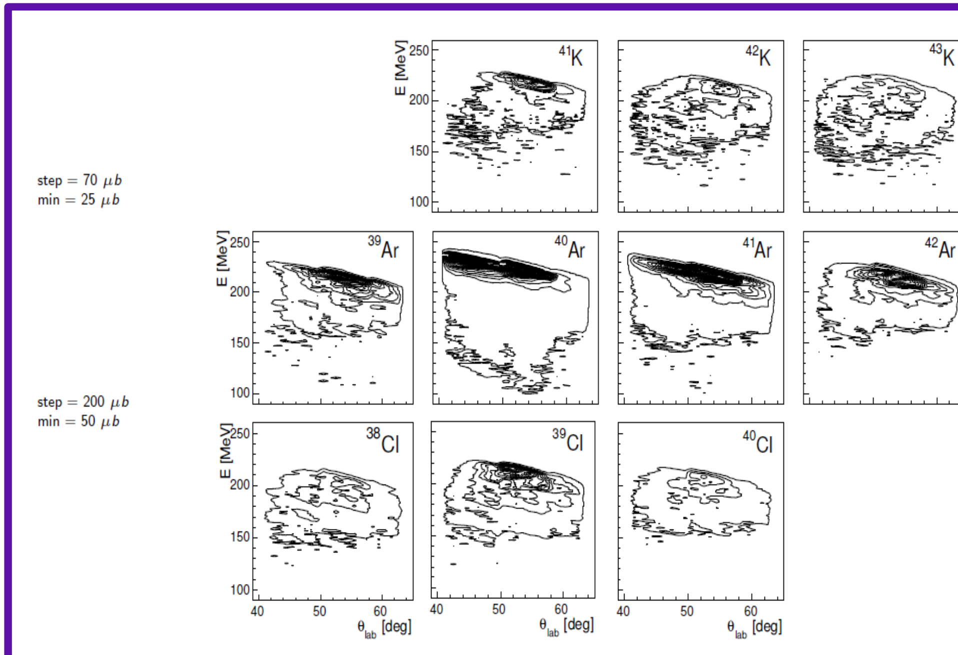
This window has its origin in the matching of the orbits before and after the transfer process.

