Possibilities offered by high intensity stable beams for reaction mechanism studies at Coulomb barrier energies

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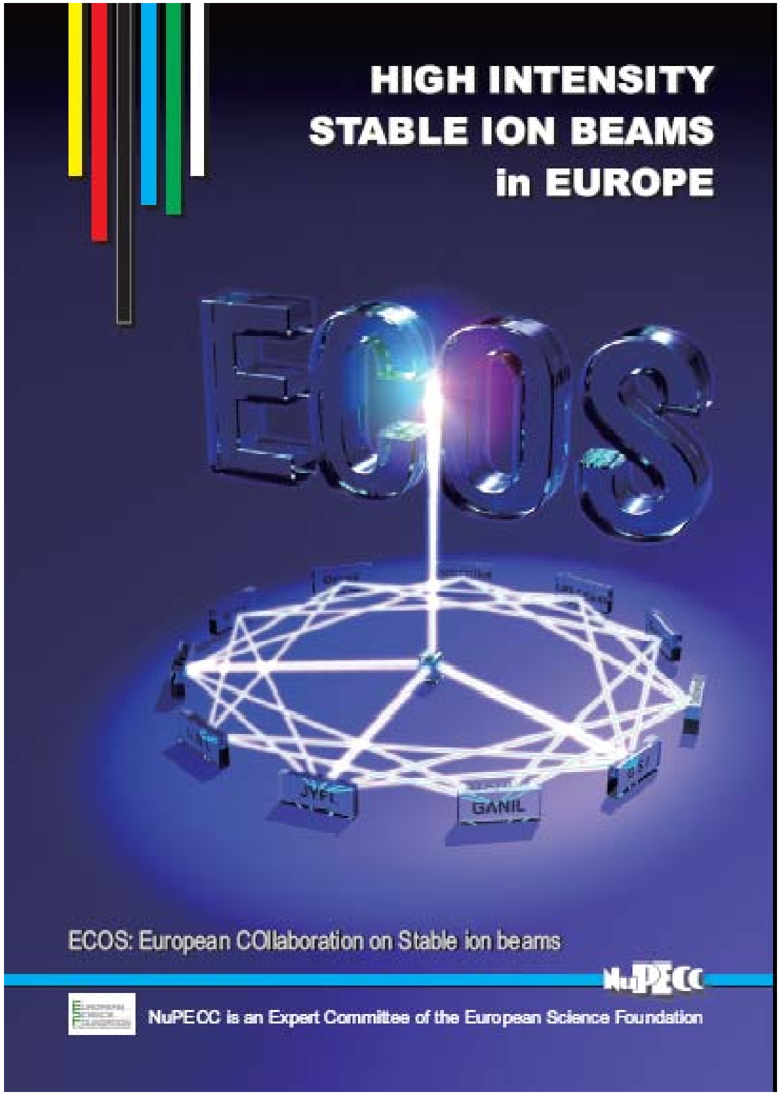
ECOS 2012, Villa Vigoni (Como Lake)
18-21 June, 2012

