New opportunities offered by heavy ion transfer reactions

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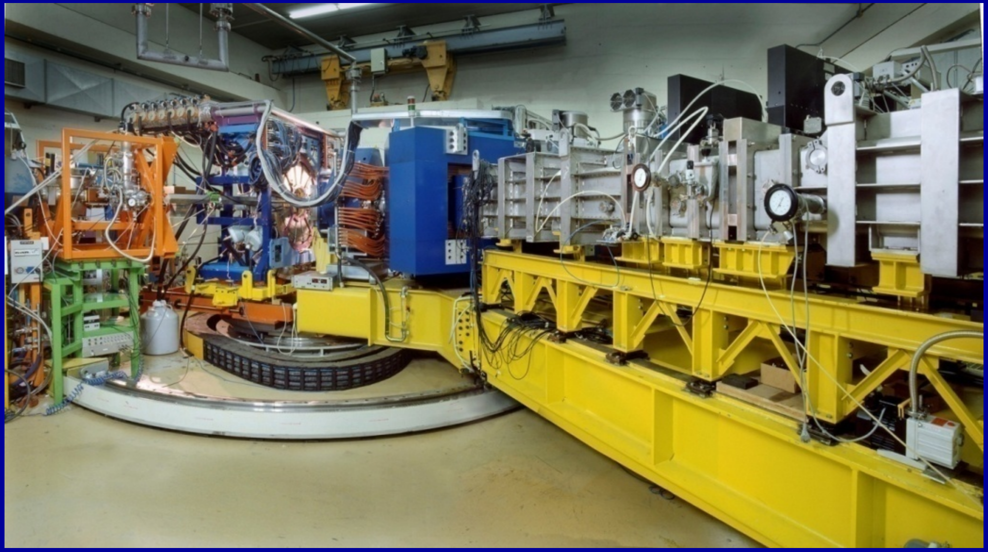
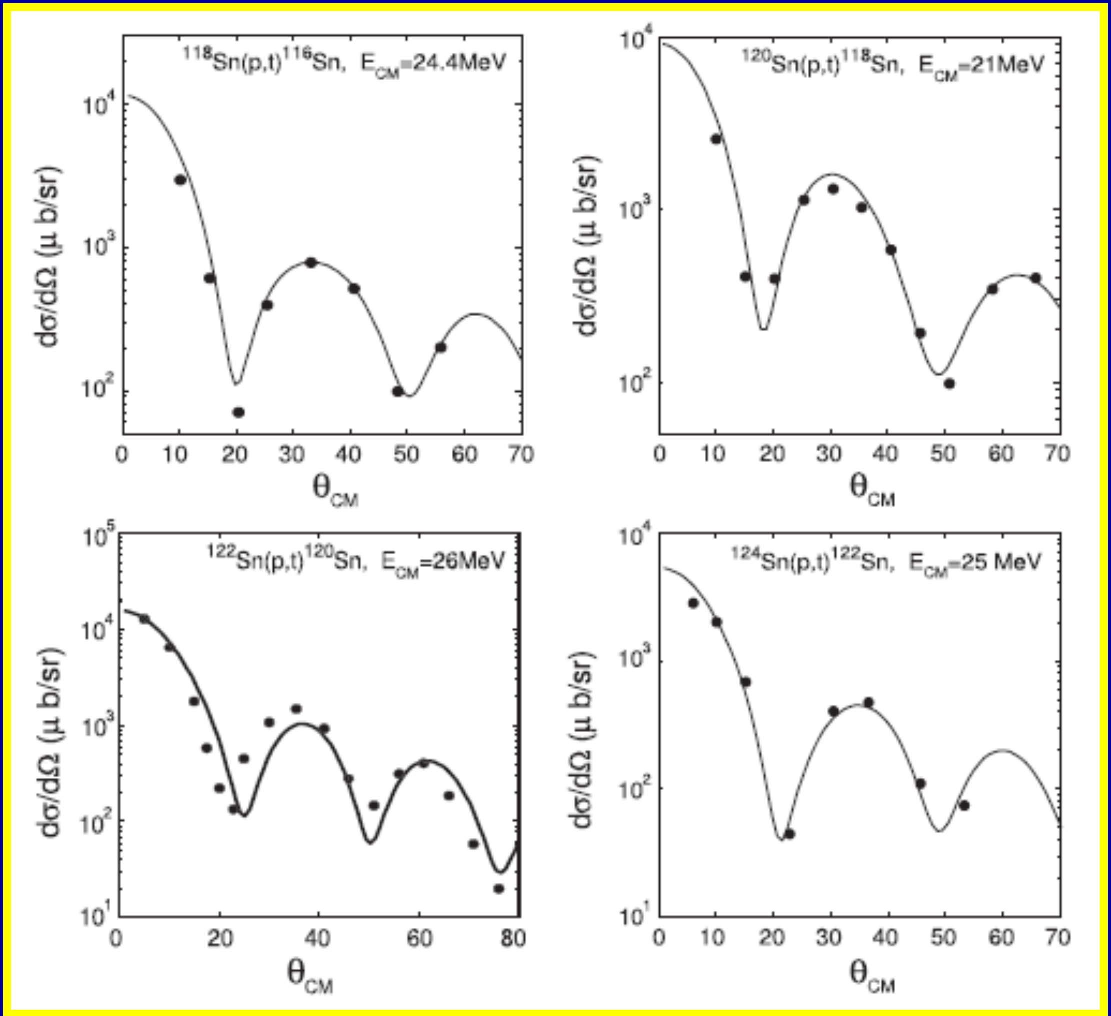


NUSPRASEN Workshop on Nuclear Reactions,
Warsaw (Poland) - January 22-24, 2018

Part I
nucleon nucleon correlations

Part II
production of neutron-rich nuclei

(p,t) reactions : absolute cross sections

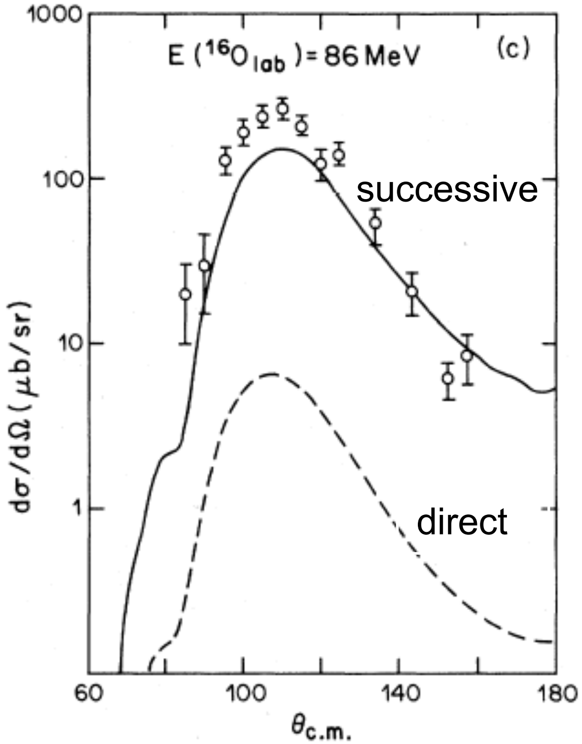


recently performed calculations for two neutron transfer reactions match the experimental data with high accuracy

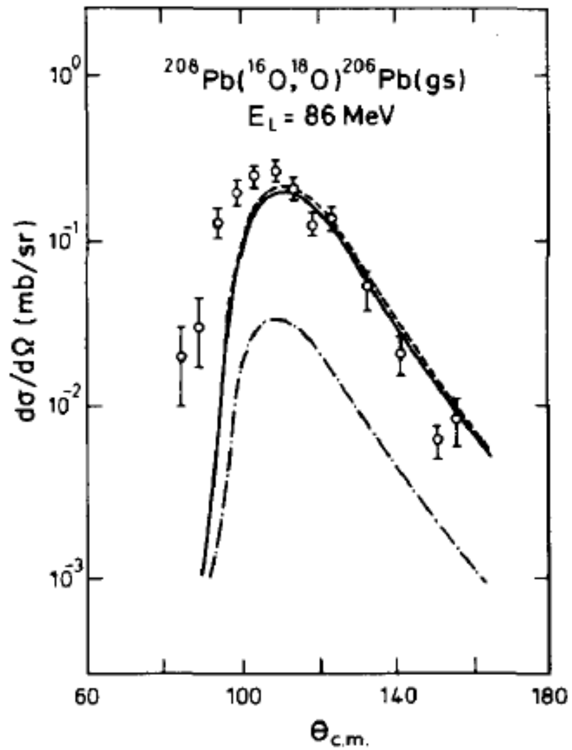
G.Potel et al.,PRL107(2011)092501

Absolute cross sections for one and two-nucleon transfer reactions

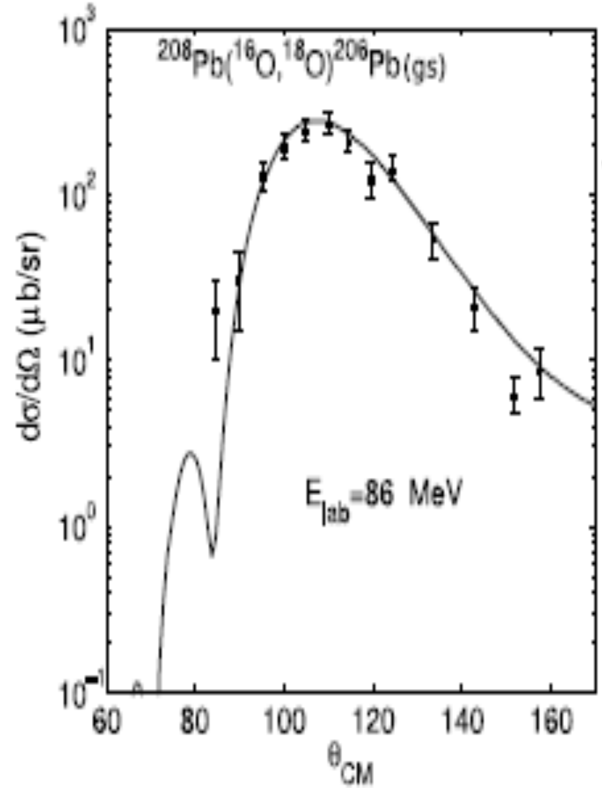
$^{208}Pb(^{16}O,^{18}O_{g.s.})^{206}Pb$



