# Recent measurements on neutron transfer reactions at deep sub-barrier energies with PRISMA

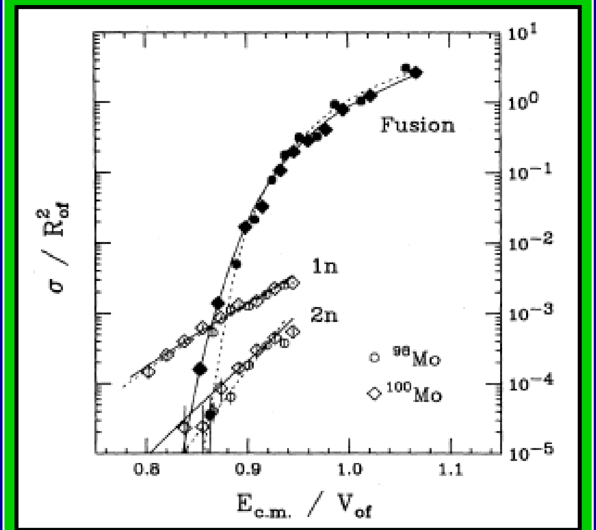
**L.Corradi**

*Laboratori Nazionali di Legnaro – INFN, Italy*

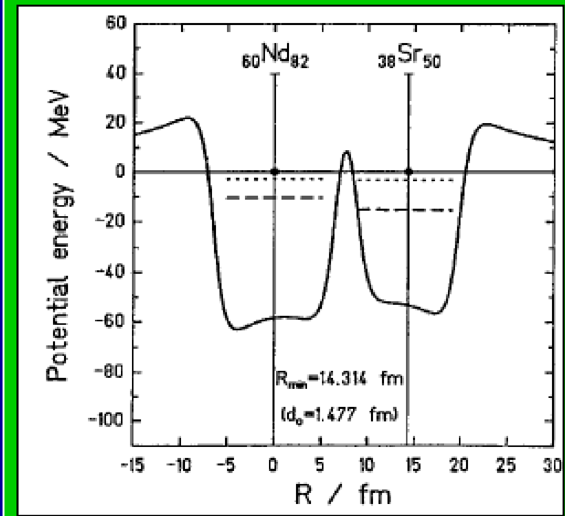
LEA - Orsay, November 14-16, 2011

# Why should we measure at sub-barrier transfer ?

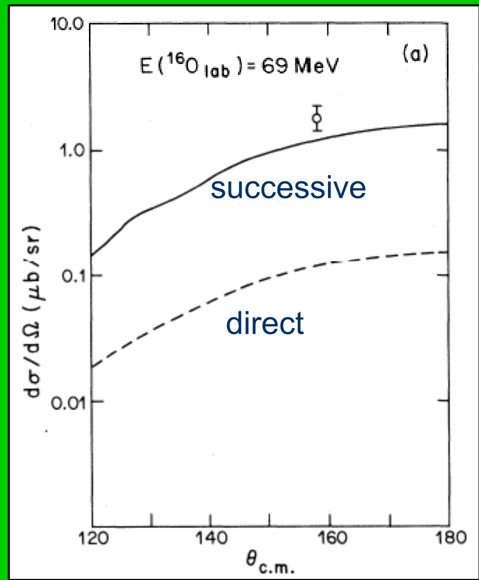
**one probes transfer and fusion in an overlapping range of energies and angular momenta**




**one probes tunnelling effects between interacting nuclei , which enter into contact through the tail of their density distributions**




**one can better study the interplay between single and multiple particle transfers**




L.Corradi, G.Pollarolo and S.Szilner, J.Phys.G36(2009)113101 (Special Topic)

## Transfer studies at energies below the Coulomb barrier : theoretical advantages

few reaction channels are opened → one reduces uncertainties with nuclear potentials

Q-value distributions get much narrower → one can probe nucleon correlation close to the ground states

## Transfer studies at energies below the Coulomb barrier : experimental difficulties

Angular distributions are backward peaked and in direct kinematics projectile-like particles have low kinetic energy

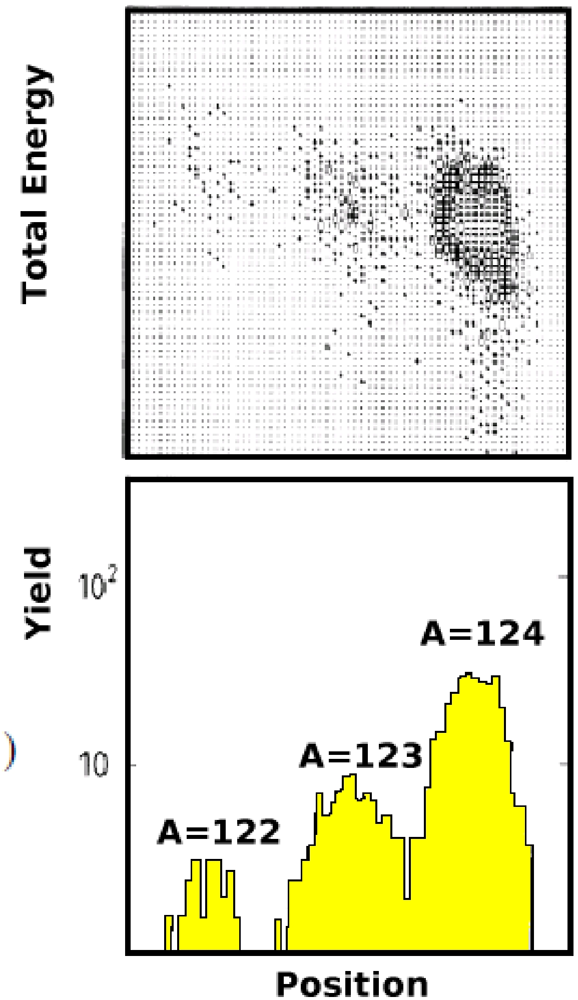
A complete identification of final reaction products in A, Z and Q-values becomes difficult

Cross sections get very small (need for high efficiency)

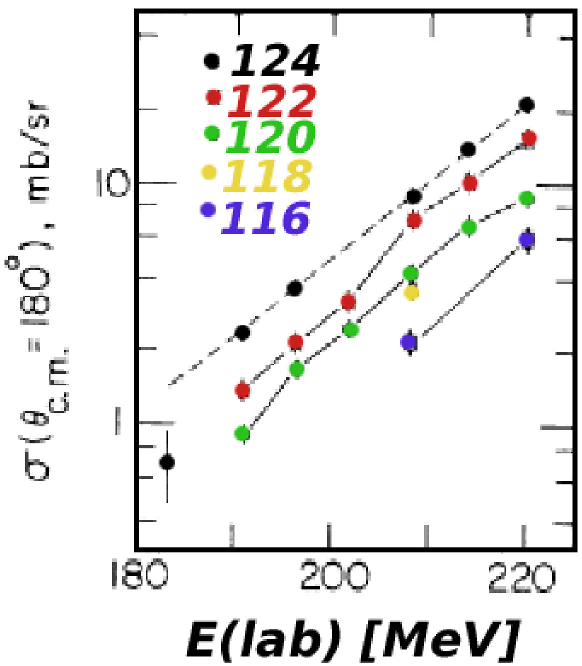
2 solutions have been pioneered so far :

- using Recoil Mass Separators
- using Magnetic Spectrometers with inverse kinematics

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


measurements have been performed at subbarrier energies but for only one nucleon transfer and with very poor Q-value resolution



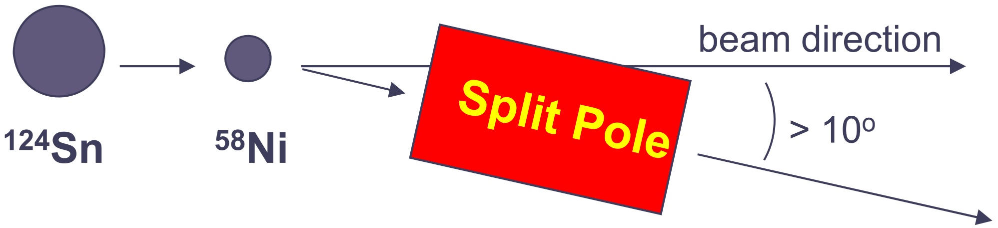

$$\alpha = \sqrt{\frac{2\mu B}{\hbar^2}}$$

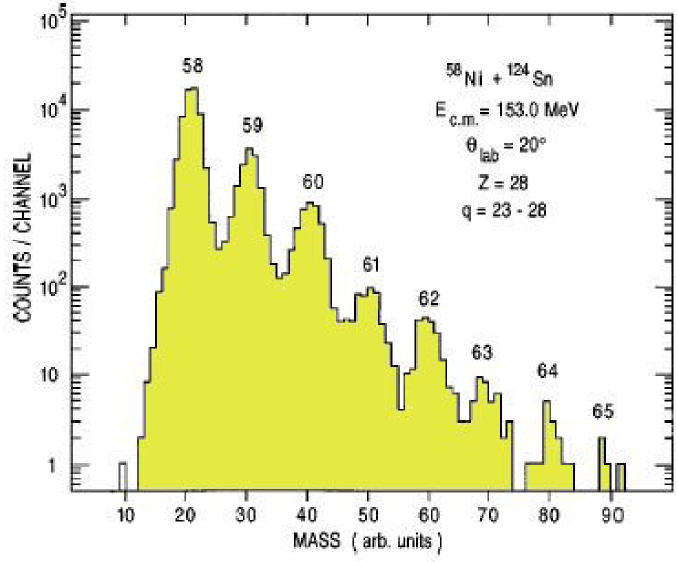
$$\frac{P_{tr}}{\sin(\theta_{c.m.}/2)} \propto \exp(-2\alpha D)$$

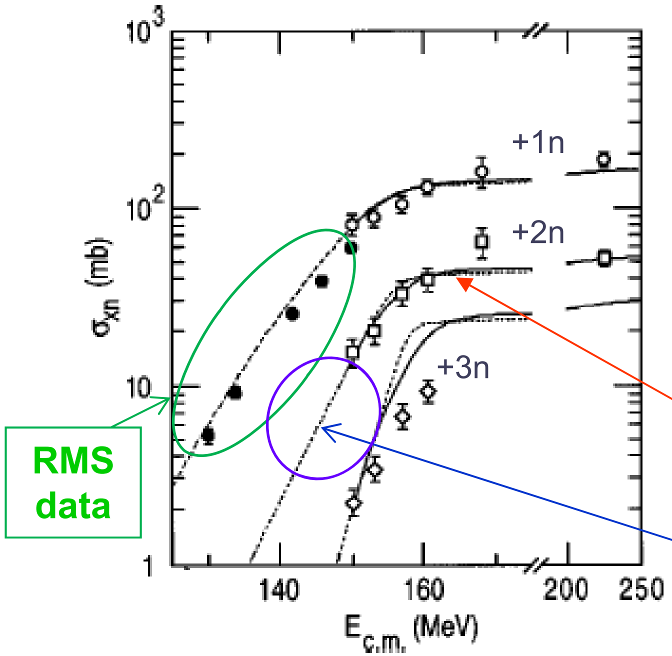
slopes consistent with the binding energies for +1n channels

R.Betts et al., PRL59(1987)978

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




**successive+direct pair transfer**

$$F_{2n}(r) = \alpha_{2n} V_0 \frac{d}{dr}\left[1+\exp\left(\frac{r-R_0}{a_{2n}}\right)\right]^{-1}$$

**lacking of data for +2n in the deep sub-barrier region**

H.Esbensen et al., PRC57(1998)2401

C.L.Jiang et al., PRC57(1998)2393

Deep sub-barrier transfer in $^{96}Zr+^{40}Ca$ studied with PRISMA

PHYSICAL REVIEW C **84**, 034603 (2011)

# Single and pair neutron transfers at sub-barrier energies

L. Corradi,[1] S. Szilner,[1,4] G. Pollarolo,[3] G. Colò,[7] P. Mason,[2] E. Farnea,[2] E. Fioretto,[1] A. Gadea,[8] F. Haas,[6] D. Jelavić-Malenica,[4] N. Mărginean,[5] C. Michelagnoli,[1] G. Montagnoli,[2] D. Montanari,[2] F. Scarlassara,[2] N. Soić,[4] A. M. Stefanini,[1] C. A. Ur,[2] and J. J. Valiente-Dobón[1]

[1]*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy*

[2]*Dipartimento di Fisica, Università di Padova, and Istituto Nazionale di Fisica Nucleare, I-35131 Padova, Italy*

[3]*Dipartimento di Fisica Teorica, Università di Torino, and Istituto Nazionale di Fisica Nucleare, I-10125 Torino, Italy*

[4]*Ruđer Bošković Institute, HR-10 001 Zagreb, Croatia*

[5]*Horia Hulubei National Institute of Physics and Nuclear Engineering, R-077125, Bucharest-Magurele, Romania*