G. Pollarolo et al, NPA 406 (1983) 369

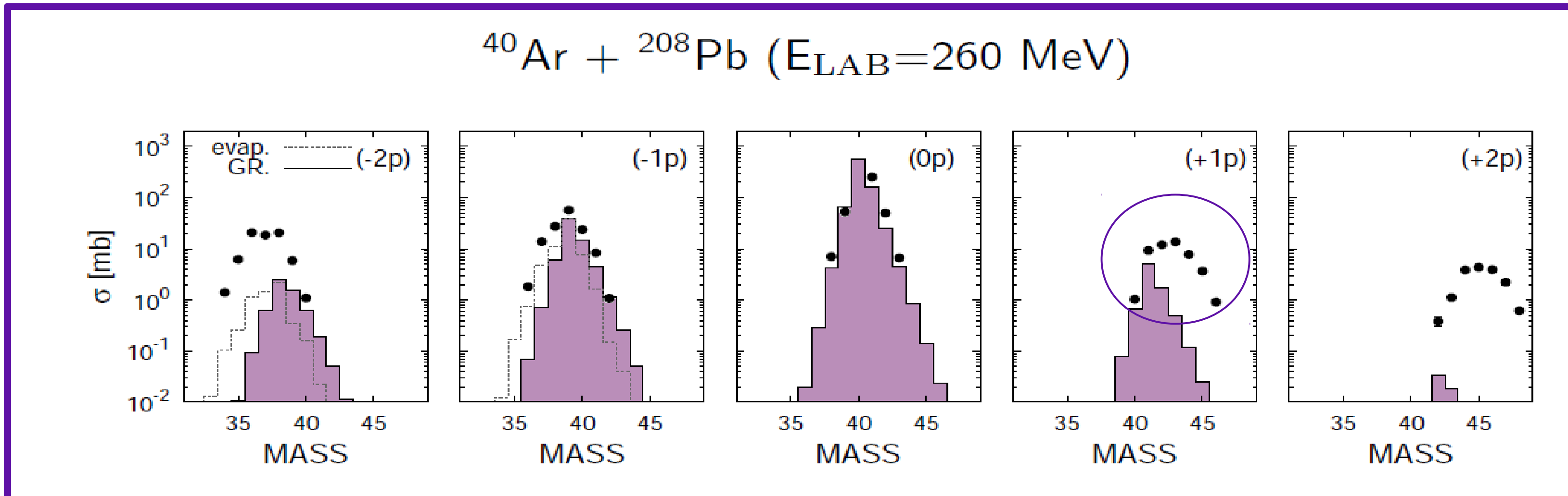
The $^{40}Ar+^{208}Pb$ system



Z- M distribution

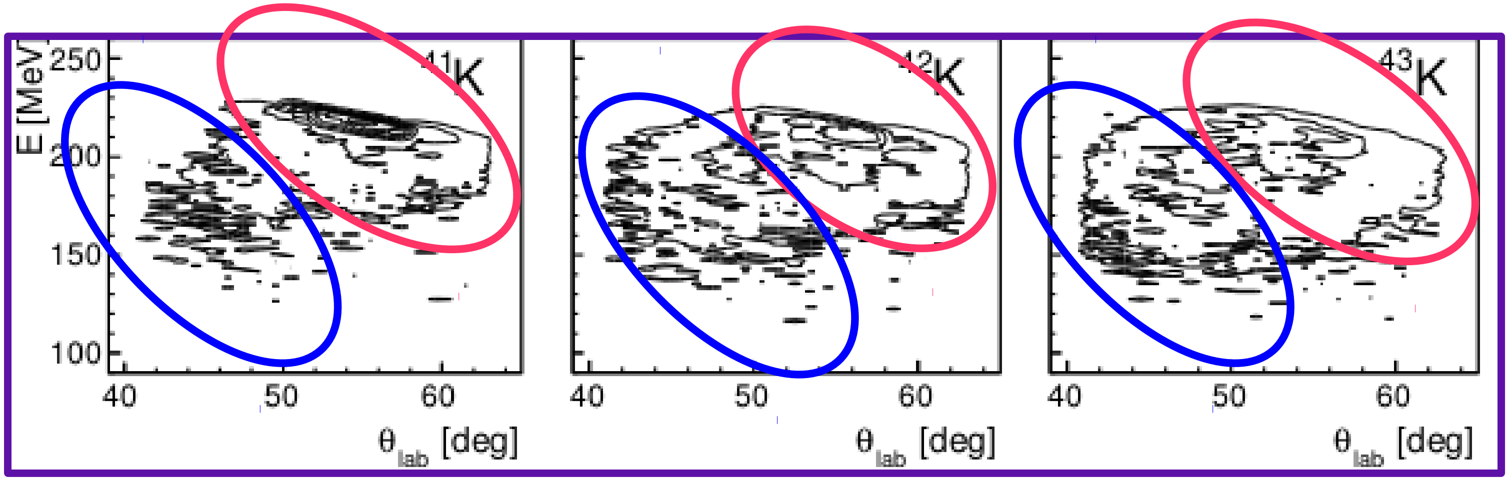


Wilczynski plots



EXP vs. GRAZING: the (+np) channel – factor 5

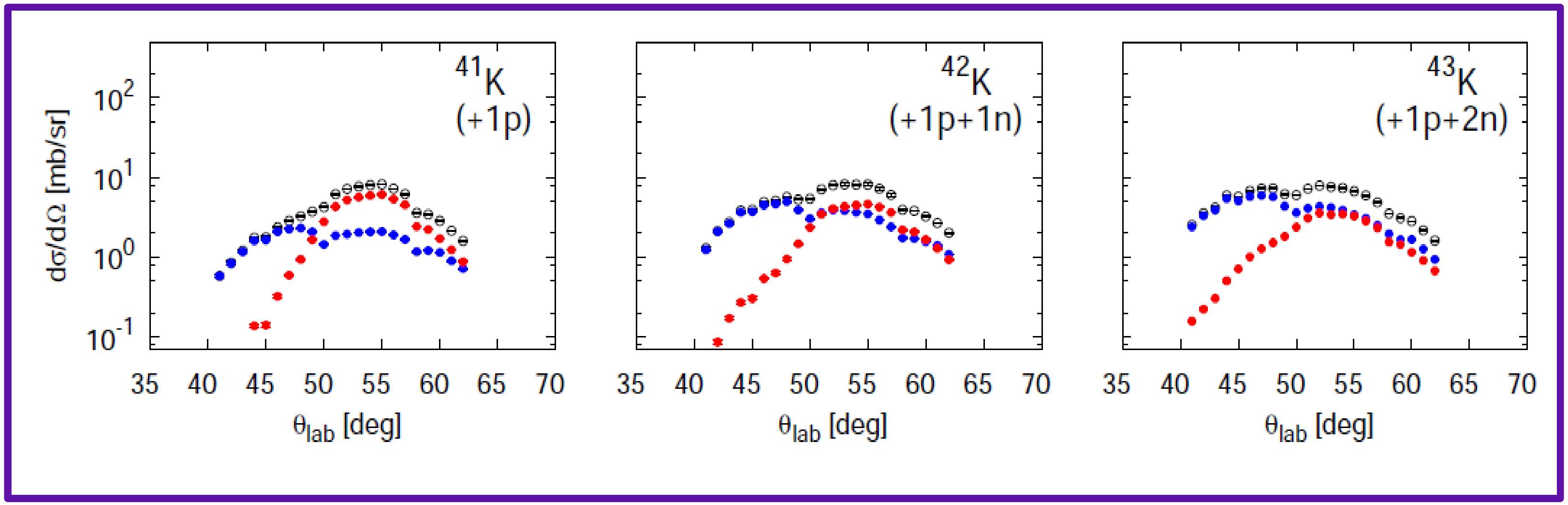