B.F.Bayman and J.Chen, PRC26(1982)1509



E.Maglione , G.Pollarolo, A.Vitturi, R.A.Broglia and A.Winther PLB162(1985)59

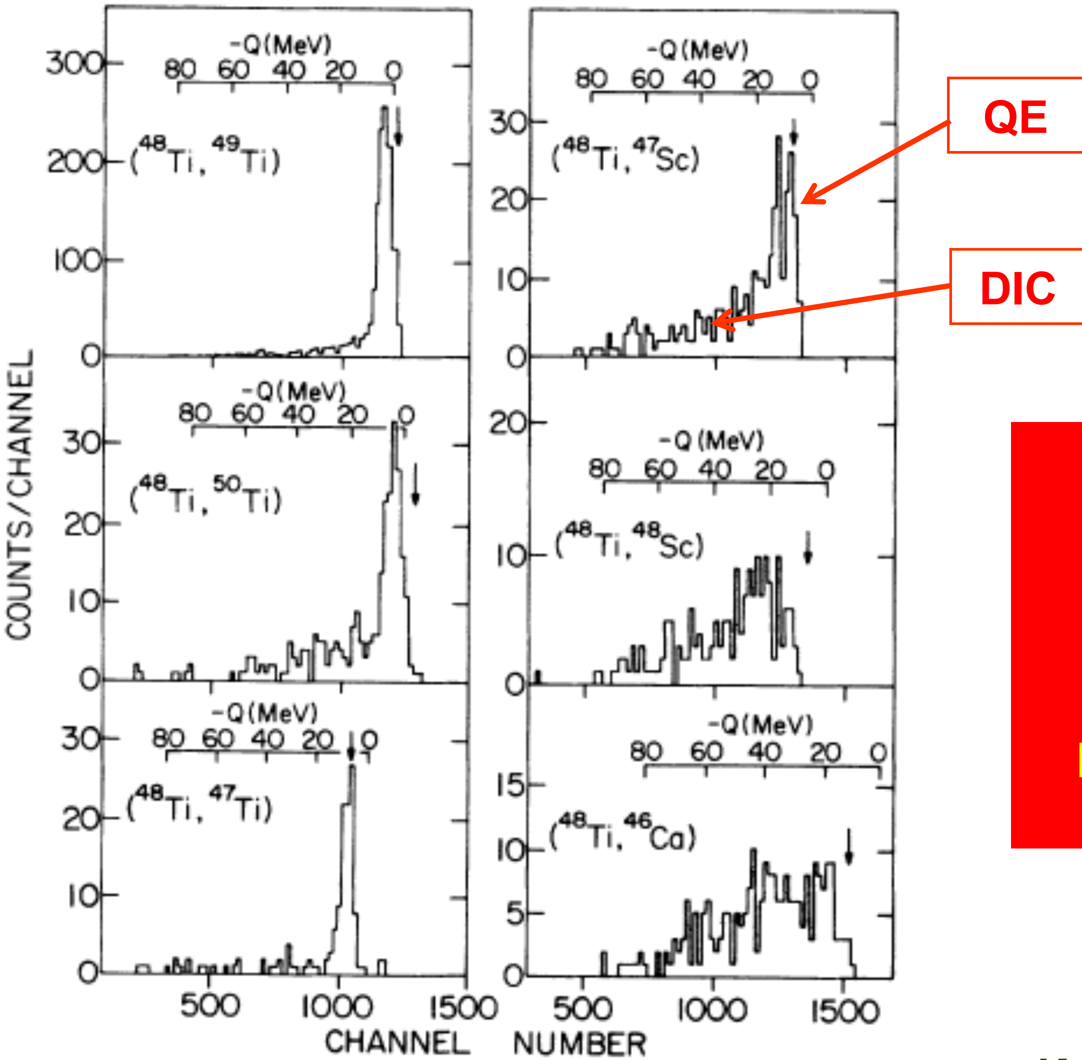


G.Potel, A.Idini, F.Barranco, E.Vigezzi and R.A.Broglia Rep.Prog.Phys.76(2013)106301

full quantum mechanical | **semiclassical** | **full quantum mechanical**

Quasi-elastic (QE) and Deep Inelastic (DIC) regime in multinucleon transfer reactions : Q-values

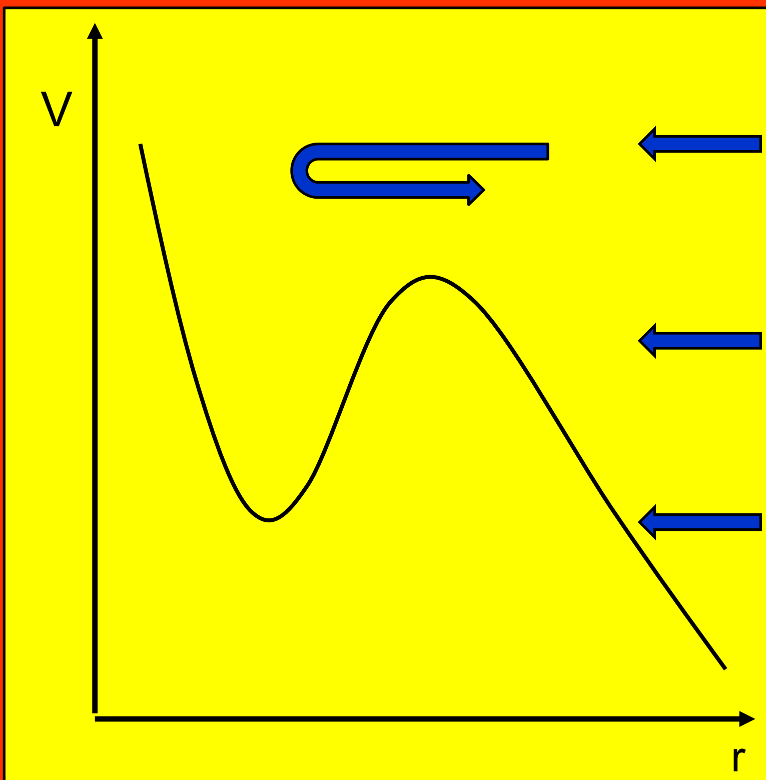
$^{48}Ti + ^{208}Pb$, E_{lab} = 300 MeV, θ_{lab} = 55°



with heavy ions the general difficulty met in both experiments and theory is to deal with limited energy resolutions and with the presence of both QE and DIC components

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

Transfer studies at energies below the Coulomb barrier: advantages

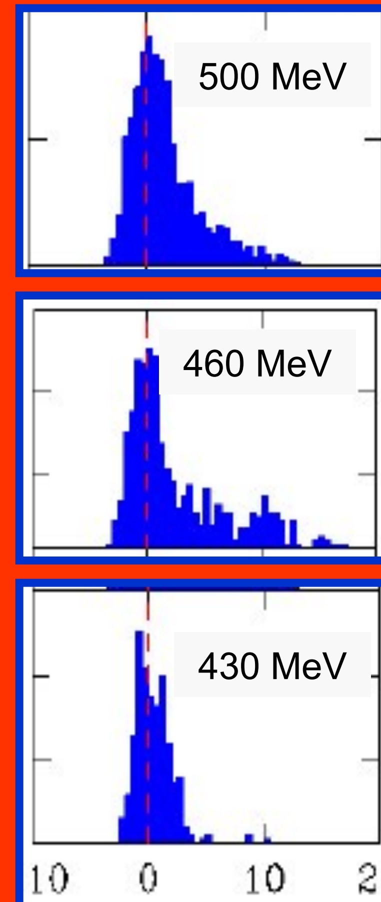


E > E_b

E ~ E_b

E < E_b

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



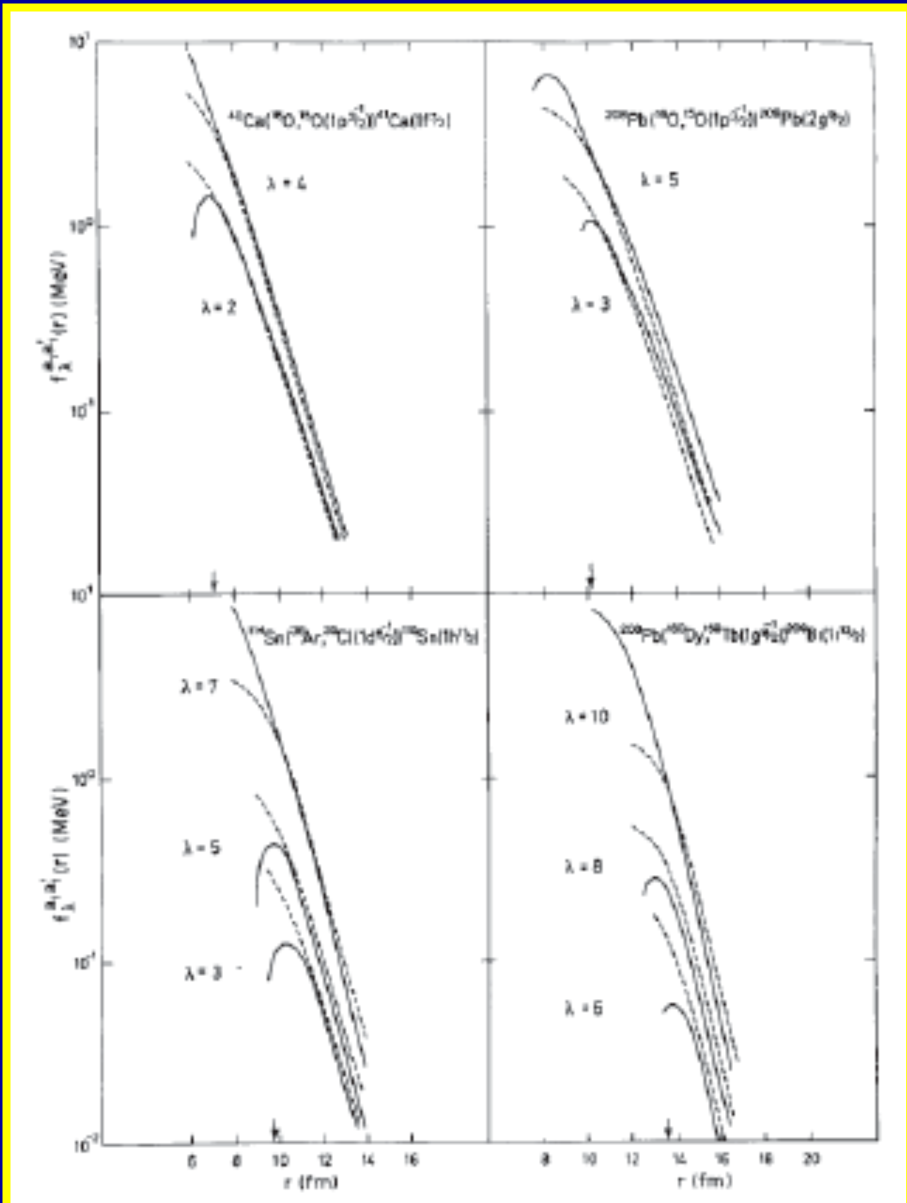
large number of open channels, DIC components

the number of open channels and uncertainties with the nuclear potential reduce

one gets very narrow Q-value distributions: no evaporation effects

below the barrier one can probe nucleon-nucleon correlations as close as possible to the ground to ground states

Quasi elastic processes : form factors



$$\langle \omega_\beta | (V_\gamma - U_\gamma) | \psi_\gamma \rangle = f_{\beta\gamma}(\vec{\kappa}, \vec{r})$$

$$f_{\beta\gamma}(\vec{\kappa}, \vec{r}) \sim \mathrm{e}^{\mathrm{i}\sigma_{\beta\gamma} t} f_{\beta\gamma}(0, \vec{r})$$

the form factor is a matrix element between initial and final states in the transfer process and reflects nuclear structure properties of the donor and acceptor binary partners

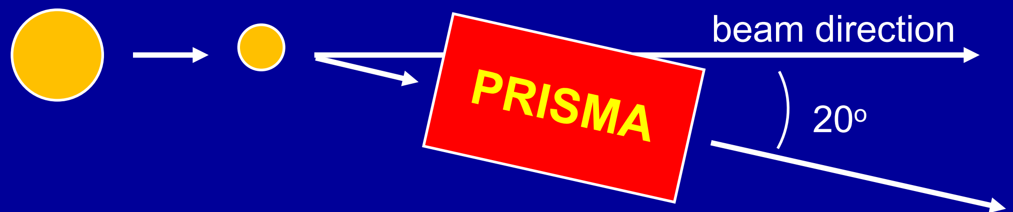
$$f_{\beta\gamma}(0, r) \propto \frac{1}{\kappa_{a_1'} r} \mathrm{e}^{-\kappa_{a_1'} r}.$$