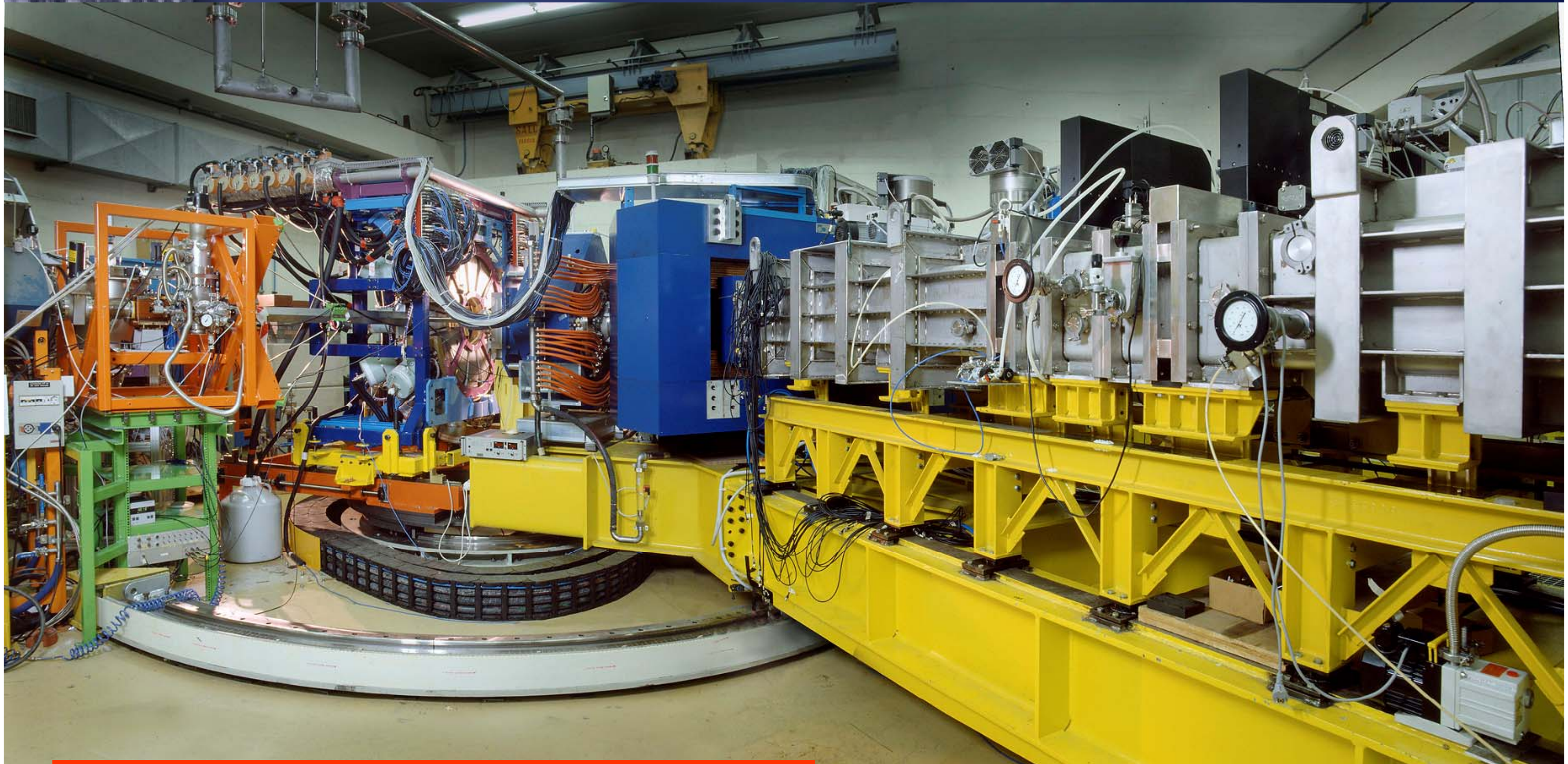
[6]*Institut Pluridisciplinaire Hubert Curien, CNRS-IN2P3, Université de Strasbourg, F-67037 Strasbourg, France*

[7]*Dipartimento di Fisica, Universitá degli Studi di Milano and Istituto Nazionale di Fisica Nucleare, I-20133 Milano, Italy*

[8]*IFIC, CSIC-Universidad de Valencia, E-46071 Valencia, Spain*

(Received 27 May 2011; published 6 September 2011)

# THE PRISMA SPECTROMETER + CLARA GAMMA ARRAY



INFN exp. PRISMA (LNL,PD,TO,Na)

INFN exp. GAMMA (LNL,PD,Fi,MI,Na,Pg)

+ broad Int. Collaboration (UK,F,D,Pl,Sp,Ro,Hr)

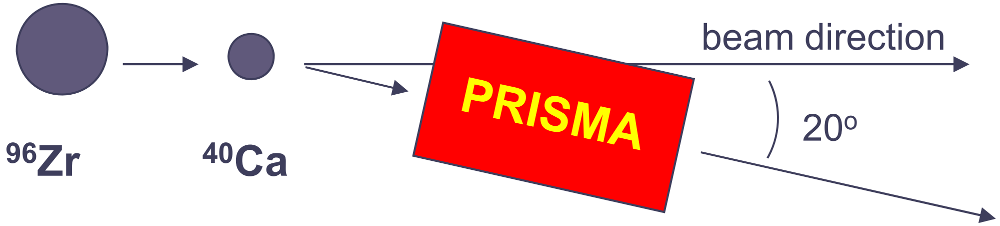
PRISMA: a large acceptance magnetic spectrometer

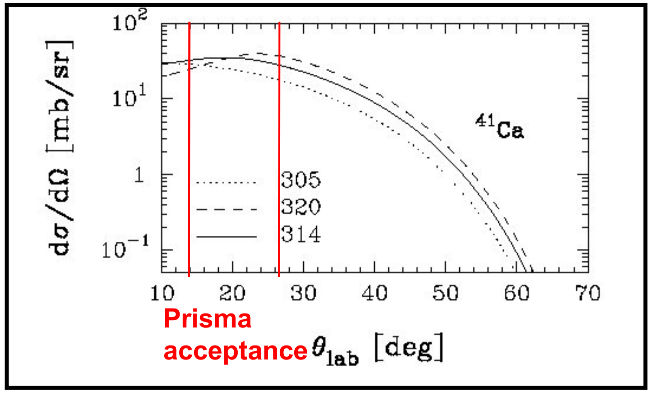
$\Omega \approx 80$ msr; $B\rho_{max} = 1.2$ Tm

$\Delta A/A \sim 1/200$

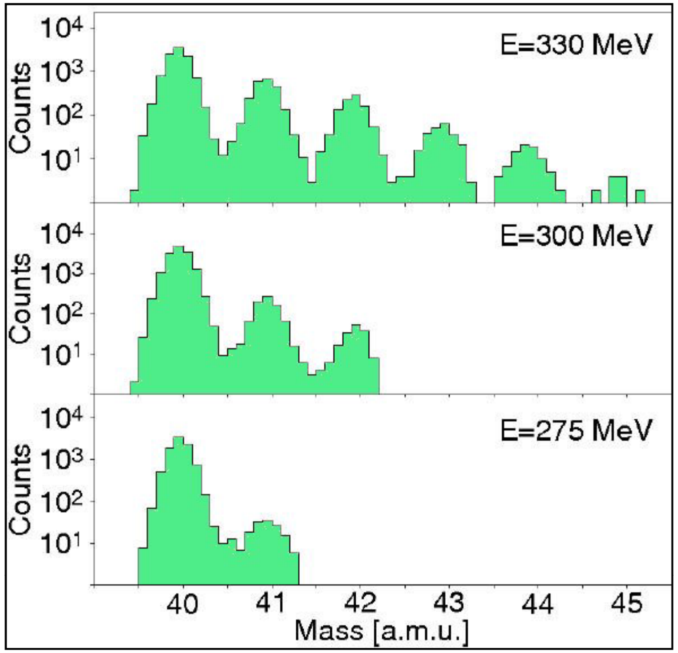
Energy acceptance $\sim \pm 20\%$

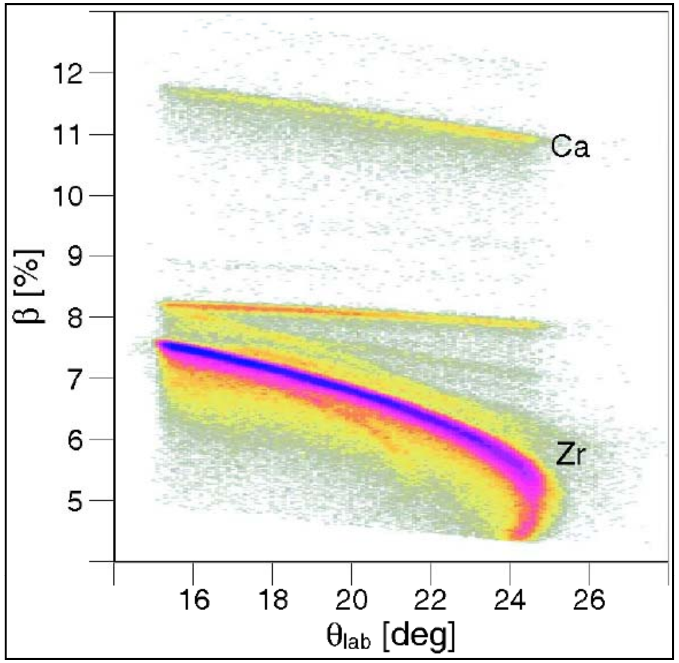
# Detection of (light) target like ions in inverse kinematics with PRISMA