The $^{40}Ar+^{208}Pb$ system



Quasi-elastic processes

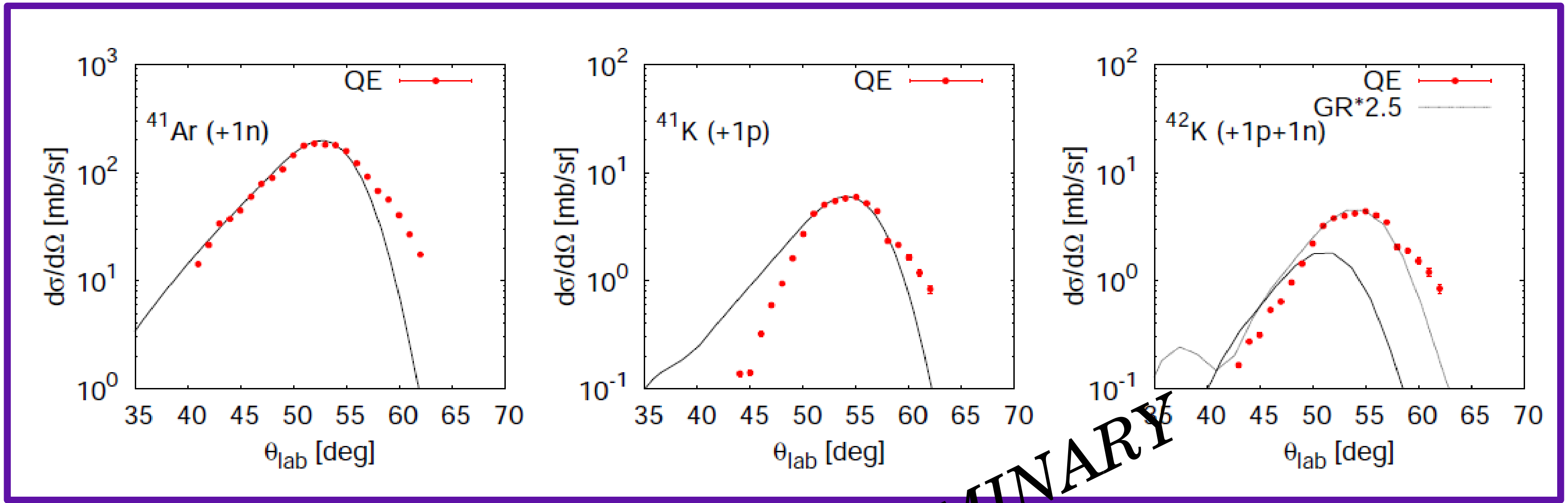
Deep-inelastic processes

Wilczynski plots, (+1p+xn) channels

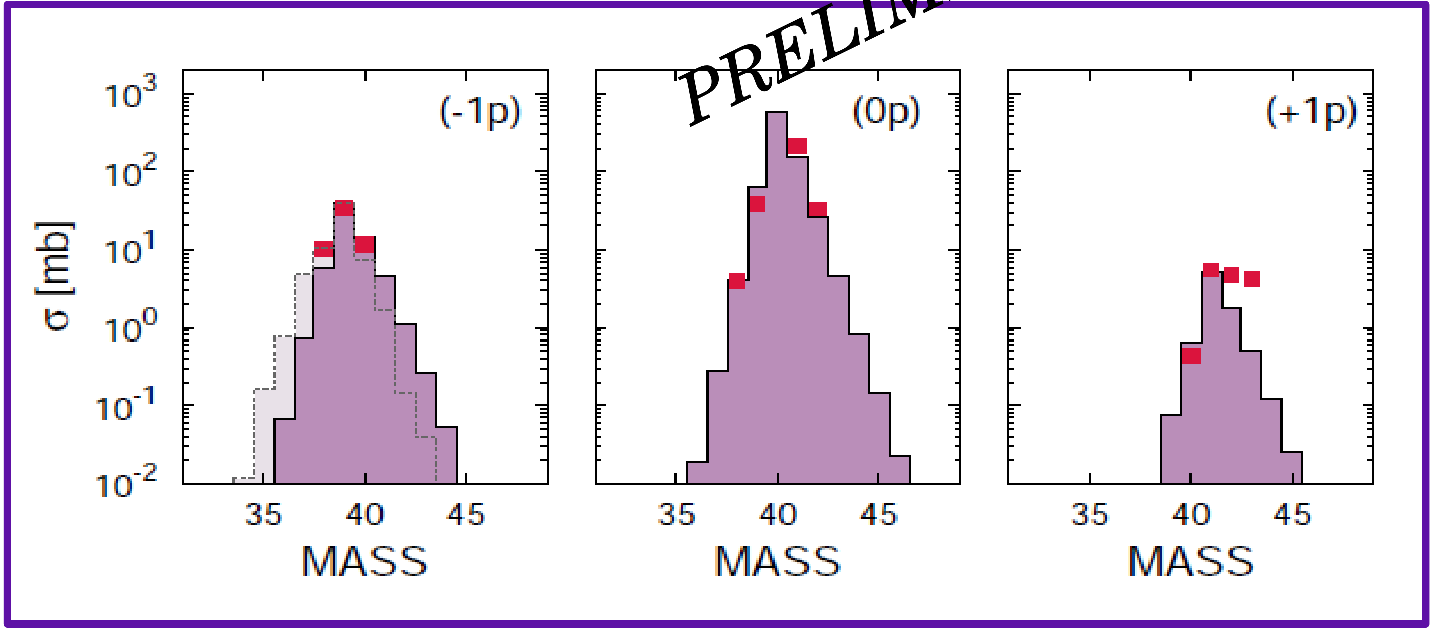


Angular distributions (integrated over energy: TOTAL, QE, DIC)

