# Aspects of the transition from quasi elastic to deep inelastic processes

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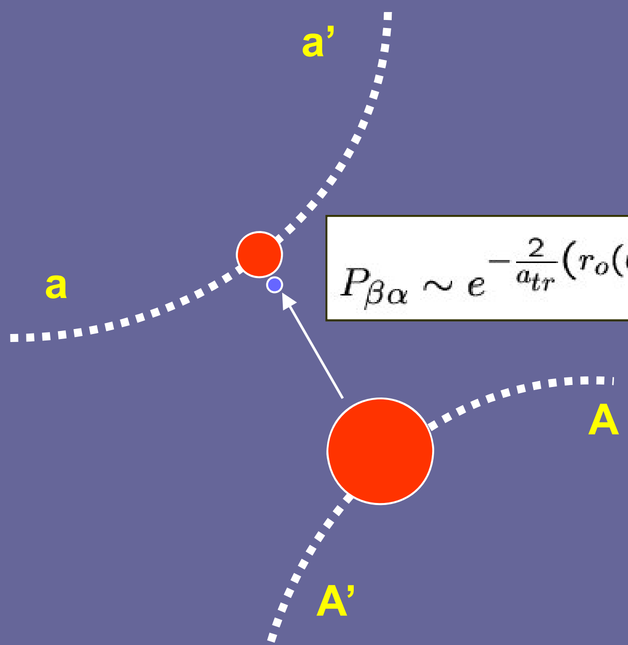
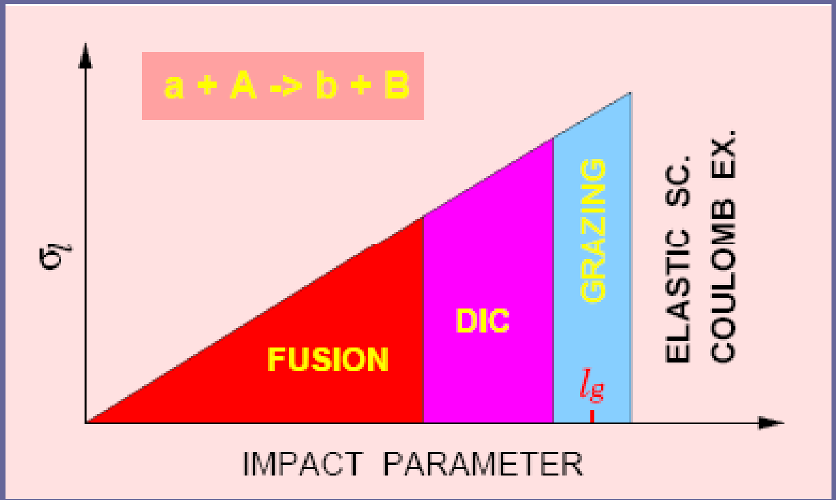
Workshop on Decoherence
ECT* Trento, April 26-30, 2010

# Transfer reactions among heavy ions




$$P_{\beta\alpha} \sim e^{-\frac{2}{a_{tr}}(r_o(\theta)-R_o)}$$




0 particle transfer (elastic and inelastic scattering)

1 particle transfer (single particle deg. of freedom)

2 particle transfer (nucleon-nucleon correlations)

N particle transfer (towards deep inelastic reactions)

# Multinucleon transfer reactions : a link between two regimes

**number of transferred nucleons**

1-2 → > 10

**degrees of freedom**

single particle transfer

pair modes

↓

macroscopic modes (N/Z)

nucleon flow

**theoretical approach**

DWBA

coupled channels

↓

diffusion models

stochastic models

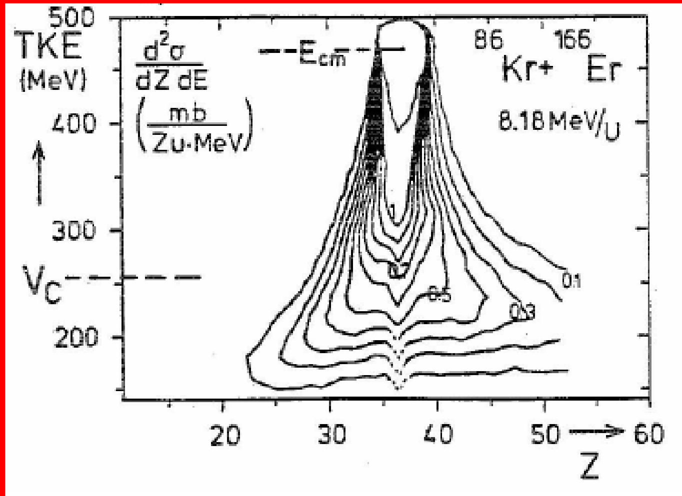
**energy loss**

few MeV → several MeV

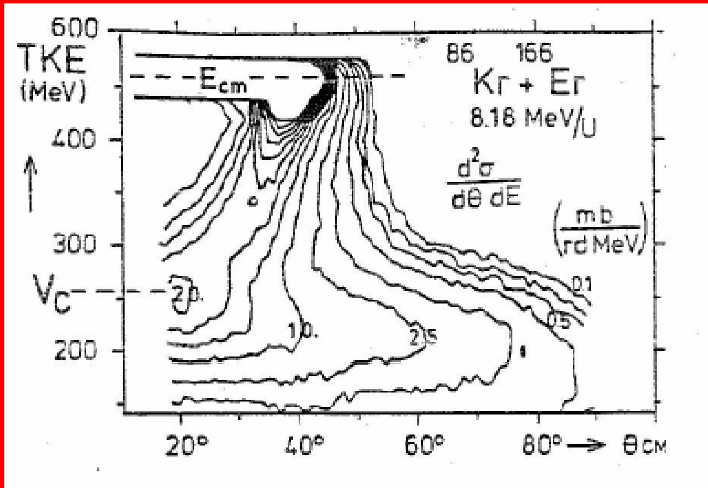
# deep inelastic processes

# Deep inelastic collisions : macroscopic view

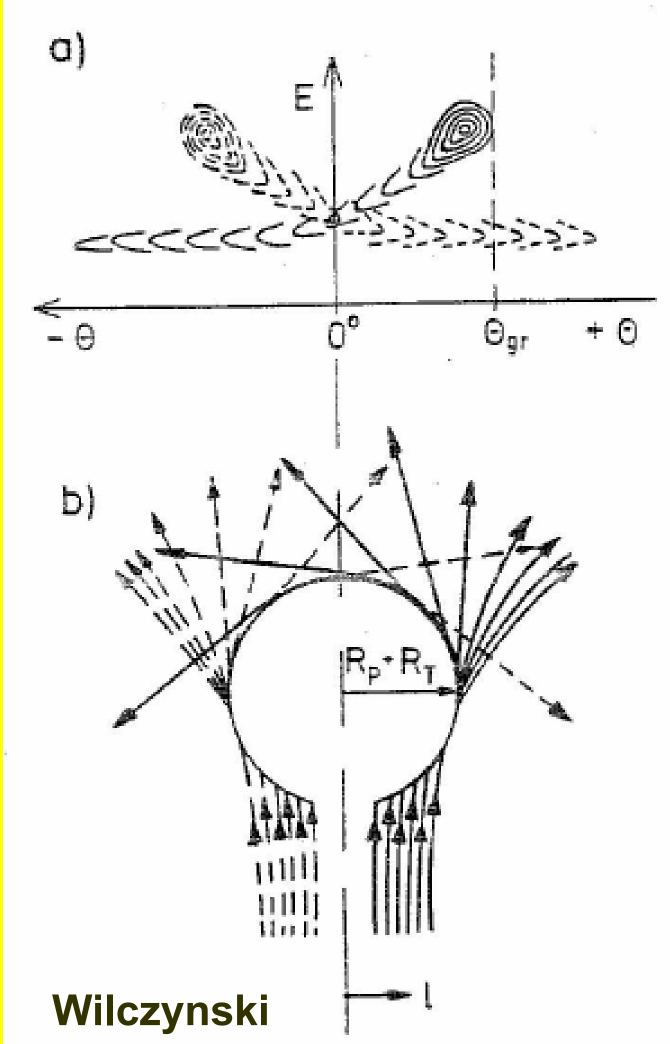
## diffusion effects on nucleons




## angular dependence of energy loss




## concept of dinuclear system




Wilczynski

# Dissipative forces : correlation between A,Z variances and energy loss

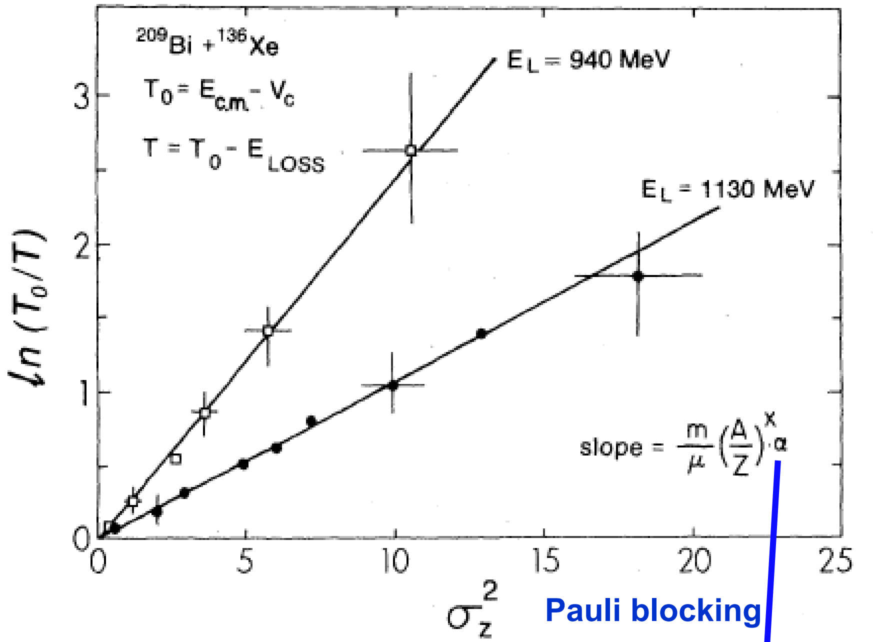
**dissipation of kinetic energy generated by the microscopic flux of nucleons**

$$\ln(T_0/T) = \frac{m}{\mu}\left(\frac{A}{Z}\right)^x \sigma_Z^2$$

$$E_{loss} = -\int_0^T \frac{dT}{dt}\,dt$$

$$\frac{-dT}{dt} = \vec{F}(t)\,\vec{u}(t) = j(t)(2u_r^2 + u_t^2)$$

$$\frac{dT(t)}{T(t)} = -\frac{m}{\mu}\,d\sigma_A^2 = -\frac{m}{\mu}\left(\frac{A}{Z}\right)^x d\sigma_Z^2$$




**Pauli blocking**

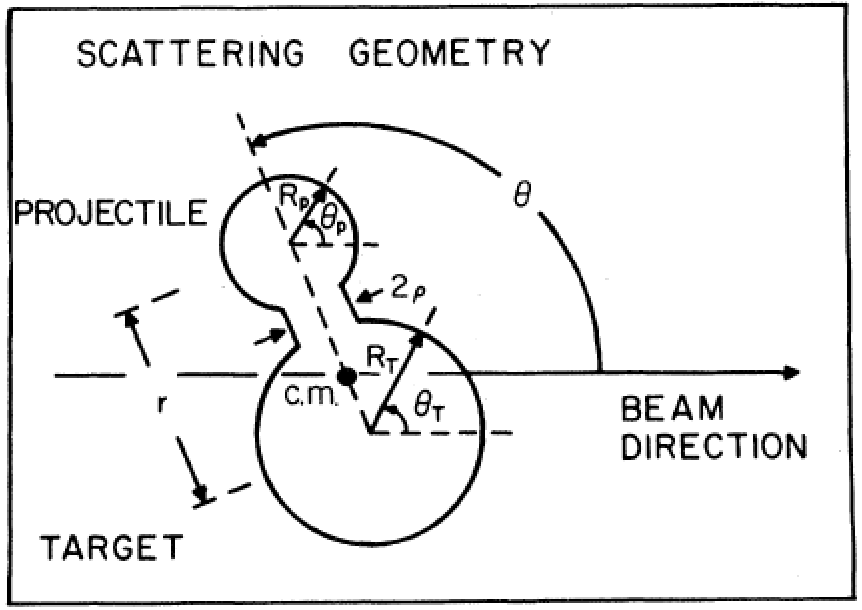
N and Z diffusion :
x=1 uncorrelated
x=2 totally correlated

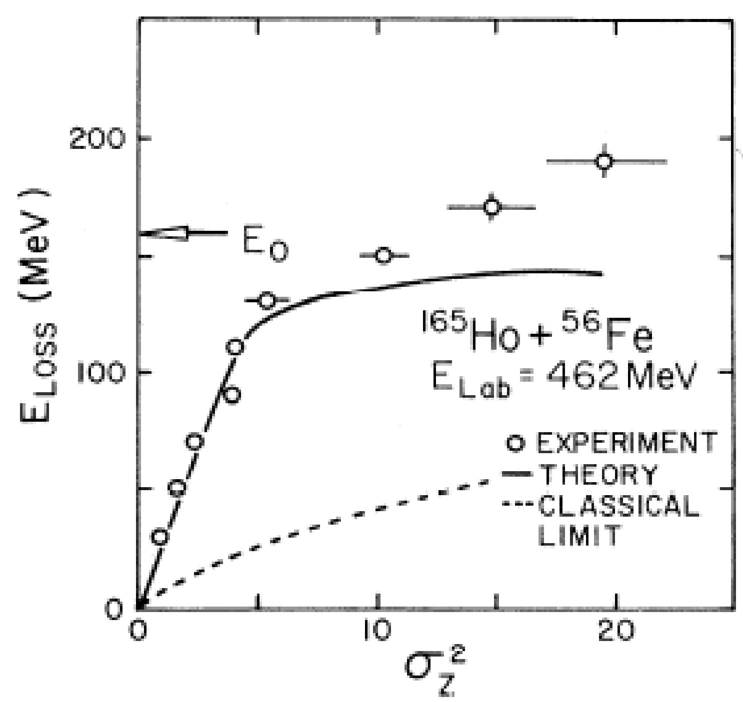
$$\sigma_A^2 = \left(\frac{A}{Z}\right)^x \sigma_Z^2$$

| $E_{lab}$ (MeV) | Experimental slope (see Fig. 16) | Classical slope $x=1$ | Classical slope $x=2$ | Quantal slope $x=1$ | Quantal slope $x=2$ |
|---|---|---|---|---|---|
| 940 | 0.25 | 0.03 | 0.08 | 0.09 | 0.23 |
| 1130 | 0.11 | 0.03 | 0.08 | 0.07 | 0.17 |

W.W.Wilcke et al., PRC22(1980)128

# Lagrange-Rayleigh equations of motion in multidimensional coordinate space




$$\left[ \frac{d}{dt}\frac{\partial}{\partial \dot{q}_i} - \frac{\partial}{\partial q_i} \right] L = -\frac{\partial}{\partial \dot{q}_i} F, \quad q_i \in \{ r, \theta, \theta_p, \theta_T \}$$

$$\frac{\partial}{\partial q_i} L = \frac{\partial}{\partial \dot{q}_i} F, \quad q_i \in \{ \rho, A_P, Z_P \}$$

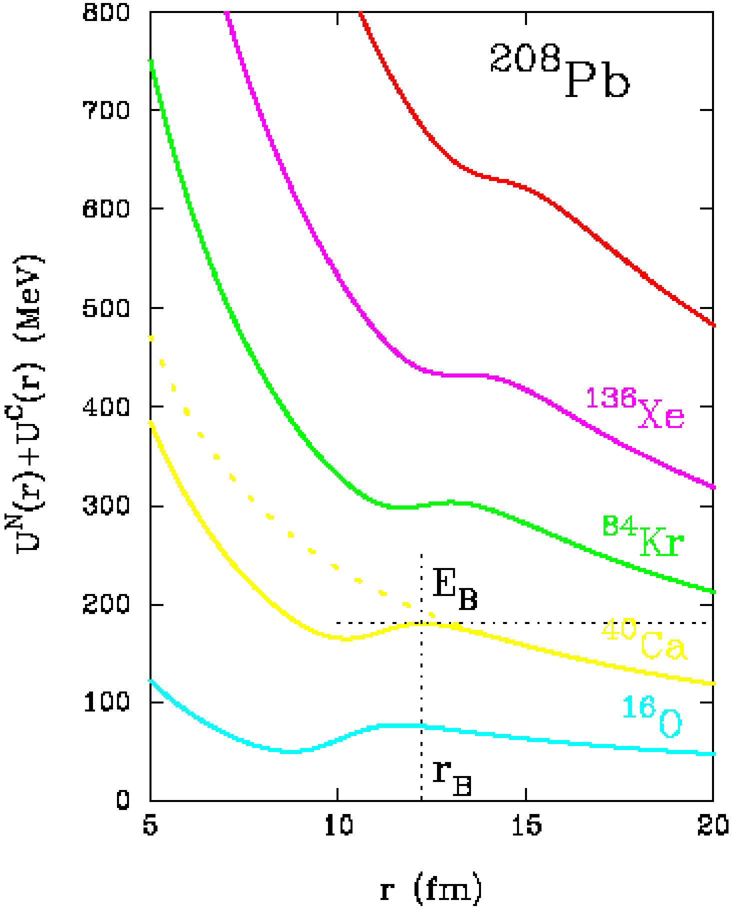
**A.D.Hoover et al., PRC25(1982)256**

the results indicate the importance of the Pauli principle

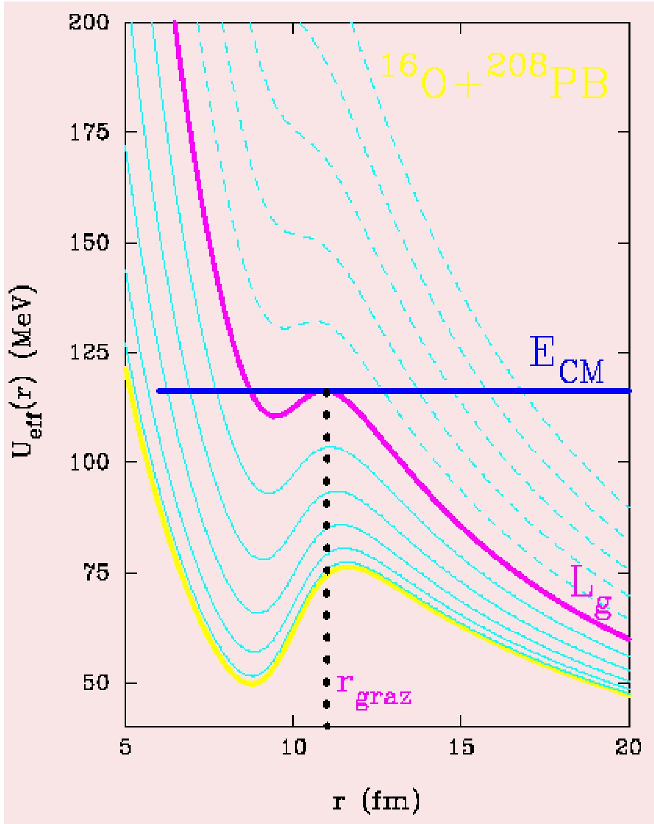
agreement is fine up to the point where the system should become strongly deformed