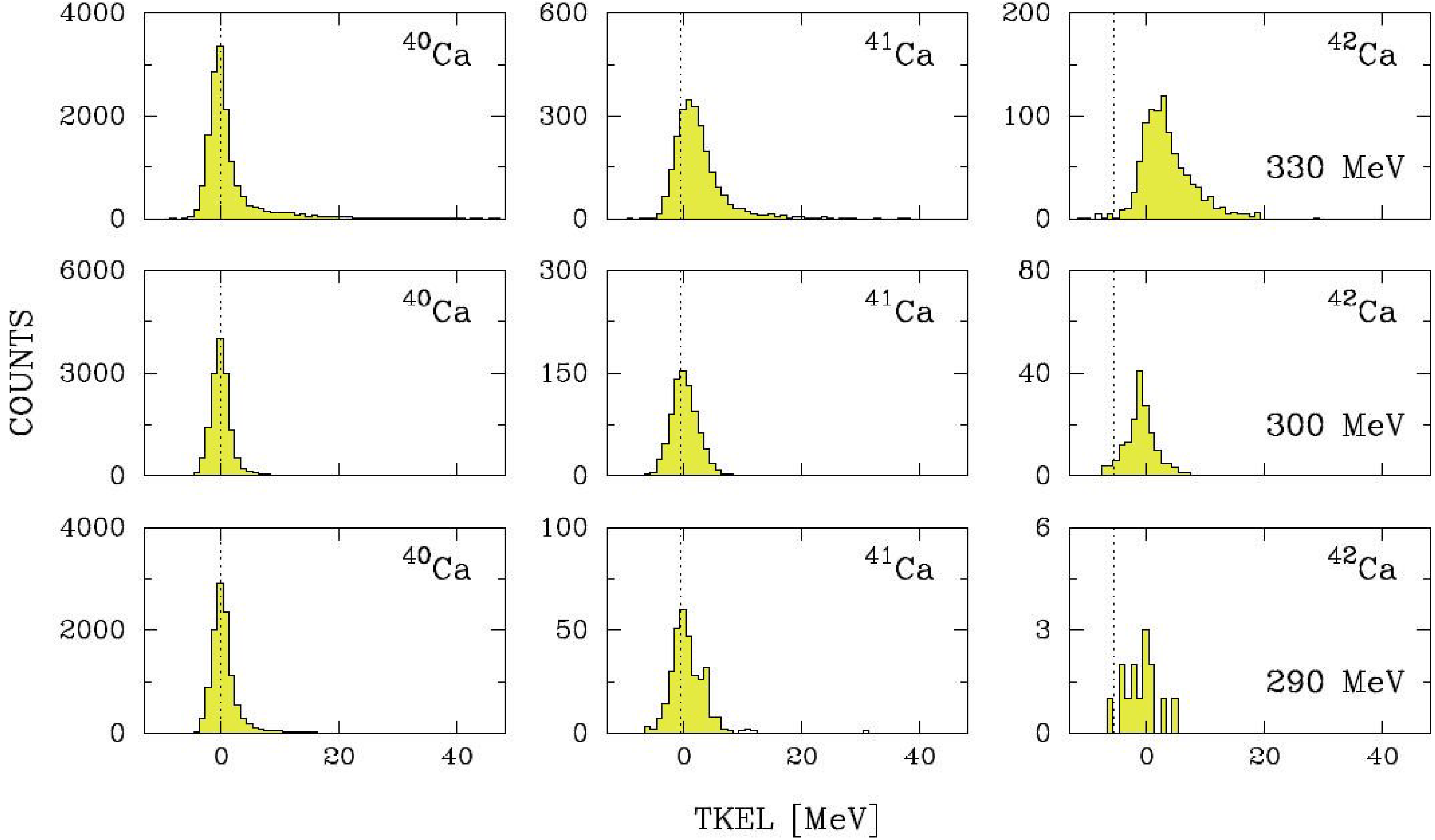




**MNT channels have been measured down to 25 % below the Coulomb barrier**



# TKEL spectra for neutron transfer channels

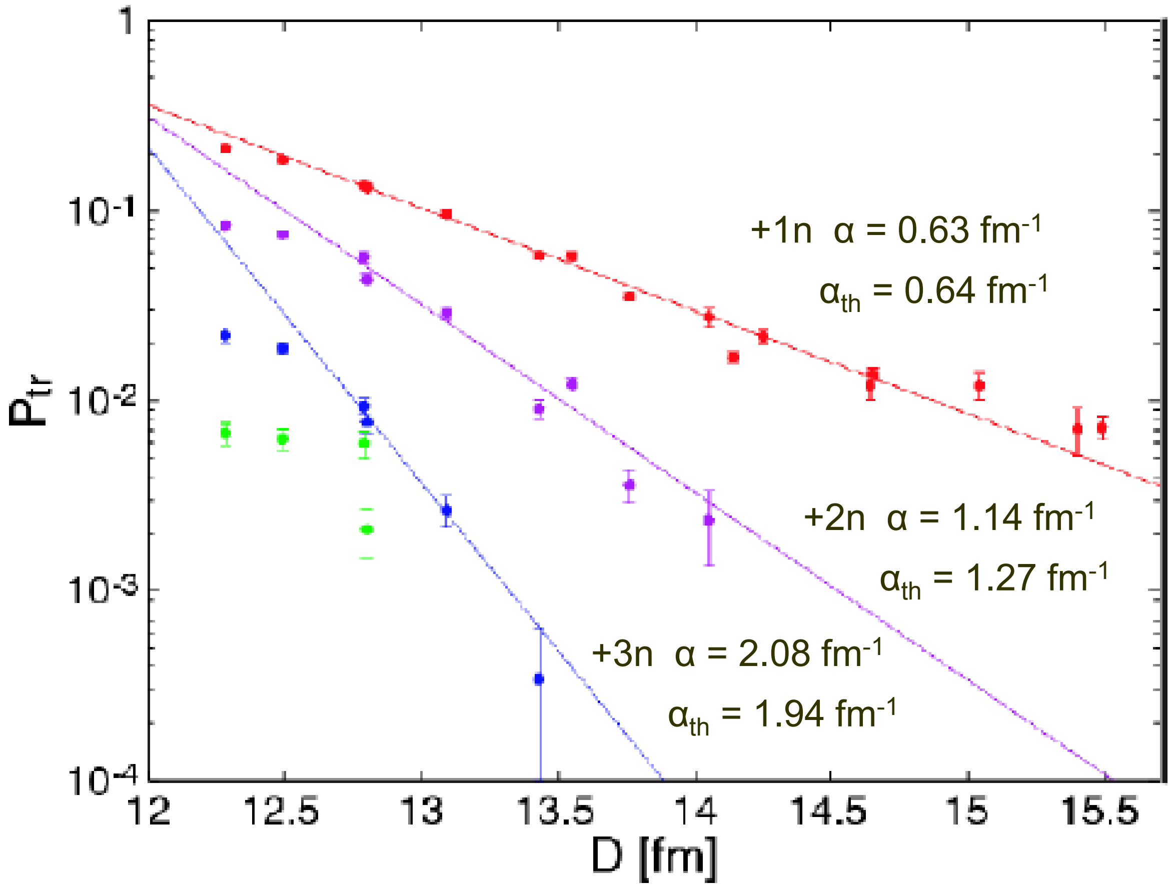



**background free spectra with transfer products at very low excitation energy :**

**no evaporation effects and cleanest conditions for data interpretation**

# Transfer probabilities for multineutron transfer in $^{96}Zr+^{40}Ca$

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

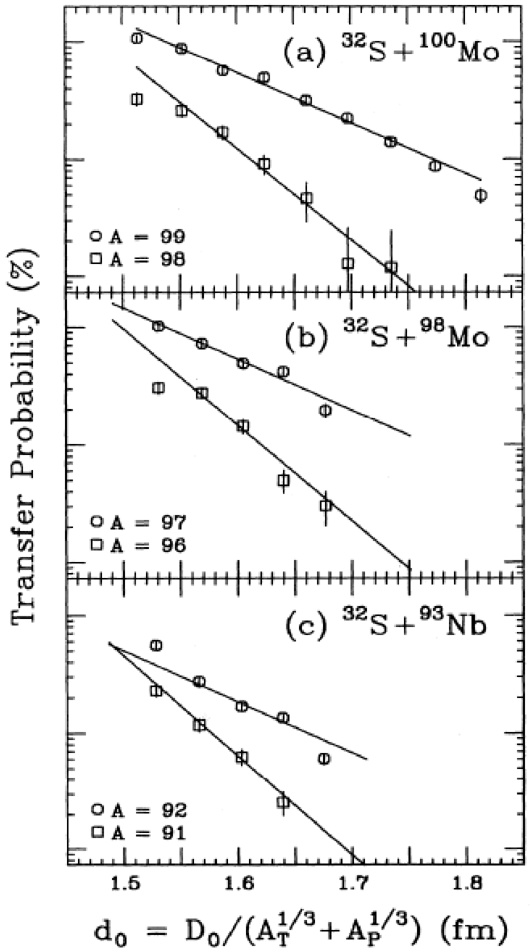


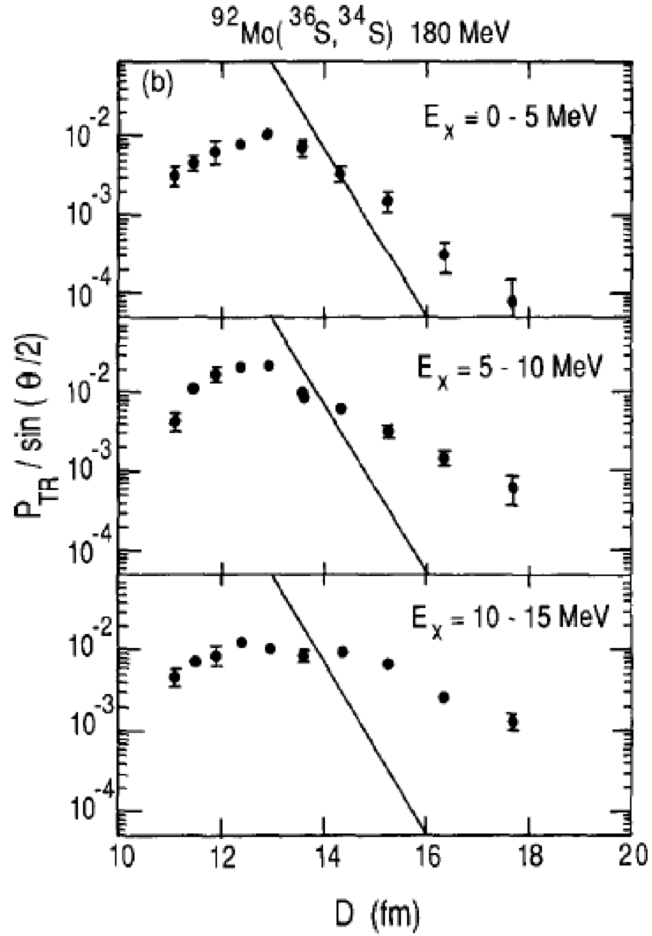

$$\alpha = \sqrt{\frac{2\mu B}{\hbar^2}}$$

$$D = \frac{Z_1 Z_2 e^2}{2E_{c.m.}}\left(1 + \frac{1}{\sin(\theta_{c.m.}/2)}\right)$$

**experimental slopes of transfer probabilities $P_{tr}$ as function of the distance of closest approach D are consistent with the binding energies**

# Slope anomaly effects in two nucleon transfer reactions

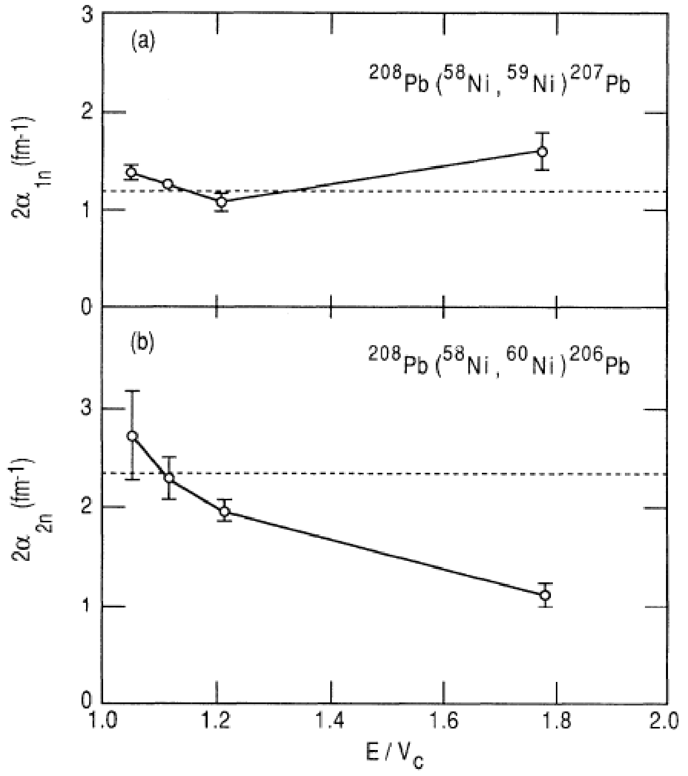


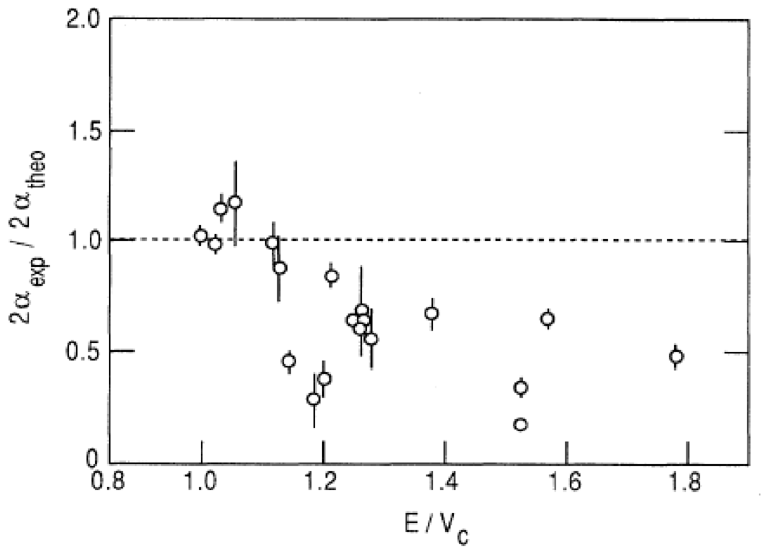

R.B.Roberts et al. PRC47(1993)R1831

A.H.Wuosmaa et al. PLB255(1991)316

# Slope anomaly effetcs in two nucleon transfer reactions



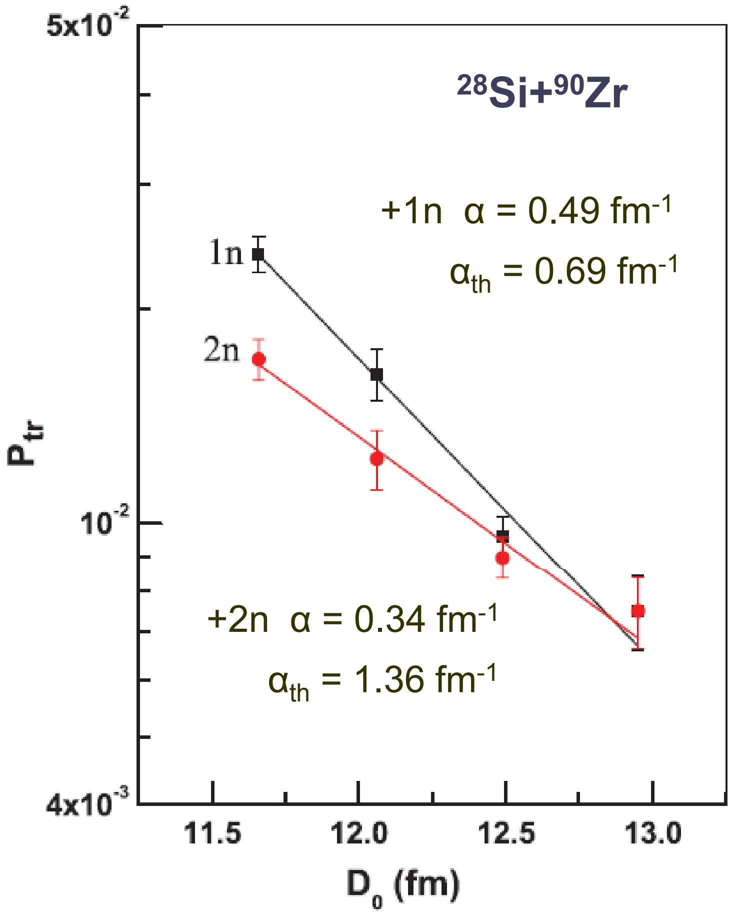

two neutron transfer reactions induced by projectiles ranging from $^{36}S$ to $^{64}Ni$ on different target nuclei