The $^{40}Ar+^{208}Pb$ system : QE ang. distribution and total cross sections



EXP vs. GRAZING (quasi-elastic): the (+np) channel – factor 2.5

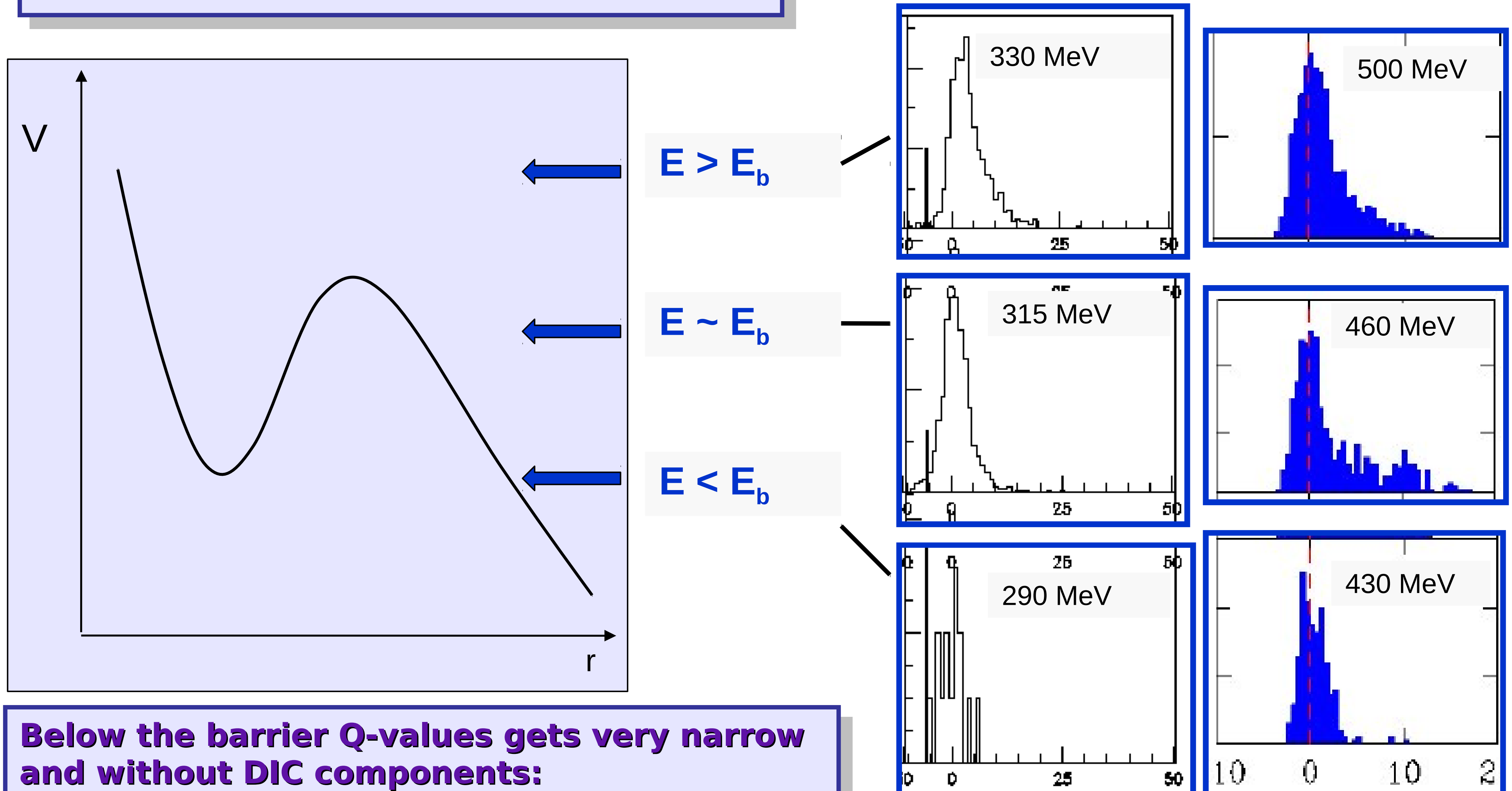


T. Mijatović, Ph.D. Thesis, 2015
Zakopane, 2014 (Acta Phys. Pol.B 46 (2015) 439)

A smooth transition between QE and DIC processes

$^{96}Zr(^{40}Ca,^{42}Ca)$ 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
2) E < E_b narrow Q-value distributions: no evaporation effects

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

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

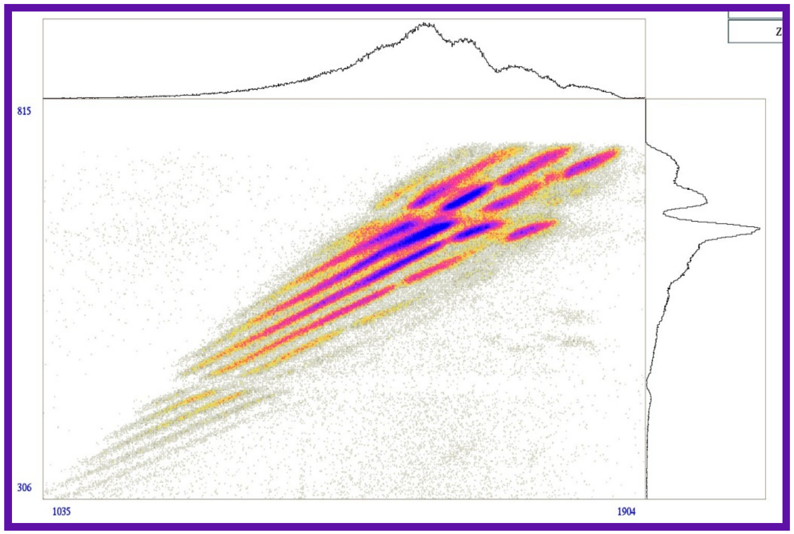
^{60}Ni+^{116}Sn: detection of (light) target like ions in inverse kinematics with PRISMA

excitation function:

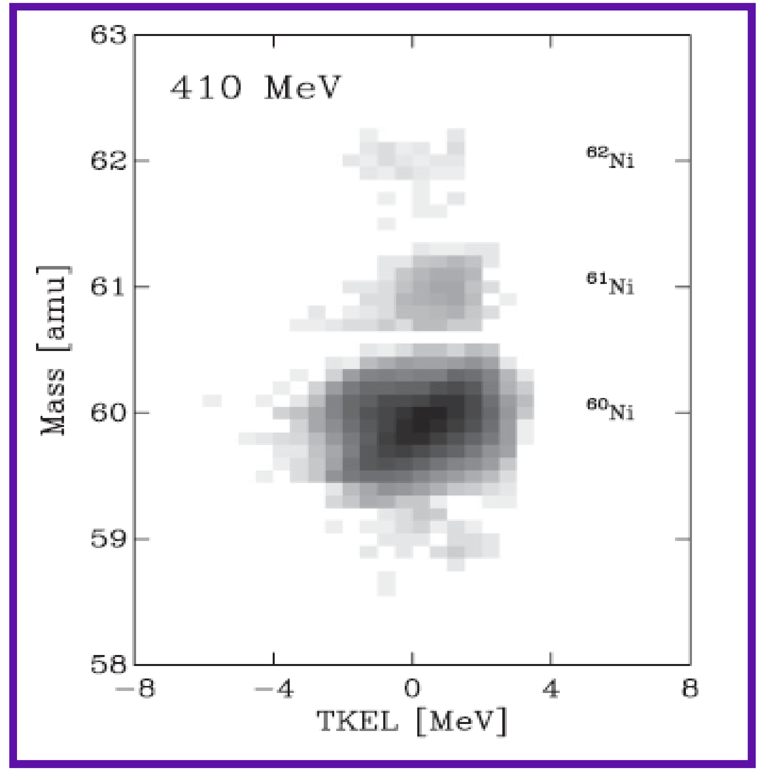
E_{beam} = 410 MeV – 500 MeV

(D ~ 12.3 to 15.0 fm)

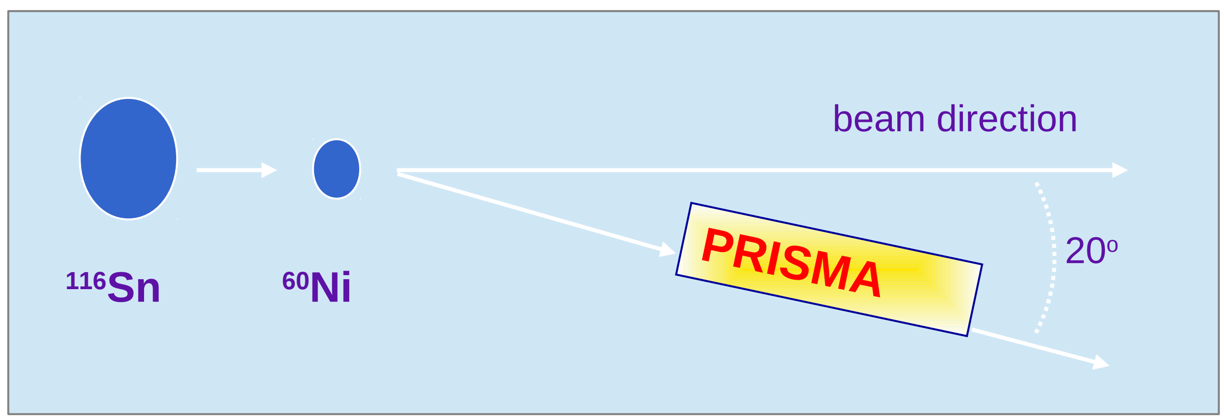
Rv [a.u.]