# Two basic concepts for the interaction (nuclear+Coulomb) potential

the potential pocket gets smaller as $Z_p Z_t$ increases



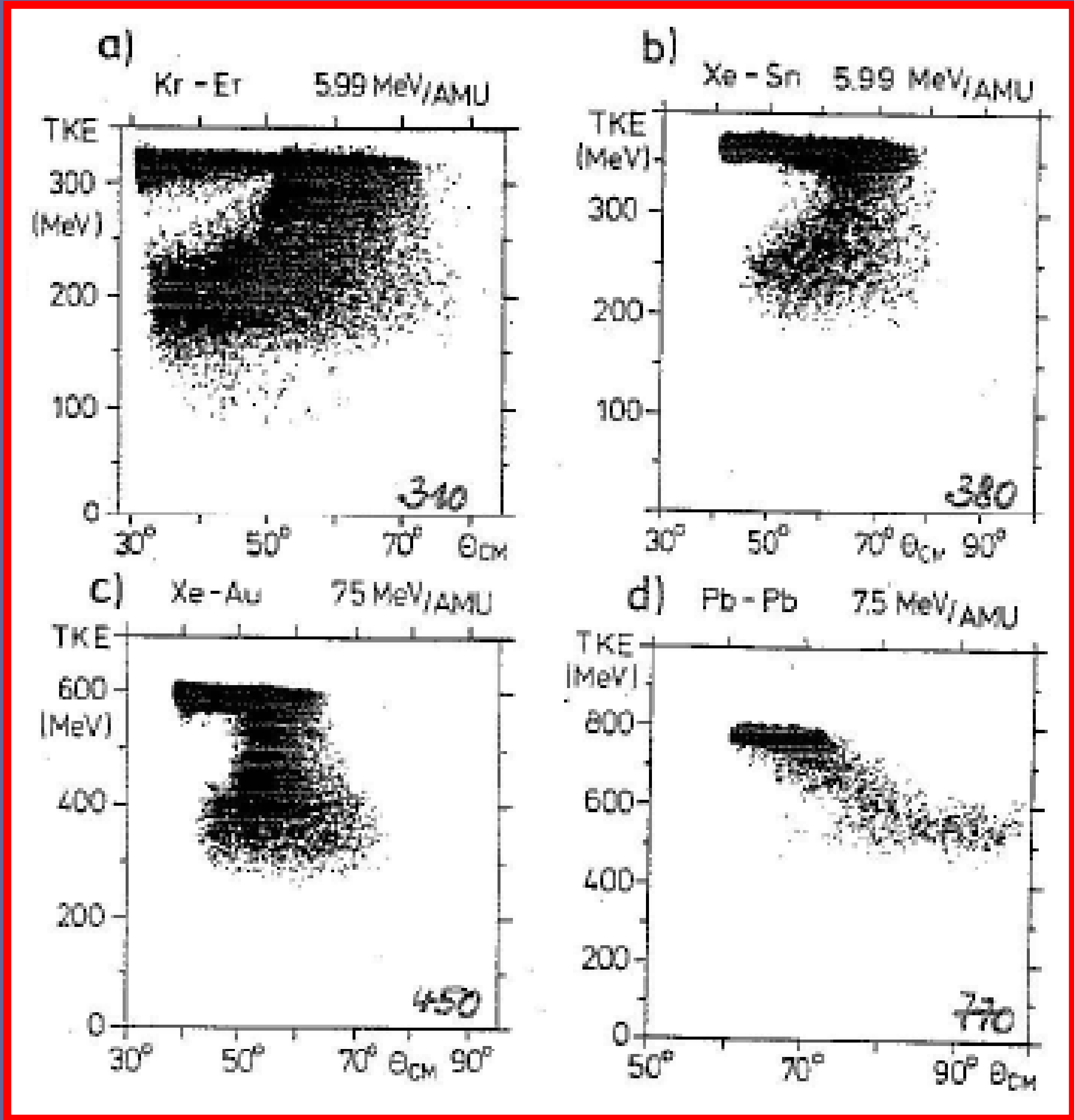

the effective potential depends on the angular momentum



# Deep inelastic collisions : how TKE-θ distributions depend on $Z_pZ_t$

orbiting

focussing




high Coulomb field

From Sahn et al (1977)

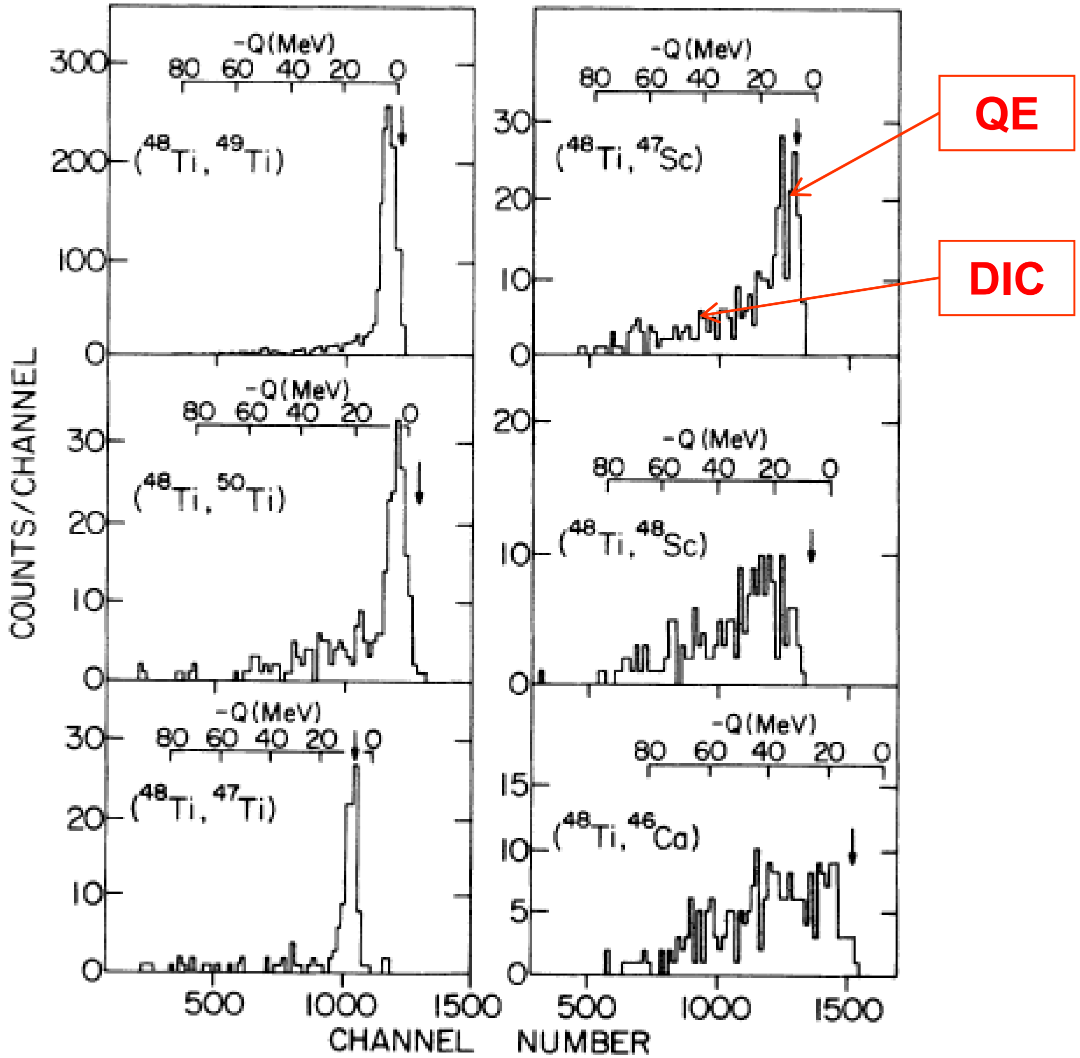
# quasi elastic processes

# Quasi-elastic regime in multinucleon transfer reactions : Q-values

$^{48}Ti + ^{208}Pb$

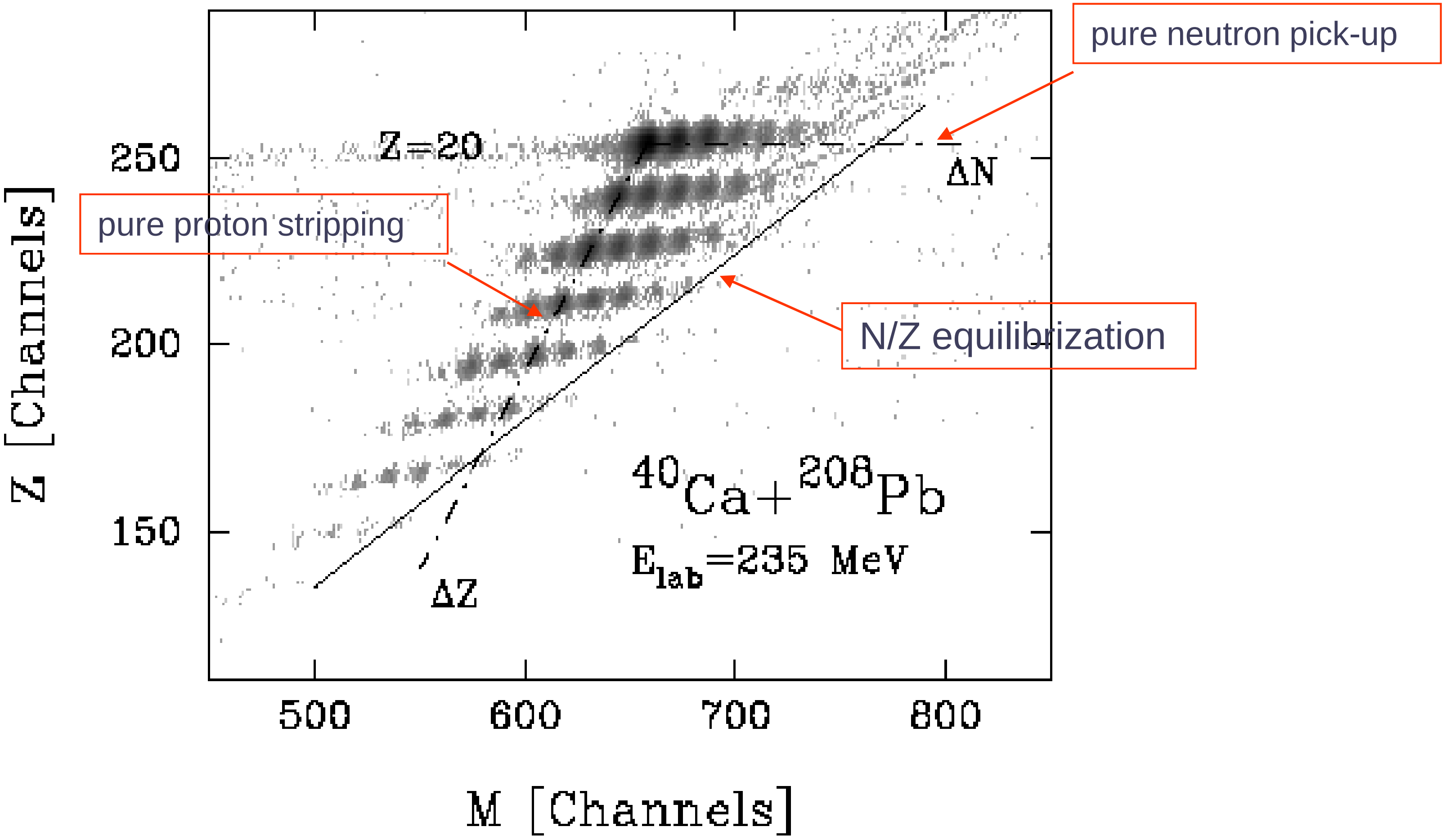
$E_{lab}$ = 300 MeV

$\theta_{lab}$ = 55°




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

# Quasi-elastic regime in multinucleon transfer reactions : A,Z yields




S.Szilner et al, Phys.Rev.C71(2005)044610

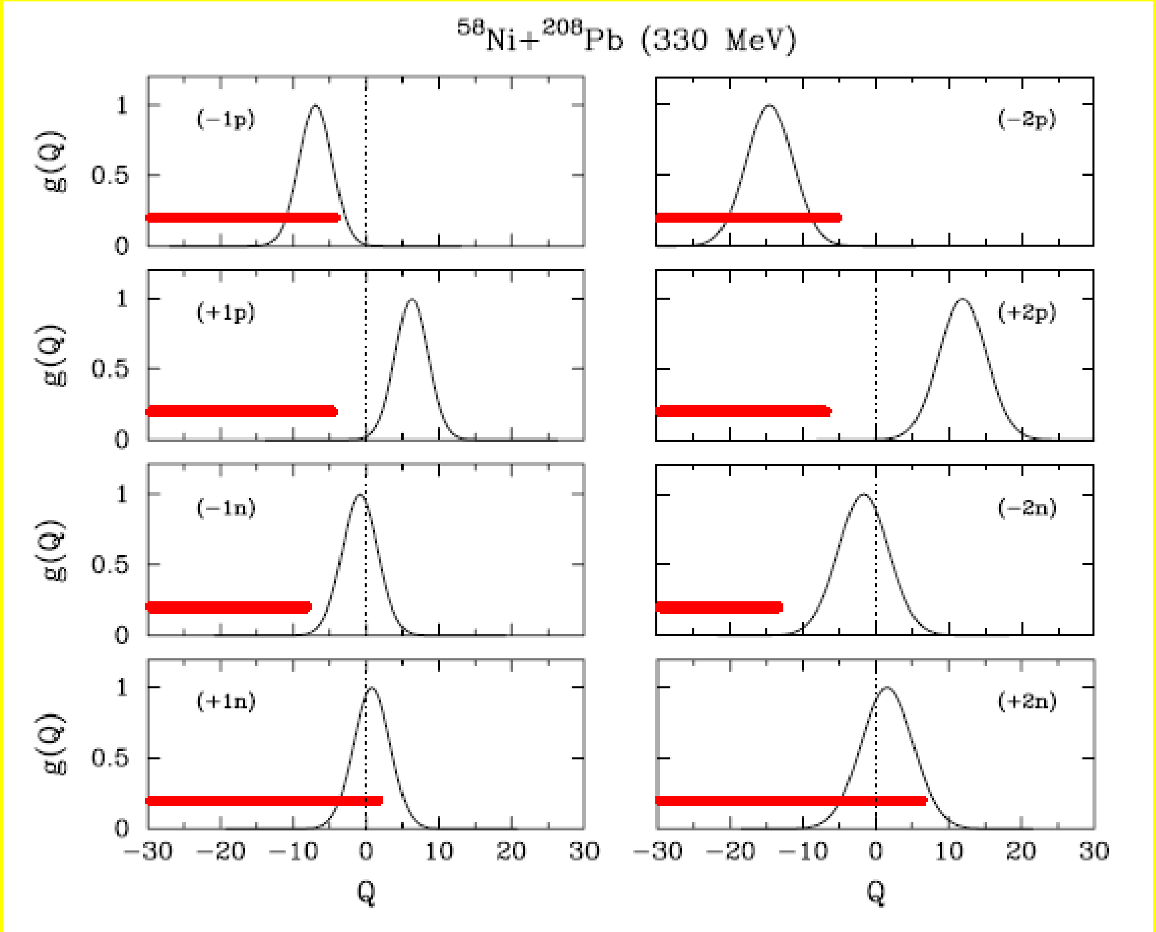
# Quasi elastic processes : optimum Q-value

**cut-off function**

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

**transfer probability**

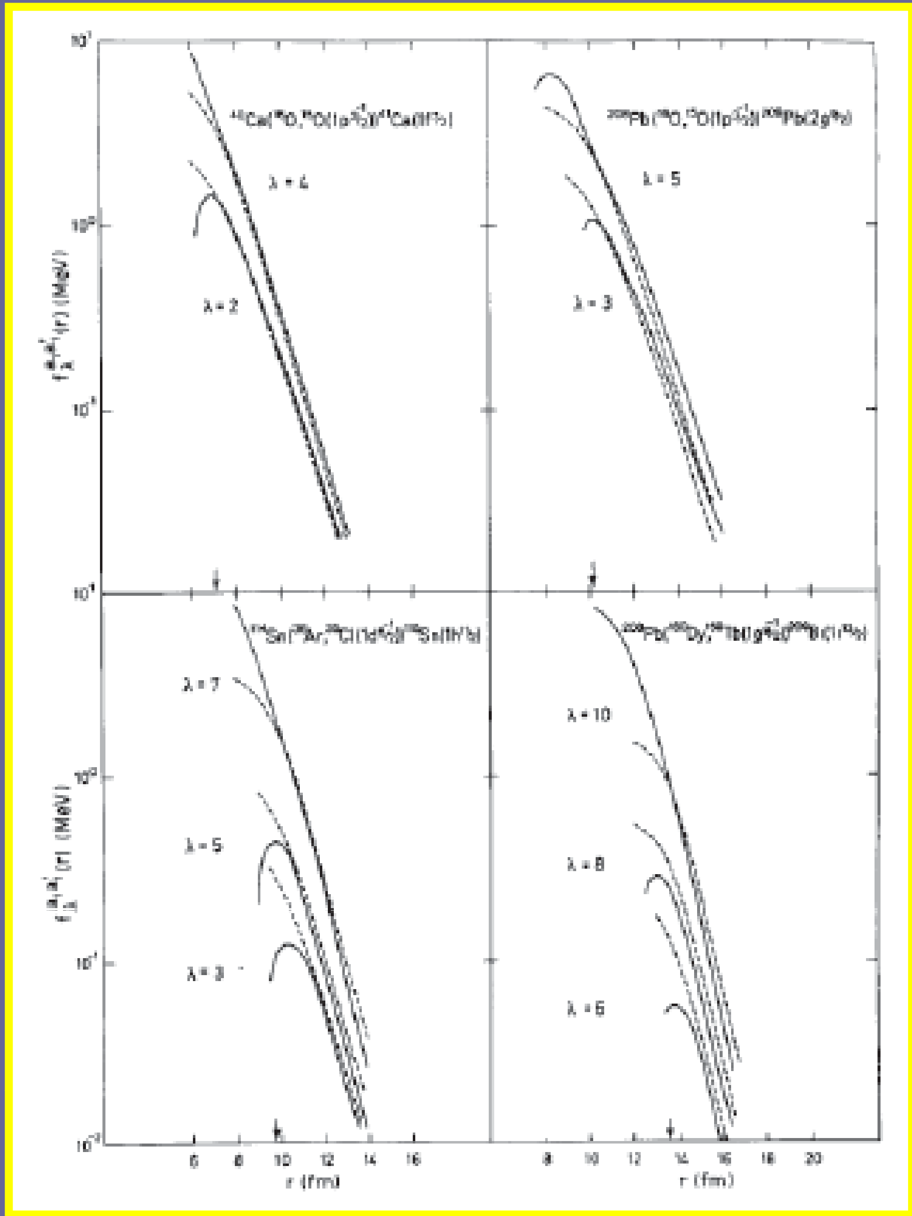
$$P_{\beta\alpha} = \sqrt{\frac{1}{16\pi\hbar^2 |\ddot{r}_0| \kappa_{a'_1}}} |f_{\beta\alpha}(0, r_0)|^2 g(Q_{\beta\alpha})$$




**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, NPA406 (1983)369

# Quasi elastic processes : form factors




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

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

**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**

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

**the form factor has an exponential shape in its tail region**

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

# Semiclassical theory

The time evolution of a heavy-ion reaction is described by the following system of coupled equations :

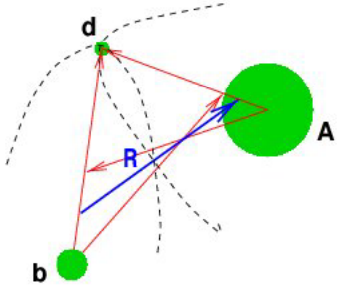
$$i\hbar\dot{c}_\beta(t) = \sum_\alpha < \beta|H_{int}|\alpha > c_\alpha(t)e^{\frac{i}{\hbar}(E_\beta-E_\alpha)t+i(\delta_\beta-\delta_\alpha)}$$

$$i\hbar\dot{\Psi}(t) = (H_0 + H_{int})\Psi(t)$$

$$\Psi(t) = \sum_\beta c_\beta(t)\psi_\beta e^{\frac{i}{\hbar}E_\beta t}$$

where $\psi_\alpha$ are the channels wave function (asymtotic states)

$$\psi_\alpha(t) = \psi^a(t)\psi^A(t)e^{i\delta(\vec{R})}$$




E.Vigezzi and A.Winther, Ann.of Phys. 192, 432 (1989)

A.Winther, Nucl.Phys.A572,191(1994)

A.Winther, Nucl.Phys.A594,203(1995)

The intrinsic Hamiltonian is:

$$\hat{H}_0 = \sum_i^{(a)} \epsilon_i a_i^\dagger a_i + \sum_{\lambda\mu}^{(a)} \hbar\omega_\lambda a_{\lambda\mu}^\dagger a_{\lambda\mu} + (A)$$

and the interaction

$$\hat{V}_{int}(t) = \hat{V}_{tr}(t) + \hat{V}_{in}(t) + \Delta U_{aA}(t)$$

contains the well known **form-factors for inelastic excitation** of the surface modes and for **one-particle transfer** (both for protons and neutrons).