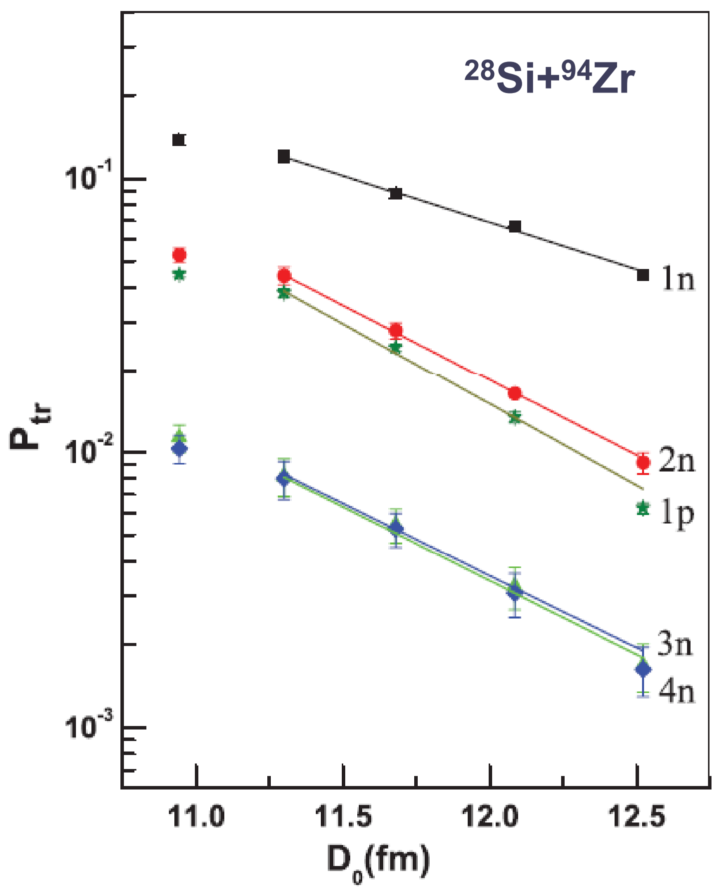



**in increasing the bombarding energy, deep inelastic components contribute more and more**

K.E.Rehm et al. PRC47(1993)2731

# One and two nucleon transfer reactions $^{28}Si+^{90,94}Zr$

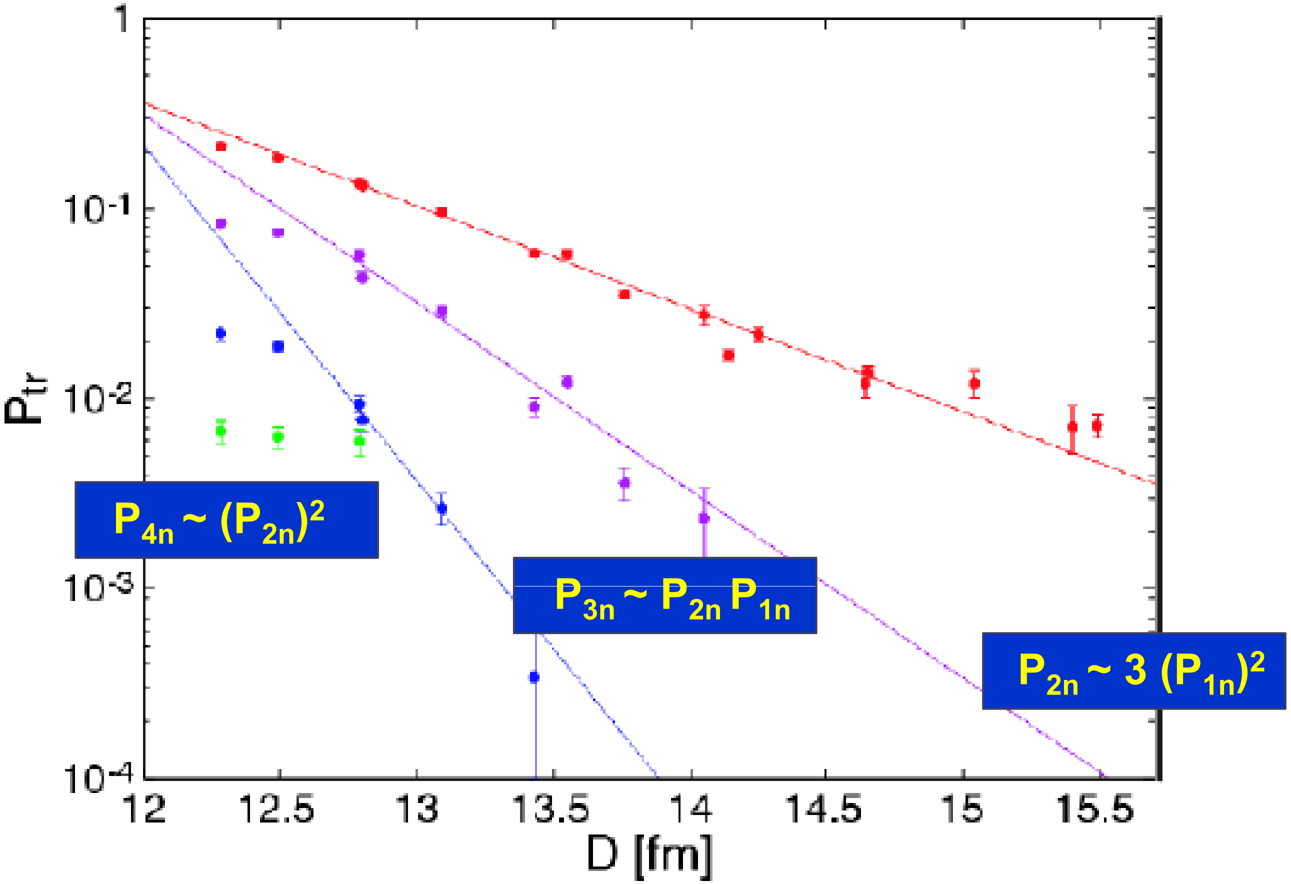



S.Kaikal et al. PRC83(2011)054607

# Transfer probabilities for multineutron transfer in $^{96}Zr+^{40}Ca$

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

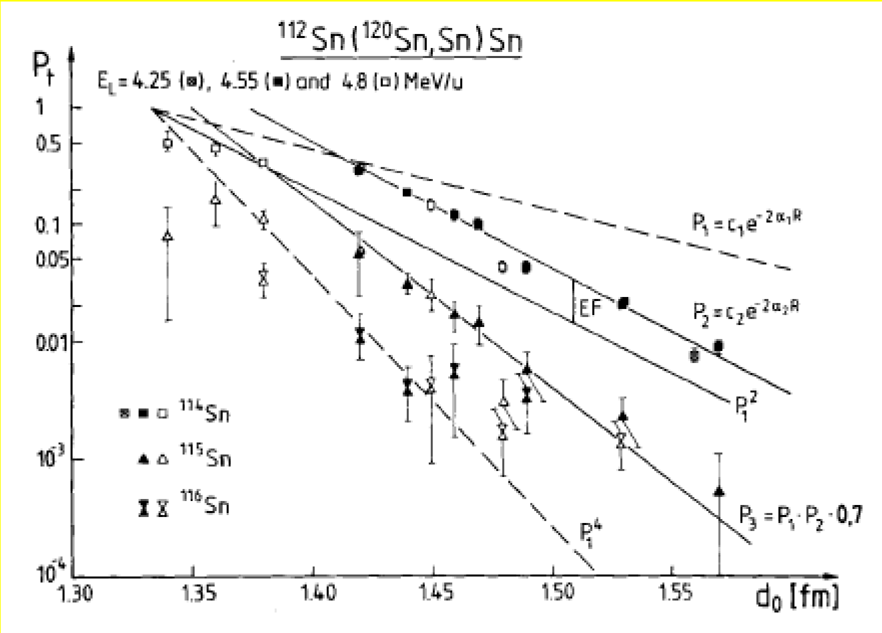



$$D = \frac{Z_1 Z_2 e^2}{2E_{c.m.}}\left(1 + \frac{1}{\sin(\theta_{c.m.}/2)}\right)$$

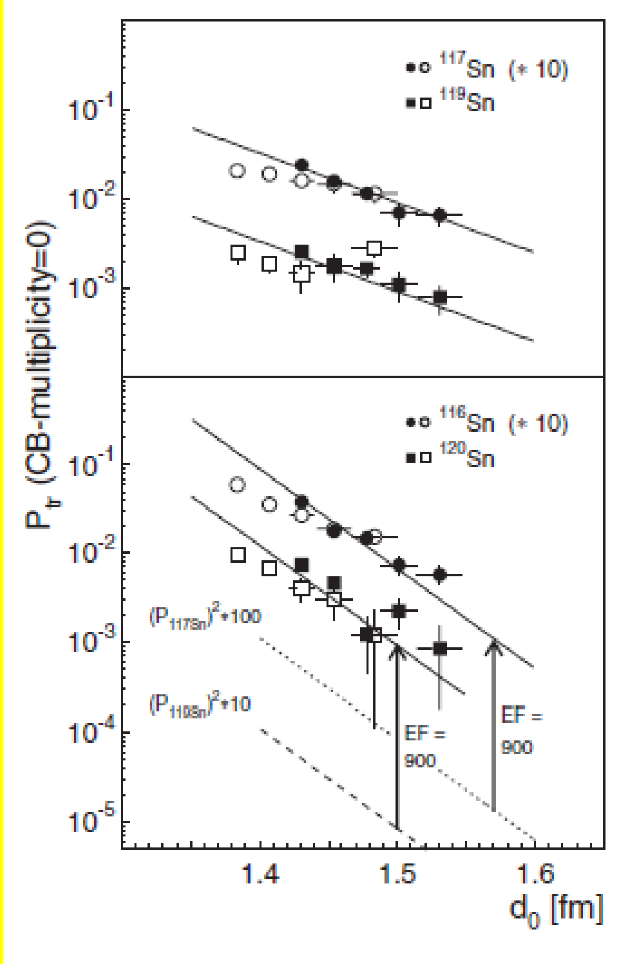
# Enhancement factors in two nucleon transfer reactions

enhancements of two particle transfer probabilities compared to simple estimates based on independent particle transfer have been observed in many systems

## $^{120}Sn+^{112}Sn$ magnetic spectrometer data

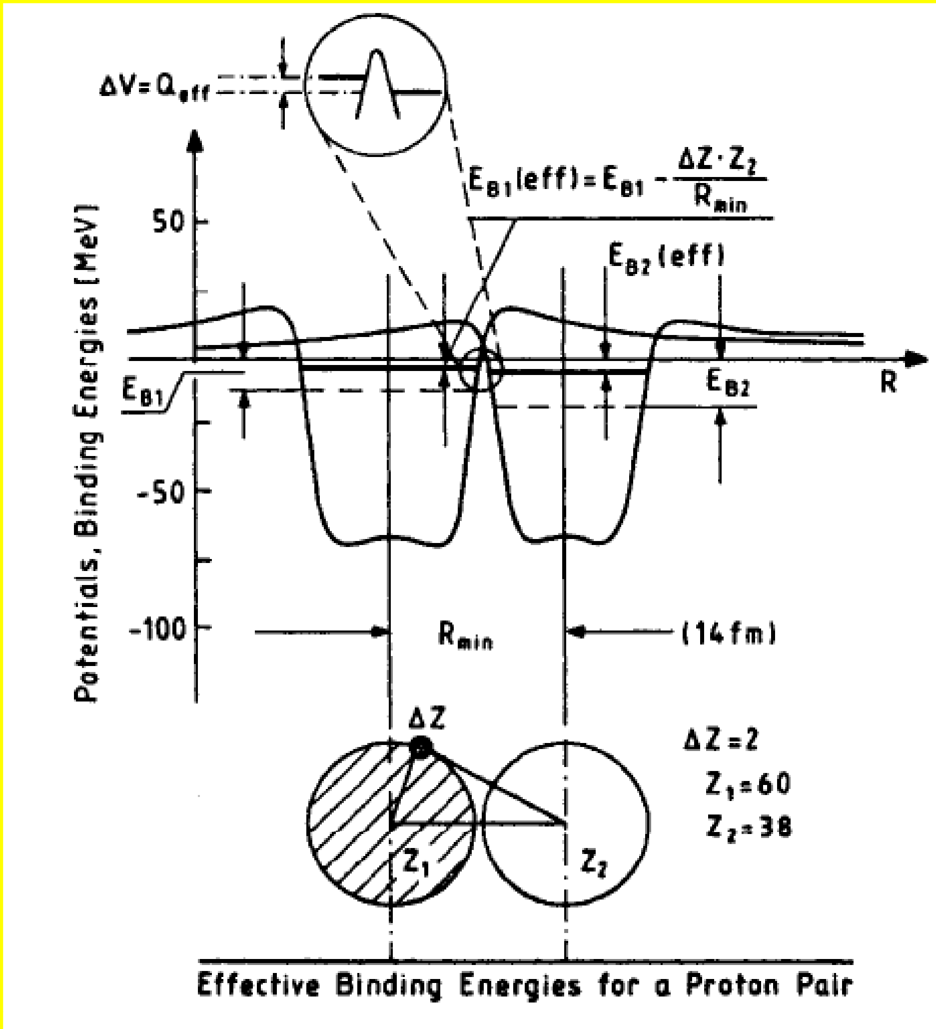



## $^{206}Pb+^{116}Sn$ particle-γ data




W.von Oertzen and A.Vitturi, Rep.Prog.Phys.64(2001)1247

# Enhancement factors in two nucleon transfer reactions

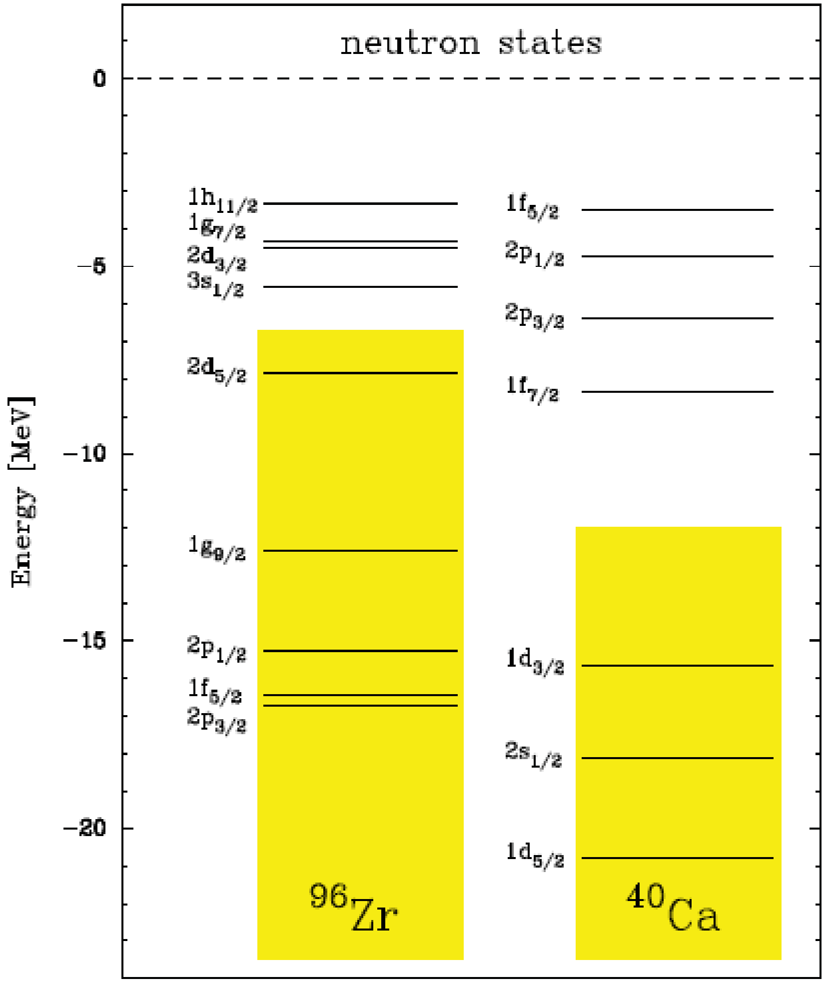



**transfer can be seen as a tunnelling effect, with analogs in solid state physics (superconductivity, Cooper pairs, Josephson effect)**