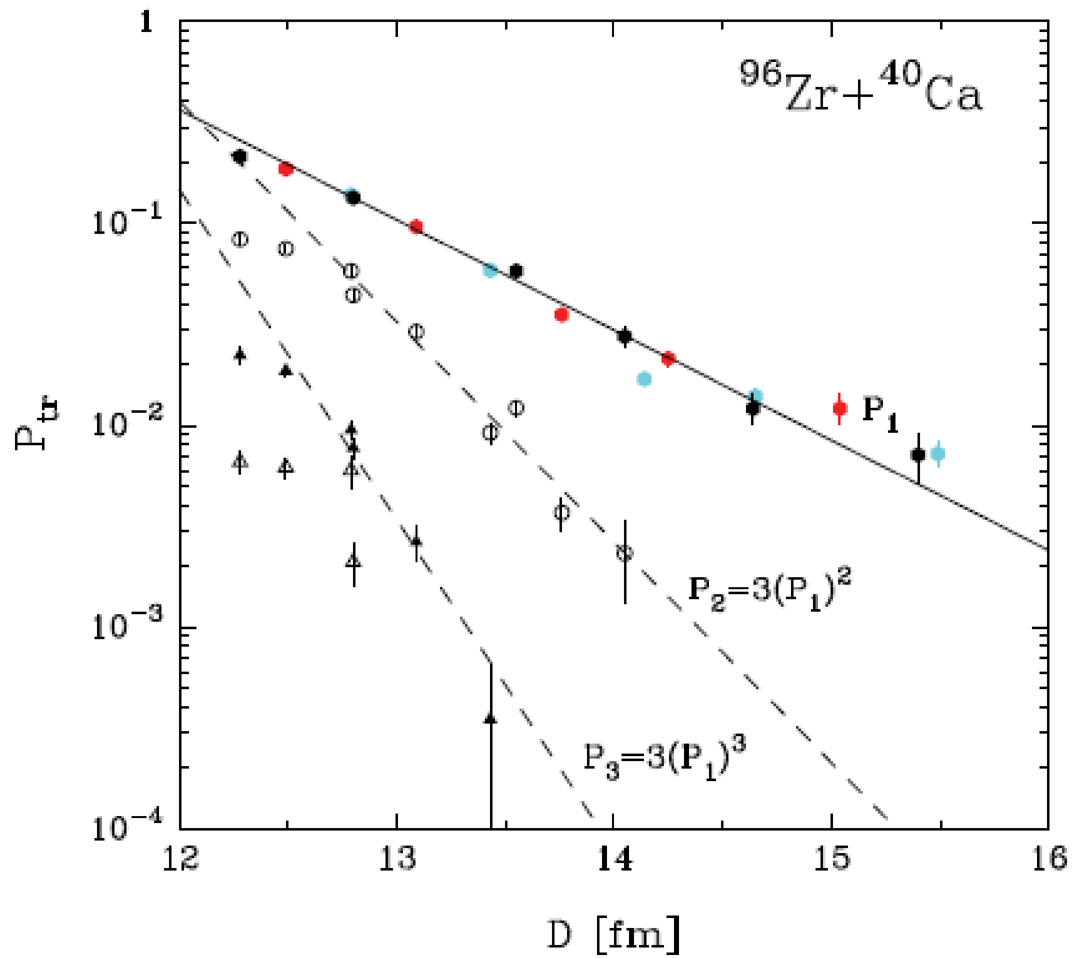
Energy [a.u.]



excellent channel separation at D ~ 15 fm



Experimental transfer probabilities



P_{tr} slope

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

B → binding energy

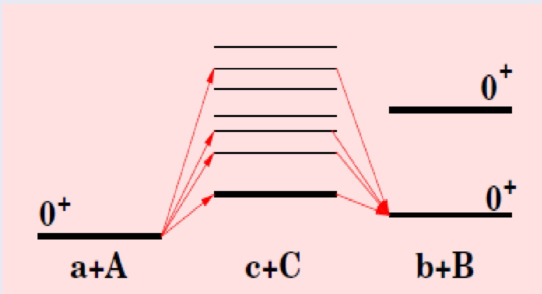
slopes of P_{tr} vd D are as expected from the binding energies (tail of the formfactor)

a bare phenomenological analysis shows an "enhanced" pair transfer, $P_{2n} \sim 3\,(P_{1n})^2$ and $P_{3n} \sim P_{1n}(P_{2n}) \sim 3\,(P_{1n})^3$