The **time dependence** of the matrix elements is obtained by solving the Newtonian equations for the relative motion in the nuclear plus Coulomb field. For the nuclear potential we use the **Akyüz-Winther parametrisation** that describes quite well elastic scattering data for several projectile and target combinations.

**Program GRAZING**

**www.to.infn.it/~nanni**

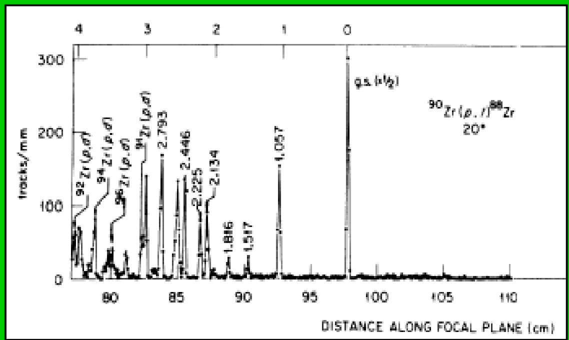
**(G.Pollarolo)**

# linking QE and DIC processes

# Magnetic spectrometers for transfer reaction studies

| 70's | 80's - 90's | recent years |
|---|---|---|
| Light ions (Q3D) | Heavy ions spectrometers | Tracking spectrometers |

**70's — Light ions (Q3D)**

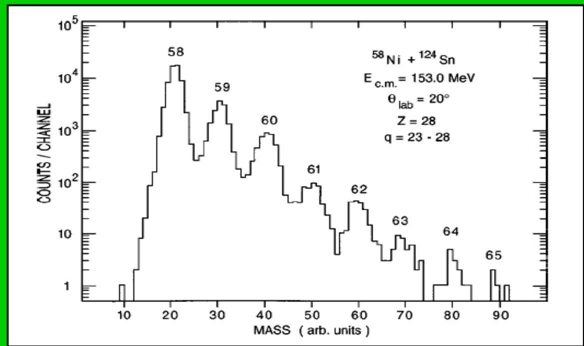



single particle levels (shell model)

nucleon-nucleon correlations (pair transfer)

3-5 msr

**80's - 90's — Heavy ions spectrometers**



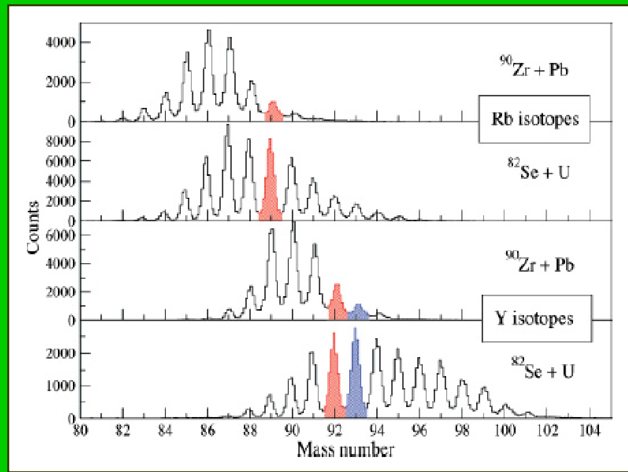

A,Z yields

cross sections

Q-value distributions

5-10 msr

**recent years — Tracking spectrometers**

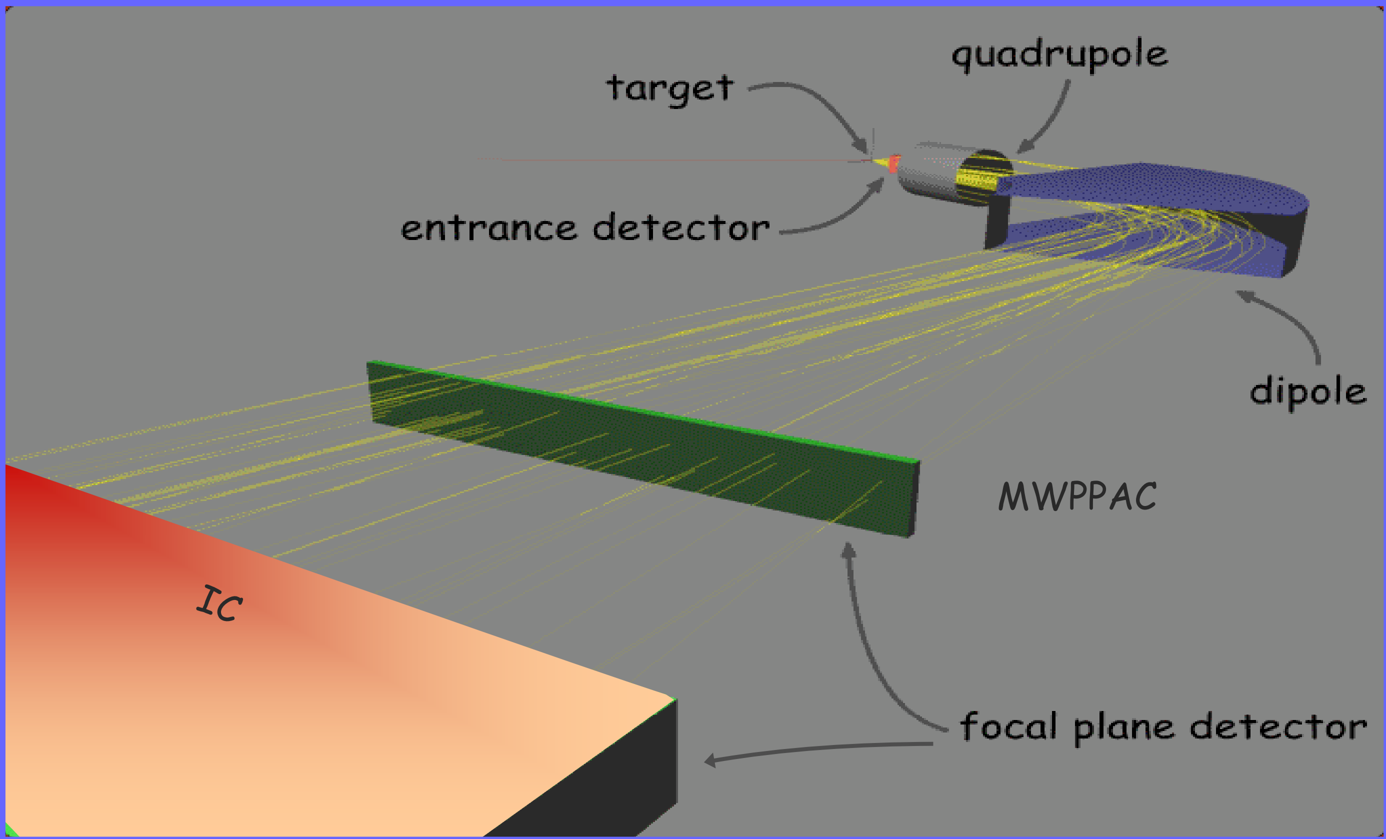



Reaction mechanism

Gamma spectroscopy

80-100 msr

# PRISMA spectrometer – trajectory reconstruction




$$T = \frac{S(\theta, \phi)}{v}$$

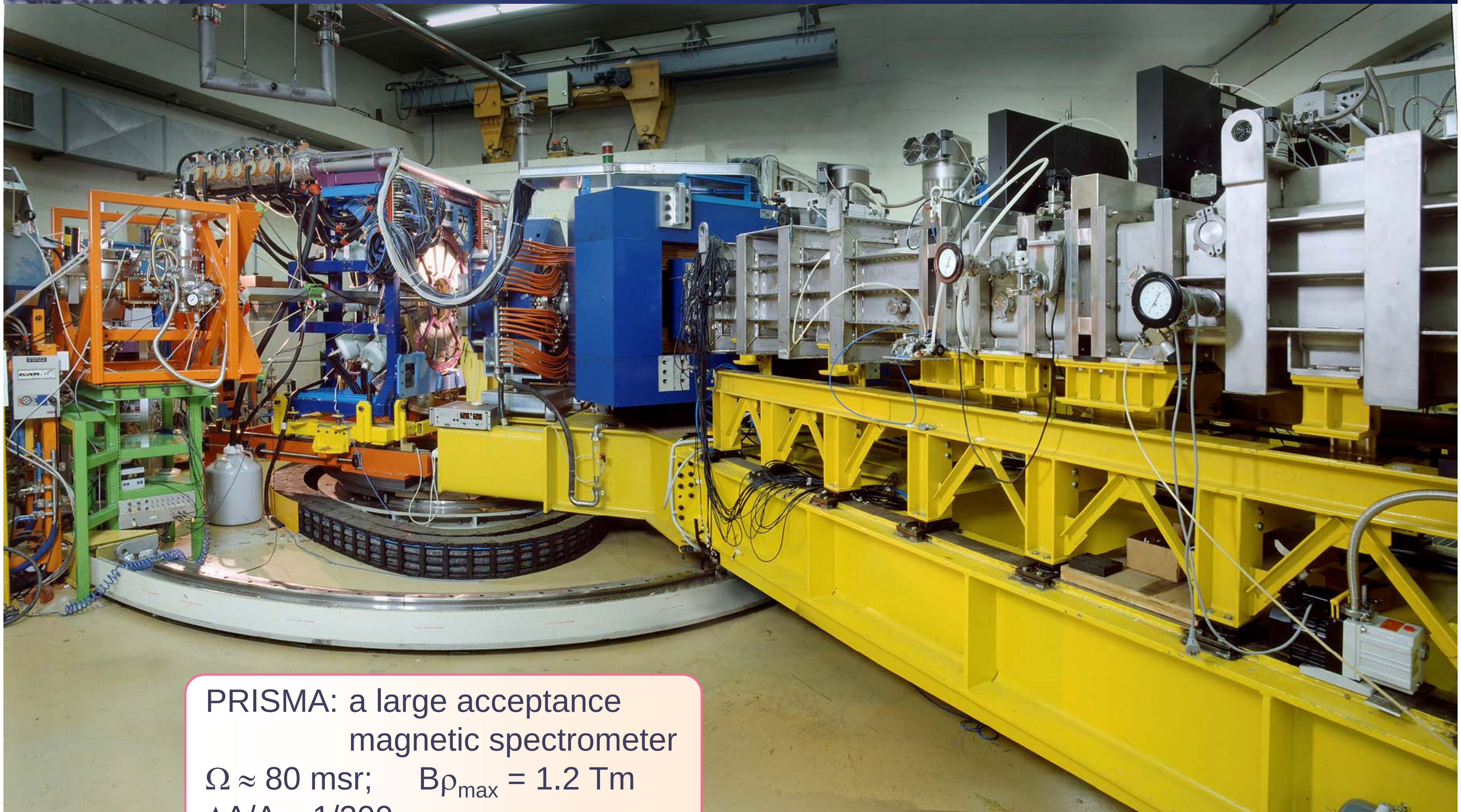
$$B\rho = A \cdot \frac{v}{q} \propto X$$

$$q = \frac{2}{S(\theta, \phi)} \cdot \frac{E \cdot T}{B\rho(\theta, \phi)}$$

A physical event is composed by the parameters:

- position at the entrance — x, y
- position at the focal plane — X, Y
- time of flight — TOF
- energy — DE, E

# THE PRISMA SPECTROMETER + CLARA GAMMA ARRAY



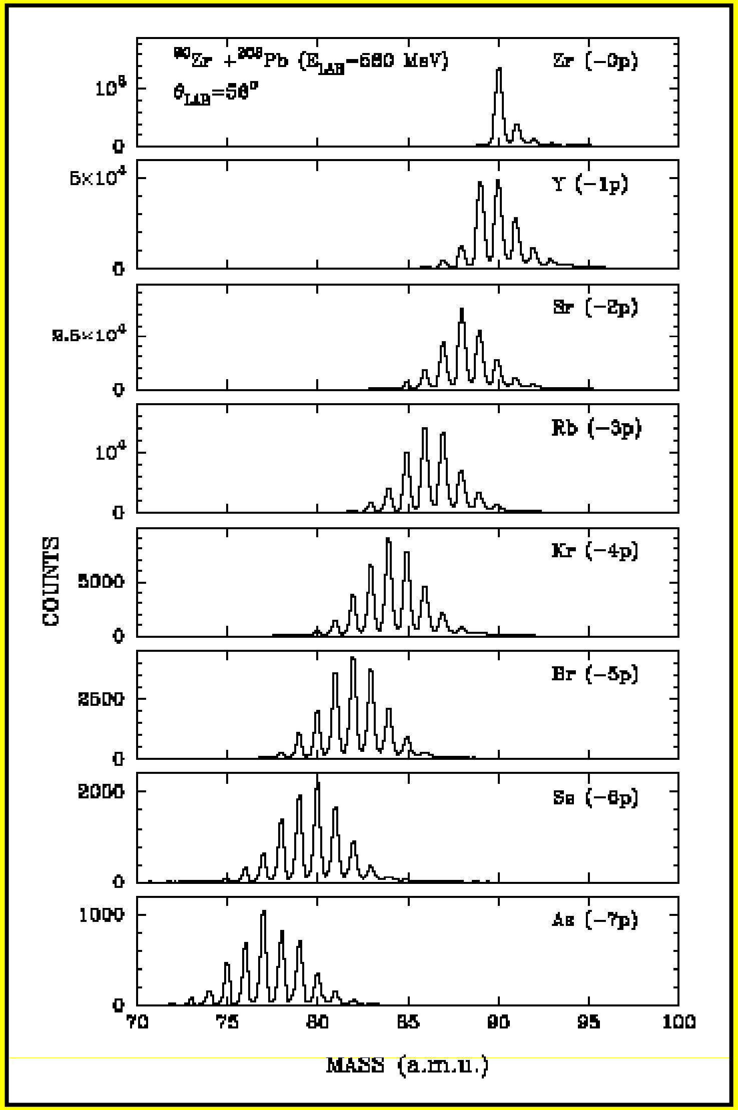
PRISMA: a large acceptance magnetic spectrometer

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

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

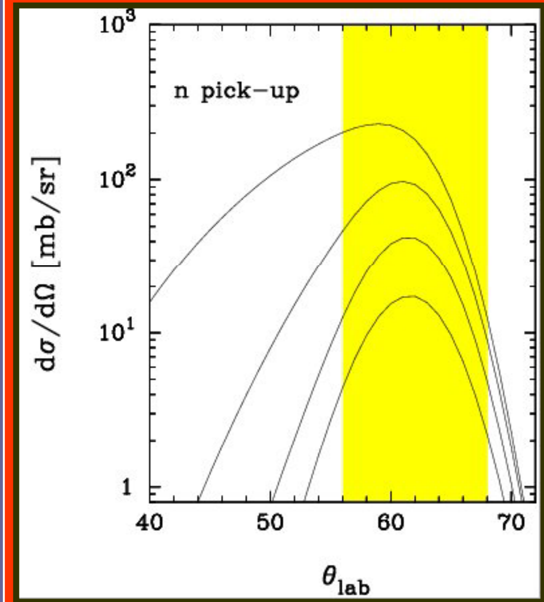
Energy acceptance $\sim \pm 20\%$

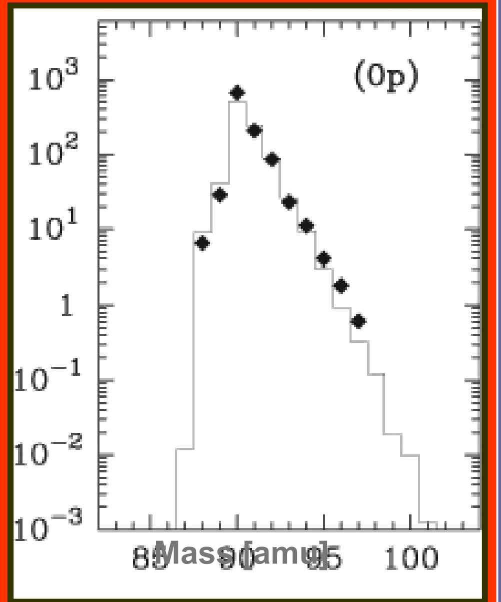
# Multineutron and multiproton transfer channels near closed-shell nuclei