W.von Oertzen and A.Vitturi, Rep.Prog.Phys.64(2001)1247

**Can we understand microscopically the origin of the enhancement factors ?**

# One particle transfer (semiclassical theory)



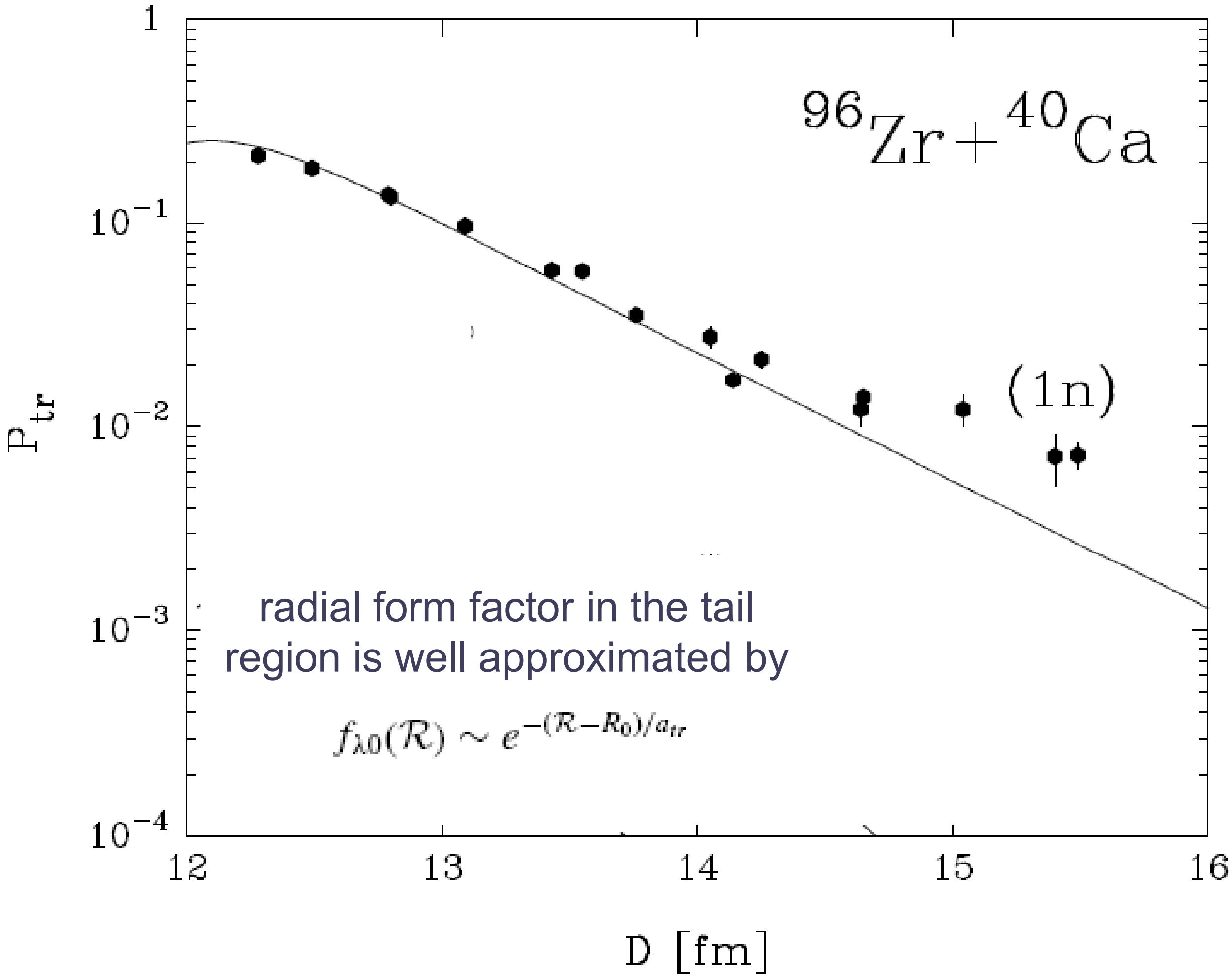

to obtain the total transfer probability we summed over all possible transitions that can be constructed from the single particle states in projectile and target

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

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

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

## Comparison between experimental and theoretical transfer probabilities



## Two particle transfer (semiclassical theory, microscopic calculations)

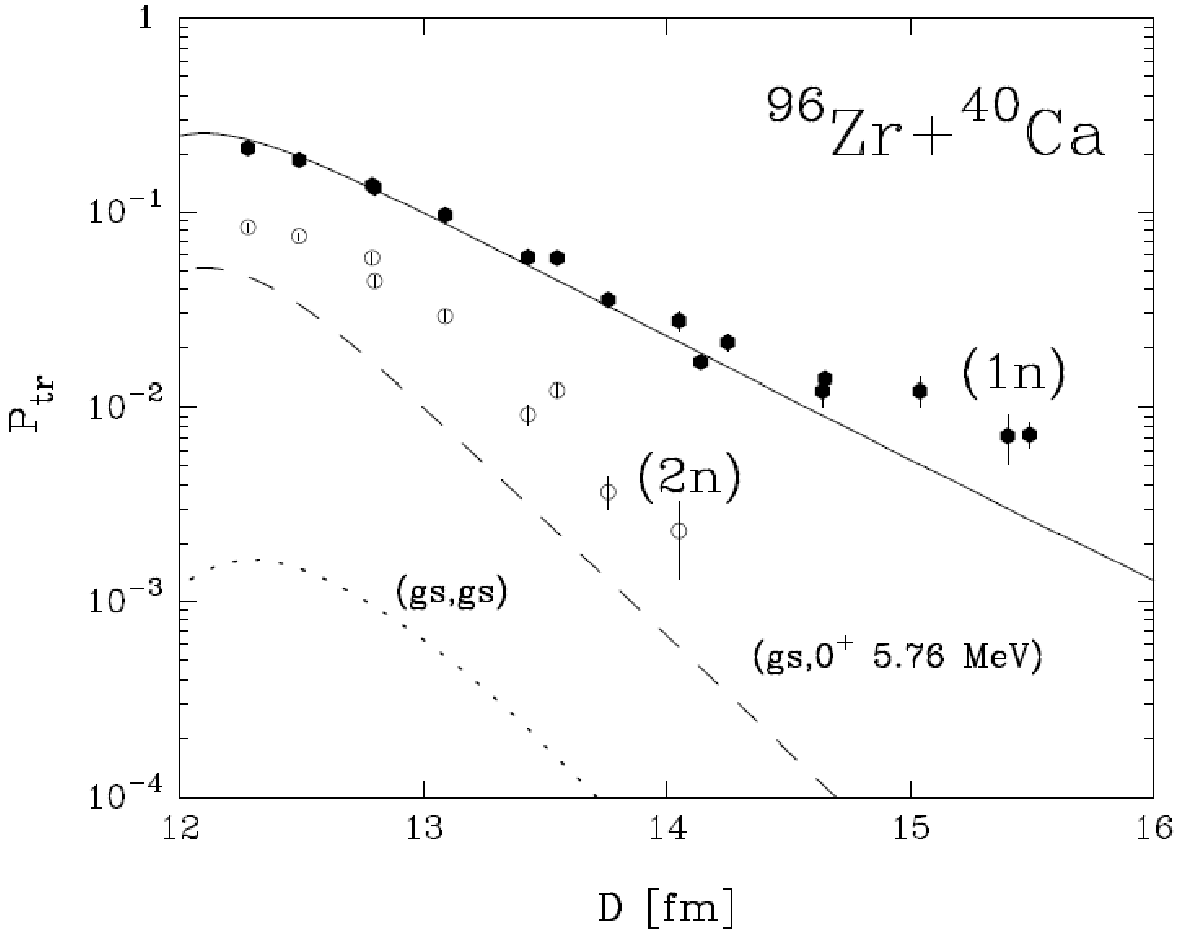
**3 terms : simultaneous, orthogonal and successive**

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

**only the successive term contributes to the transfer amplitude**

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

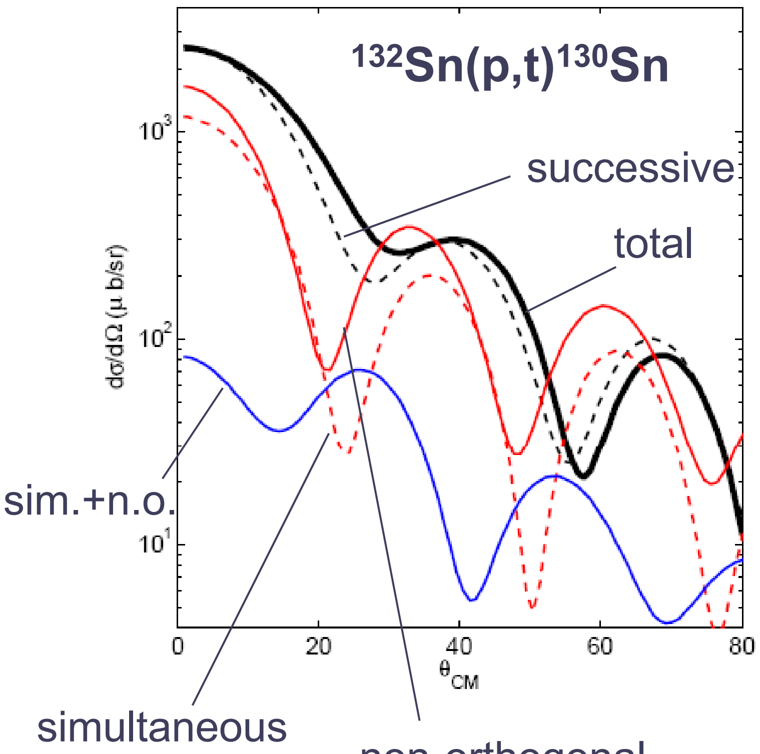
# Comparison between experimental and theoretical transfer probabilities