Studies of reaction mechanisms outlined in ECOS2006



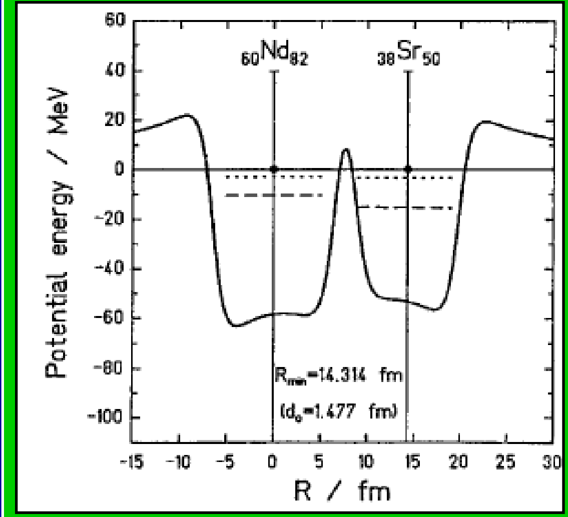
Near and sub barrier transfer reactions

Near and sub barrier fusion reactions

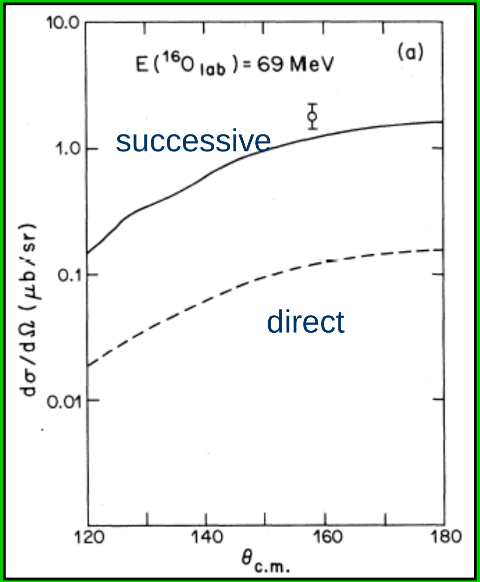
Sub-barrier transfer reactions

Why should we measure transfer at sub-barrier energies ?

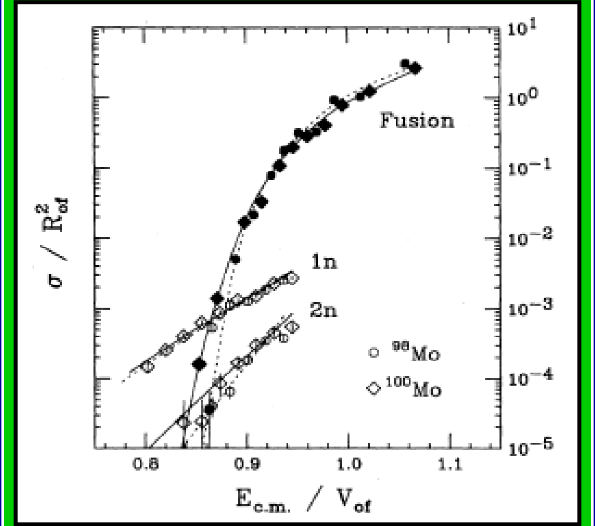
one probes tunnelling effects between interacting nuclei , which enter into contact through the tail of their density distributions



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

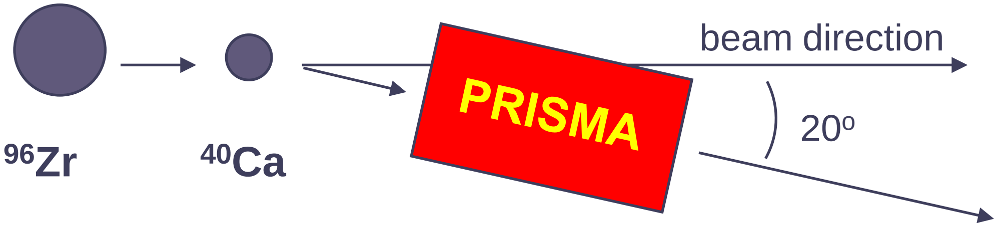


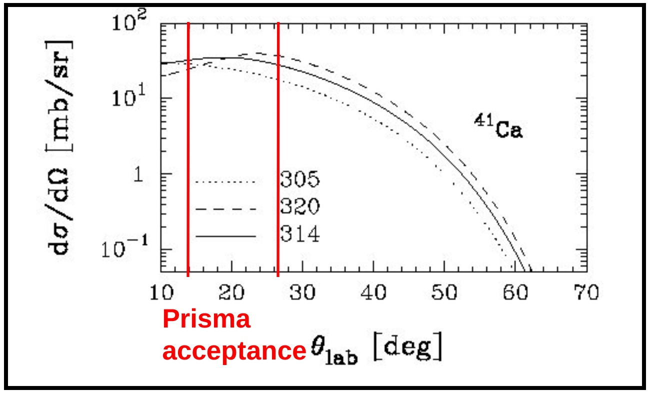
one probes transfer and fusion in an overlapping range of energies and angular momenta