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

pure neutron pick-up channels

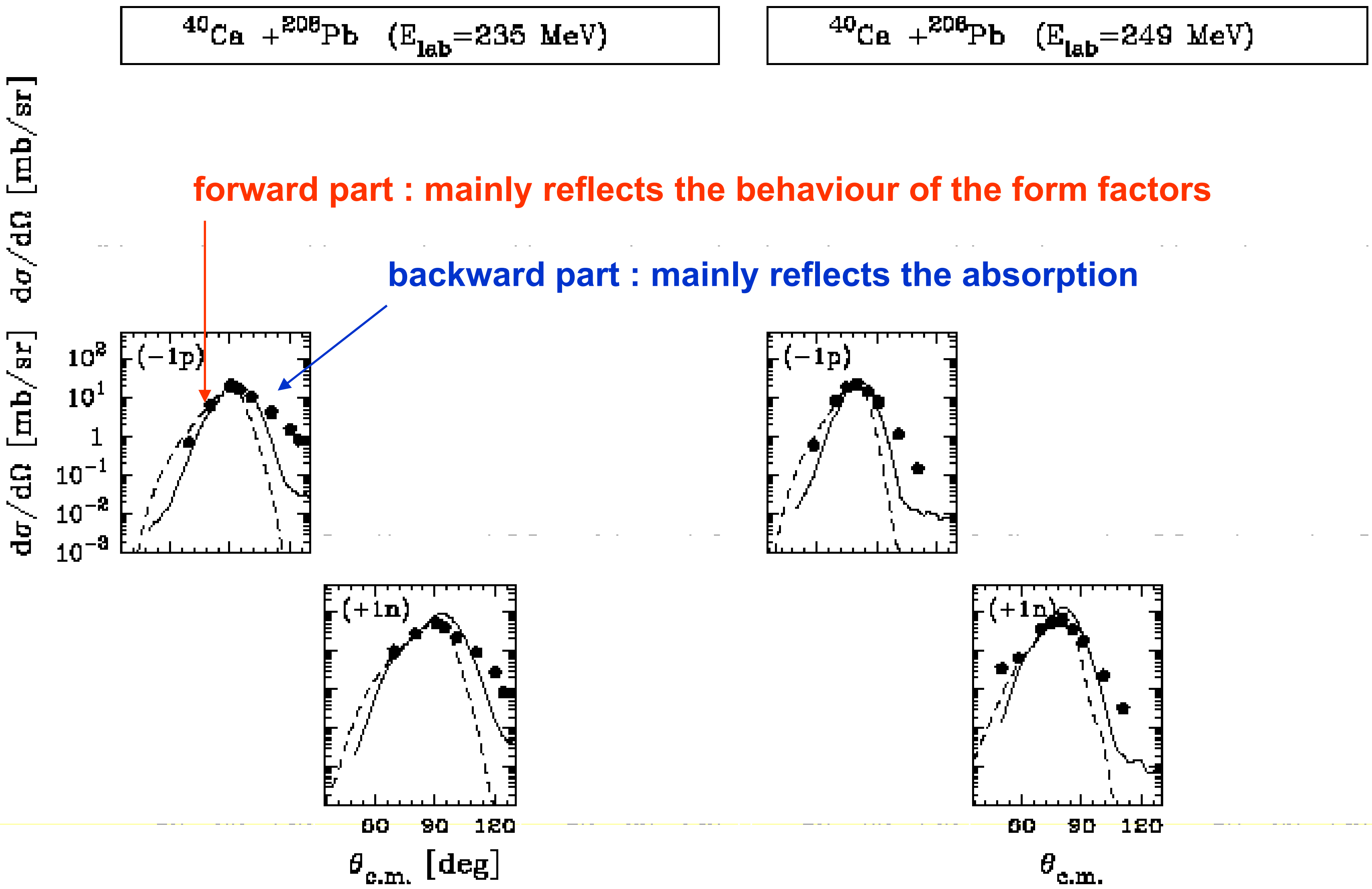


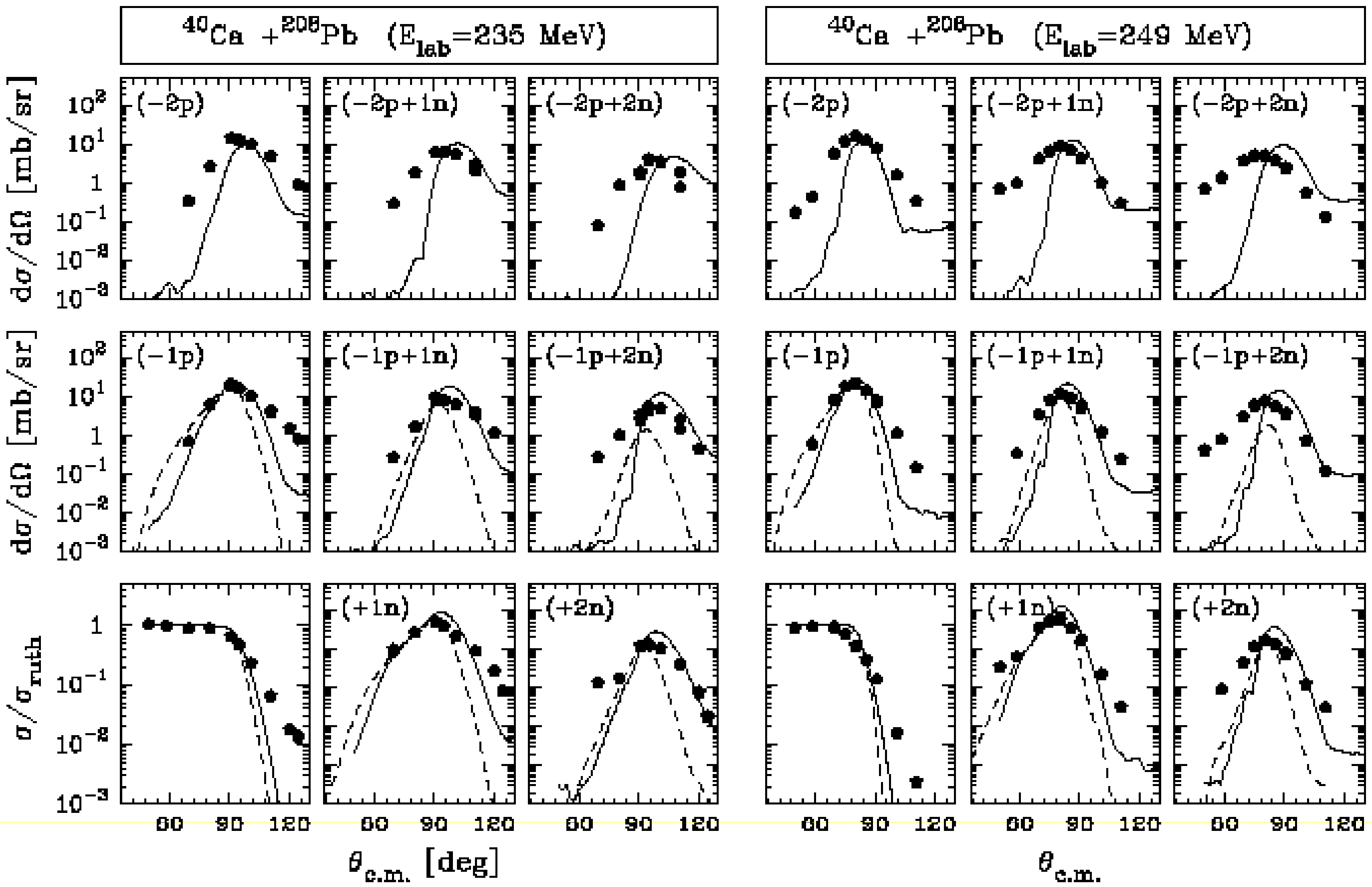

PRISMA spectrometer data

GRAZING code calculations

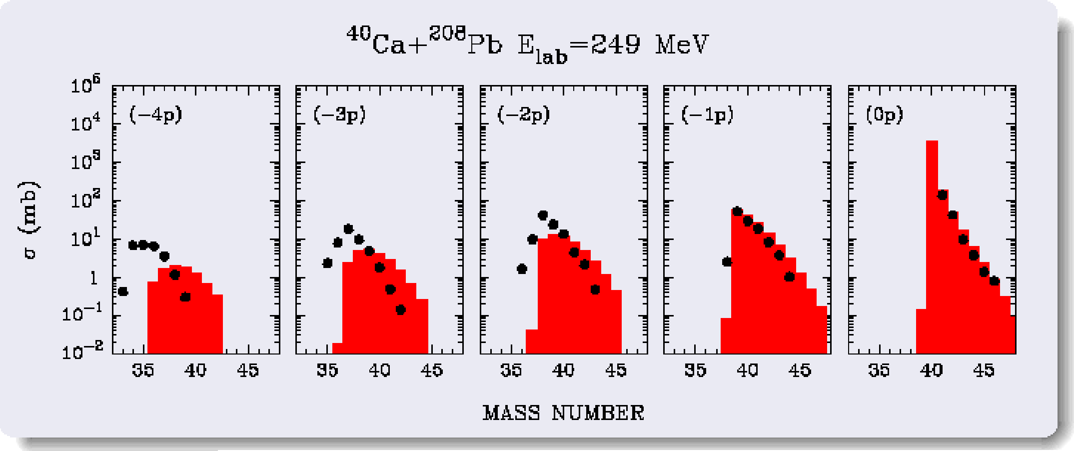
# Differential cross sections



# Differential cross sections



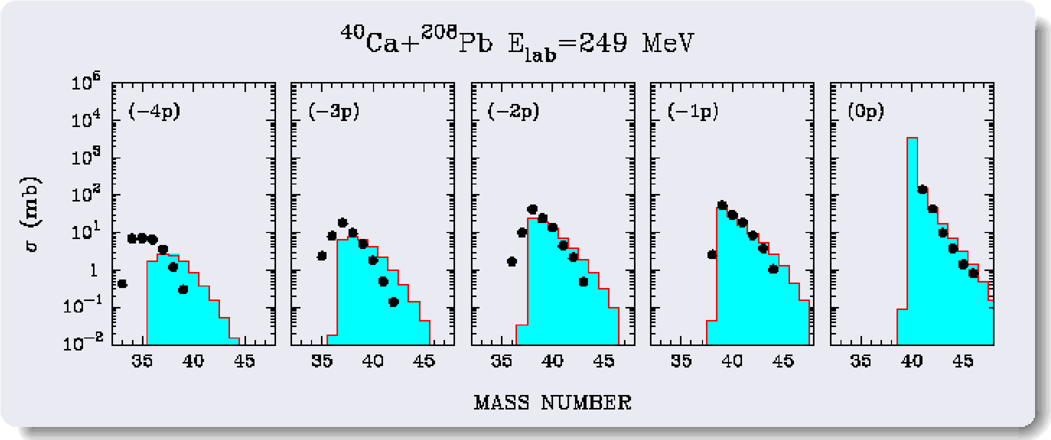
**multinucleon transfer : experiment vs. theory**




1pt

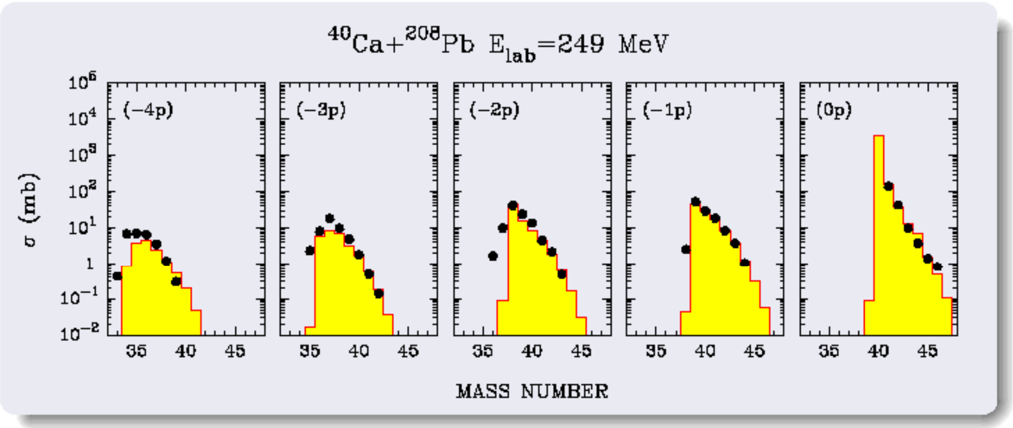
data : LNL

theory : GRAZING code and CWKB




1pt+2pt

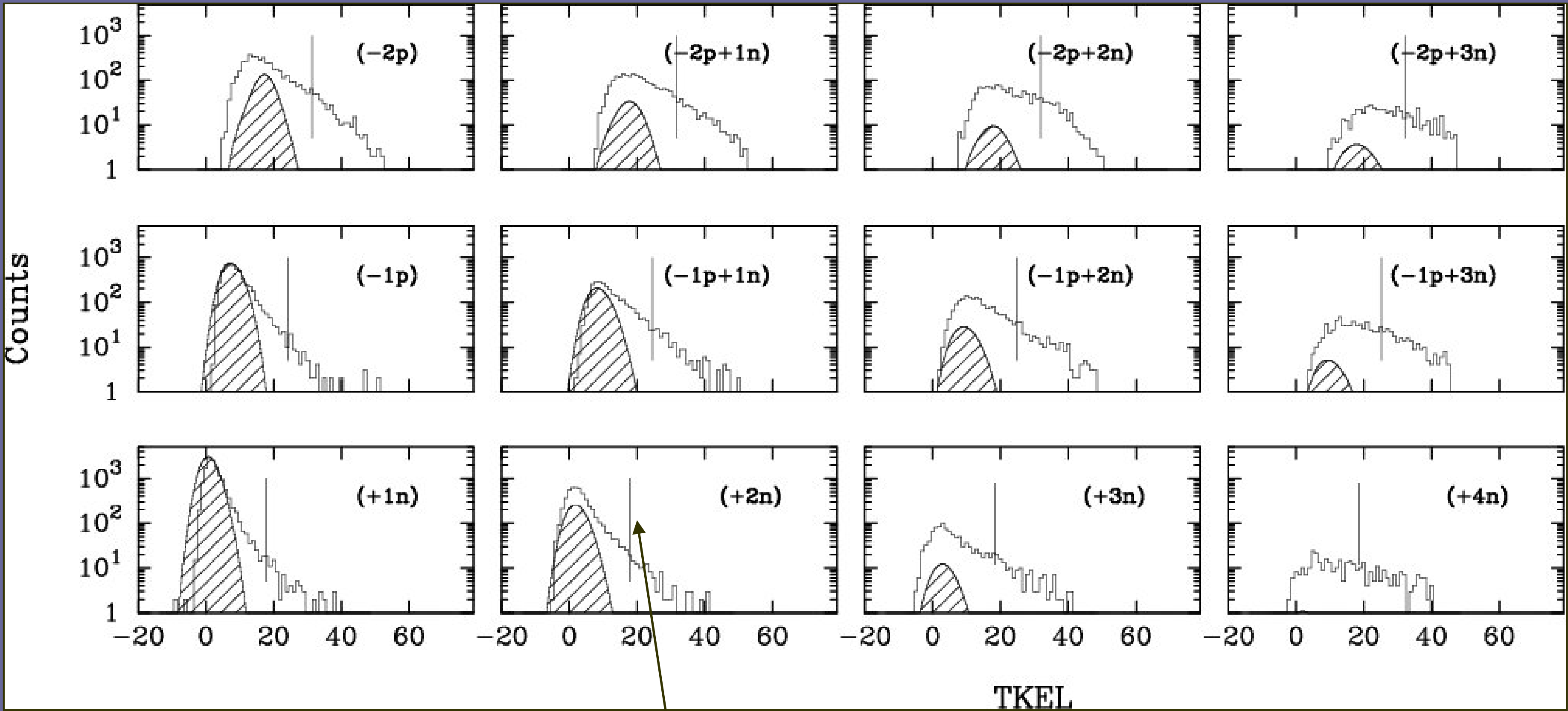
$$F_{fi}^{pair}(r) = \beta_p \frac{\partial V^{opt}(r)}{\partial A}$$




+Evap.

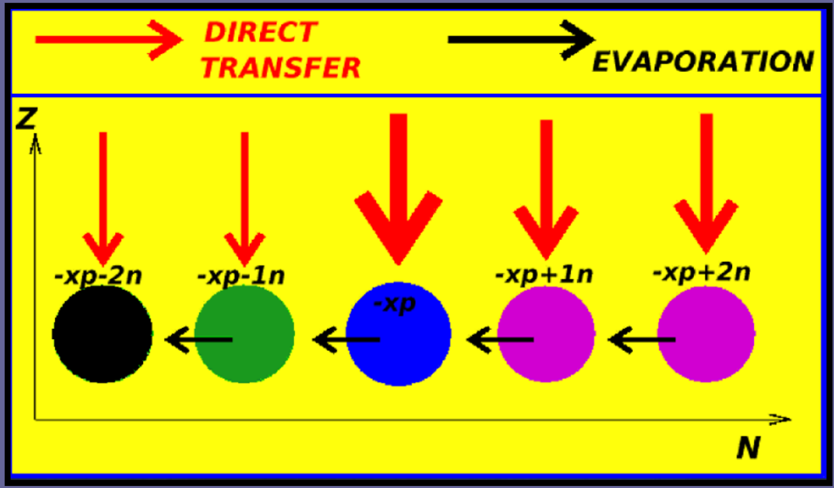
L.Corradi et al, J.Phys. G36(2009)113101 (Topical Review)

# Total kinetic energy loss distributions in $^{40}Ca+^{208}Pb$ $E_{lab}$=235 MeV $\theta_{lab}$=84°

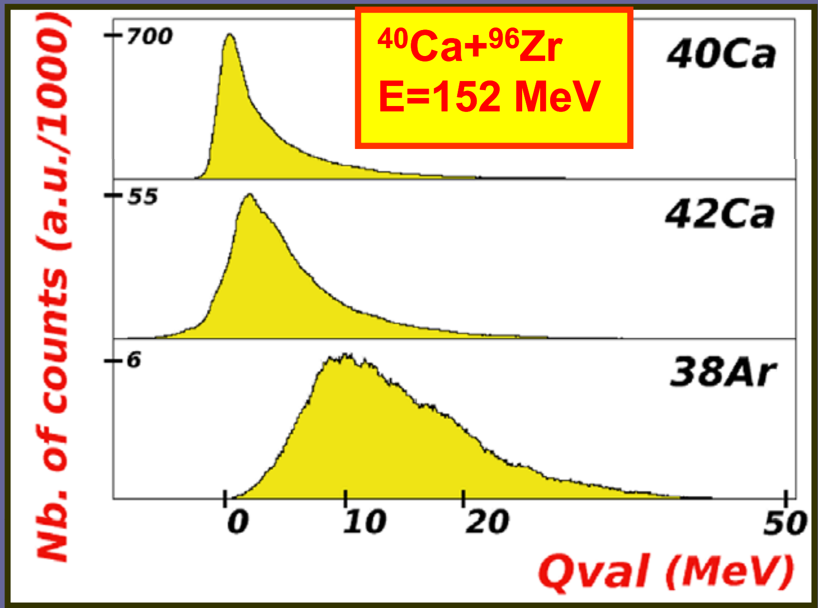


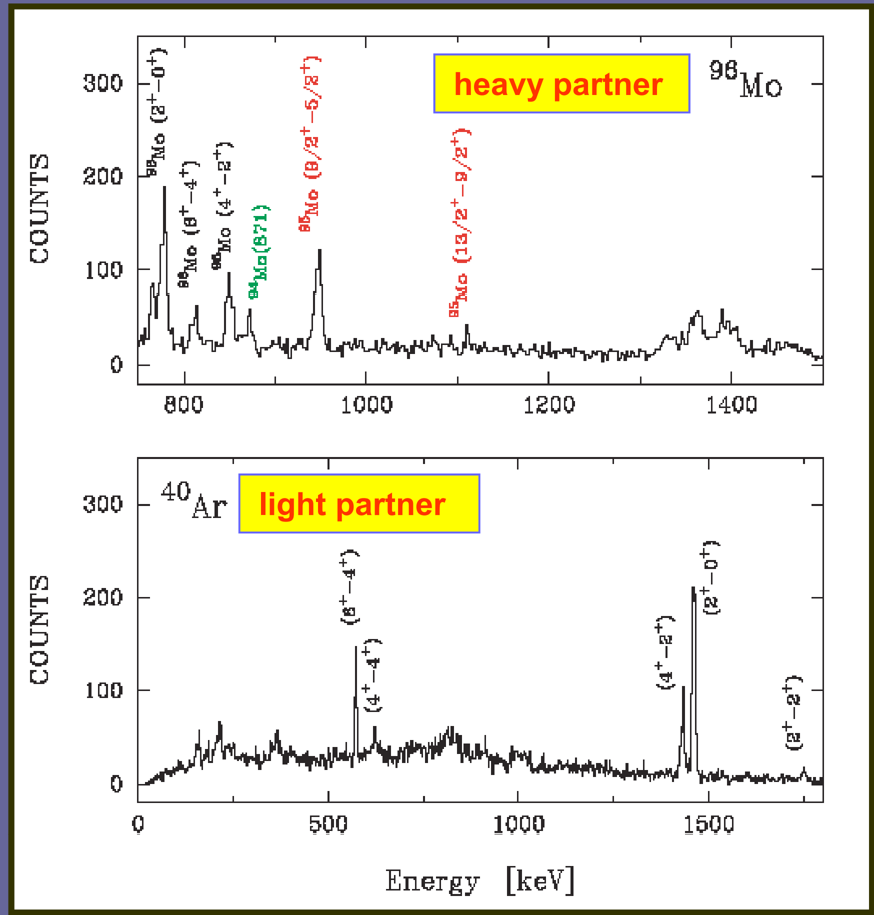

TKEL corresponding to the two-touching sphere configuration
(maximal amount of energy that can be lost in binary collisions)