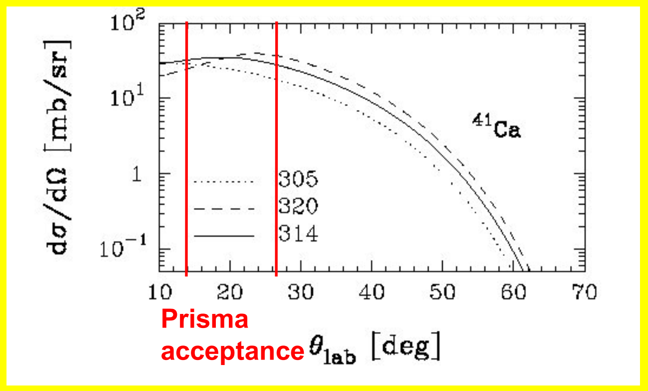
the form factor has an exponential shape in its tail region

J.M.Quesada et al, NPA442 (1985)381

Detection of (light) target like ions in inverse kinematics with PRISMA

^{96}Zr ^{40}Ca L.Corradi et al, PRC84(2011)034603



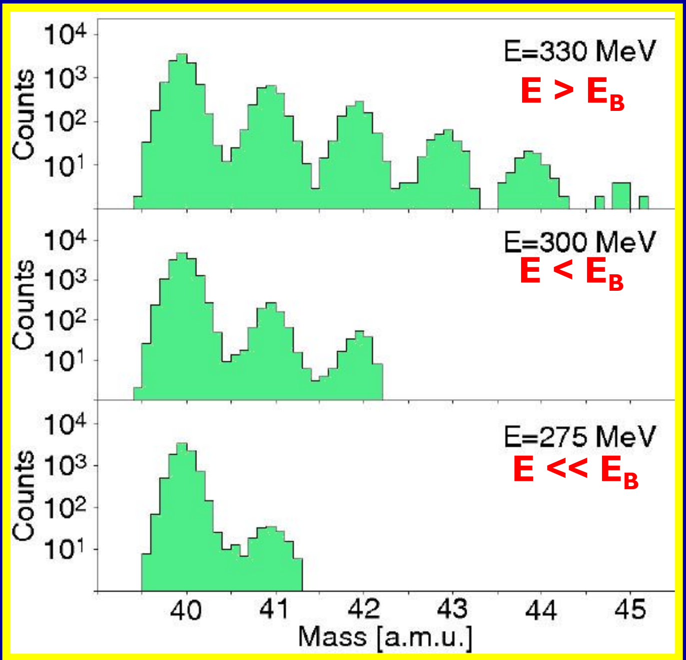


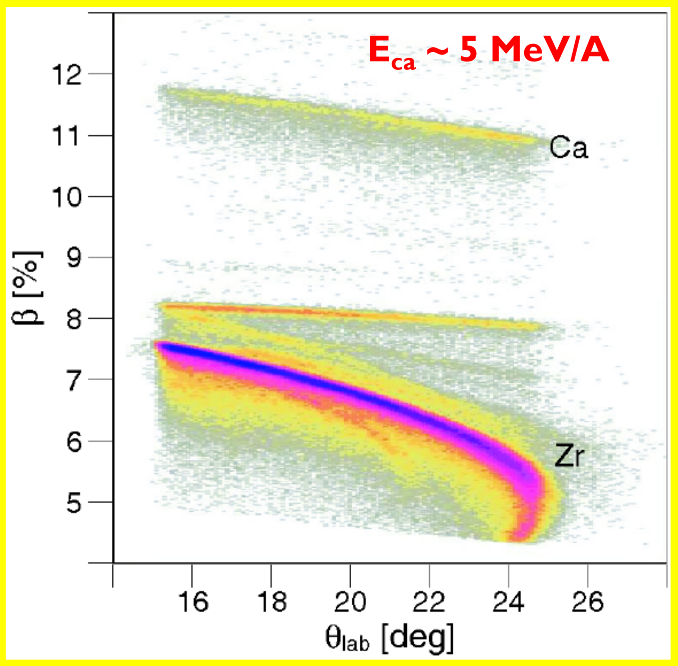
^{116}Sn ^{60}Ni D.Montanari et al, PRL113(2014)052501

^{92}Mo ^{54}Fe S.Szilner et al, in analysis phase

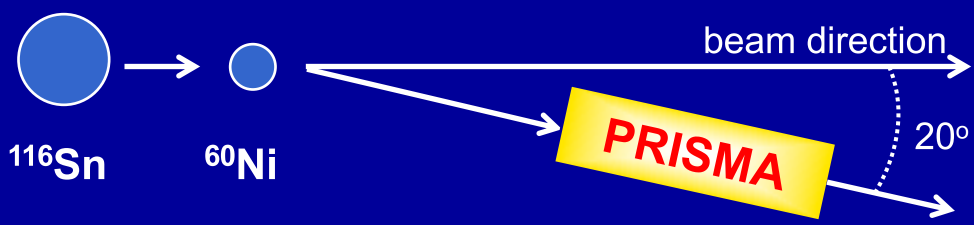
^{206}Pb ^{118}Sn L.Corradi et al, scheduled on Feb. 2018

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

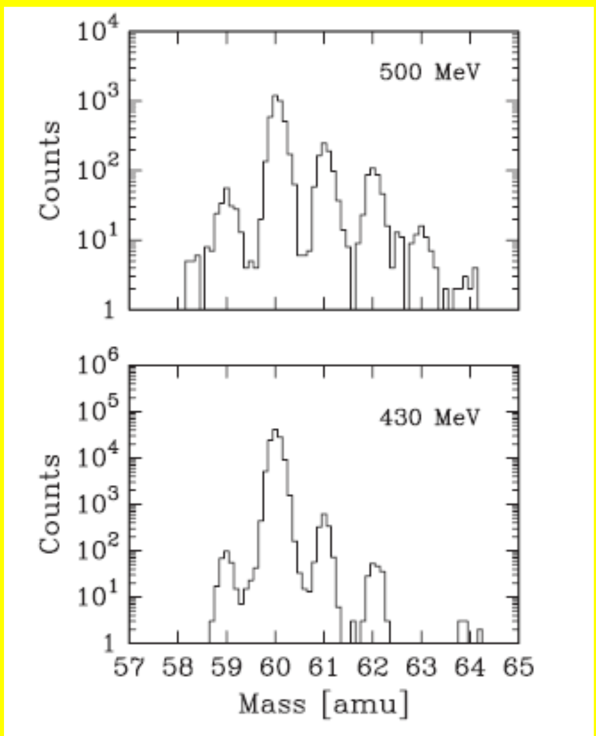




Detection of (light) target like ions in inverse kinematics with PRISMA



excellent mass resolution at energies below the Coulomb barrier

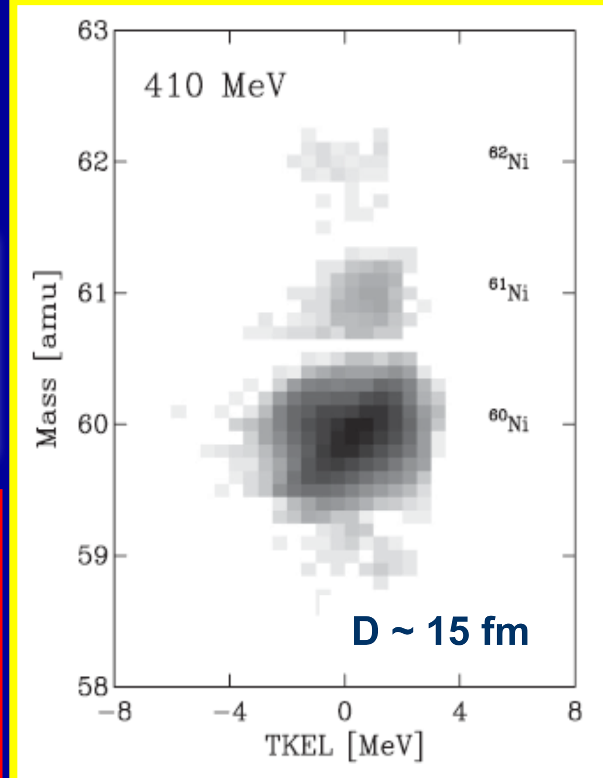


Excitation function

E_{beam} = 410 – 500 MeV

(D ~ 12.3 to 15.0 fm)

ground to ground state Q-values very close to optimum Q-values (~ 0 MeV)

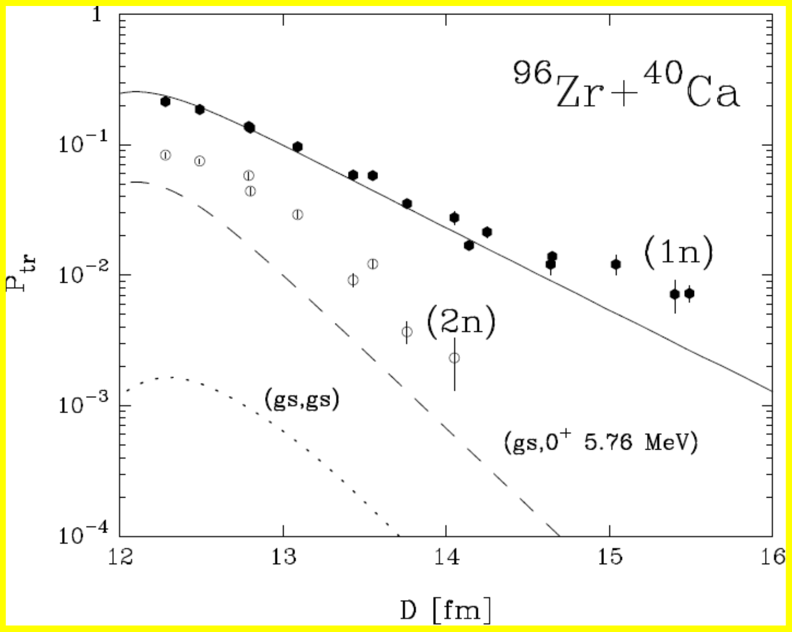


g.s. Q-values	+1n	+2n	+3n	+4n
^{96}Zr + ^{40}Ca	+ 0.51	+ 5.53	+ 5.24	+ 9.64
^{116}Sn + ^{60}Ni	- 1.74	+ 1.31	- 2.15	- 0.24

D.Montanari et al., INPC2013 and PRL2014

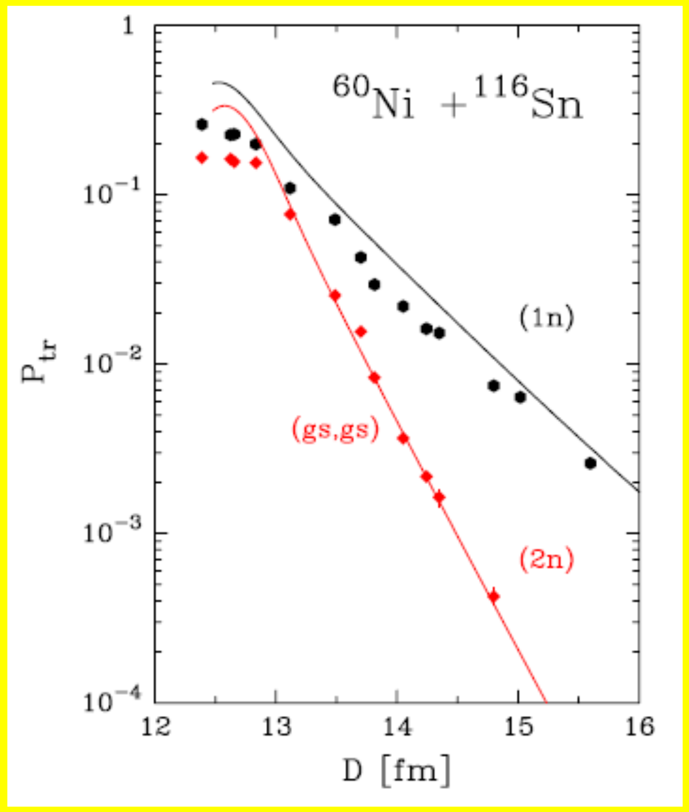
Transfer probabilities : comparison between exp and microscopic theory