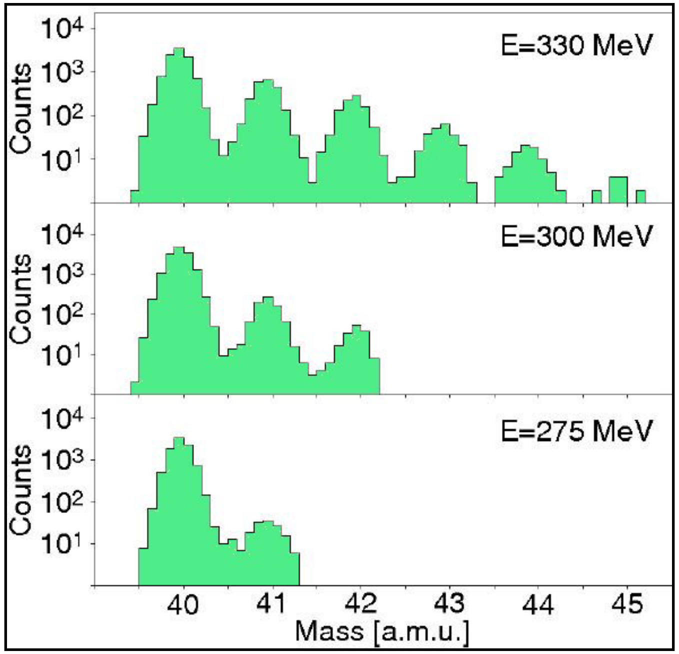
L.Corradi, G.Pollarolo and S.Szilner, J.Phys.G36(2009)113101 (Special Topic)

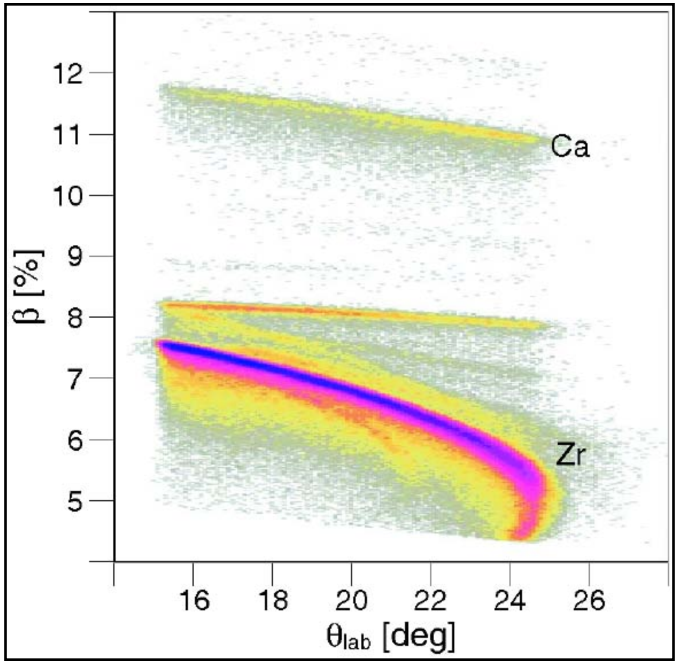
Detection of (light) target like ions in inverse kinematics with PRISMA