# Evaporation processes in multinucleon transfer reactions

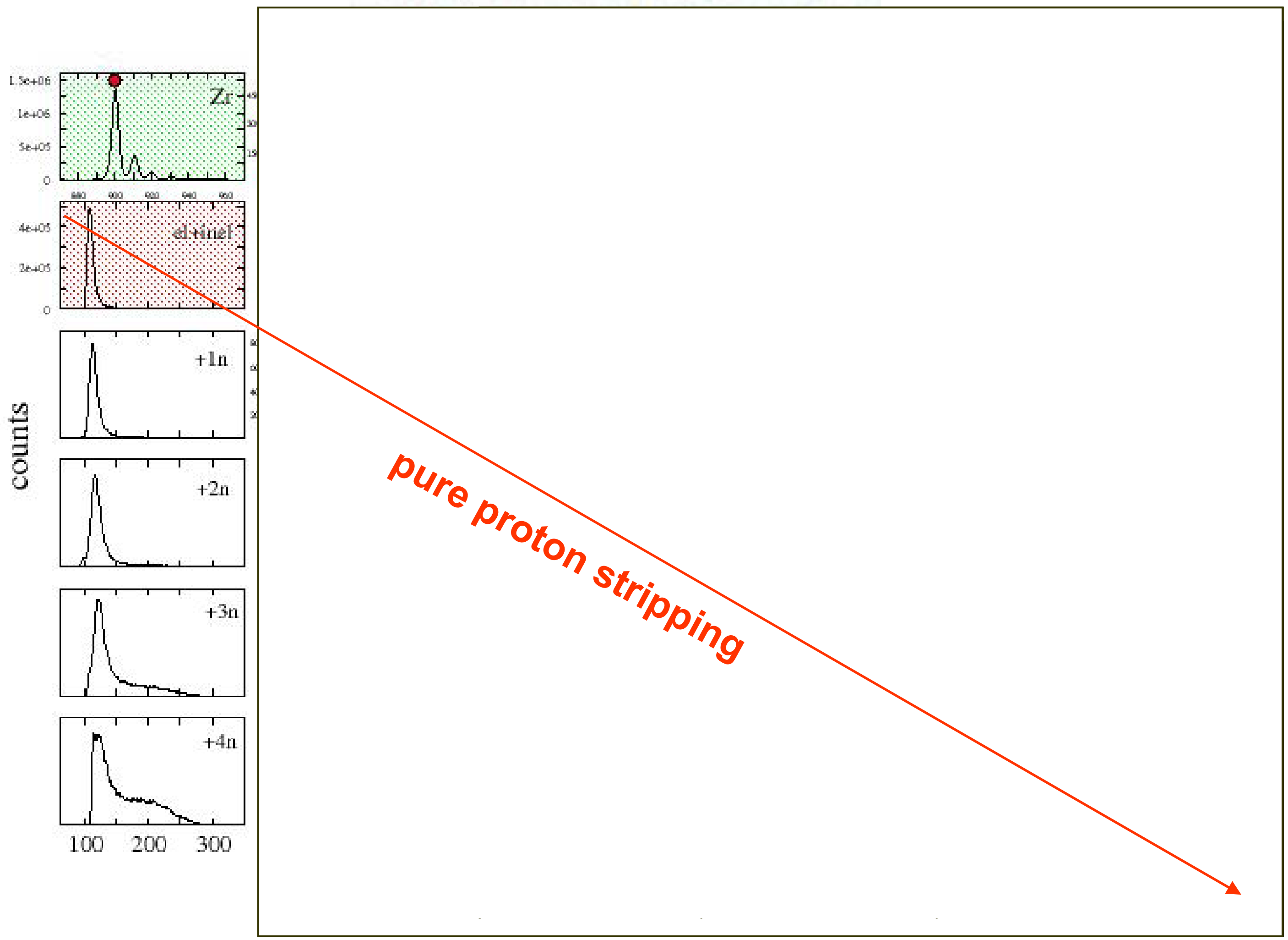



## Direct identification with PRISMA+CLARA



# TKEL distributions – transition from QE to DIC processes



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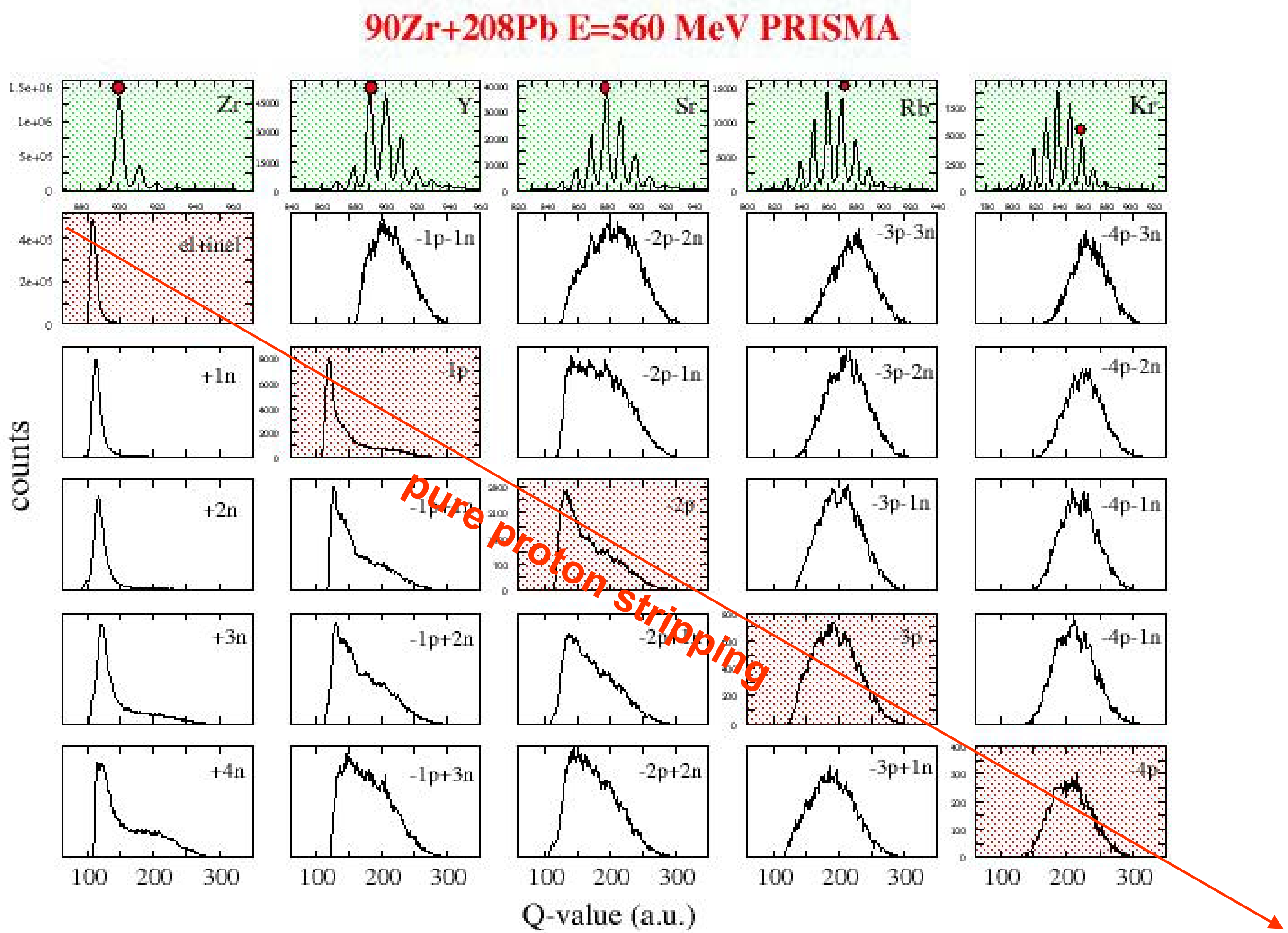
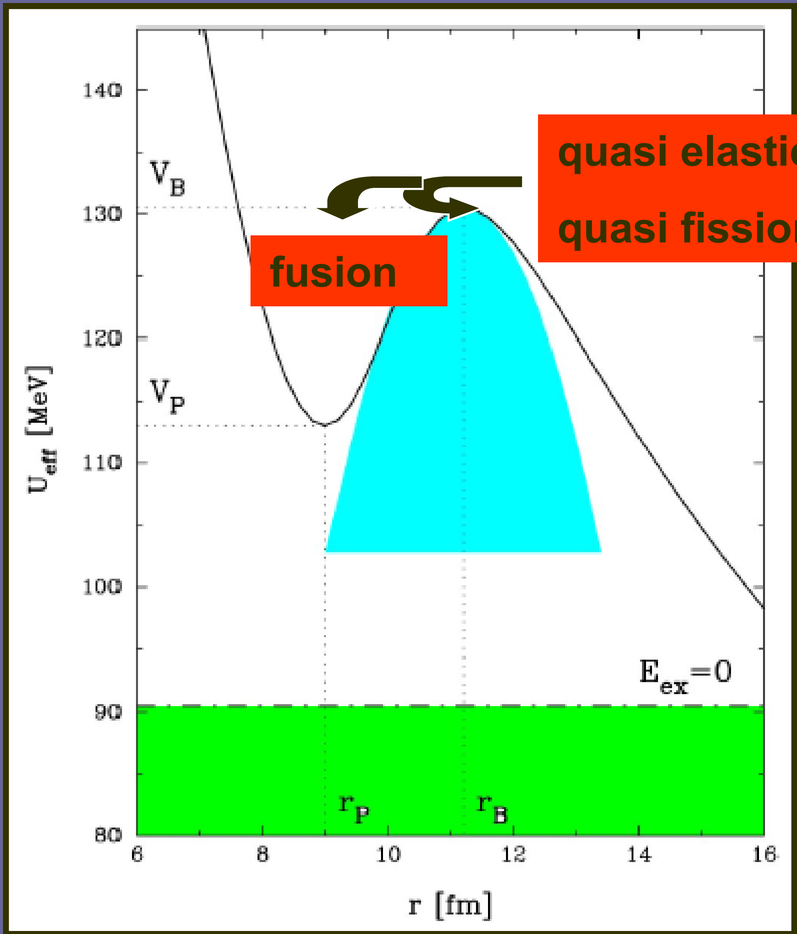
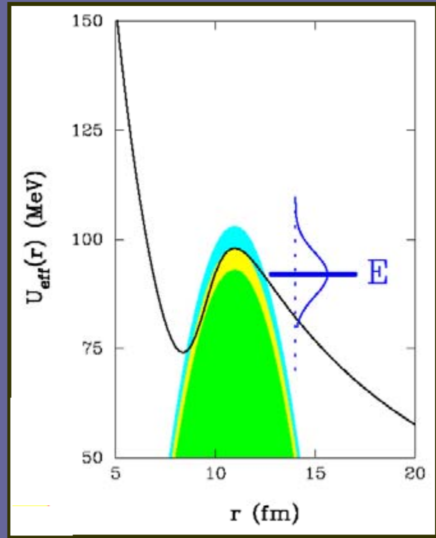


# connection with sub-barrier fusion reactions

# Correlation between reaction channels



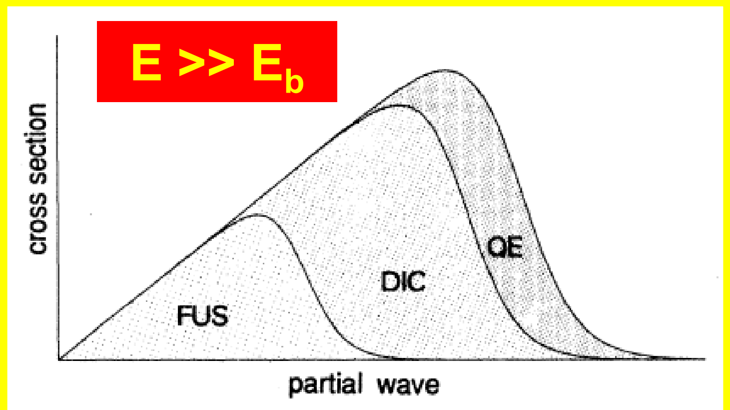

In the presence of couplings the energy of relative motion is not well defined. An exchange of energy from the relative motion to the intrinsic degrees of freedom takes place

$$\sigma(E) = \sum_l \frac{\pi\hbar^2}{2m_{aA}E}(2l+1)T_l(E)$$

$$T_l(E) = \int_{-\infty}^{+\infty} P(E_r)T_l(E-E_r)dE_r$$

$$E_r = \hat{H}(t) - \frac{(\mathbf{L}-\mathbf{I})^2 - \mathbf{L}^2}{2m_{aA}r^2}$$

# Which range of partial waves are covered by DIC ?




the simple-minded picture that correlates the energy loss with impact parameters has been used to describe reactions in terms of classical trajectories subject to dissipative forces

more elaborated schemes had to take into account fluctuations around the average behaviour. Among these, quantal fluctuations associated with couplings to instrinsic excitation channels have been shown to be important

a straightforward manifestation of large fluctuations is the lack of correlation between impact parameters and energy loss

C.H.Dasso et al, PRC39(1989)2073

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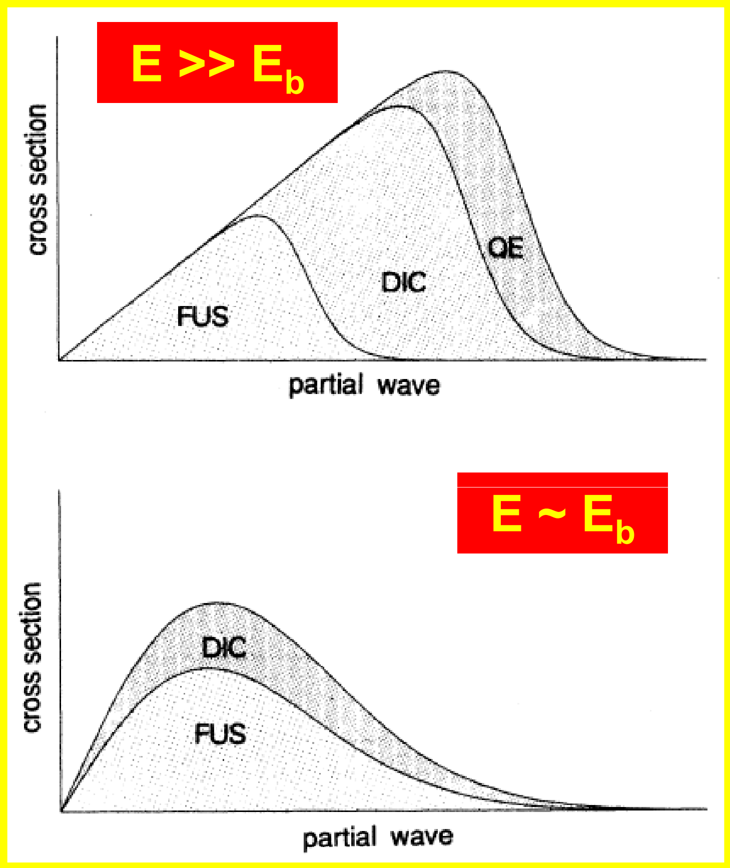


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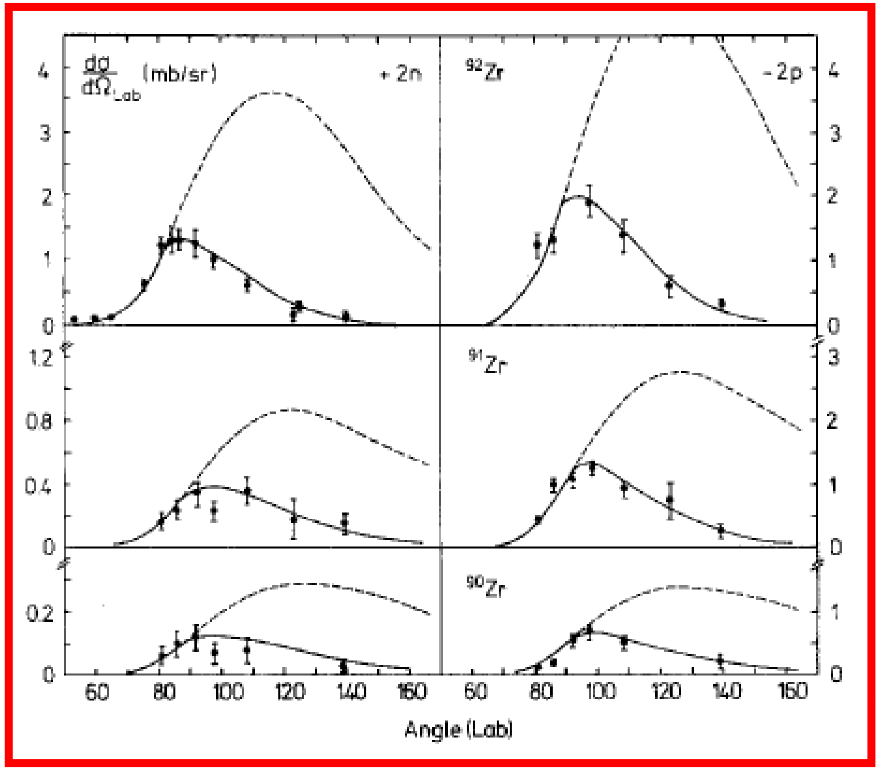
C.H.Dasso et al, PRC39(1989)2073