$Q_{g.s.}$ for +2n + 5.5 MeV , far from Q_{opt} (~ 0 MeV)



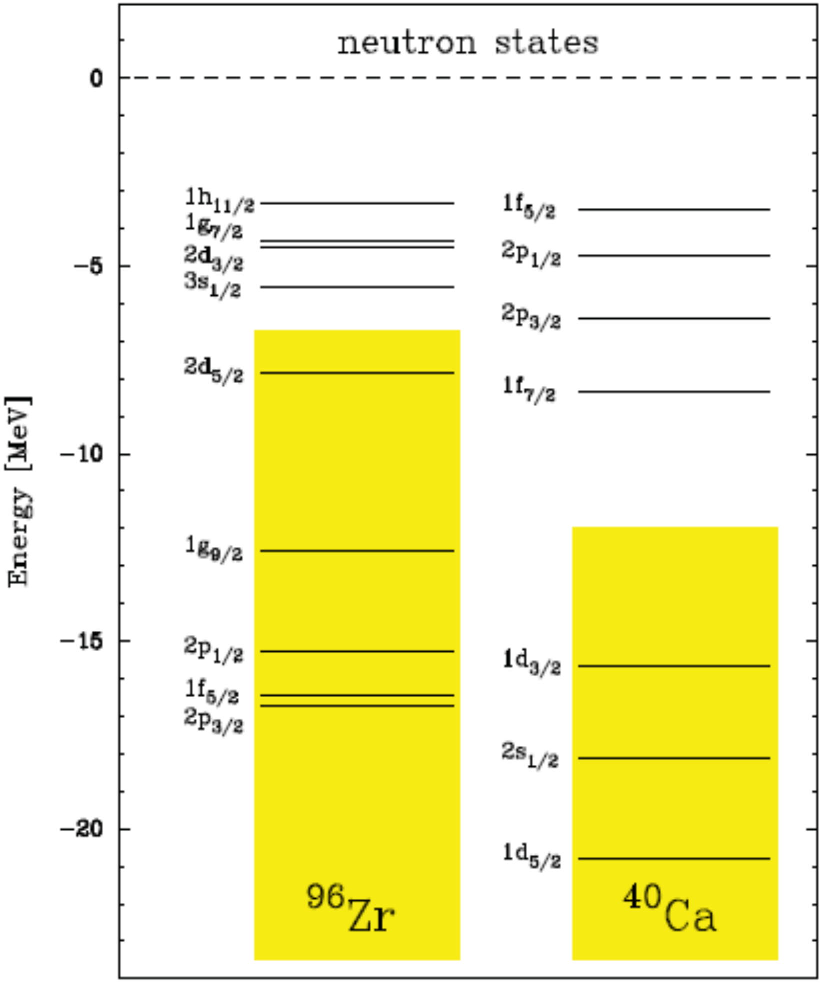
L.Corradi, S.Szilner, G.Pollarolo et al, PRC84(2011)034603

$Q_{g.s.}$ for +2n very close to Q_{opt} (~ 0 MeV)



D.Montanari, L.Corradi, S.Szilner, G.Pollarolo et al, PRL113(2014)052501

One particle transfer (semiclassical theory)



to obtain the total transfer probability we summed over all possible transitions that can be constructed from the single particle states in projectile and target

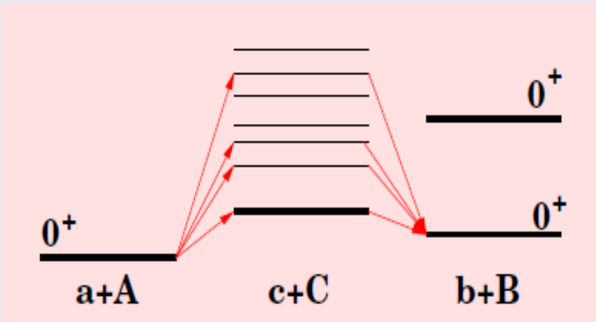
the set of single particle states covers a full shell below the Fermi level for ^{96}Zr and a full shell above for ^{40}Ca

$$c_\beta(\ell) = \frac{1}{i\hbar}\int_{-\infty}^{+\infty} \langle \psi_\beta | (V_\alpha - U_\alpha) | \psi_\alpha \rangle_{\mathcal{R}} e^{i(E_\beta - E_\alpha)t/\hbar} dt$$

$$P_\beta(\ell) = P_{(a_1, a_1')}(\ell) = \sum_{m_1', m_1} |c_\beta(\ell)|^2$$

Two particle transfer (semiclassical theory, microscopic calculations)

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



3 terms : simultaneous, orthogonal and successive

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

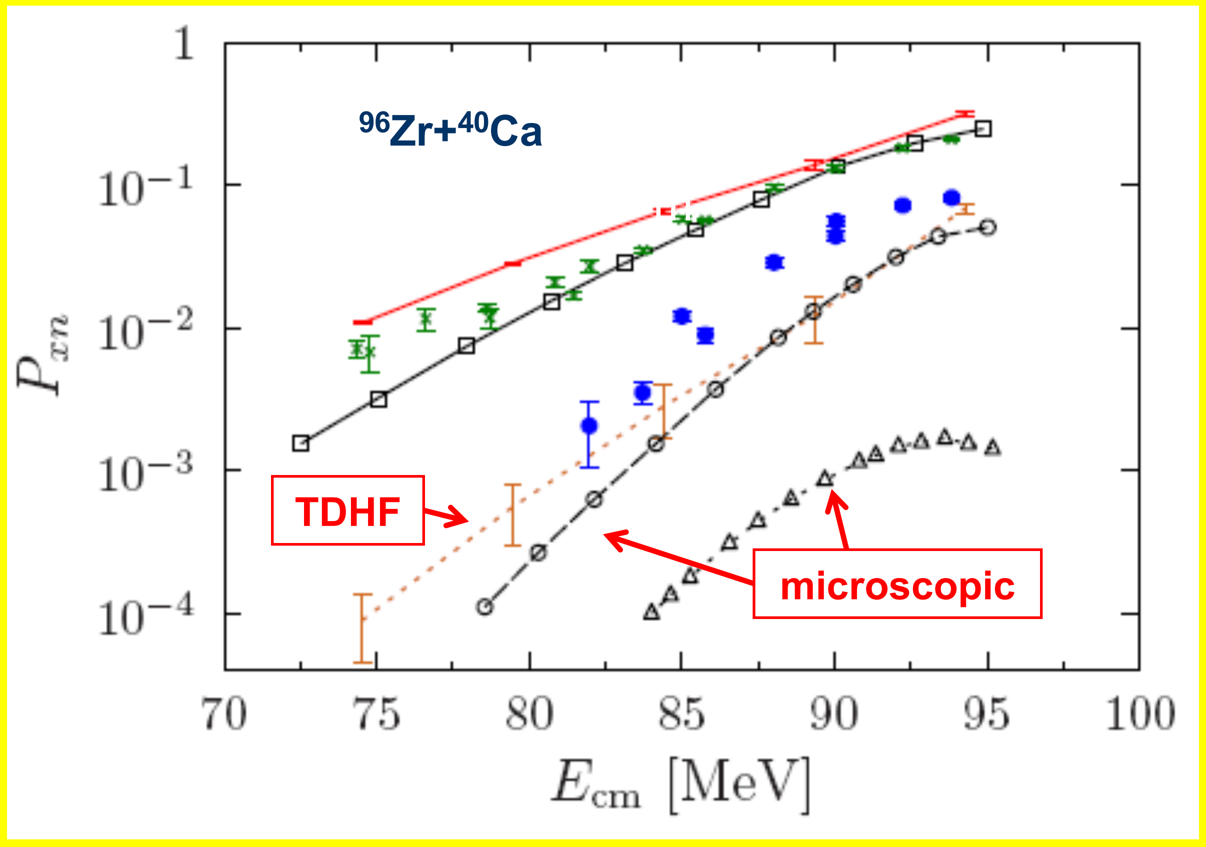
only the successive term contributes to the transfer amplitude

only the 0+ to 0+ transitions can be reduced to a simple expression

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

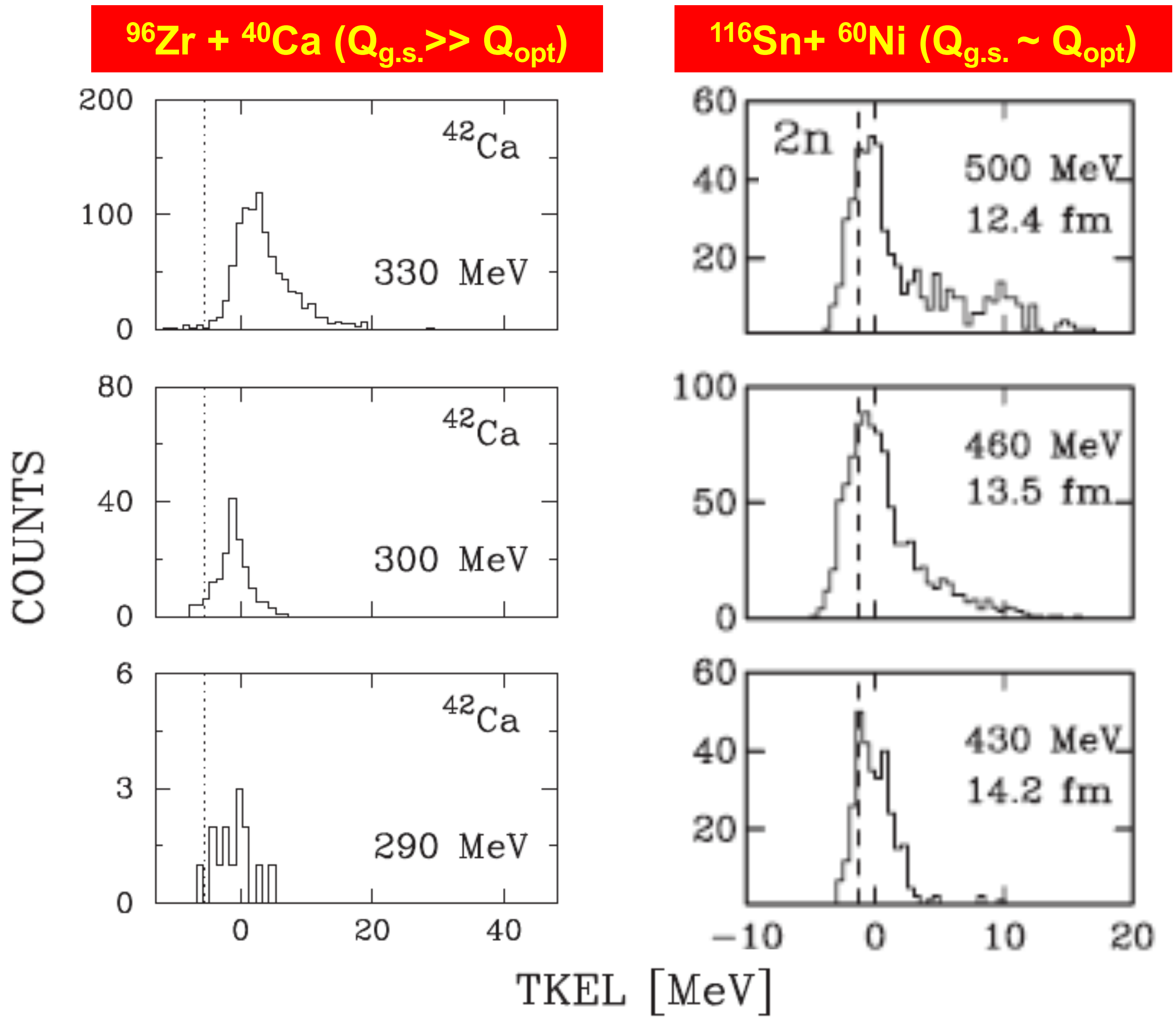
Sub-barrier transfer : comparison between data and TDHF calculations