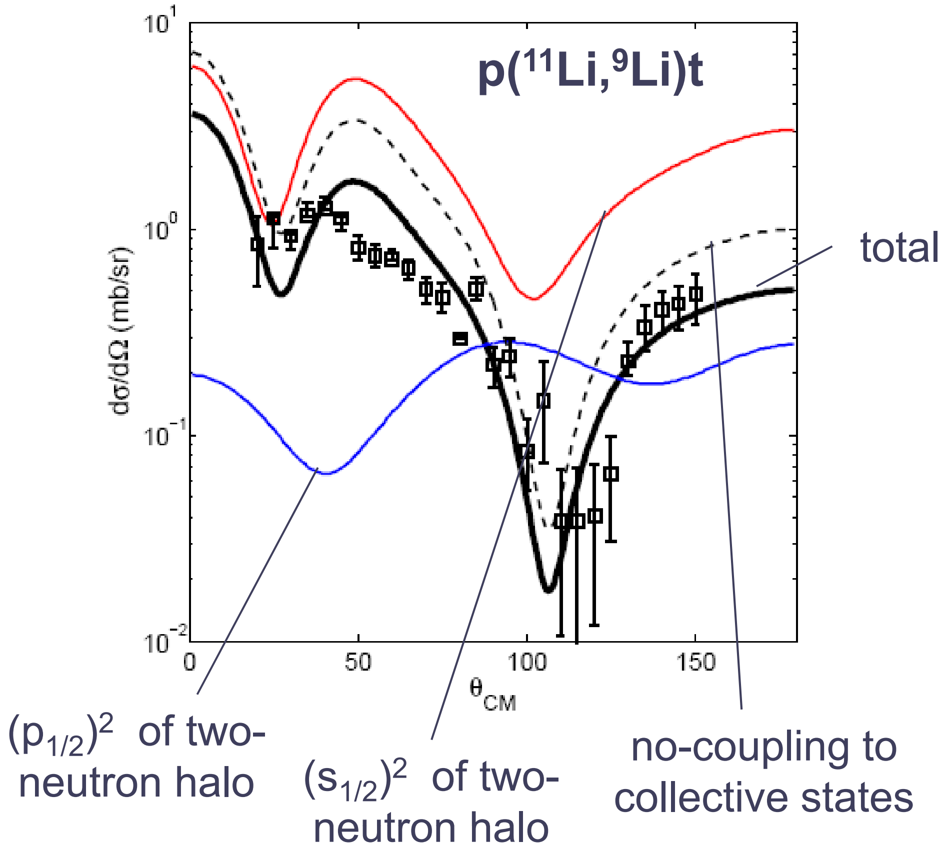

L.Corradi, S.Szilner, G.Pollarolo et al, PRC84(2011)034603

# Pairing interaction in transfer reactions with light nuclei

**the successive term dominates**

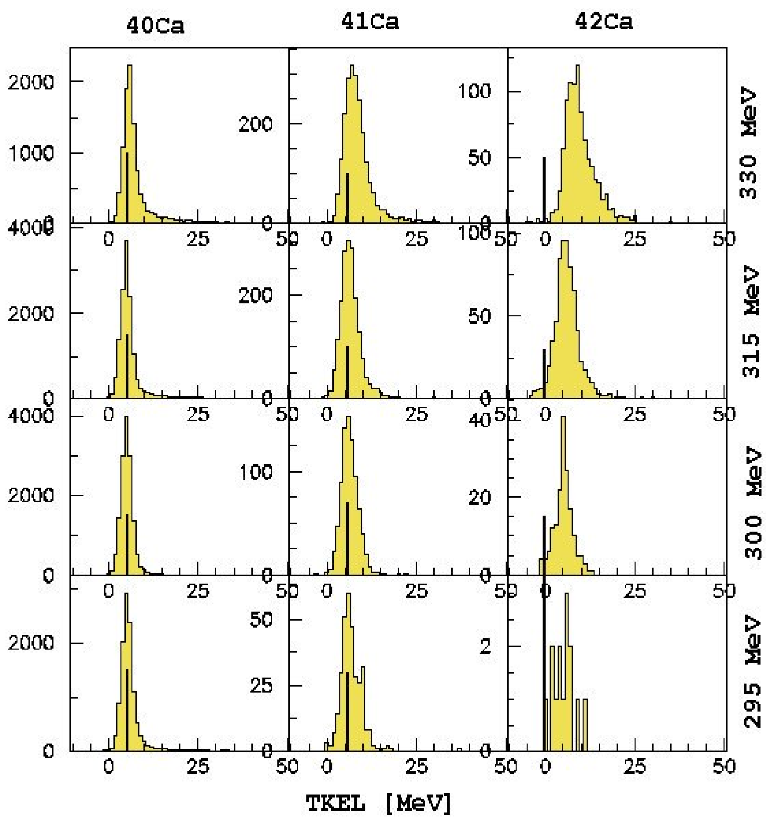


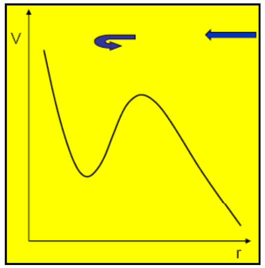

**evidence of phonon mediated pairing interaction**



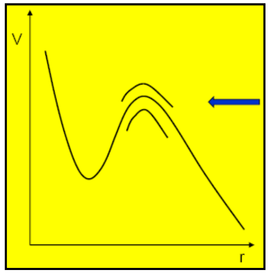

G.Potel et al, Fusion11 St.Malo' and PRL105(2010)172502

# Total kinetic energy loss distributions

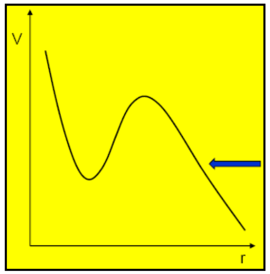


**$E > E_b$**
**onset of DIC components**



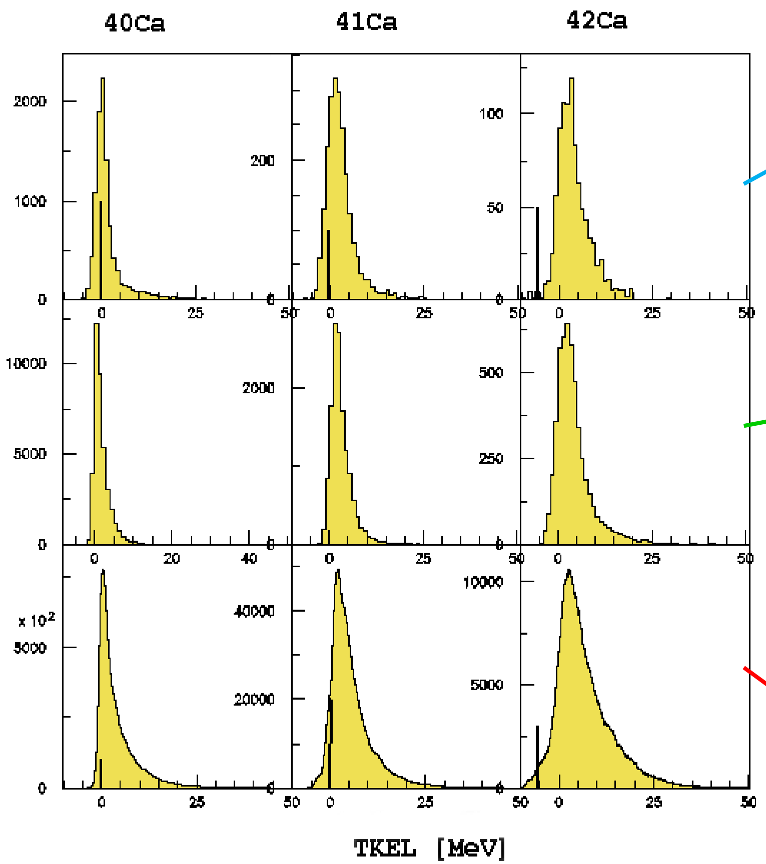
**$E \sim E_b$**
**transfer and fusion are comparable**



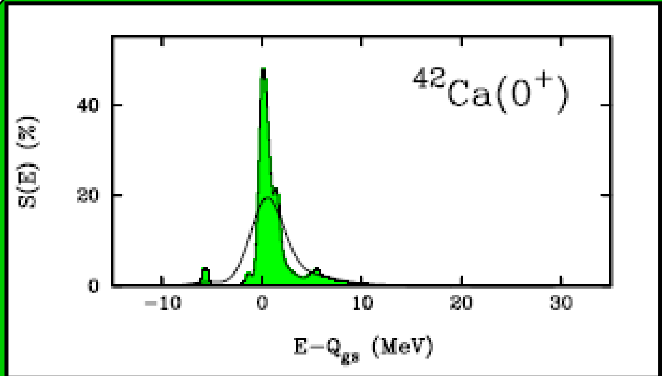
**$E < E_b$**
**transfer dominates over fusion**

**the spectra of +1n and +2n channels have a maximum that moves to higher TKEL with the bombarding energy, in agreement with the energy dependence of $Q_{opt}$ .The width is constant below the barrier and grows above it reflecting the opening of other reaction channels**

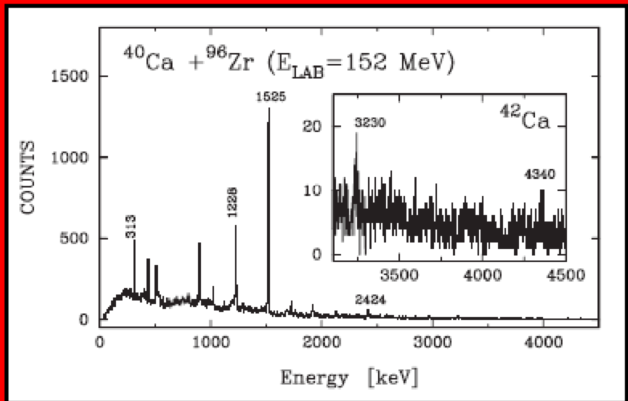
# Total kinetic energy loss distributions




$^{96}Zr$+$^{40}Ca$ 330 MeV
PRISMA this work




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



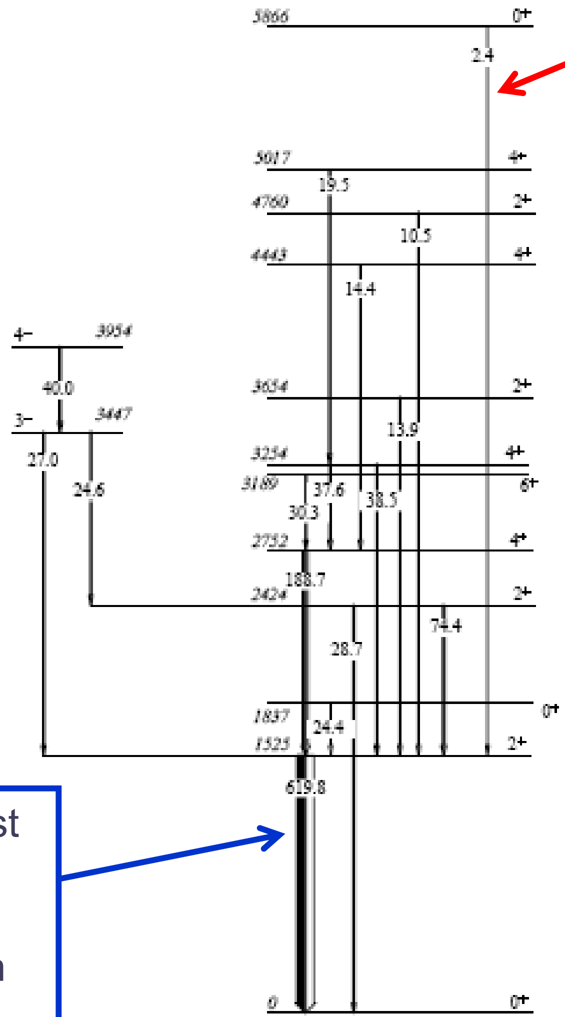

$^{40}Ca$+$^{96}Zr$ 152 MeV – PRISMA+CLARA
S.Szilner et al, PRC7(2007)024604

# Excited states population in the +2n channel – PRISMA+CLARA exp

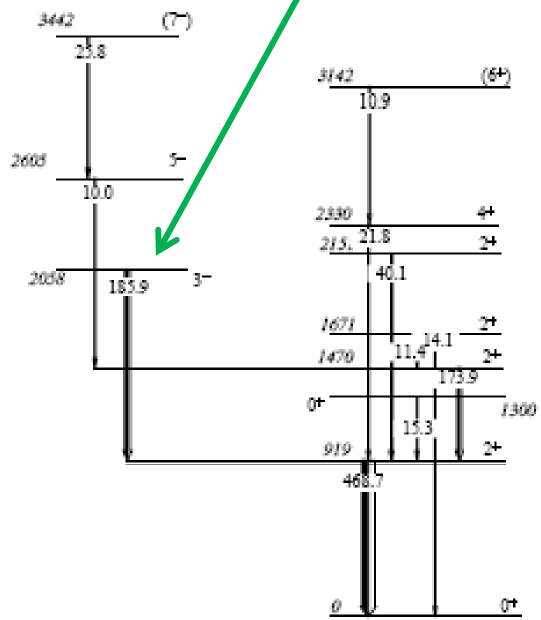
hints of decay from high lying $0^+$ states in $^{42}Ca$

strong population of negative parity states in $^{94}Zr$

only 60% of the last $2^+$ - $0^+$ transition in $^{42}Ca$ can be accounted for from observed feeding




42Ca




94Zr

# Summary

We performed first measurements on sub-sub-barrier transfer reactions exploiting inverse kinematics and making use of the high resolution and large acceptance spectrometer PRISMA

Data look very promising. Slopes for multineutron pick-up channels are consistent with binding energies. Comparison with microscopic calculations show the importance of J=0 pair transfer (populating $0^+$ states) and of states of higher spin and negative parity (recoil term)

Next experiments : $^{116}$Sn+$^{60}$Ni, nuclei of superfluid character

PRISMA+AGATA (gamma-particle), D.Montanari et al April 2011

PRISMA (excitation function), L.Corradi et al January 2012

**L.Corradi[1], S.Szilner[3], G.Pollarolo[4], E.Farnea[2], E.Fioretto[1], A.Gadea[5], F.Haas[7], D.Jelavec-Malenica[3], N.M.Marginean[6], P.Mason[1], C.Michelagnoli[2], G.Montagnoli[2], D.Montanarii[2], F.Scarlassara[2], N.Soic[3], A.M.Stefanini[1], C.Ur[2], J.J.Valiente-Dobon[1]**

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*[2]Universita' di Padova and INFN, Italy*