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

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

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

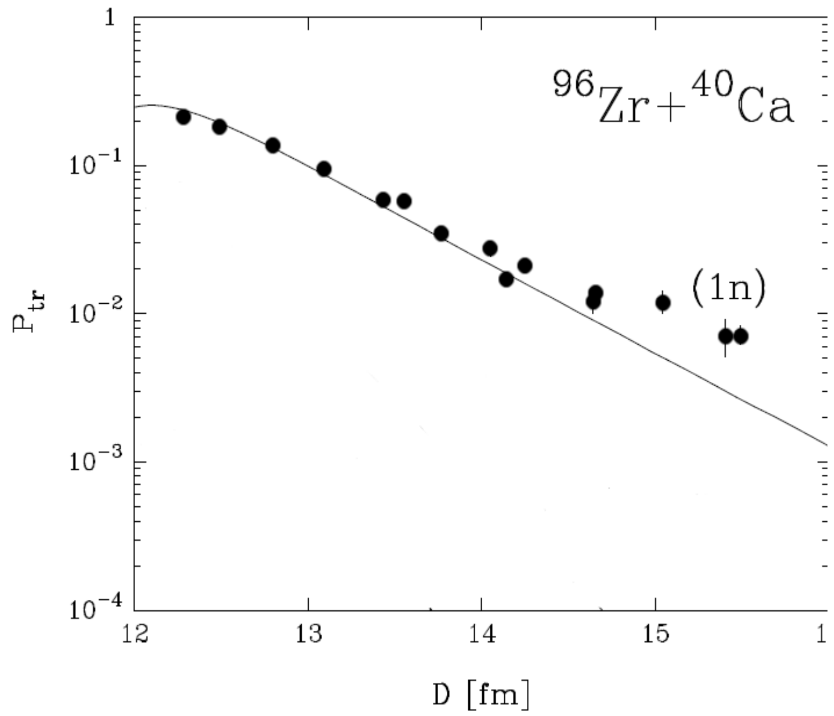


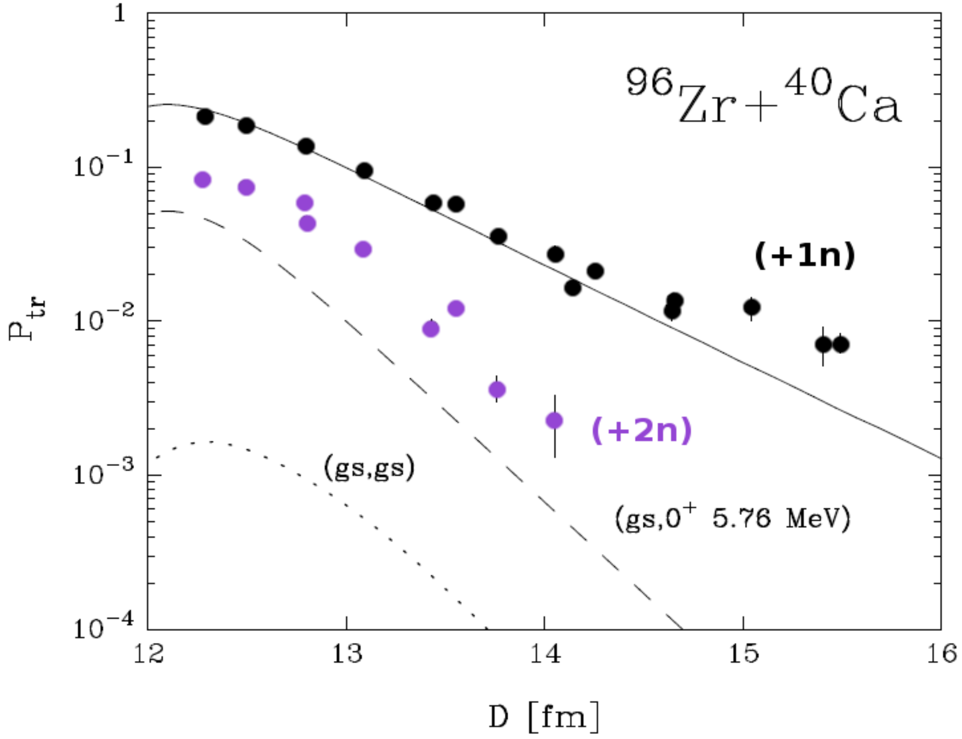
	nlj
^{116}Sn	$1g_{9/2}$
	$2d_{5/2}$
	$1g_{7/2}$
	$3s_{1/2}$
	$2d_{3/2}$
	$1h_{11/2}$
	$2f_{7/2}$
	$3p_{3/2}$
^{60}Ni	$2p_{3/2}$
	$2p_{1/2}$
	$1f_{5/2}$
	$1g_{9/2}$

3 terms : simultaneous, orthogonal and successive
only the successive term contributes to the transfer amplitude
Only 0+ to 0+ transition can be reduced to a simple expression

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

Comparison between experimental and theoretical transfer probabilities





-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

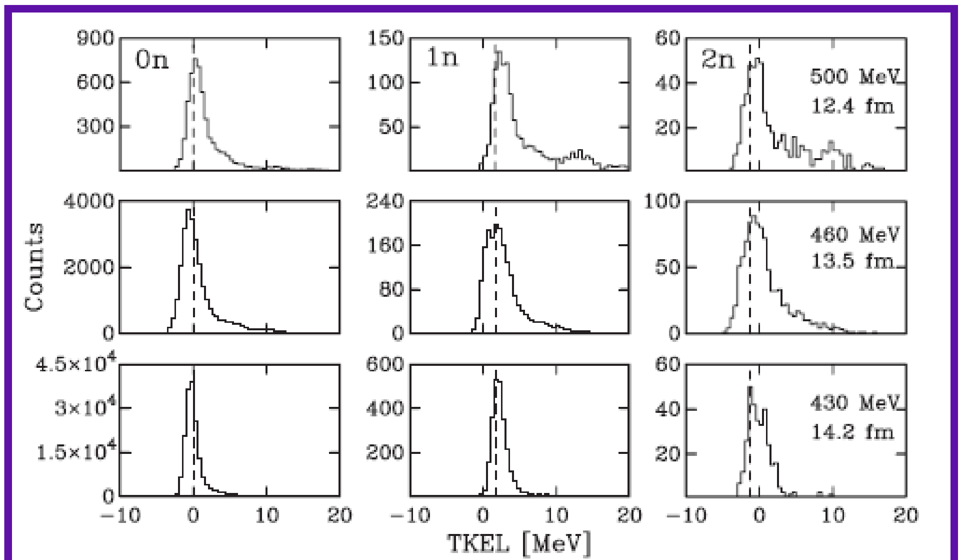
Two particle transfer (semiclassical theory, microscopic calc.)
3 terms : simultaneous, orthogonal and successive (only the successive term contributes to the transfer amplitude)