Data : Legnaro Nat. Lab.
Theory: simplified TDHF+BCS limit



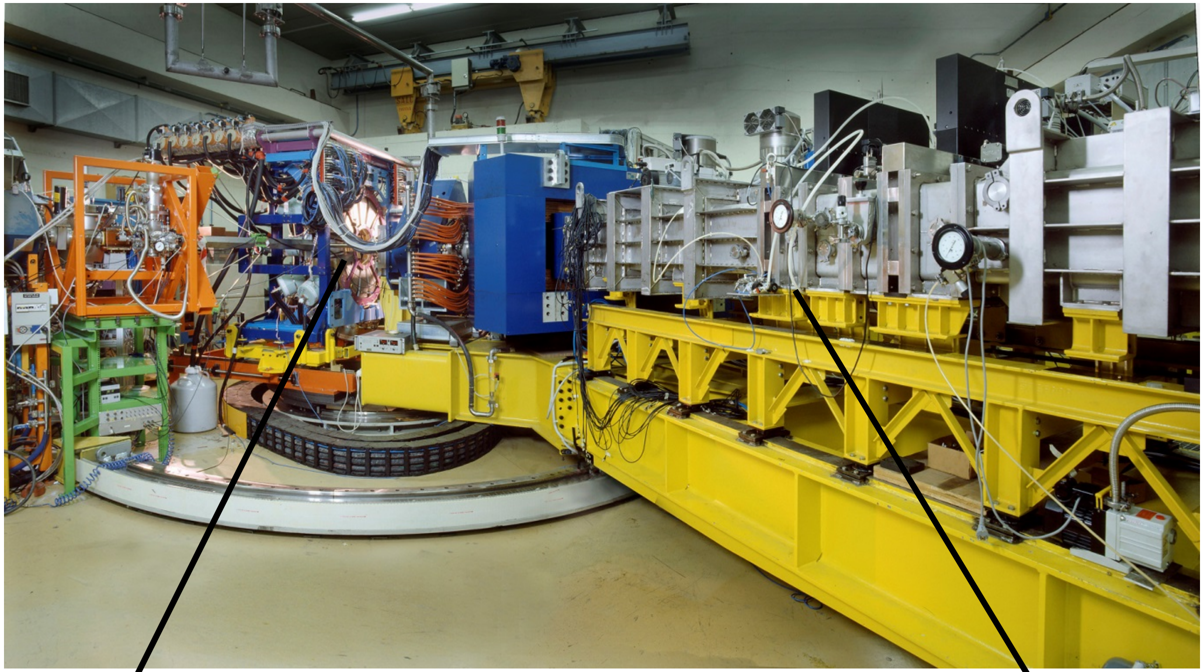
G.Scamps and D.Lacroix,
EPJ Web Conf. 86, (2015) 00042

Total kinetic energy loss distributions for the +2n channels



The key difference between the two cases lies in the relative position of the g.s. Q-values with respect to the optimum Q-values for neutrons

Probing directly the population to the ground to ground states



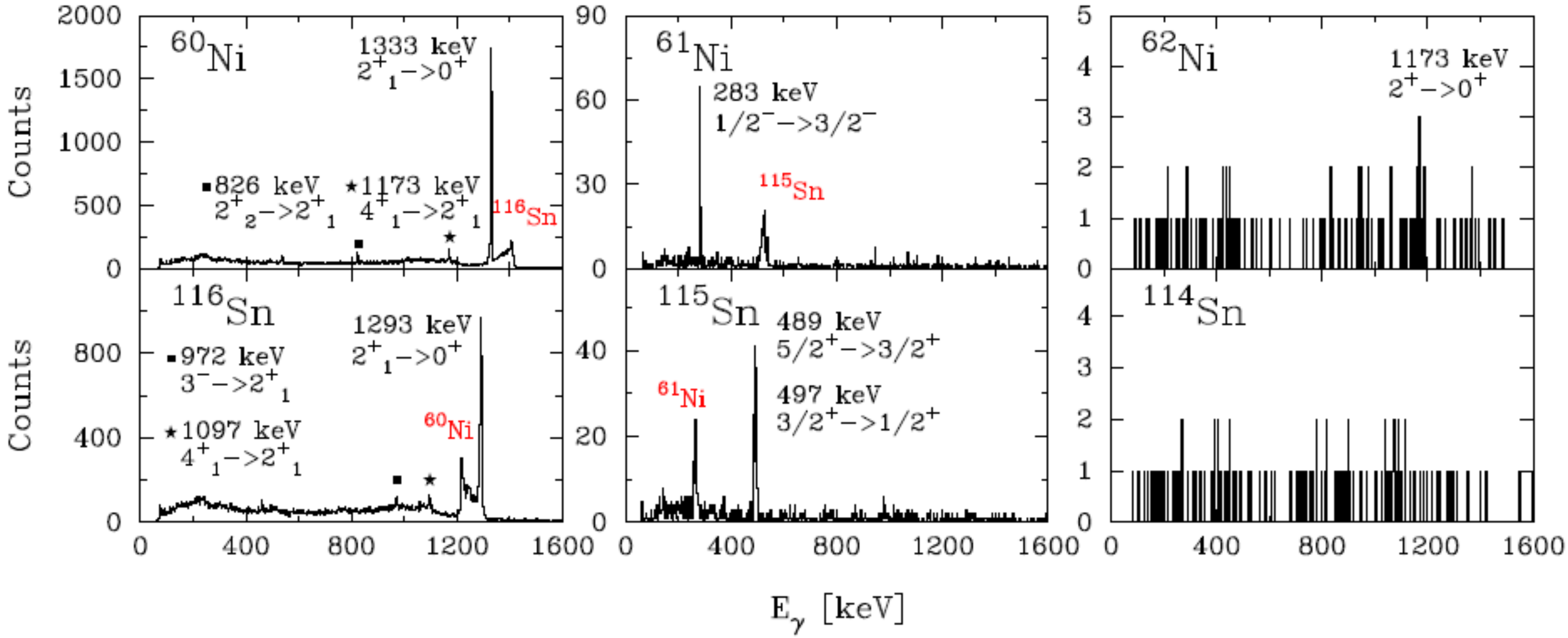
from the gamma array one gets the strength to excited states $\longrightarrow \sigma_{exc}$

from the magnetic spectrometer one gets A,Z,Q (inclusive) $\longrightarrow \sigma_{tot}$

simplifying…

$$\sigma_{g.s.} = \sigma_{tot} - \sigma_{exc}$$

Pair neutron transfer probed via γ-particle coincidence in the ^{60}Ni+^{116}Sn system at E_{LAB}=245 MeV and θ_{LAB}=70°



yields normalized to the 2^+ strength in ^{60}Ni

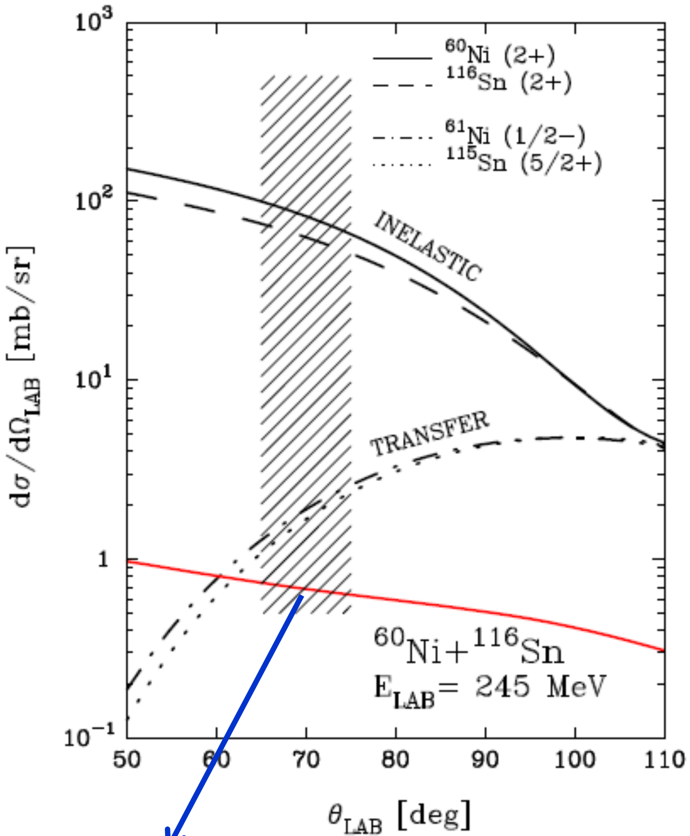
	Experiment	Theory
^{116}Sn(2^+)	0.792 ± 0.160	0.720
^{116}Sn(4^+_1)	0.042 ± 0.011	0.056
^{60}Ni(4^+_1)	0.060 ± 0.013	0.11
^{115}Sn($5/2^+$)	0.018 ± 0.003	0.037
^{61}Ni($1/2^-$)	0.014 ± 0.003	0.033
^{62}Ni(2^+)	< 0.00145	-

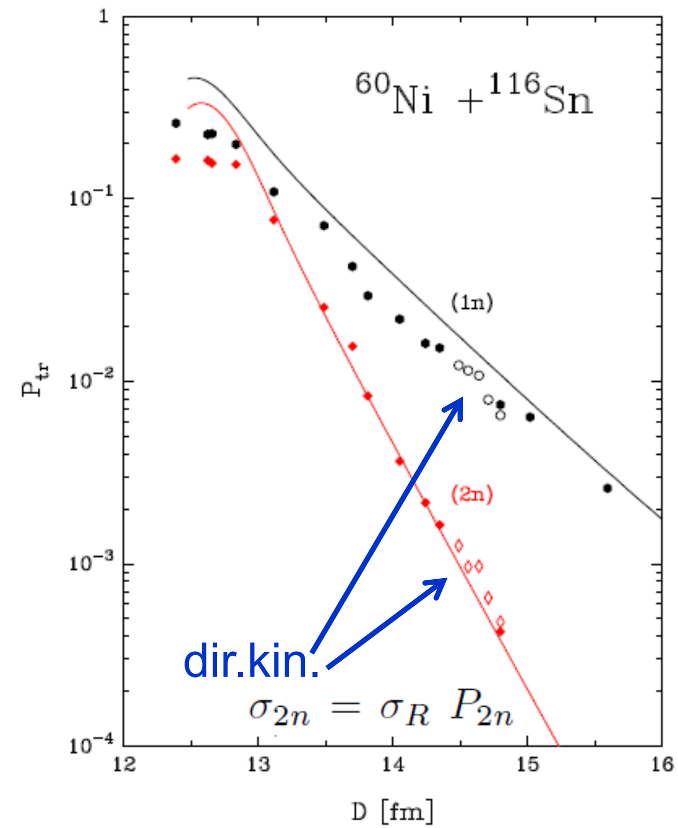
Experiment performed with PRISMA coupled to the AGATA DEMONSTRATOR