*[3]Ruđer Bošković Institute, Zagreb, Croatia*

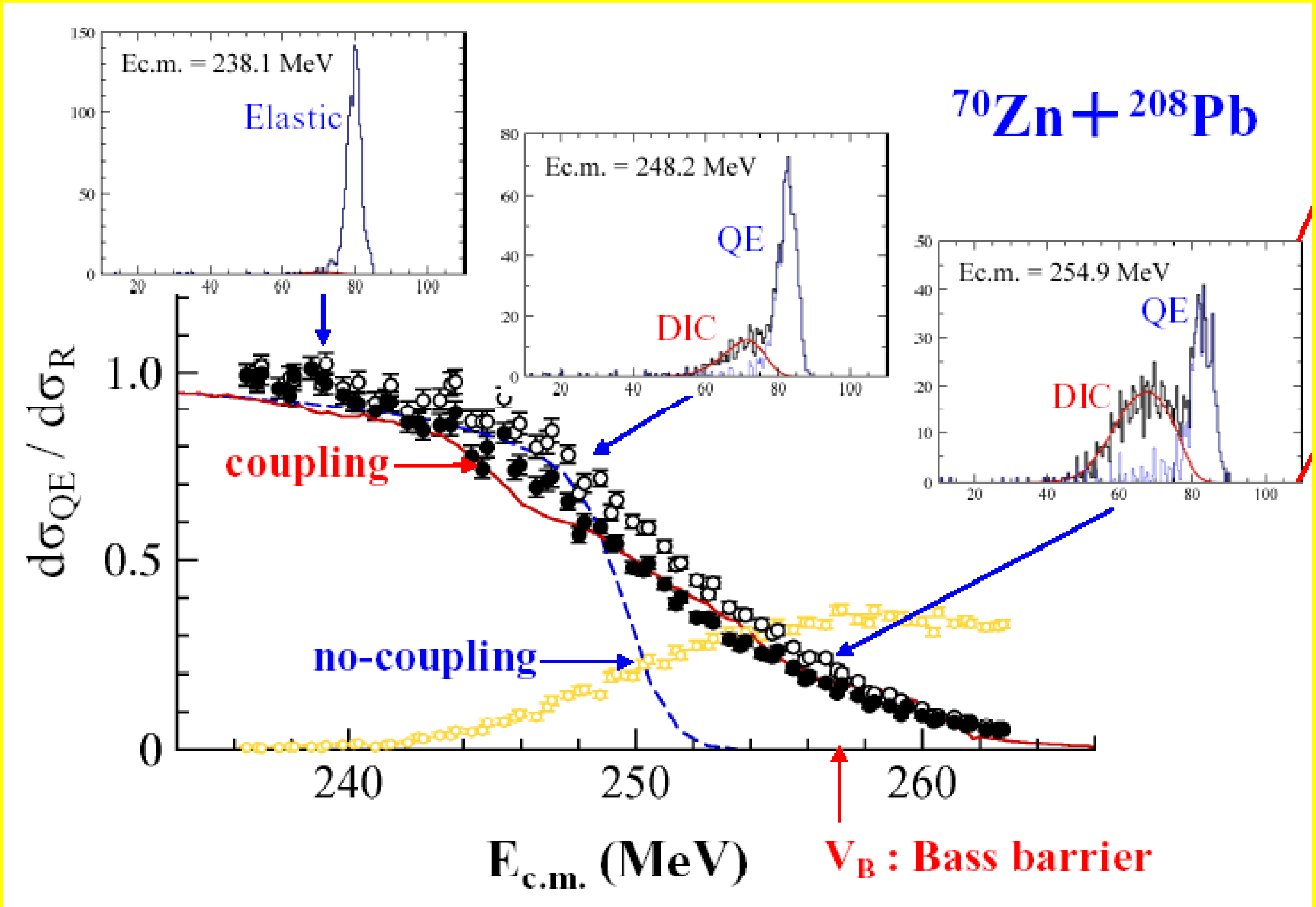
*[4]Universita' di Torino and INFN, Italy*

*[5]Instituto de Fisica Corpuscolar, CSIC, Valencia, Spain*

*[6]IFIN-HH, Bucharest, Romania*

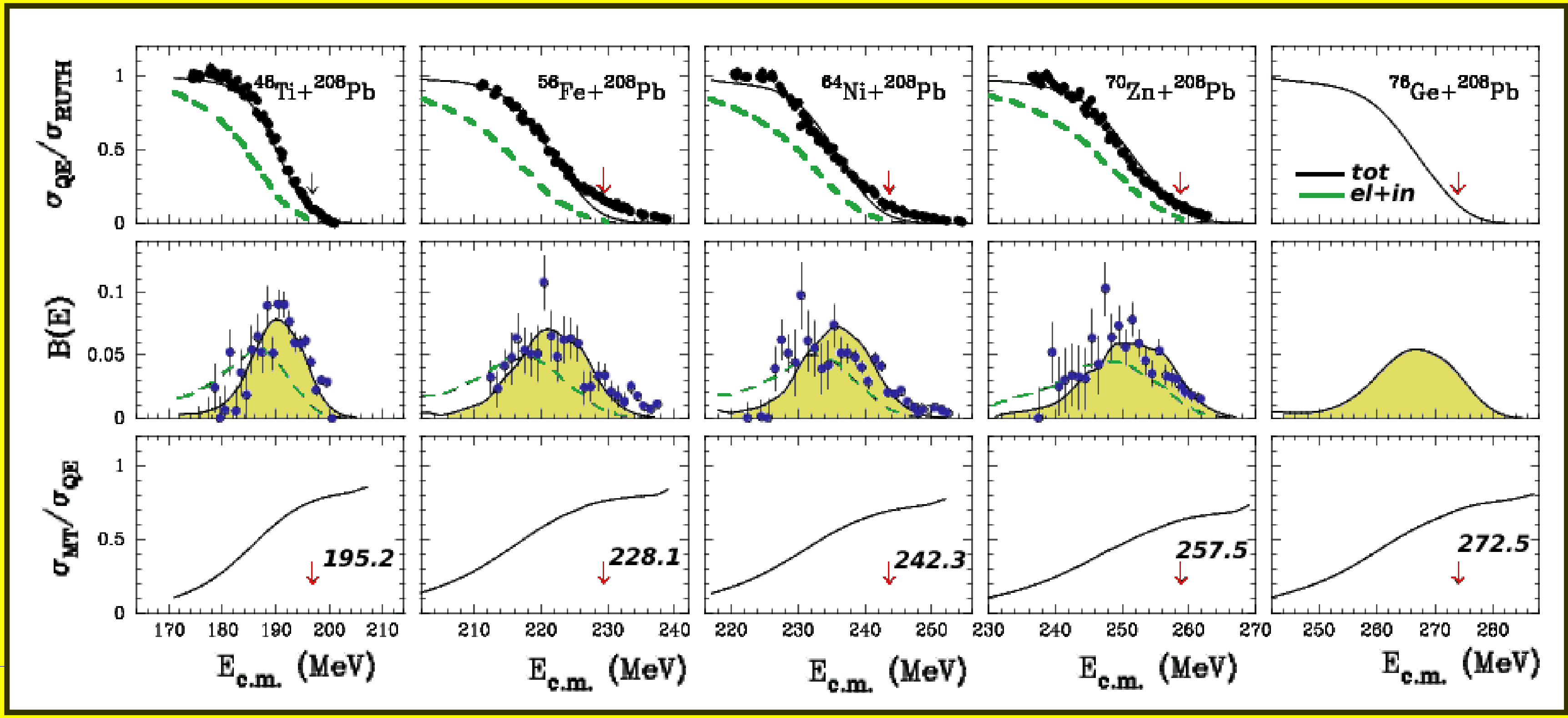
*[7]IReS, Strasbourg, France*

# Importance of properly taking into acccount DIC components in extracting quasielastic barrier distributions




S.Mitsuoka, Fusion08, Chicago

## Quasielastic barrier distributions : role of particle transfer channels




Exp. data : S.Mitsuoka et al,
Phys.Rev.Lett.99,182701(2007)

Calculations : G.Pollarolo,
Phys.Rev.Lett.100,252701(2008)

# Composition of wavefunctions for $0^+$ states

TABLE I. Wave functions for the $0^+$ ground state of $^{94}$Zr and for the $0^+$ ground state of $^{42}$Ca with its first $0^+$ excited state at 5.76 MeV (see text for more details).

| $^{94}$Zr | | | $^{42}$Ca | | | |
|---|---|---|---|---|---|---|
| $a_i$ | B.E. (MeV) | $B(a_i,a_i;0^+)$ | $a_i$ | B.E. (MeV) | $B(a_i,a_i;0^+)$ | $B(a_i,a_i;0_2^+)$ |
| $2d_{3/2}$ | $-16.730$ | $-0.0579$ | | | | |
| $1f_{5/2}$ | $-16.420$ | $-0.0734$ | | | | |
| $2p_{1/2}$ | $-15.300$ | $-0.0485$ | | | | |
| $1g_{9/2}$ | $-12.610$ | 0.1663 | | | | |
| $2d_{5/2}$ | $-7.854$ | 0.8360 | | | | |
| $3s_{1/2}$ | $-5.579$ | 0.1693 | $1f_{7/2}$ | $-8.620$ | 0.93 | 0.29 |
| $2d_{3/2}$ | $-4.476$ | 0.1617 | $2p_{3/2}$ | $-6.760$ | 0.22 | $-0.93$ |
| $1g_{7/2}$ | $-4.315$ | 0.2181 | $2p_{1/2}$ | $-4.760$ | 0.19 | $-0.16$ |
| $1h_{11/2}$ | $-3.314$ | 0.2075 | $1f_{5/2}$ | $-3.380$ | 0.21 | $-0.14$ |

# Recoil ($\lambda$-transfer)

$$\vec{Q} = \frac{m_d}{m_B}\vec{k}_\beta + \frac{m_d}{m_a}\vec{k}_\alpha$$

Transfer angular momentum $\lambda$:

$$|j_1' - j_1| \leq \lambda \leq (j_1' + j_1)$$
$$|l_1' - l_1| \leq \lambda \leq (l_1' + l_1)$$

- $\vec{Q} = 0$ **ONLY natural transitions.** Parity is conserved:

$$\Delta\pi = (-1)^{l_1'+l_1} = (-1)^\lambda$$

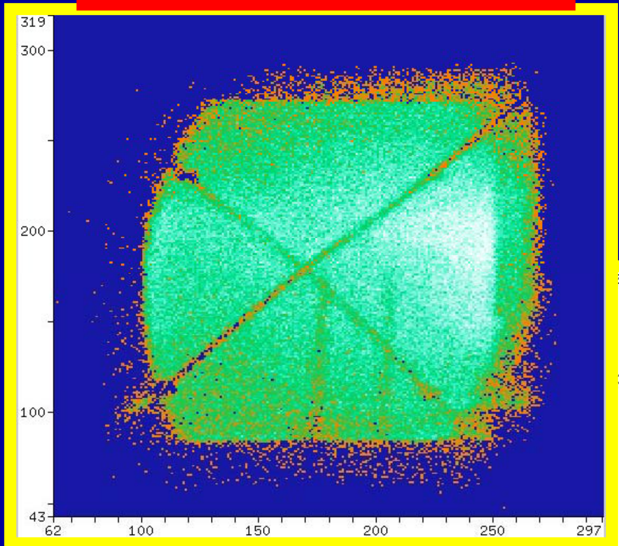
- $\vec{Q} \neq 0$ **NON-natural transition are allowed.**

$$\Delta\pi \neq (-1)^\lambda$$

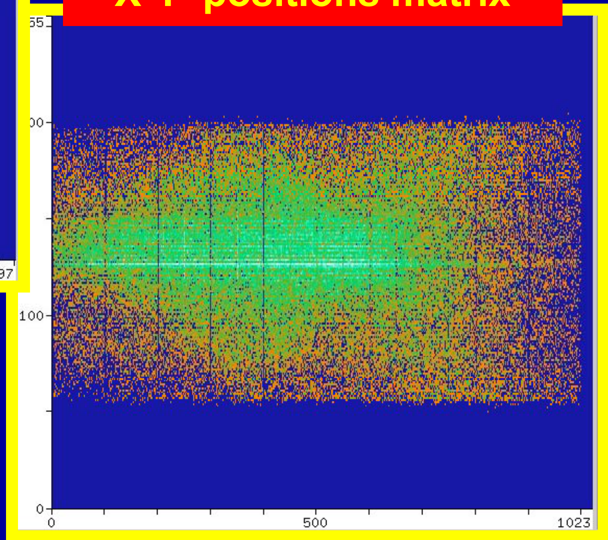
- **RECOIL IMPORTANT for two-nucleons transfer** ($\vec{Q}$ is proportional to the mass $m_d$ of the transferred particle)

# Measurement of sub-transfer reactions with PRISMA

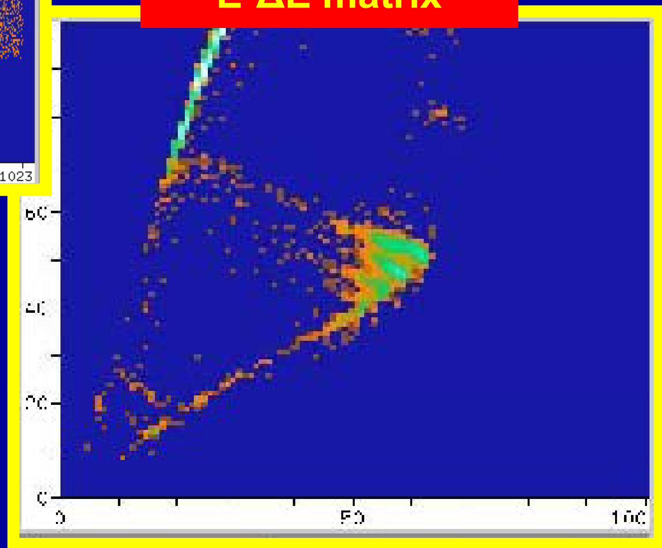
**MCP detector :**
**X-Y positions matrix**