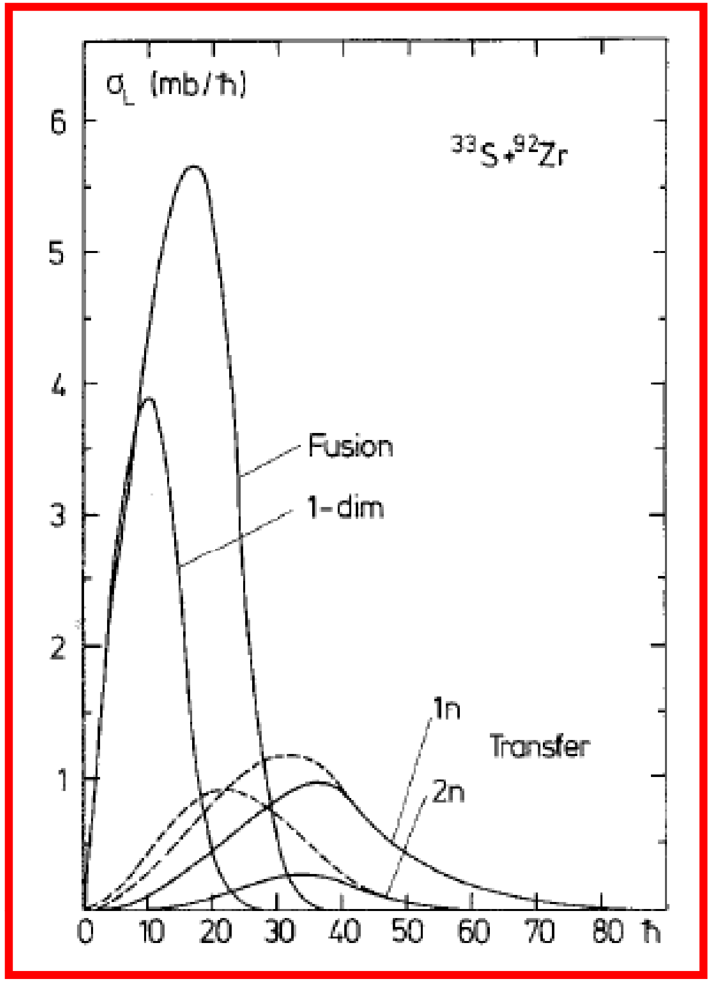
# Complete measurements of fusion and transfer in $^{33}S+^{90,91,92}Zr$

$$P_{tr}(\theta, Q) = \frac{N}{\alpha^3} \sin\frac{\theta}{2} e^{-2\alpha(D-D_c)} e^{-Q^2/2\sigma_0^2}$$

$$\frac{d\sigma}{dl} = 5\pi \left(\frac{a}{\eta}\right)^2 l \cdot \tilde{P}_{tr}(1 - P_a)$$

$$P_{tr}(\theta) = \int_{-\infty}^{Q_{gg}} \rho(Q) P_{tr}(\theta, Q) \, dQ$$

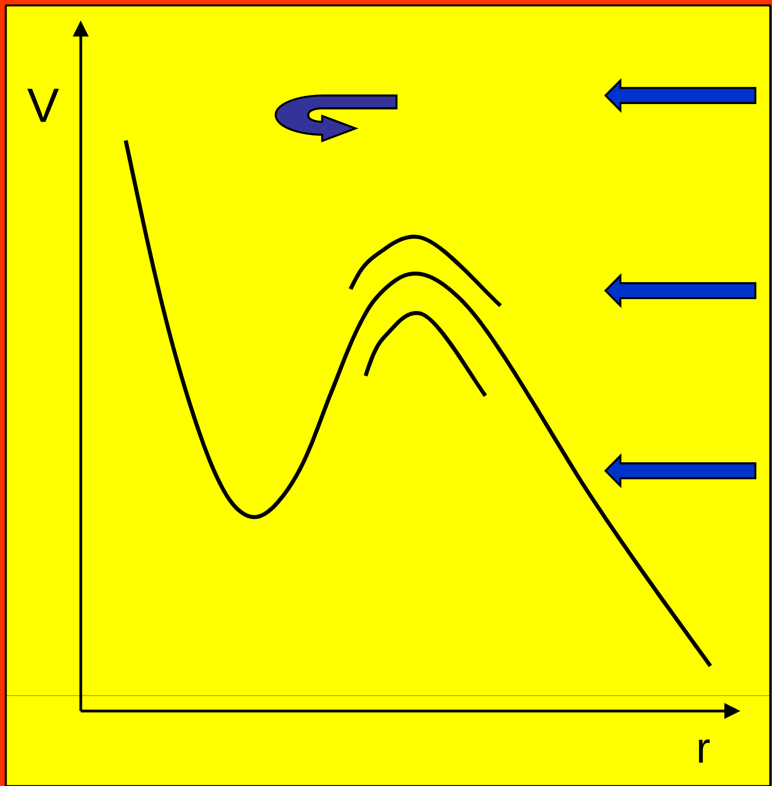



L.Corradi et al, Z.Phys.A334(1990)55

# Energy ranges probed in transfer and fusion reactions

**R** = reflected incoming flux
**T** = transmitted incoming flux




$E > E_b$

$E \sim E_b$

$E < E_b$

**R < T**
**other reaction channels have significant yield**

**σ fusion < σ capture**

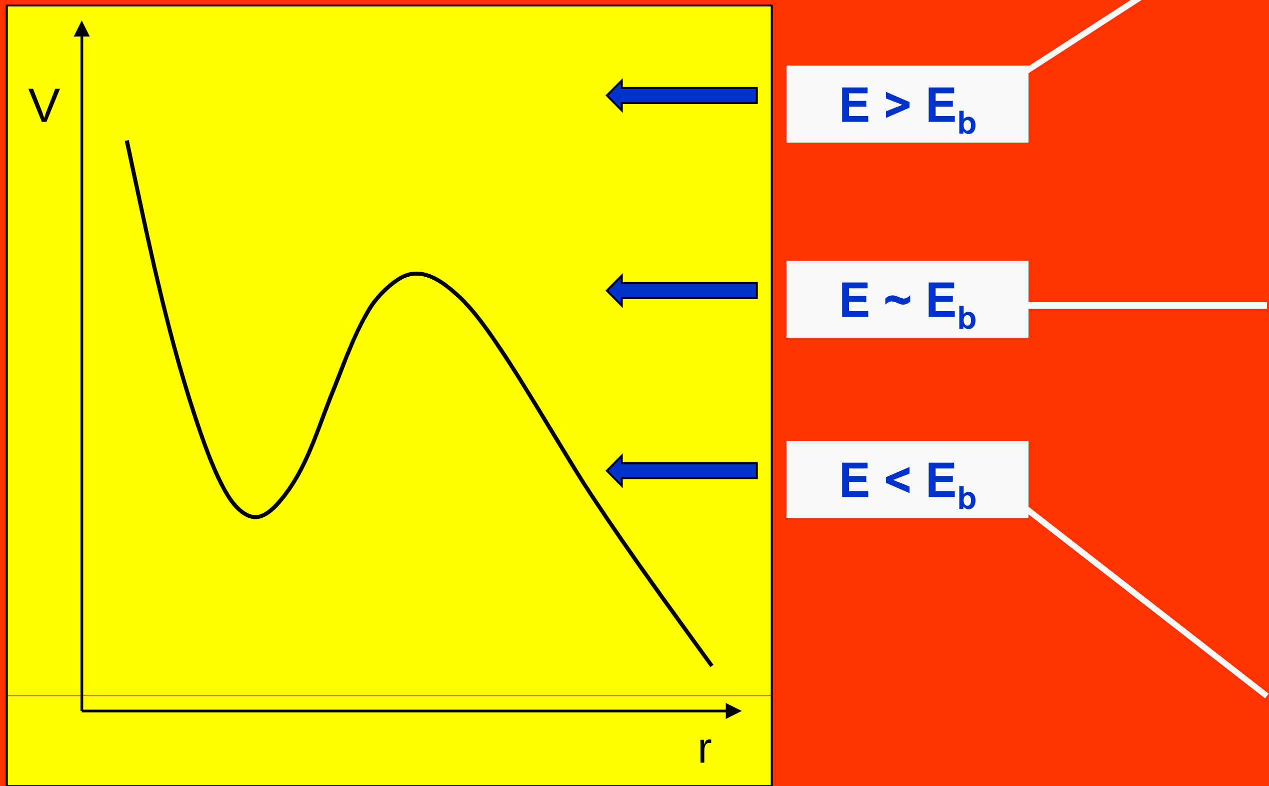
**R ~ T**
**transfer and fusion are comparable**

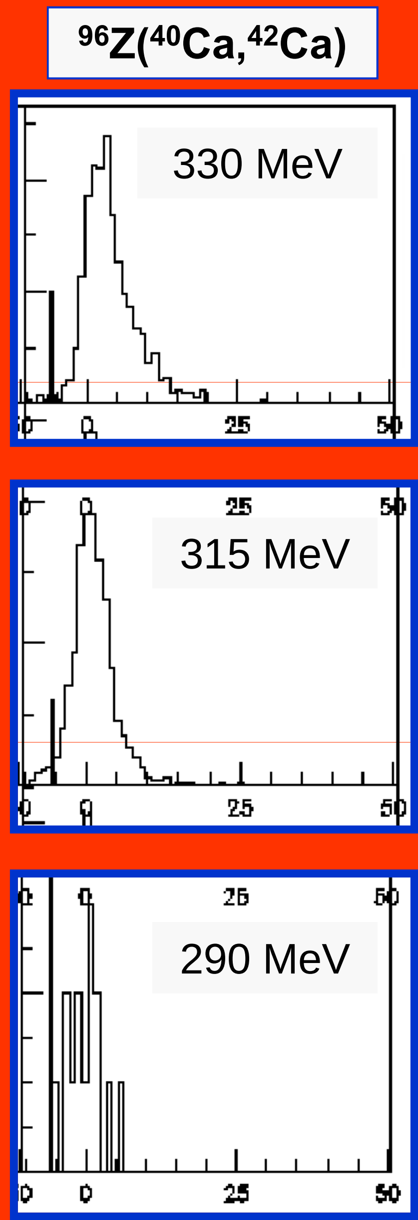
**CC effects**

**R > T**

**transfer dominates over fusion**

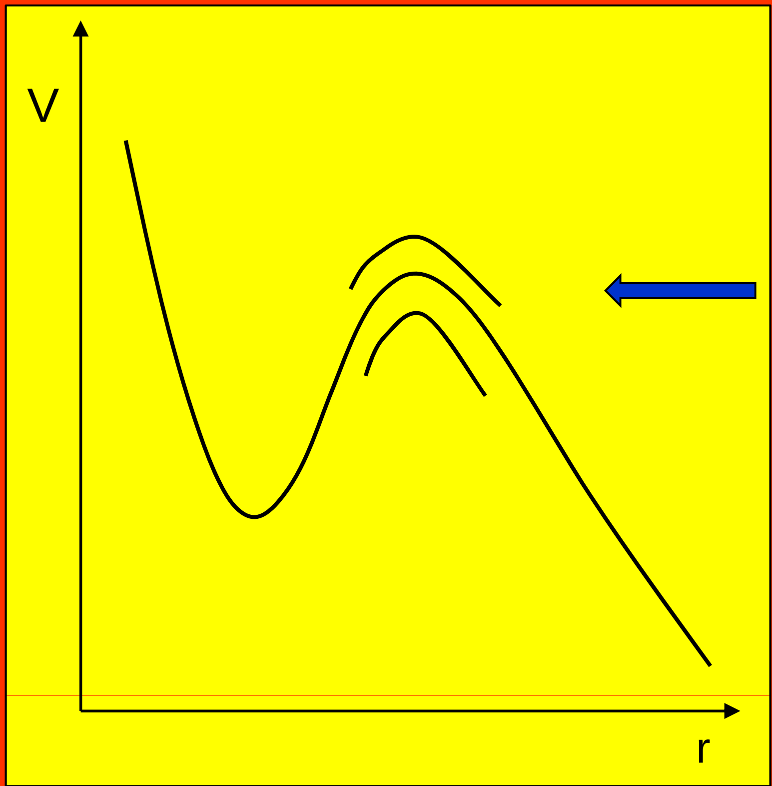
# A smooth transition between QE and DIC processes




excitation function of multineutron transfer channels
recently measured with the spectrometer PRISMA

# Near barrier energies

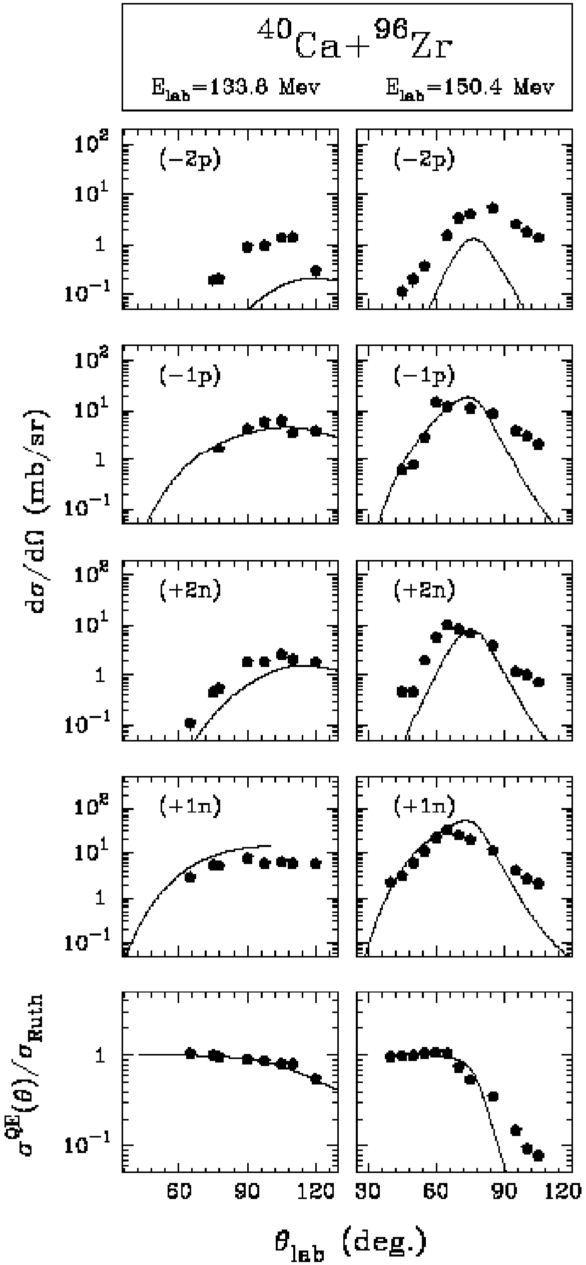



$E \sim E_b$

**$R \sim T$**
**transfer and fusion are comparable**

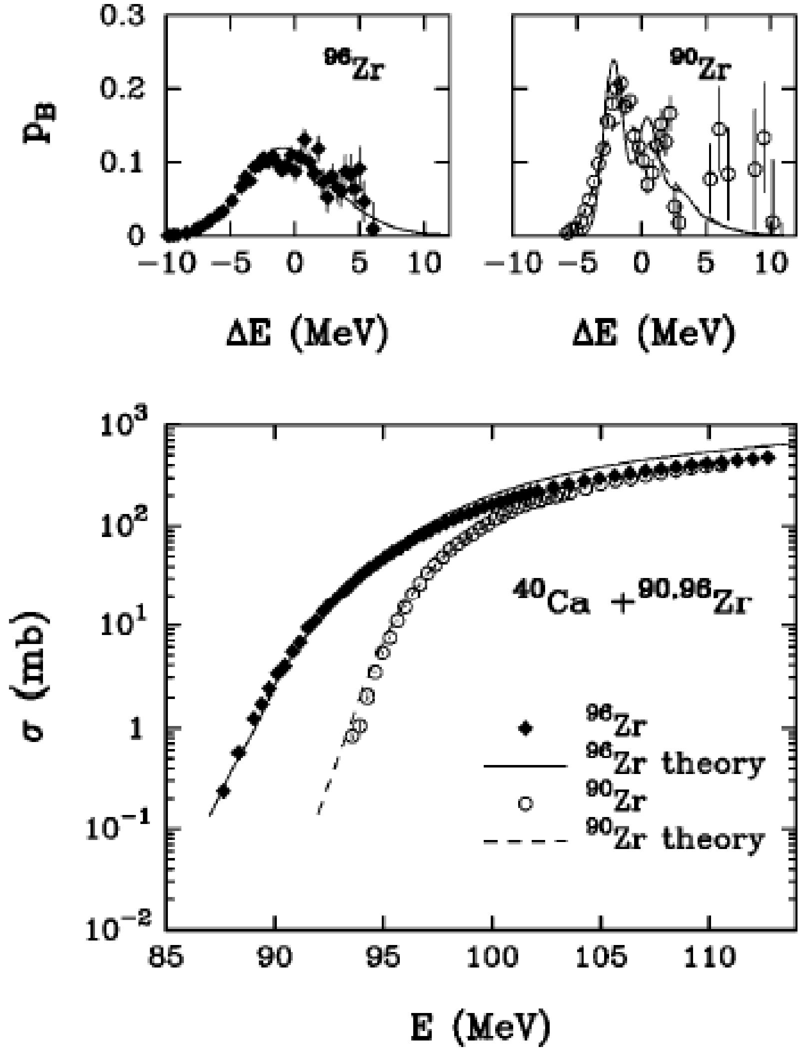
**CC effects**

# Transfer and fusion cross sections for $^{40}Ca+^{90,96}Zr$




G.Montagnoli et al., EPJA15(2002)351

GRAZING code calculations




G.Pollarolo and A.Winther, PRC62(2000)054611

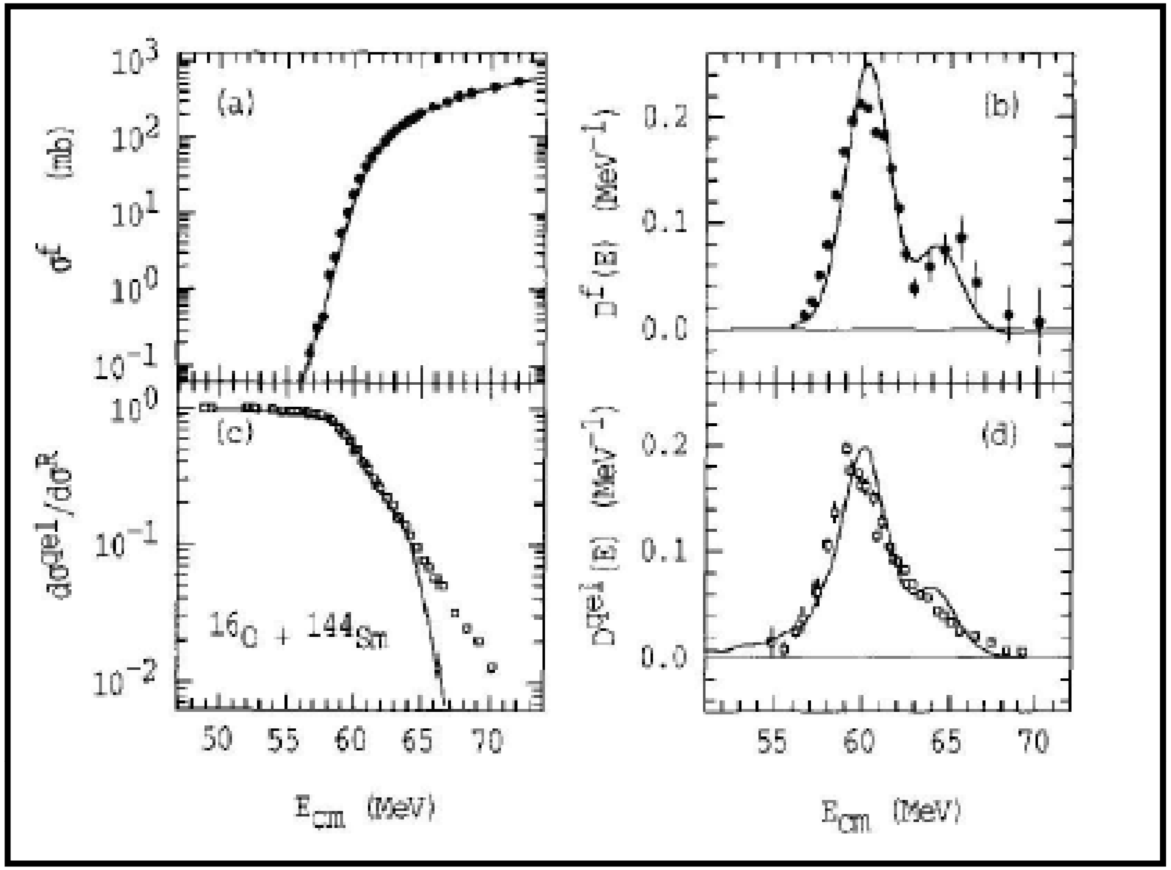
# Barrier distributions extracted from fusion and QE scattering

$$\sigma(E) = \int_0^\infty \sigma(E, V_B) D(V_B) dV_B$$

$$\sigma_{\text{fus}}(E) = \sum_i w_i \sigma(E, B_i)$$

the barrier distribution D(B) is a fingeprint of the reaction that characterizes the important couplings