D.Montanari, L.Corradi, S.Szilner, G.Pollarolo et al, PRC93(2016)054623

Pair neutron transfer probed via γ-particle coincidence

by using the strength obtained with the gamma data for the inelastic and neutron transfer channels and with information from coupled-channel calculations we were able to quote that the fraction of the 2n channel populating the ground to ground state is larger than 76 %



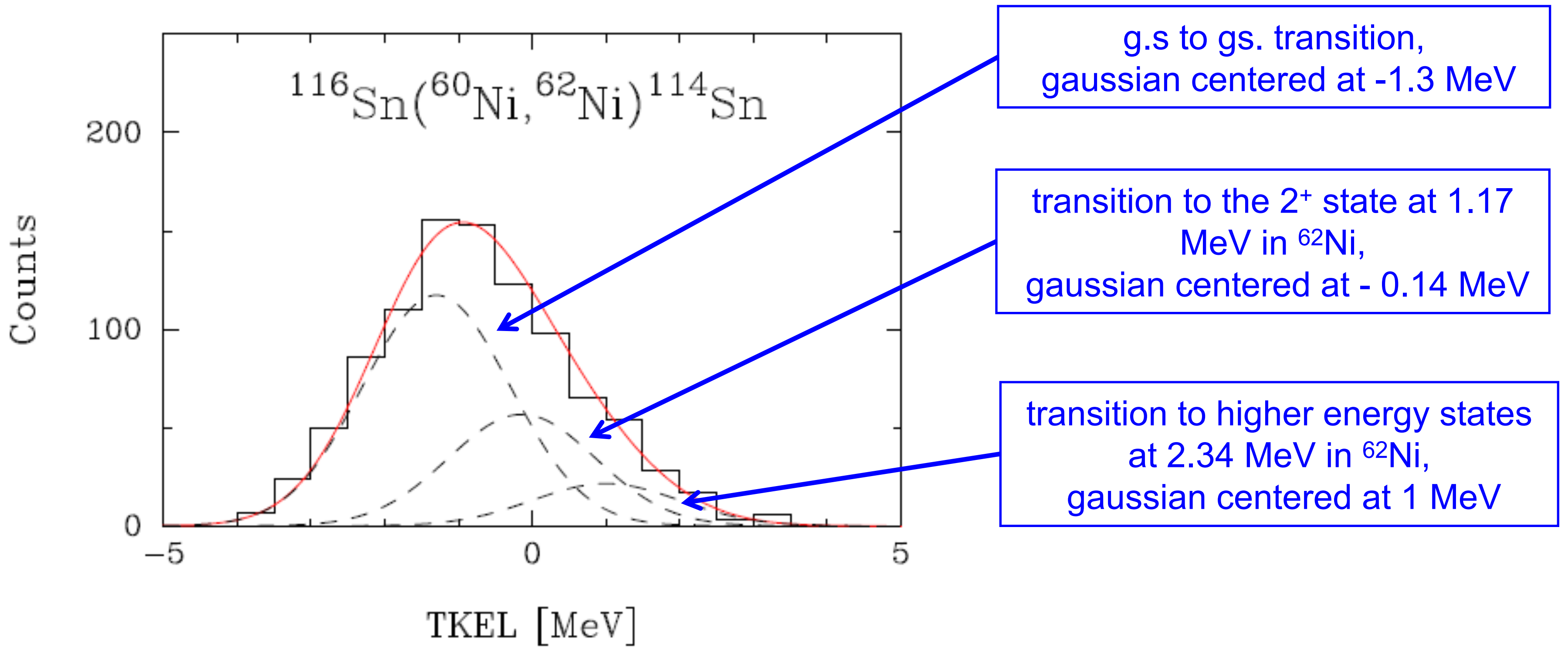


$$\sigma_R\left(1-\frac{\sigma_{el}}{\sigma_R}\right)=\sigma(2^+,{}^{60}\mathrm{Ni})\left(1+\frac{\sigma(2^+,{}^{116}\mathrm{Sn})}{\sigma(2^+,{}^{60}\mathrm{Ni})}\right)$$

consistent comparison between inverse kinematics and direct kinematics data

Pair neutron transfer probed via γ-particle coincidence

Analysis of the experimental TKEL distributions measured with PRISMA



the analysis shows that the 2+ states contribute 29% to the total transfer strength, in reasonable good agreement with the 24% estimation from the gamma strength

Sub-barrier transfer : much more work to be done

gamma-particle coincidences

proton transfer channels at large D

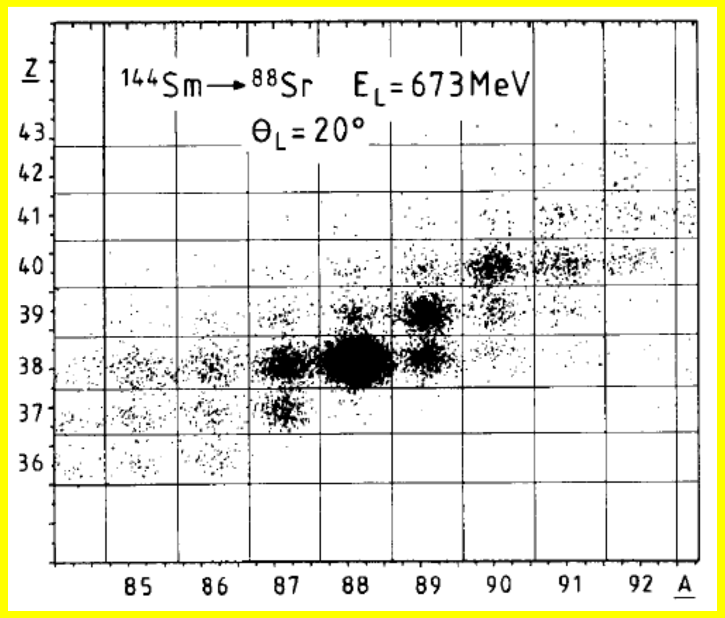
very heavy systems

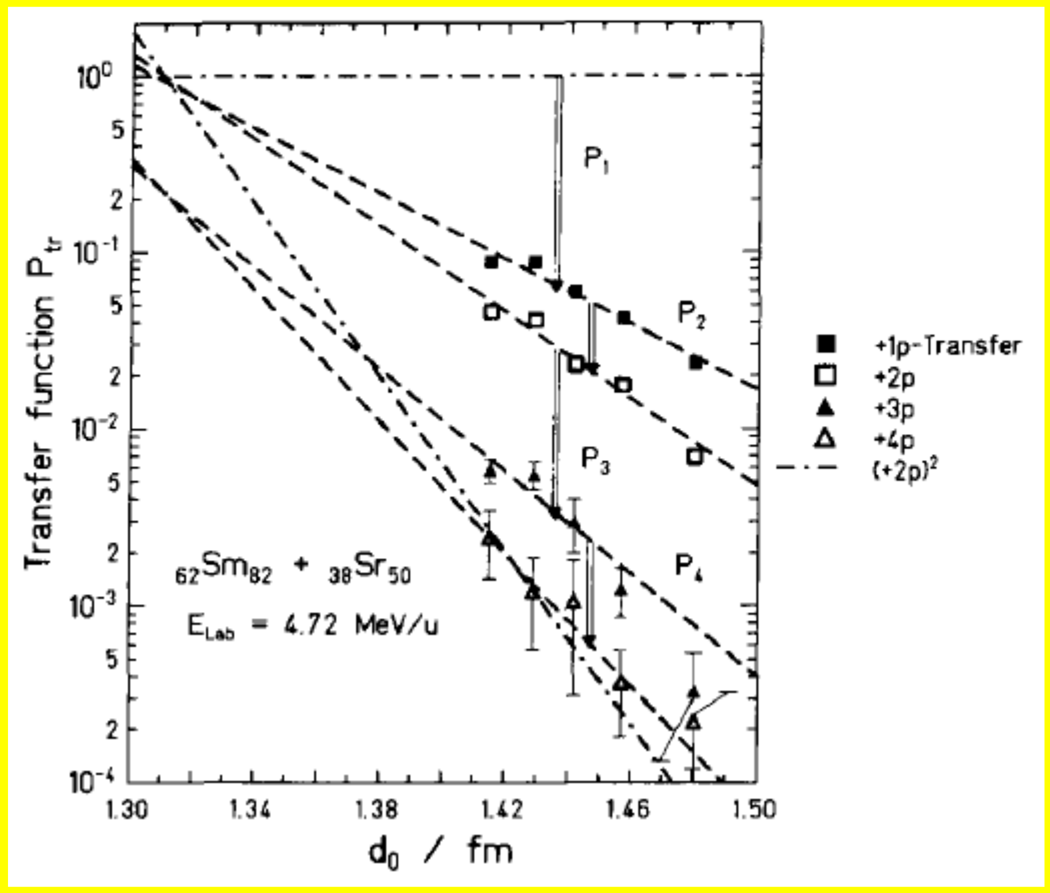
reactions with proton rich nuclei (also for np correlations)

reactions with neutron rich nuclei (density dependent forces)

need to develop calculations incorporating nn correlations,
in general for high multipolarity states

Sub-barrier transfer : proton channels



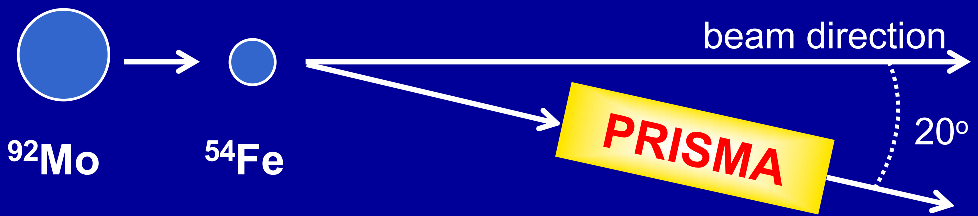


data are available, but for small D's, where absorption plays a big role

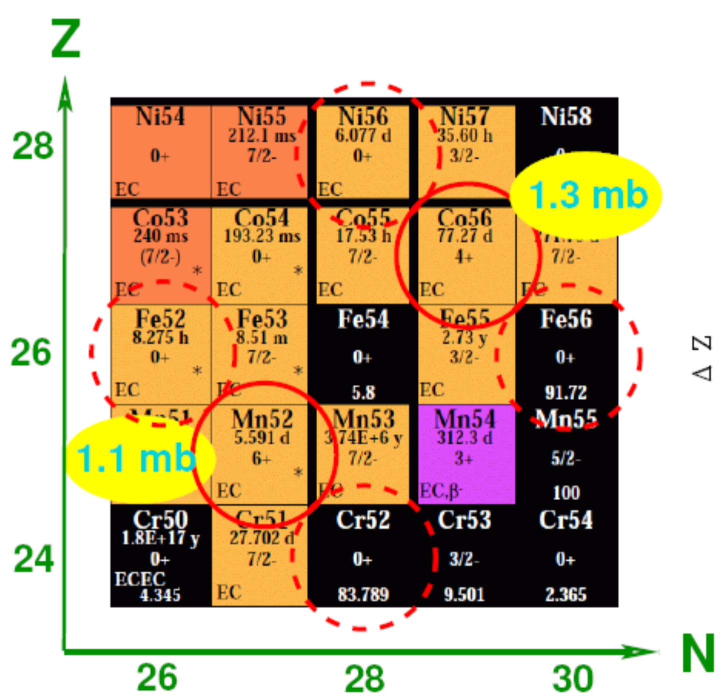
the interpretation of the enhancement factors is done at the phenomenological level