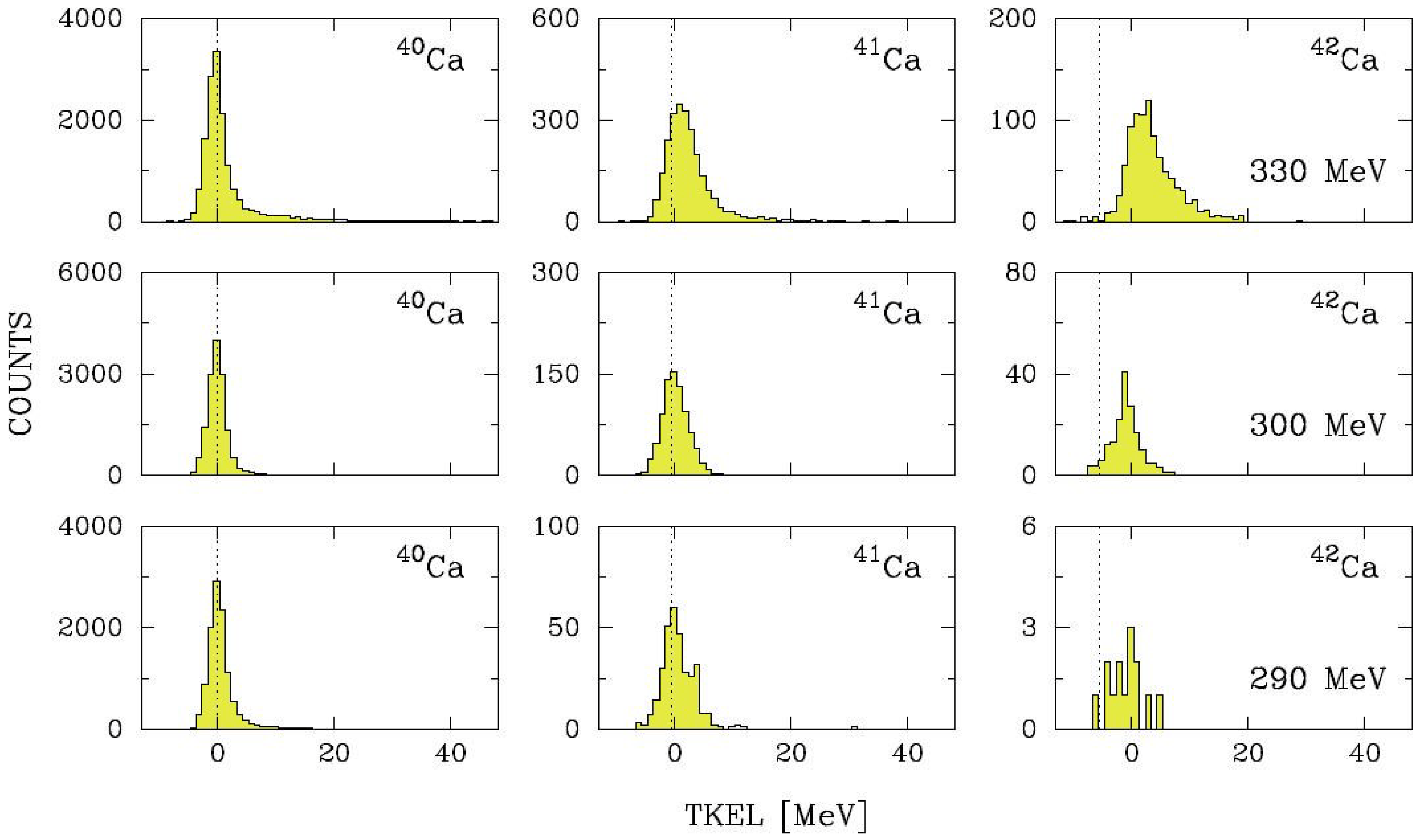


MNT channels have been measured down to 25 % below the Coulomb barrier





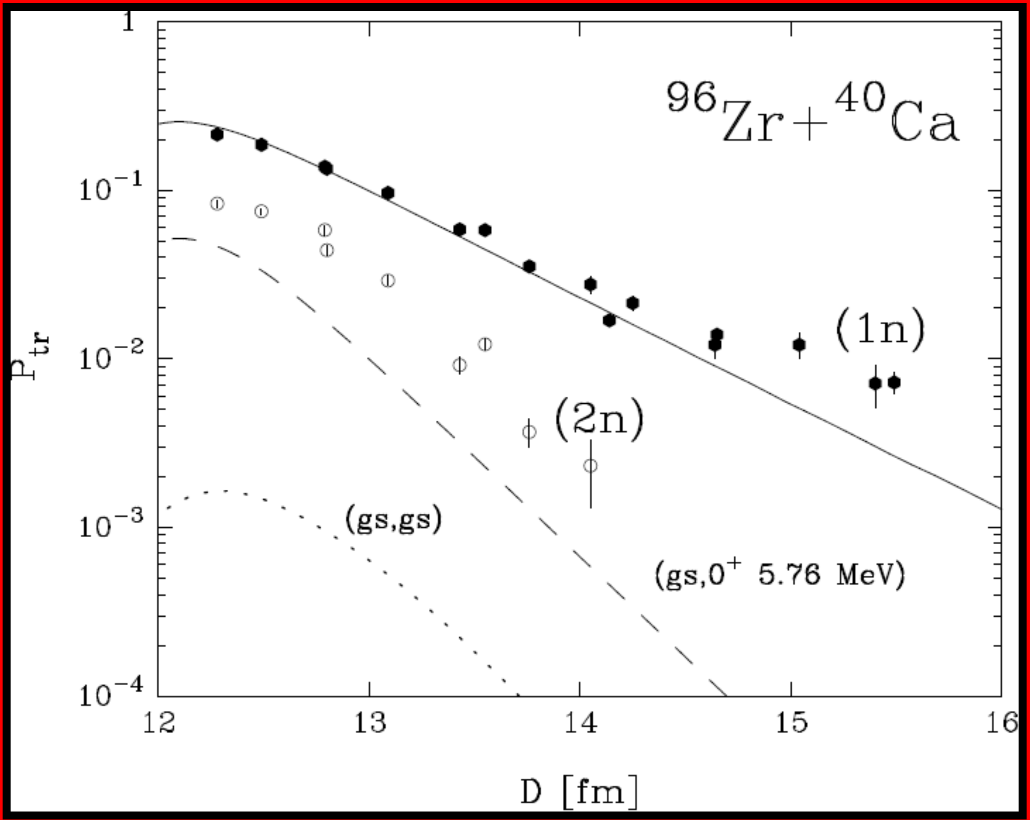
TKEL spectra for neutron transfer channels