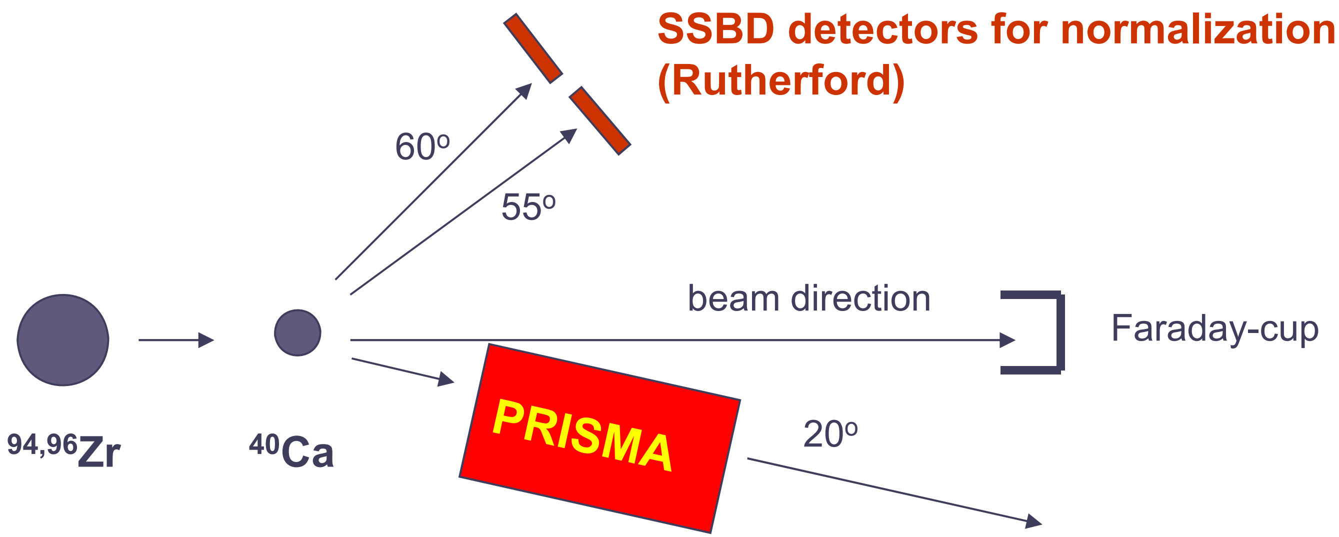

**MWPPAC detector :**
**X-Y positions matrix**




**IC detector :**
**E-ΔE matrix**



# Measurement of sub-transfer reactions with PRISMA



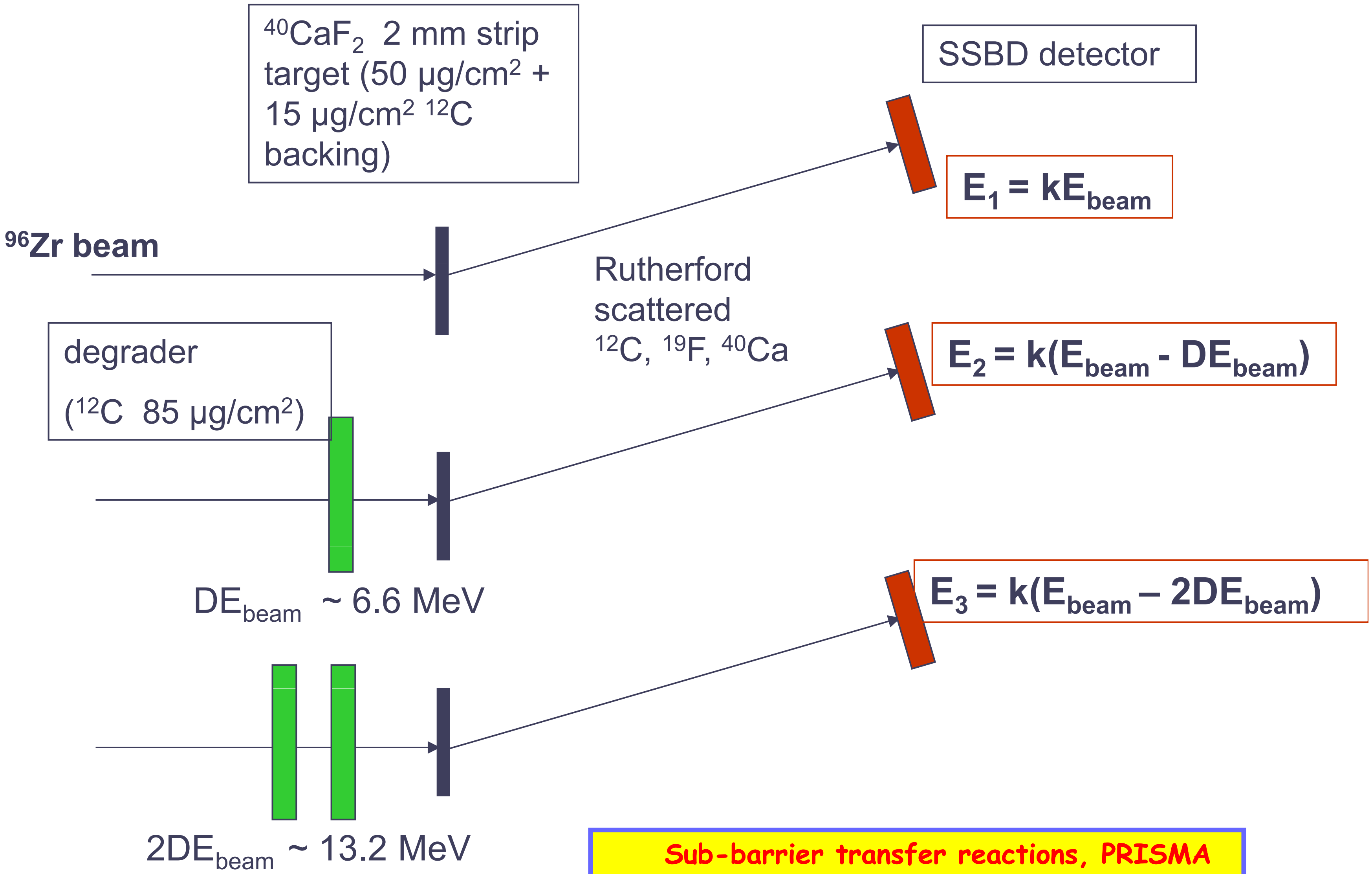

**Beam : $^{96}$Zr (0.5 - 1 pnA)**

**Target : $^{40}$Ca (50 μg/cm$^2$)**

**Energy : from 330 to 250 MeV (17 points)**

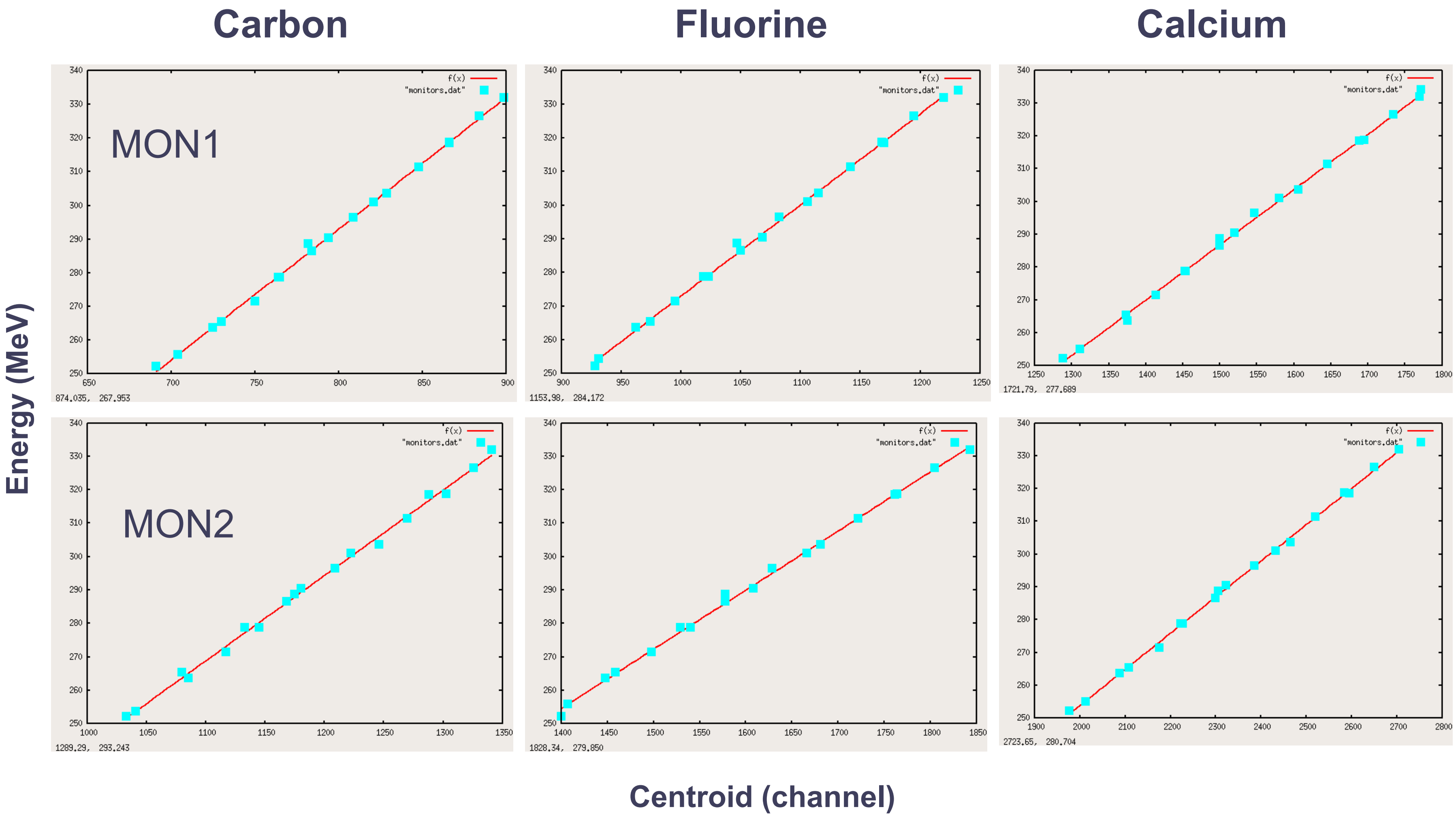
**Prisma fixed at 20° (140° in c.m.)**

# Detection of Rutherford scattered recoils




Sub-barrier transfer reactions, PRISMA
Exp.08.22 (19-25/2/2009)

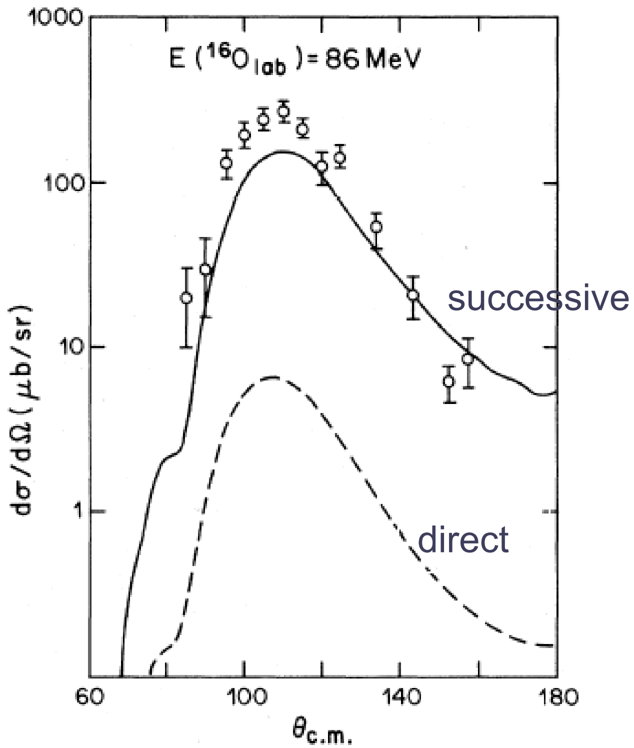
# Centroids-energy for C,F,Ca ions into the two monitors



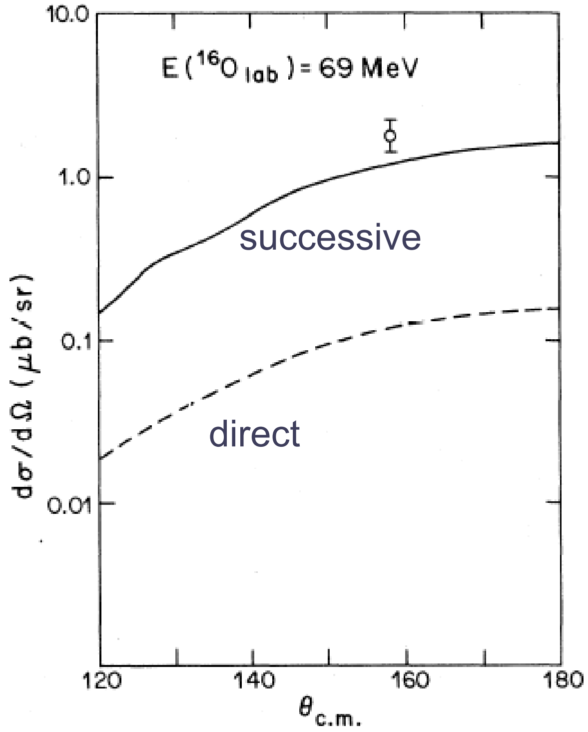
# Absolute cross sections for one and two-nucleon transfer reactions

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

$E \sim E_b$




$E \ll E_b$




one+two step calculations undepredict the data by a factor ~ 2

one+two step calculations undepredict the data by 25-30%

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