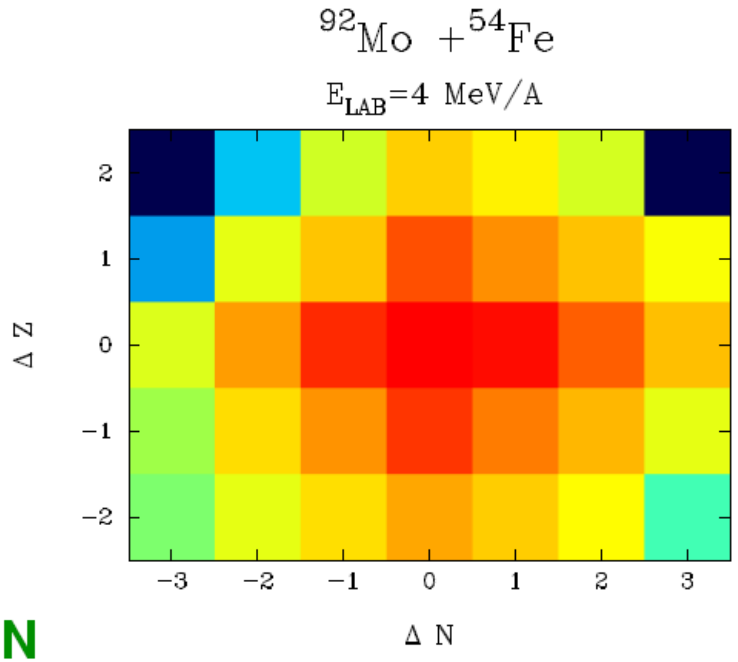
R.Kunkel et al., PLB208(1988)355

Sub-barrier transfer : np correlations in proton-rich nuclei



Study of pair-correlation properties, populating at once ±(nn), ±(pp) and ±(np) close to the N = Z = 27 region





S.Szilner, L.Corradi et al,

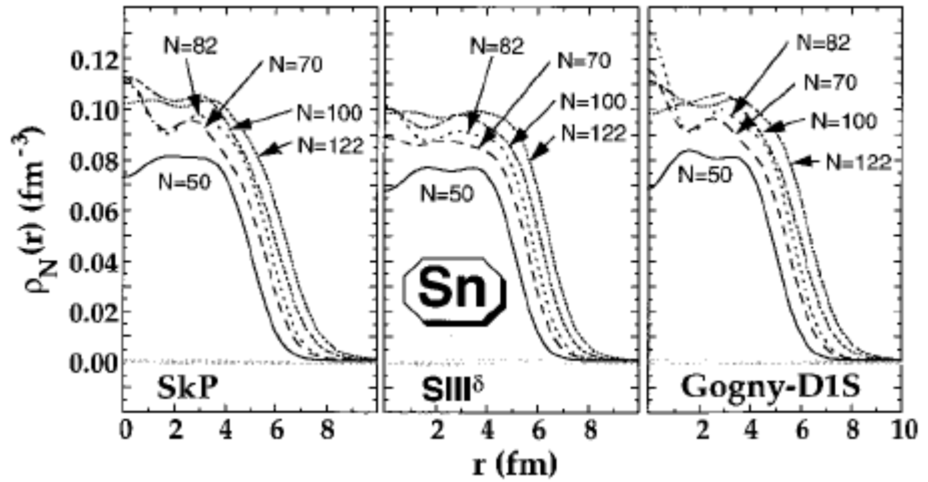
Sub-barrier transfer : neutron rich nuclei

with RIB's, through the behaviour of transfer probabilities we may be able to probe, for instance

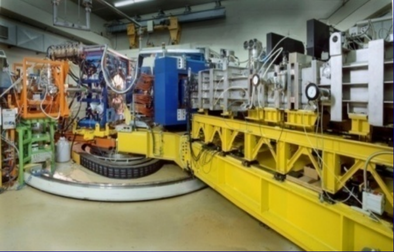
- onset of density dependent forces

$$V_{eff} = \delta(\vec{r}_1 - \vec{r}_2)\left(v_0 + v_p\left(\frac{\rho((\vec{r}_1 + \vec{r}_2)/2)}{\rho_c}\right)^p\right)$$

- neutron density profile



J.Dobaczewski et al., PRL72(1994)981



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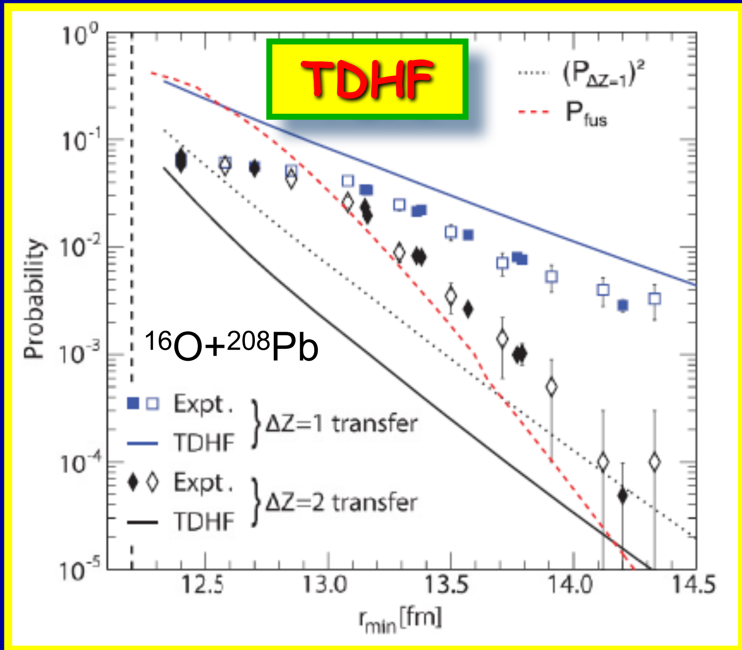
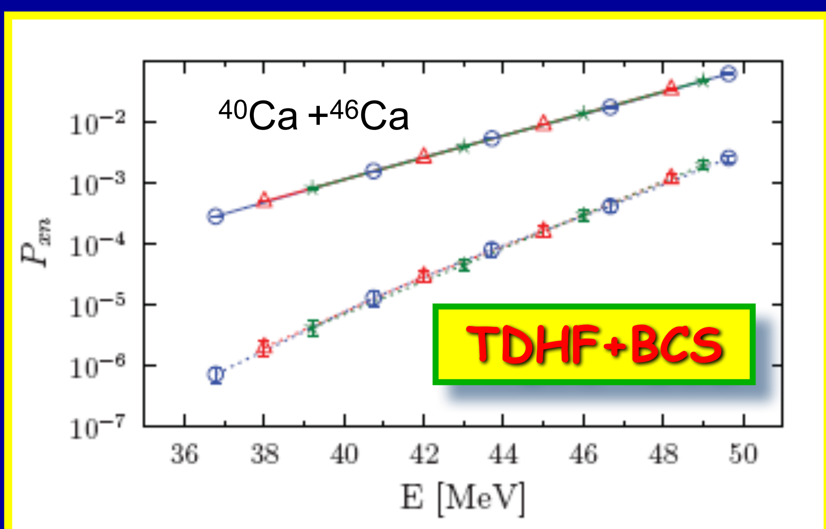
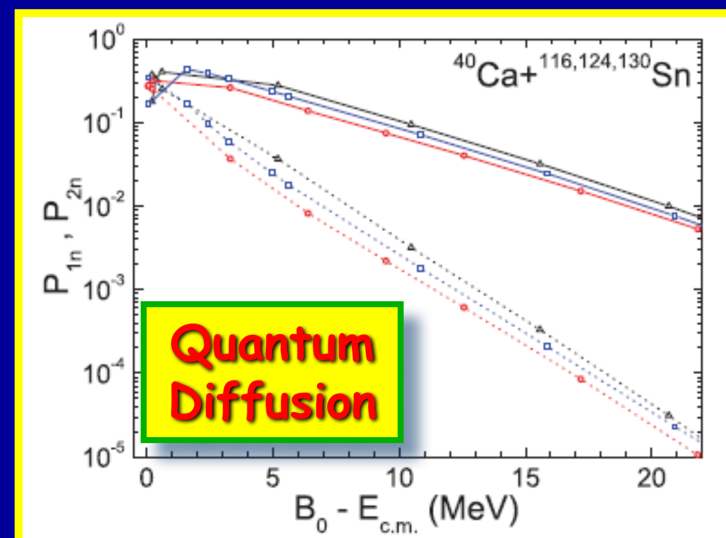
Sub barrier transfer reactions with heavy ions: new exp data are attracting a renewed interest in the theoretical community



C.Simenel, PRL105(2010)192701
M.Evers et al, PRC84(2011)054614

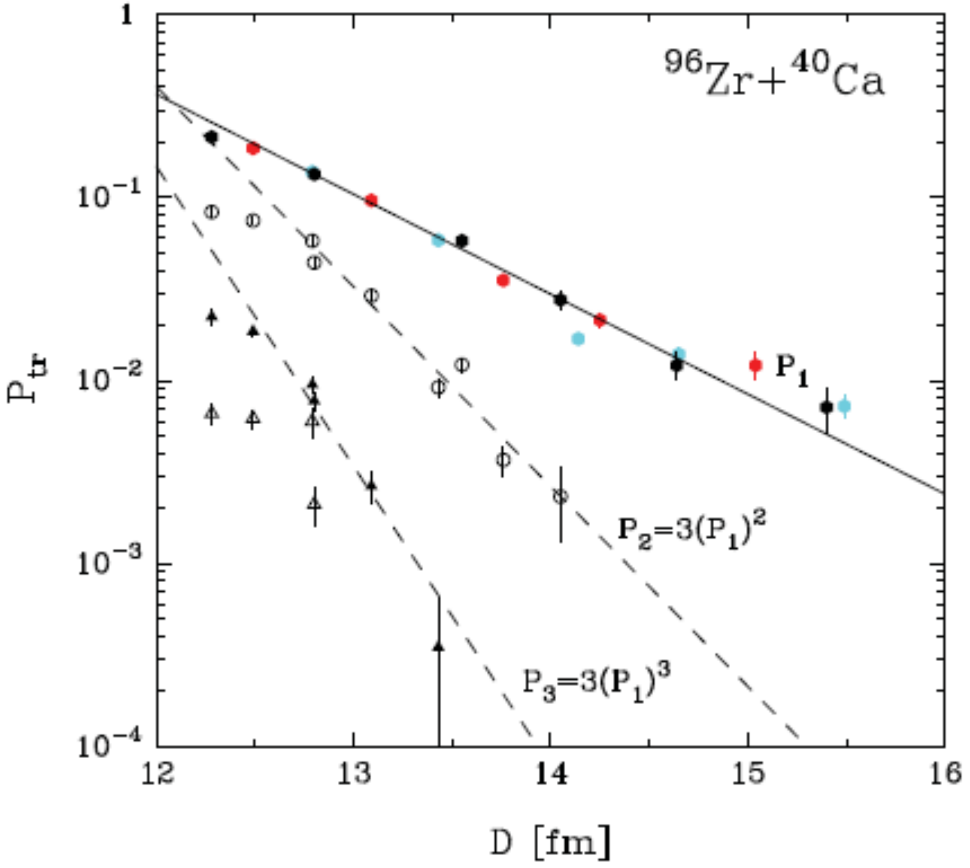


G.Scamps and D.Lacroix, PRC87(2013)014605



V.V.Sargsyan et al, PRC88(2013)064601

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}~ 3 $(P_{1n})^2$ and P_{3n}~ $P_{1n}(P_{2n})$ ~ 3 $(P_{1n})^3$