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

no evaporation effects and cleanest conditions for data interpretation

Comparison between experimental and theoretical transfer probabilities



microscopic calculations based on semiclassical theory

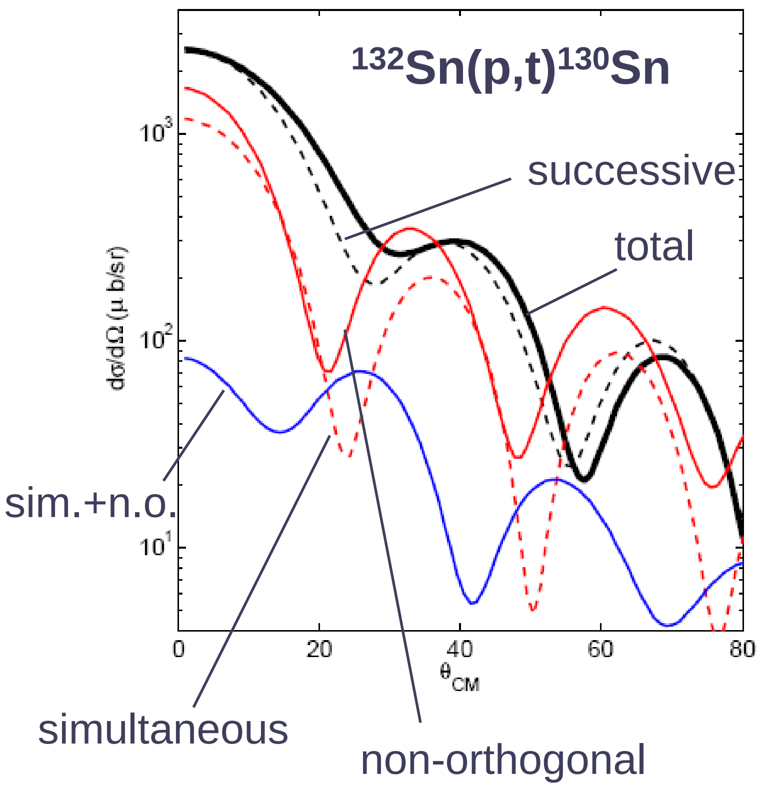
importance of high energy 0^{+} states and of states of different multipolarity

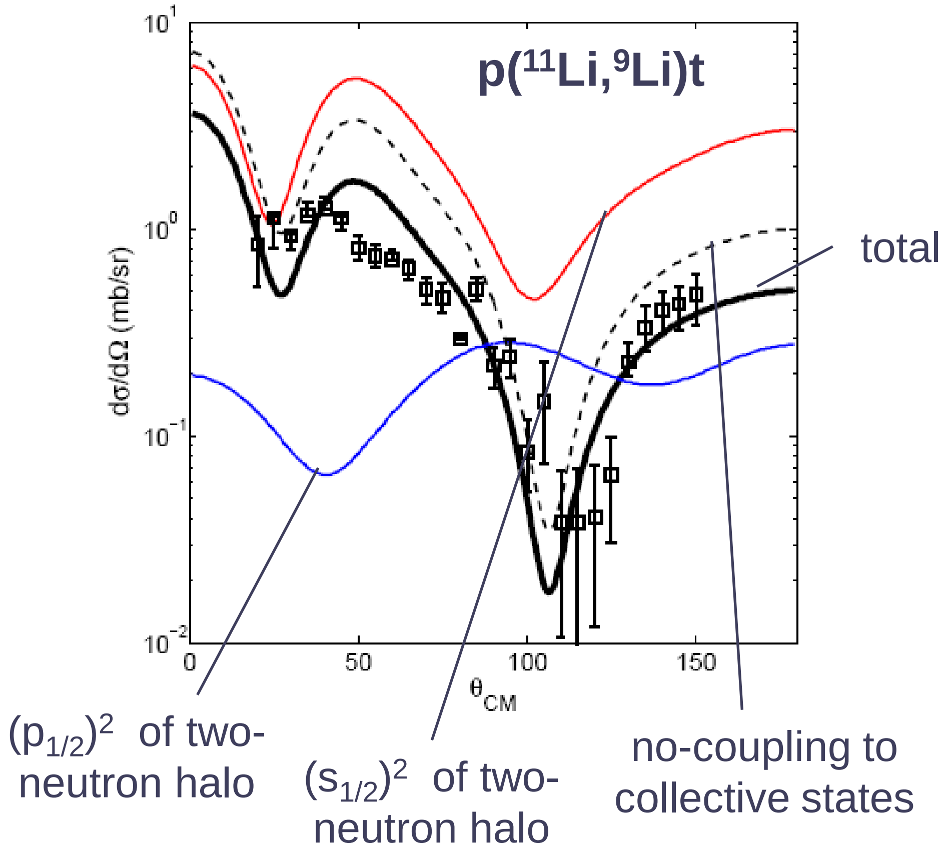
L.Corradi, S.Szilner, G.Pollarolo et al, PRC84(2011)034603