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

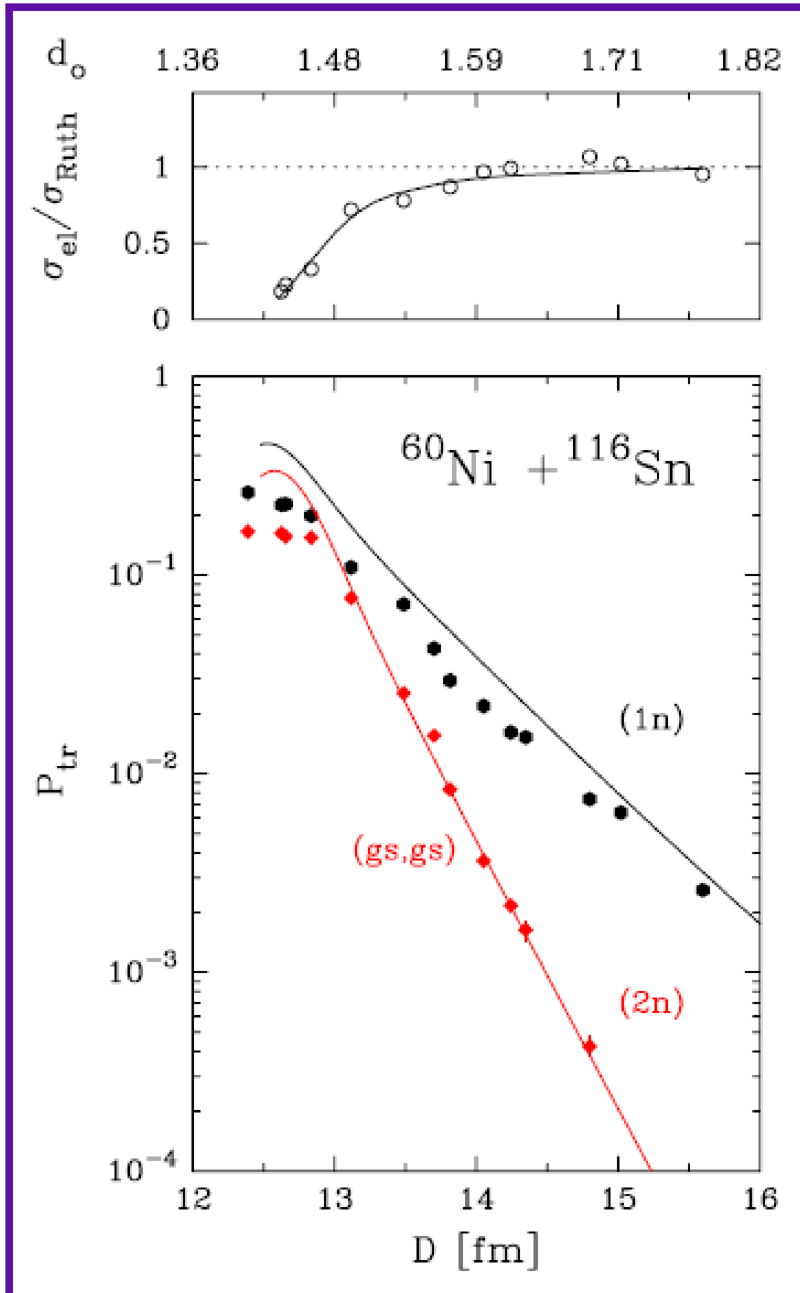
^{60}Ni+^{116}Sn: neutron pair transfer far below the Coulomb barrier

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

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

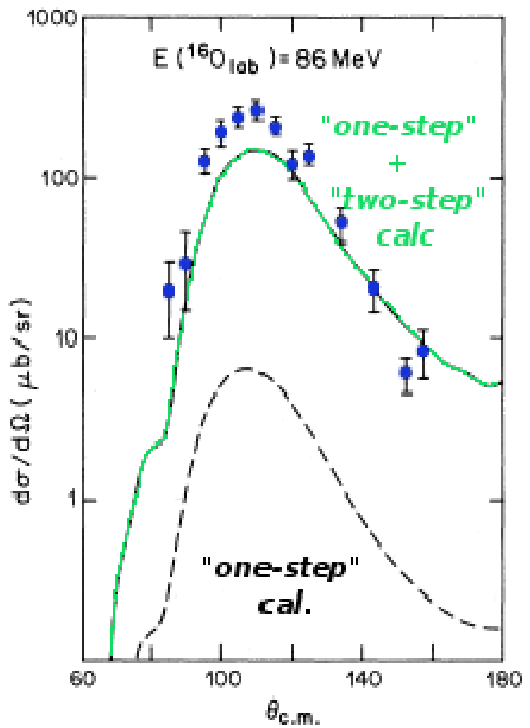


Absolute cross sections for one and two-nucleon transfer reactions

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

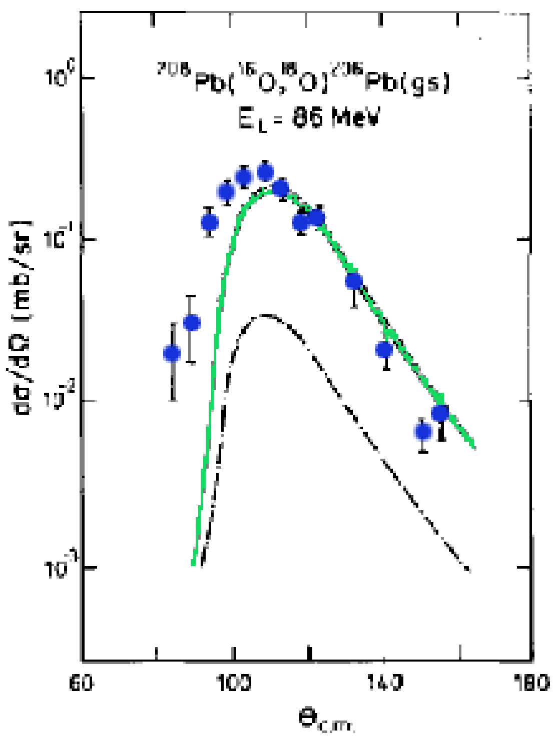
______successive+simultaneous
- - - - - -simultaneous

full quanto-mechanical



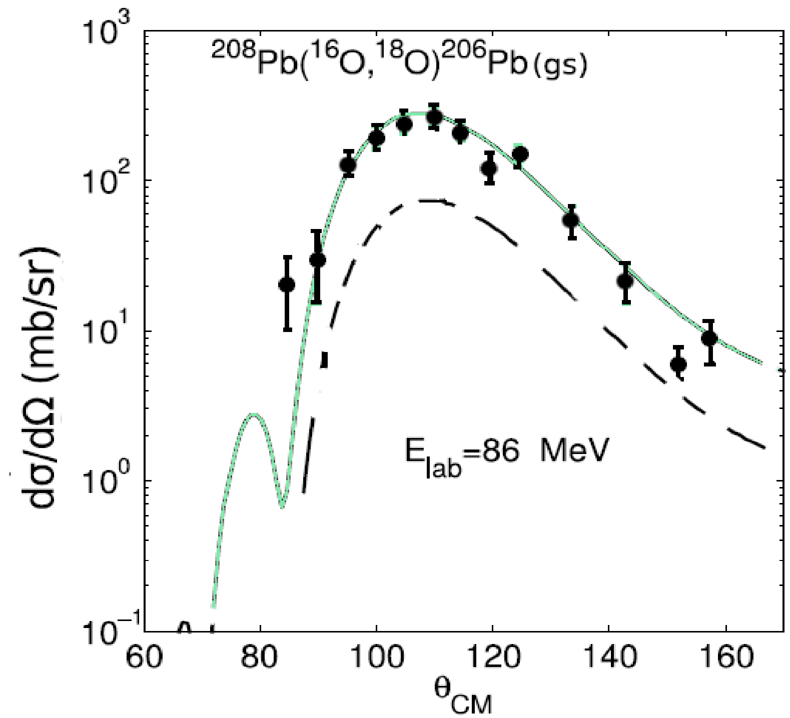
B.F.Bayman and J.Chen,
Phys. Rev. C 26 (1982) 1509