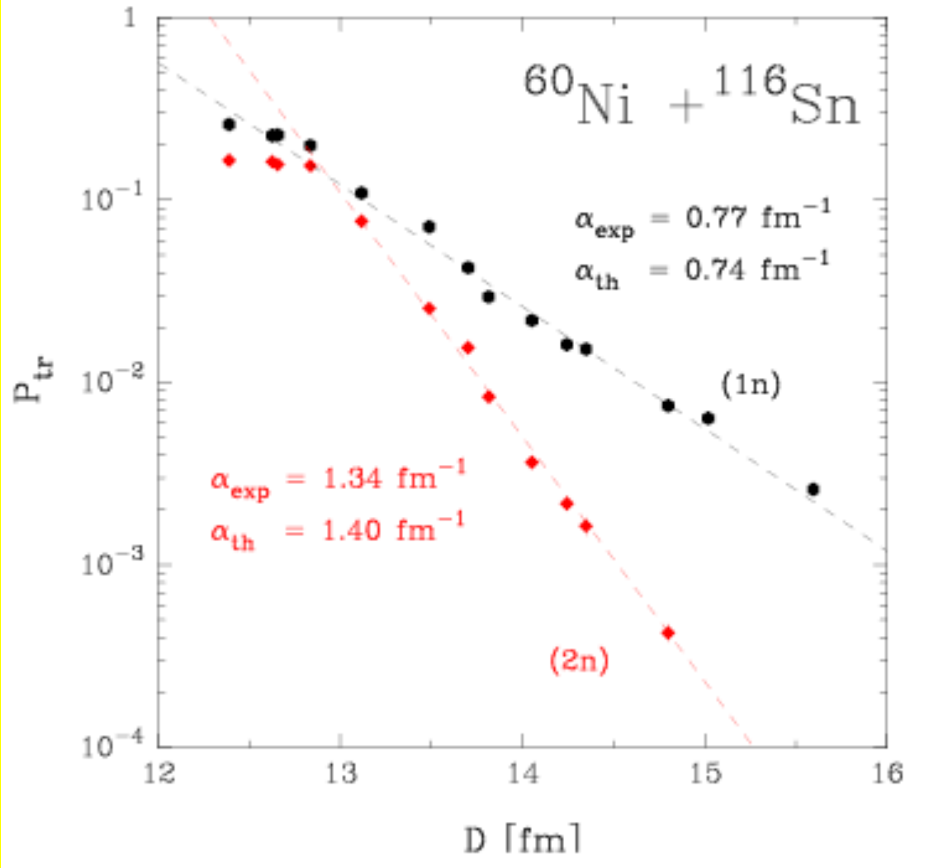
L.Corradi et al, PRC84(2011)034603

P_{tr} slope

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

B → binding energy

The $^{60}Ni+^{116}Sn$ system : experimental results

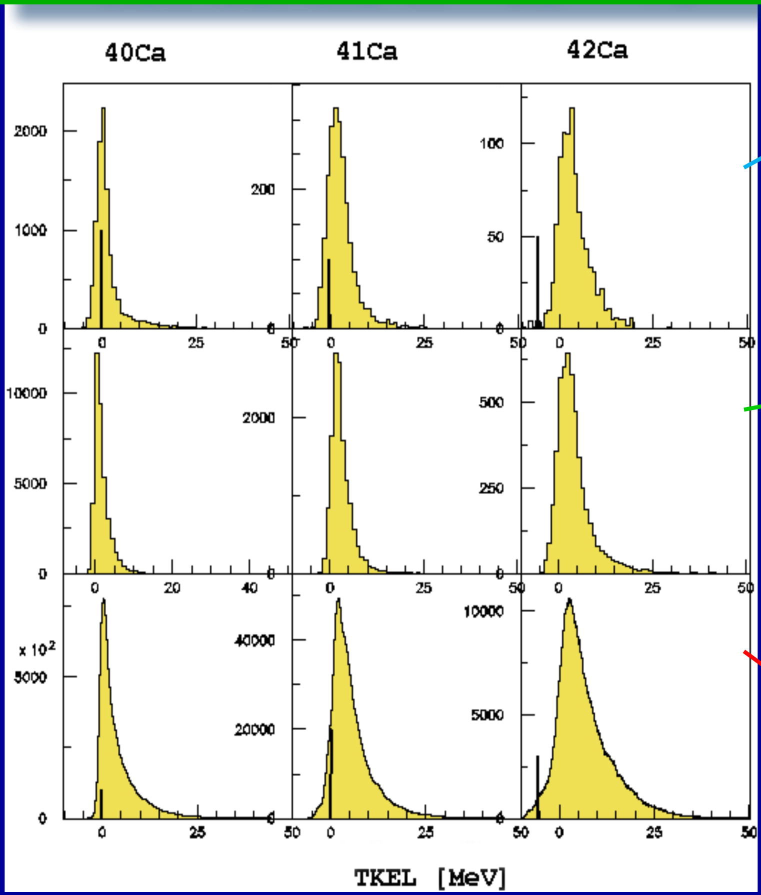


experimental slopes well match the ones expected from the binding energies

one gets an enhancement factor ~ 5.5, i.e. significantly larger than usual for pure neutron transfer

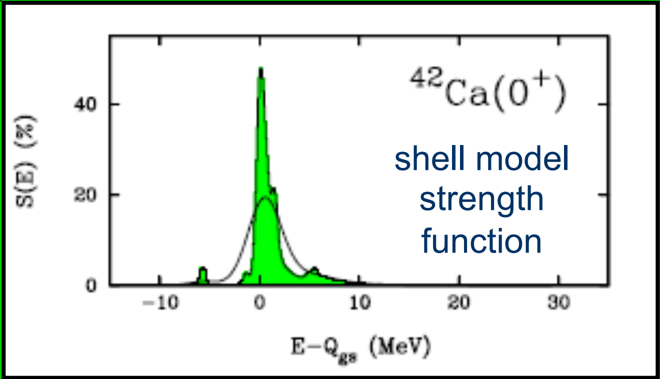
Sub-barrier transfer : gamma-particle coincidences

Total Kinetic Energy Loss distributions in $^{40}Ca+^{208}Pb$

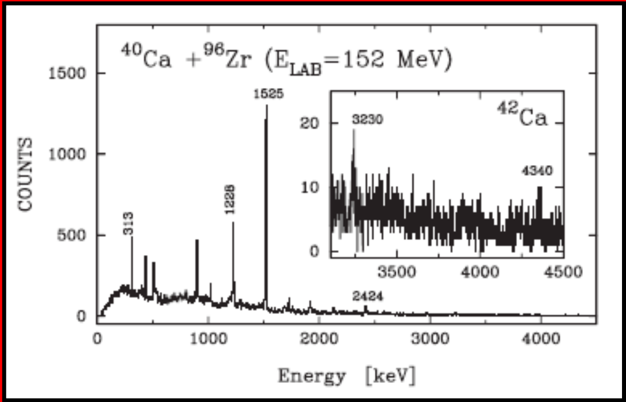


strong population close to the pairing vibrational region in ^{42}Ca

$^{96}Zr+^{40}Ca$ 330 MeV - PRISMA
L.Corradi et al. PRC84(2011)034603

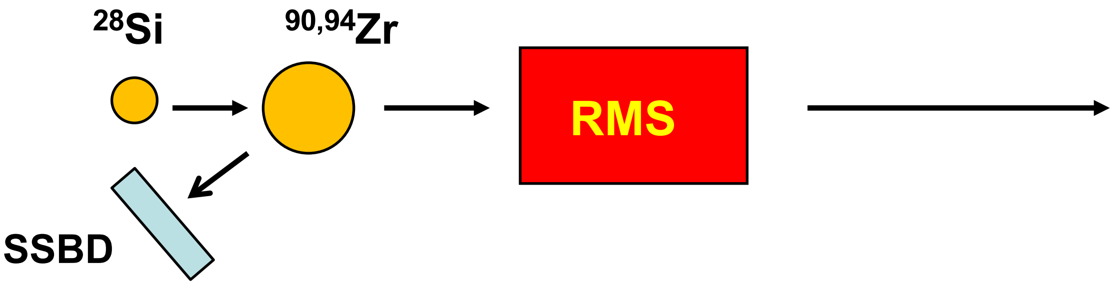


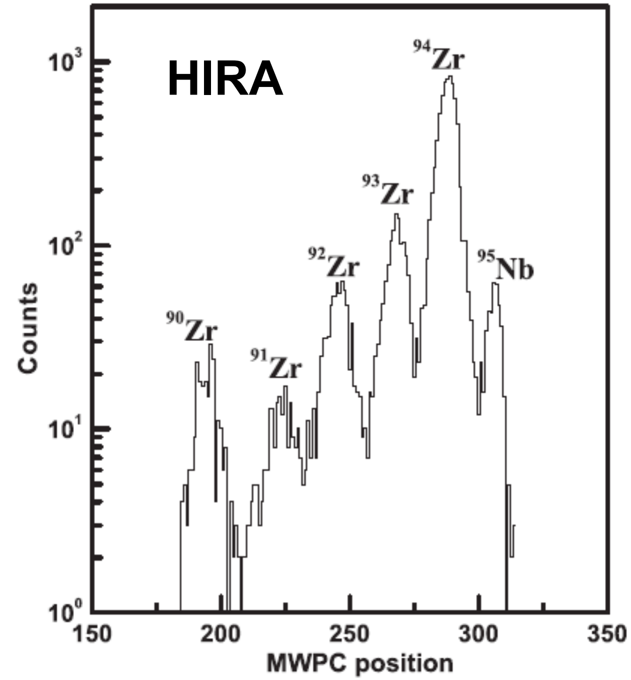
$^{40}Ca+^{208}Pb$ 236 MeV - PISOLO
S.Szilner et al PRC71(2005)044610

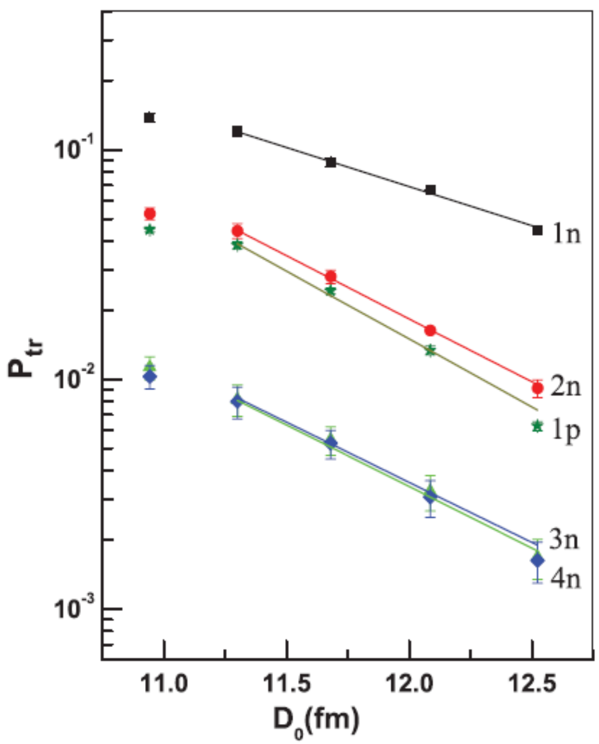


$^{40}Ca+^{96}Zr$ 152 MeV – PRISMA+CLARA
S.Szilner et al, PRC7(2007)024604

Detection of (heavy) target like ions with recoil mass spectrometers







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

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

data collected for multinucleon transfer in the range 11-12.5 fm

slopes much lower than those expected from binding energies

S.Kaikal et al., PRC83(2011)054607