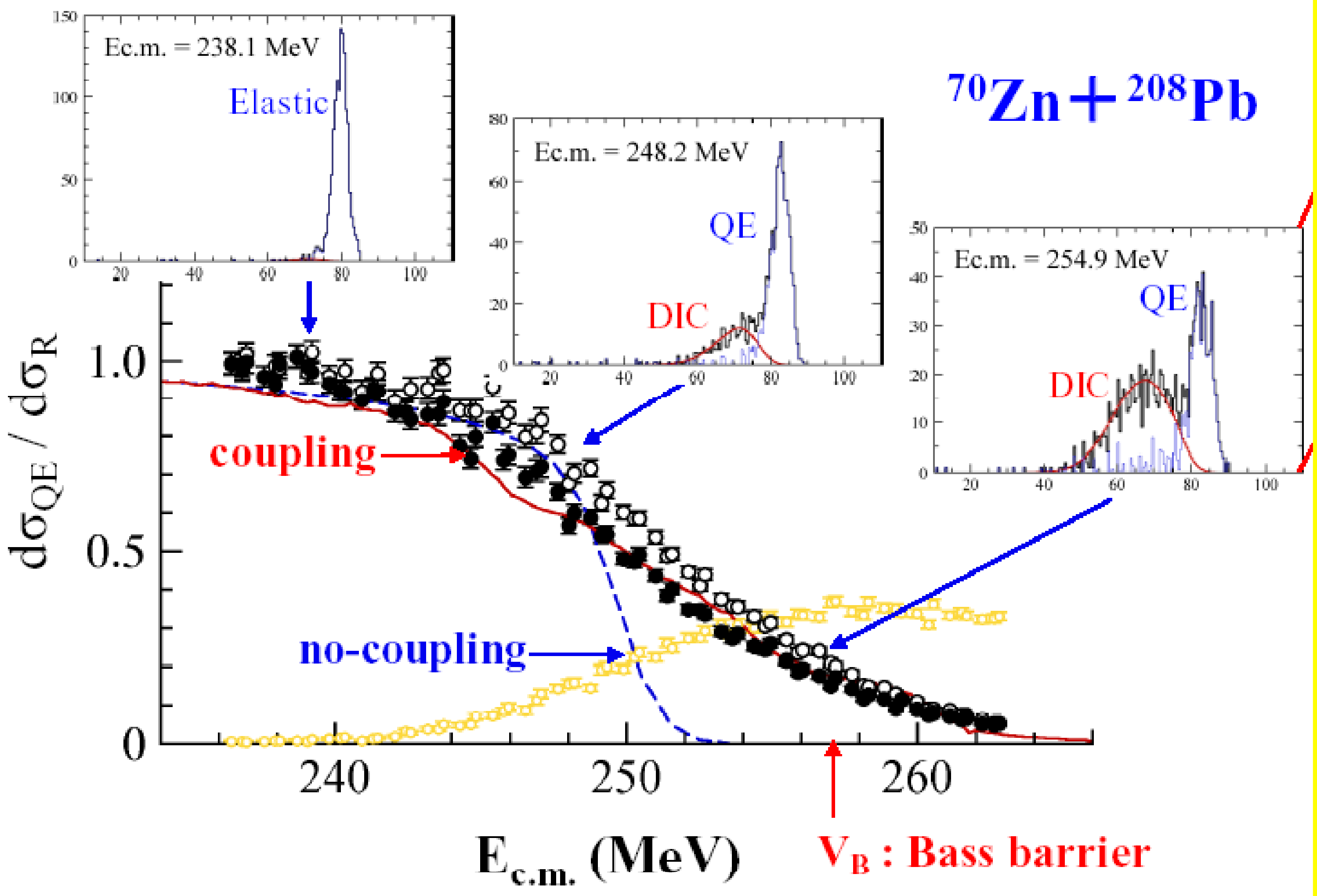
D(B) can be derived from fusion and from quasi-elastic scattering (but DIC must be properly considered)




$$D_{\text{fus}}(E) = \frac{d^2[E\sigma_{\text{fus}}(E)]}{dE^2}$$

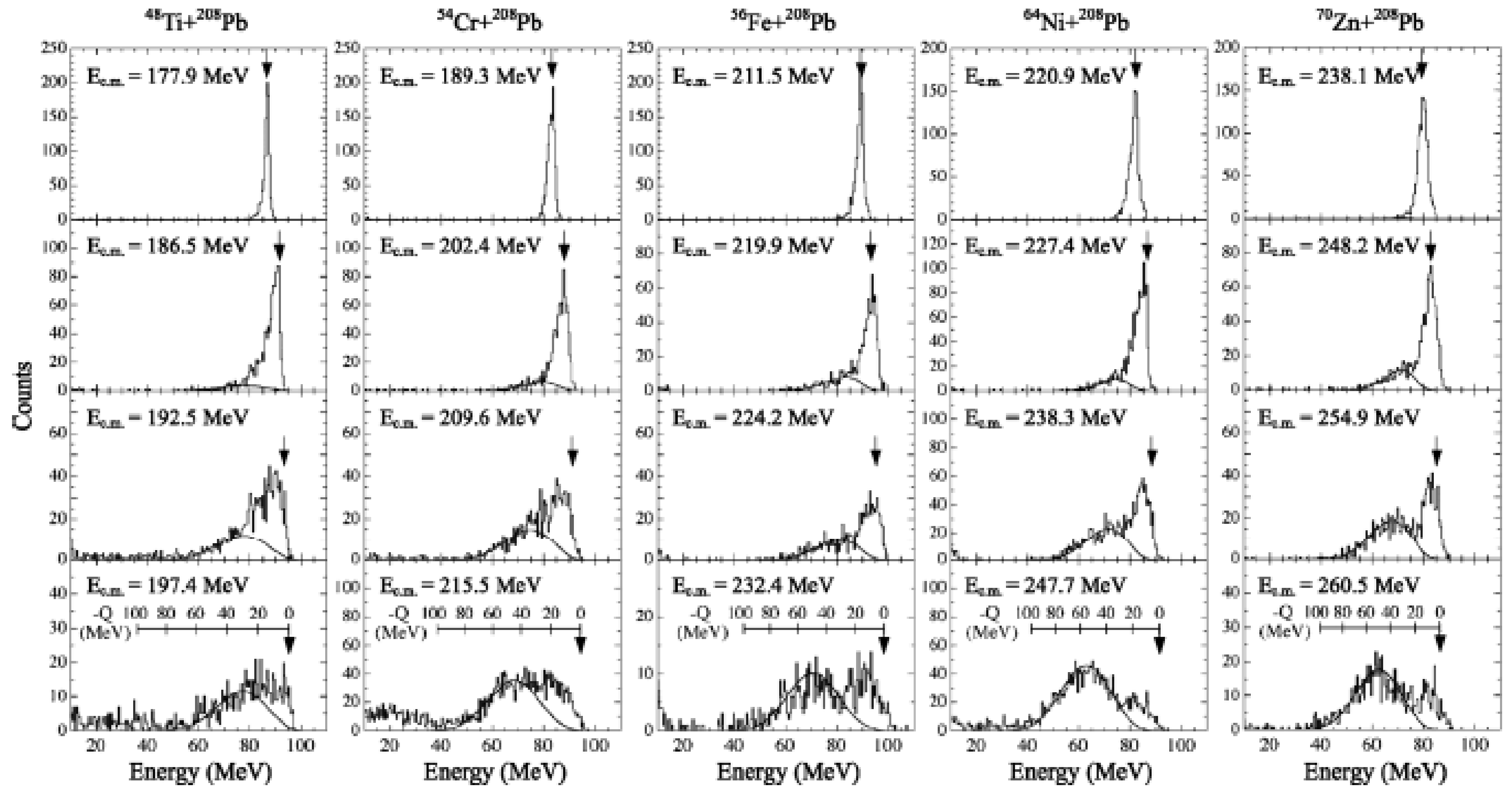
$$D_{\text{qel}}(E) = -\frac{d}{dE}\left[\frac{\sigma_{\text{qel}}}{\sigma_{\text{Ruth}}}(E)\right]$$

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



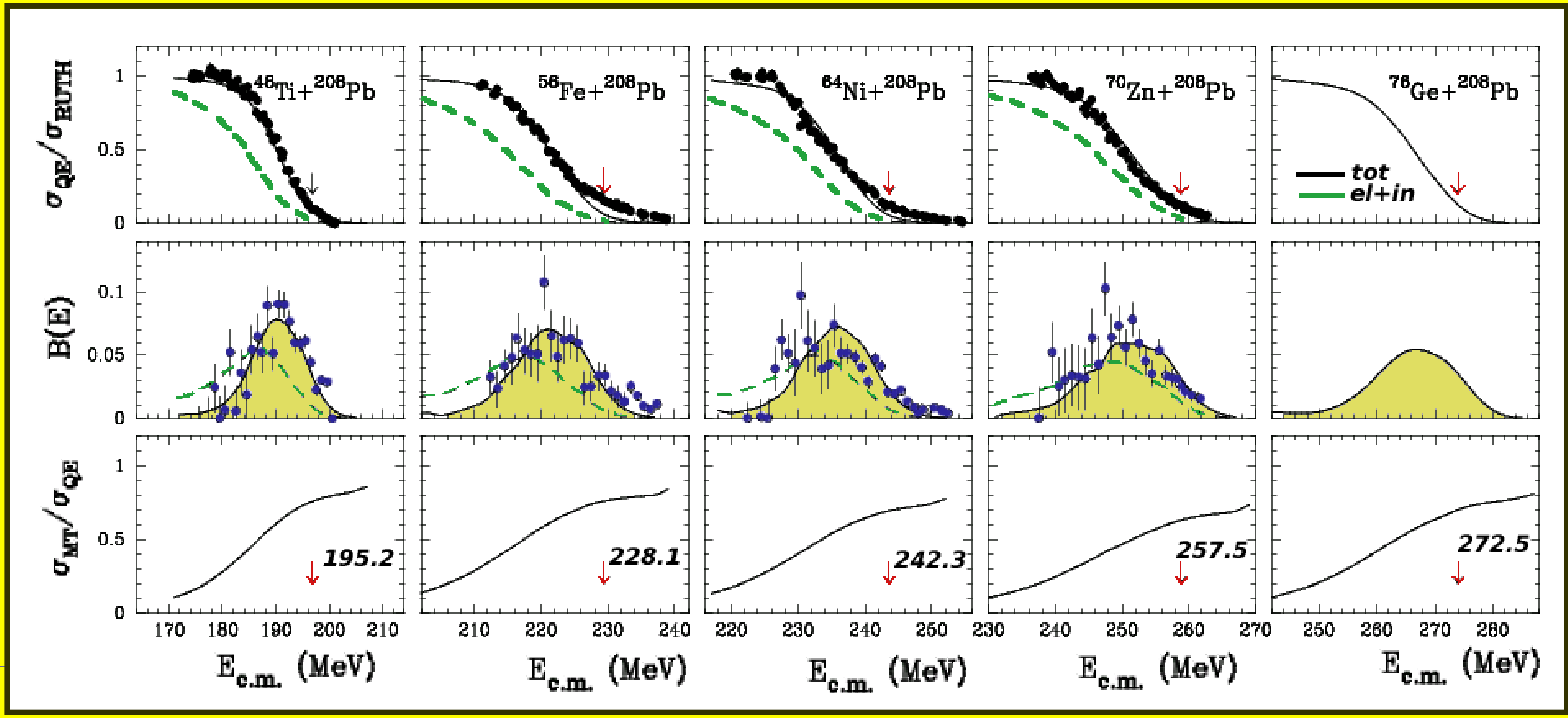

S.Mitsuoka, Fusion08, Chicago

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




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

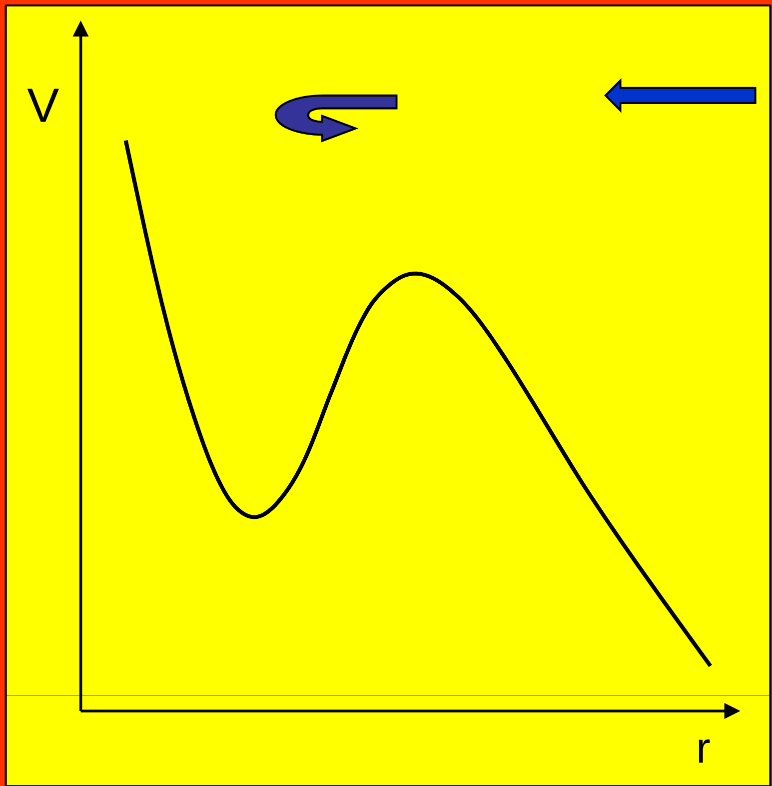
# Quasielastic barrier distributions : role of particle transfer channels




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

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

# Energies above the barrier

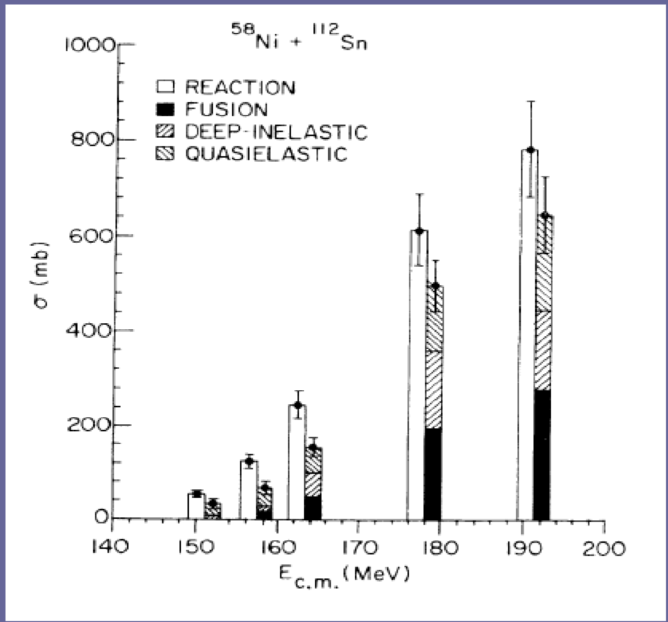


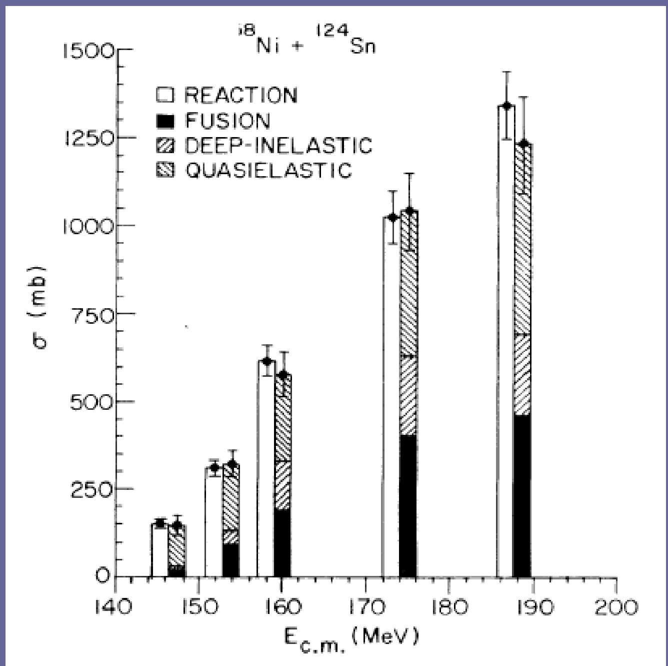

$E > E_b$

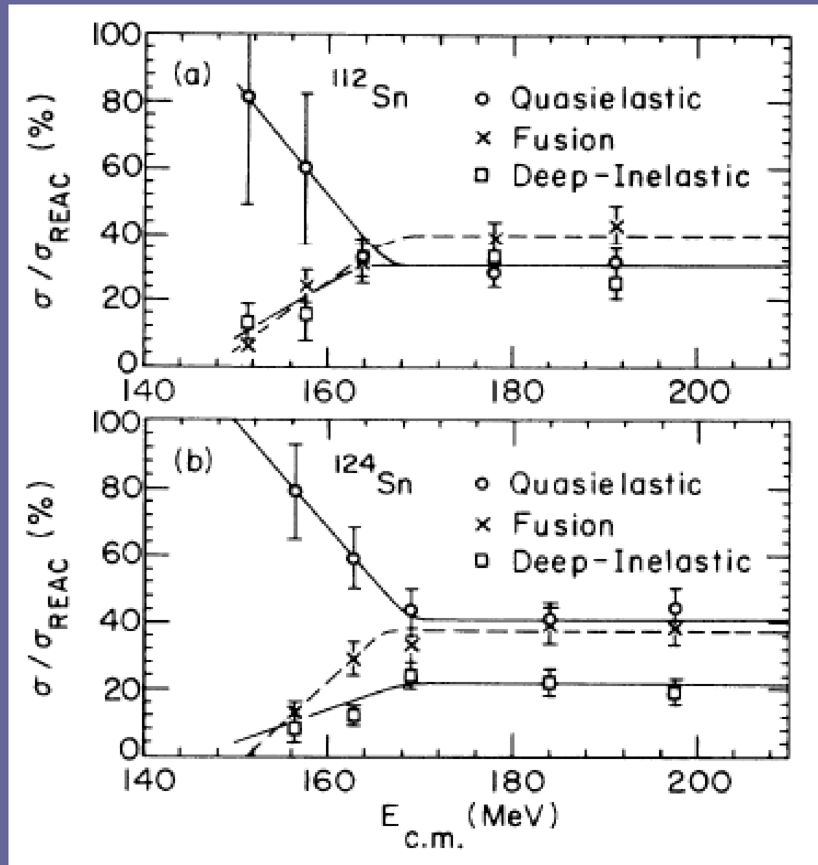
**R < T**
**other reaction channels have significant yield**