semi-classical



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

full quanto-mechanical



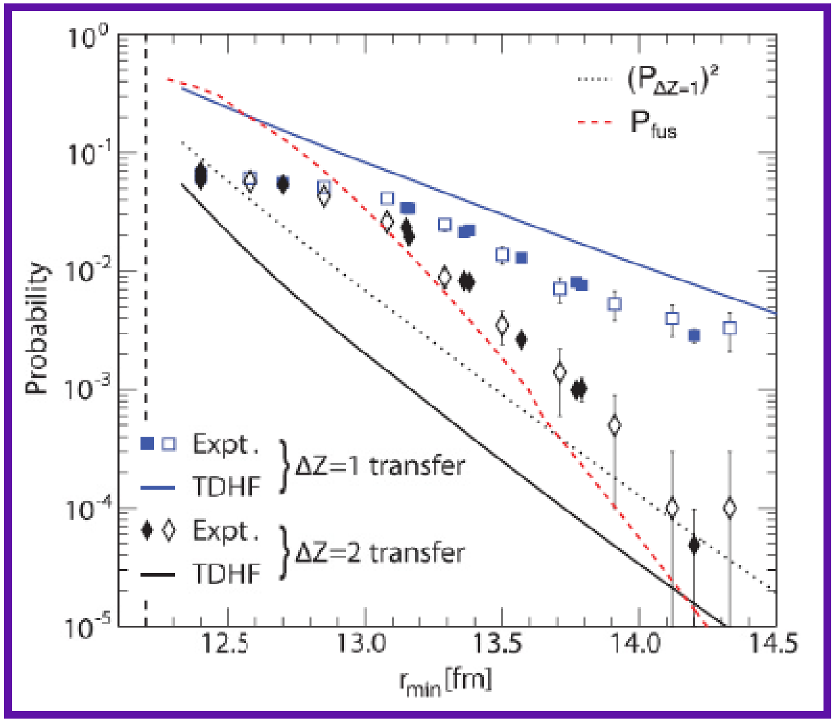
G.Potel, A.Idini, F.Barranco, E.Vigezzi
and R.A.Broglia, Rep. Prog. Phys. 76
(2013) 106301;

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

Sub-barrier transfer : TDHF or TDHF+BCS

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

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

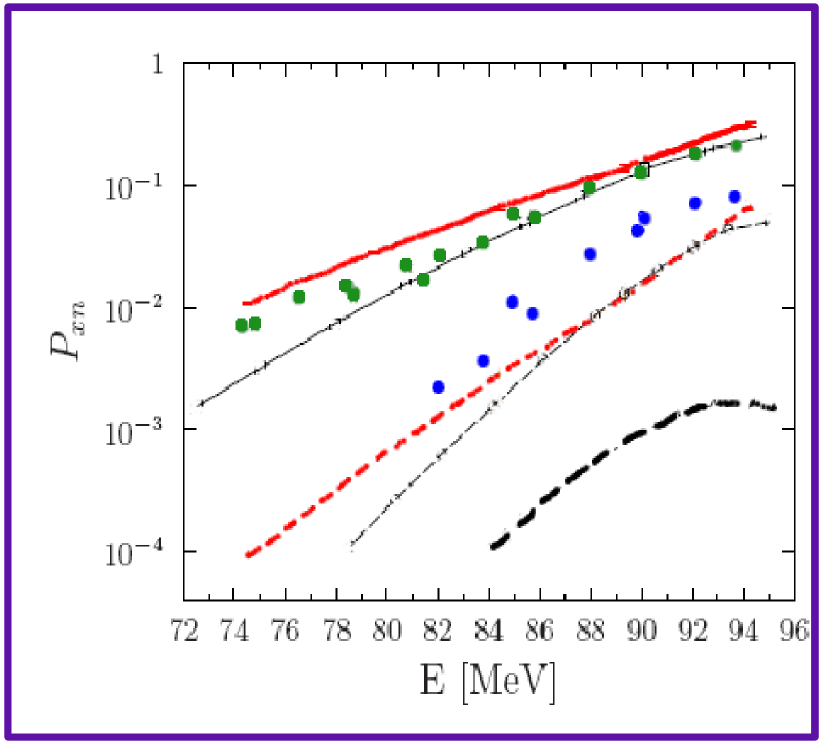


C.Simenel, PRL105(2010)192701

M.Evers et al, PRC84(2011)054614

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

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



L.Corradi et.al., Phys. Rev. C 84 (2011) 034603
EXP (1n) and (2n);
(1n) c.c.; (2n) (g.s. →g.s.)
(g.s. → 0+ at ~6MeV)

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

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 fine details of such processes.

✓The total, differential cross sections and individual state yield distribution reflect a strong interplay between single-particle and collective degrees of freedom and the reaction dynamics: transfer reactions are sensitive to the transferred angular momentum (good matching), the nuclear matrix element contains the spectroscopic information (both of the projectile and target).

✓The importance of components responsible for the couplings (phonon-single particle), and for particle correlations (residual interaction)

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

OUTLOOK:
gamma-particle coincidences
proton transfer channels at large D
proton rich nuclei (np correlations)
neutron rich nuclei (density dependent forces)
very heavy systems
microscopic calculations for high multipolarity states

L. Corradi, T. Mijatović, E. Fioretto, A. Gadea, D. Montanari, A.M. Stefanini, J.J. Valiente-Dobon, E. Farnea, G. Montagnoli, C.A. Ur, S. Lunardi, C. Michelagnoli, N. Marginean, F. Haas, S. Courtin, D. Lebhertz, A. Goasduff, M.-D. Salsac
D. Jelavić Malenica, N. Soić
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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.

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