**σ fusion < σ capture**

## Partition of the total reaction cross section

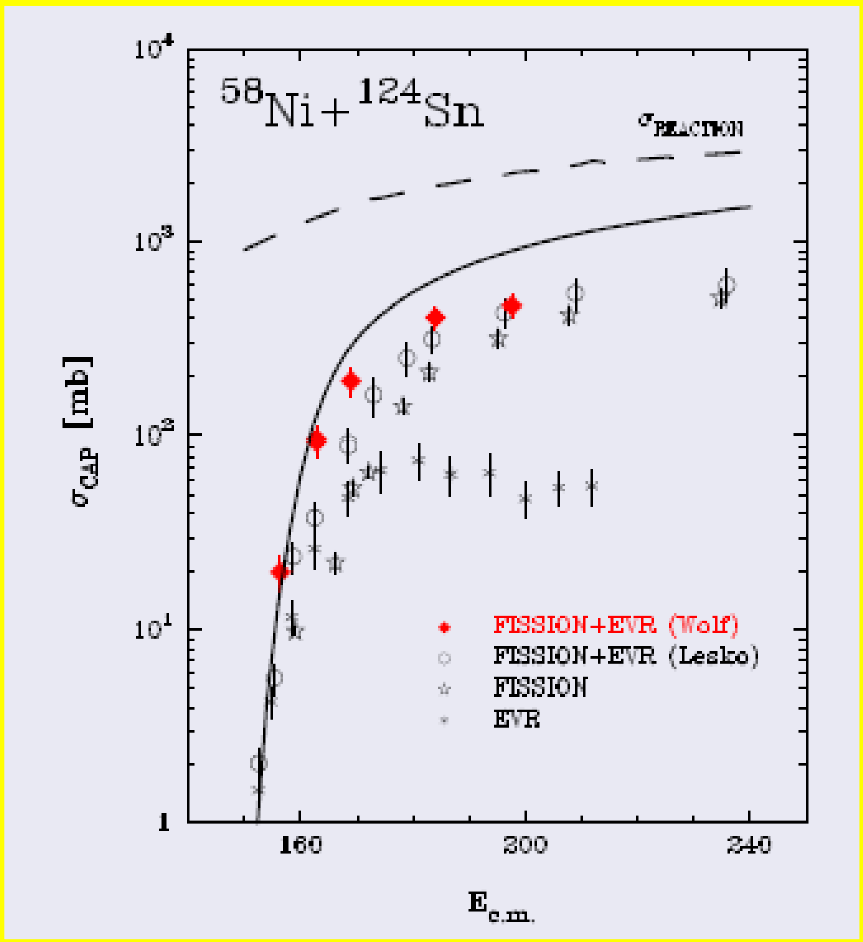


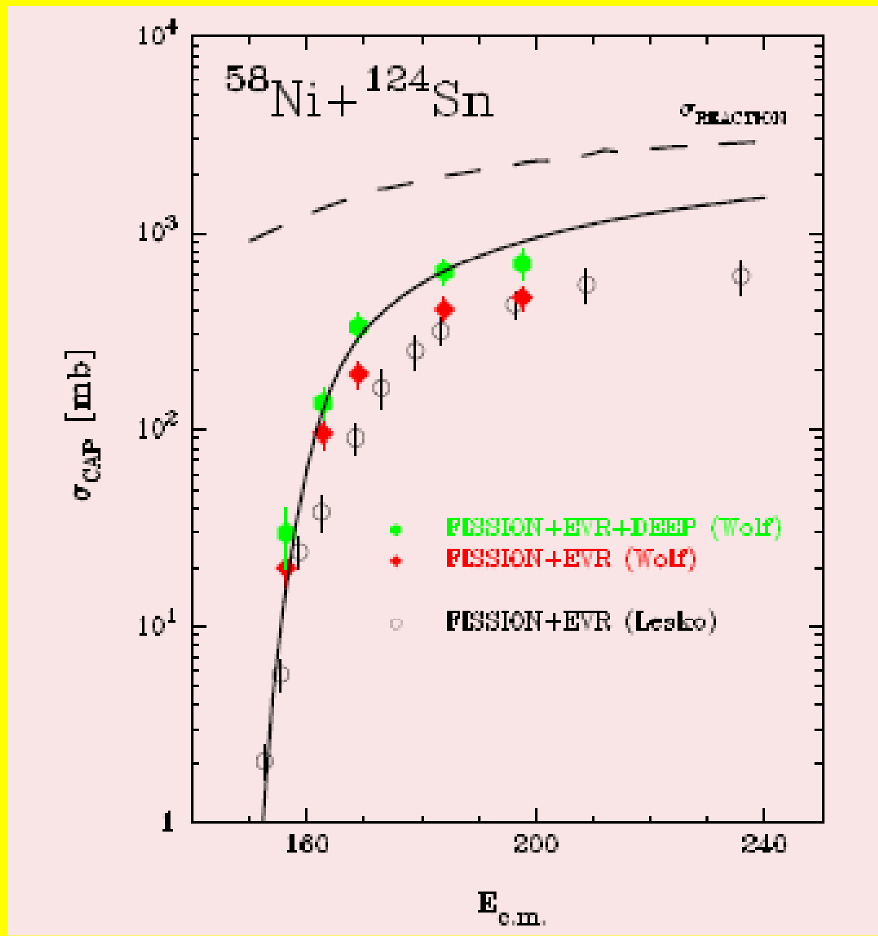




F.L.H.Wolfs, PRC36(1987)1379

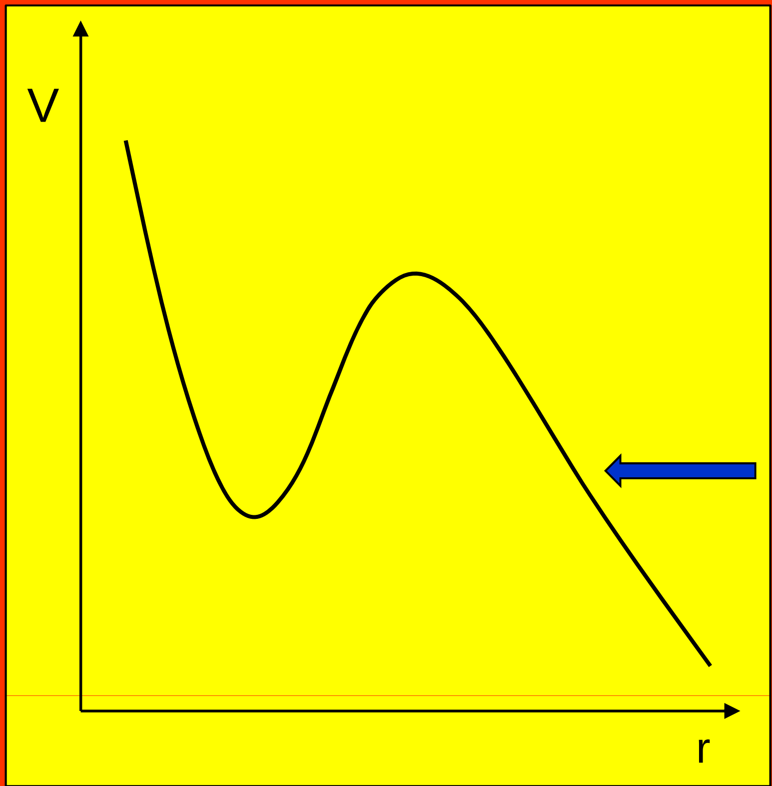
# Overall comparison among reaction channels : the $^{58}Ni+^{124}Sn$ system




G.Pollarolo, NN2006, Rio de Janeiro

# Energies below the barrier




$E < E_b$

**R > T**

**transfer dominates over fusion**

# Transfer studies at energies below the Coulomb barrier

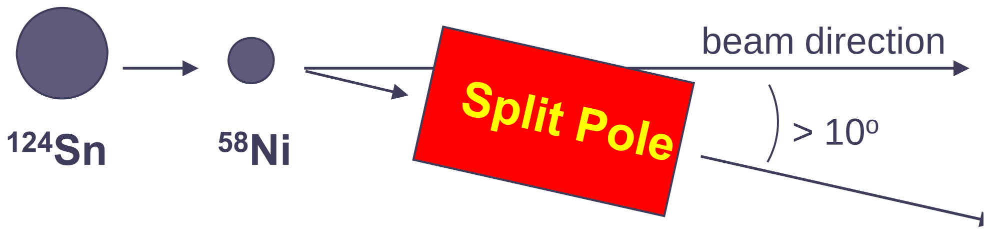
$$\sigma_{tr} \sim e^{-\frac{2}{\hbar}\int W(r(t))dt} \sum \left| \int F_{if}(r(t)) e^{i\omega_{if}} dt \right|^2$$

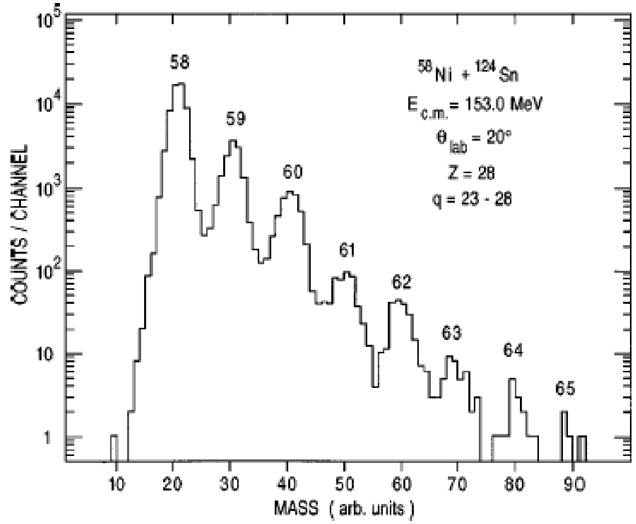
few reaction channels are opened → W(r) is small

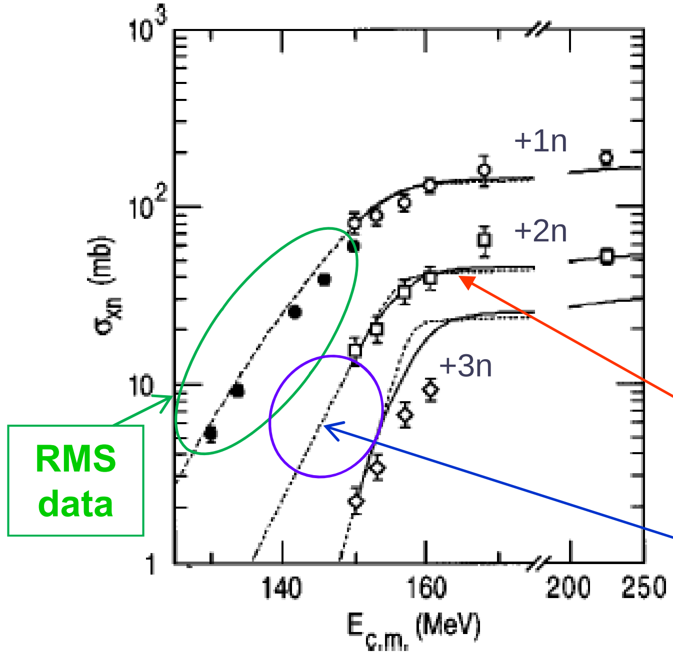
$F(r)_{inel}$ has a decay length ~ 0.65 fm
$F(r)_{tr}$ has a decay length ~ 1.3 fm → nuclear couplings are dominated by transfer processes

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

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




**successive+direct pair transfer**

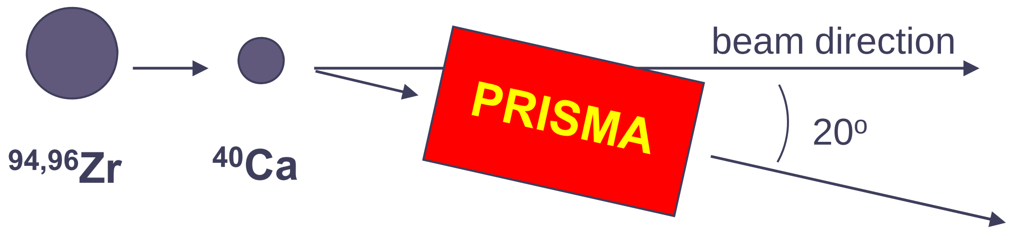
$$F_{2n}(r) = \alpha_{2n} V_0 \frac{d}{dr}\left[1 + \exp\left(\frac{r - R_0}{a_{2n}}\right)\right]^{-1}$$

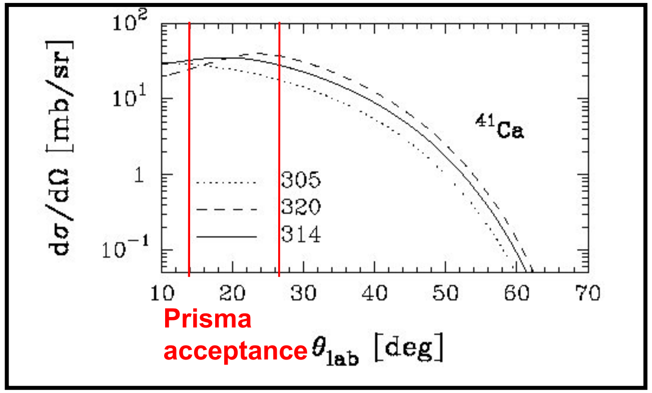
**lacking of data for +2n in the deep sub-barrier region**

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

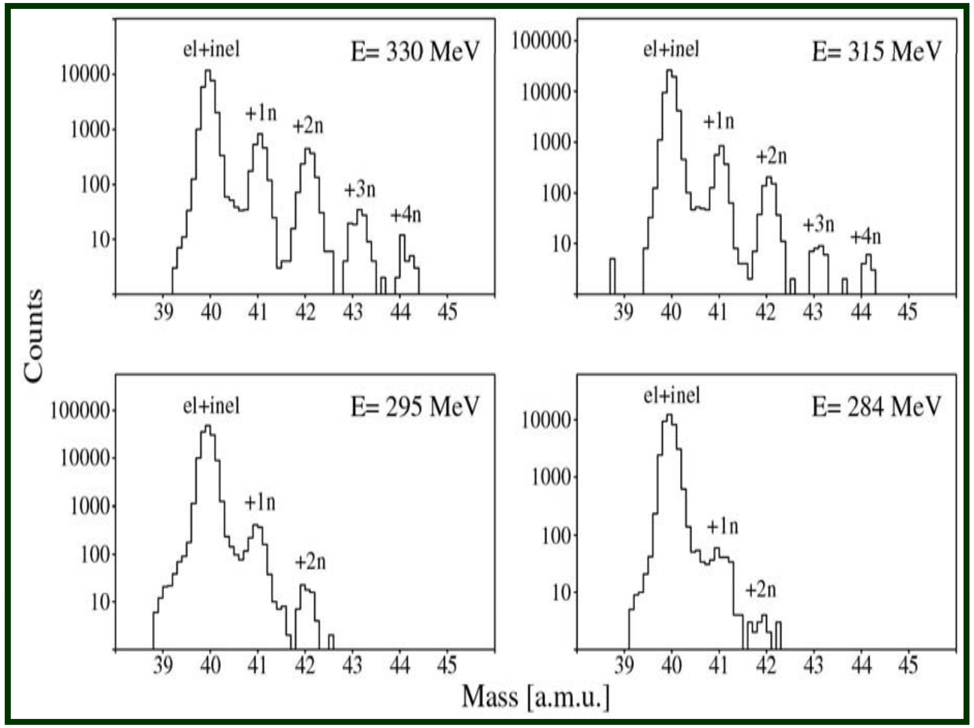
C.L.Jiang et al., PRC57(1998)2393

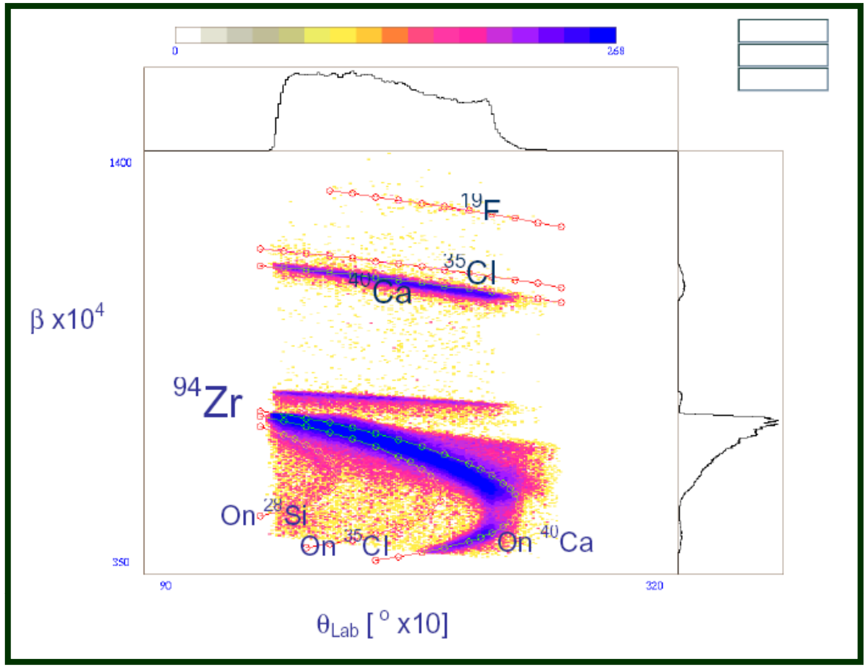
# Detection of (light) target like ions in inverse kinematics with PRISMA



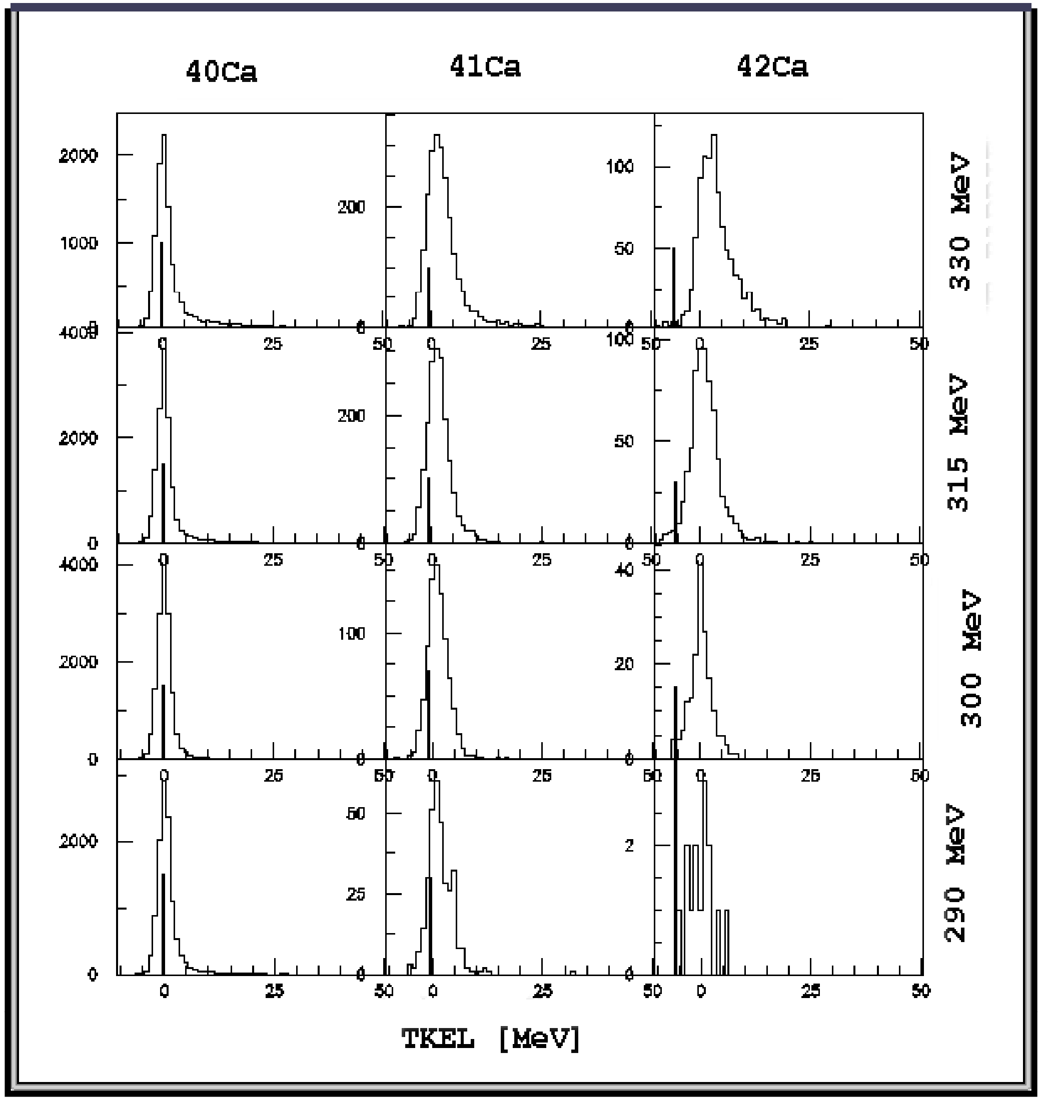

**MNT channels have been measured down to 25 % below the Coulomb barrier**




L.Corradi et al, LNL exp. March 2009

# Sub barrier transfer transfer reactions in $^{96}Zr+^{40}Ca$



## Some few remarks

In heavy ion reactions there is a smooth transition between QE and DIC processes

The relative strength of the two processes depends on bombarding energy and number of transferred nucleons

There have been recently significant advances in the overall understanding of the underlying mechanism in terms of elementary degrees of freedom, i.e. surface vibrations, single particle and pair transfer