Pairing interaction in transfer reactions with light nuclei

the successive term dominates

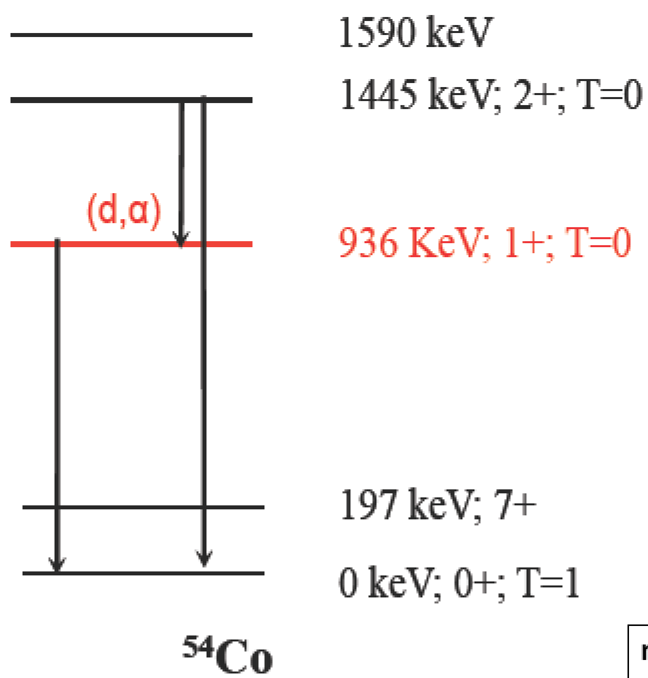
evidence of phonon mediated pairing interaction

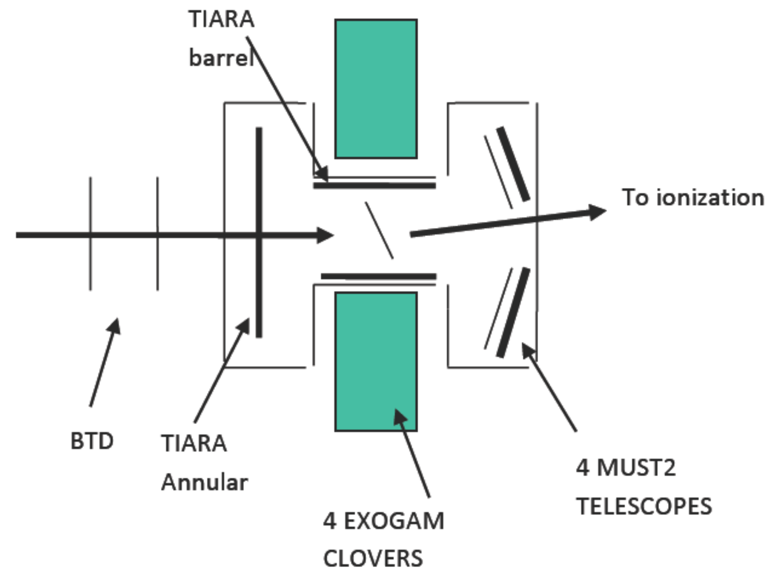




G.Potel et al, Fusion11 St.Malo' and PRL105(2010)172502

Study of np pairing via two-nucleon transfer reactions

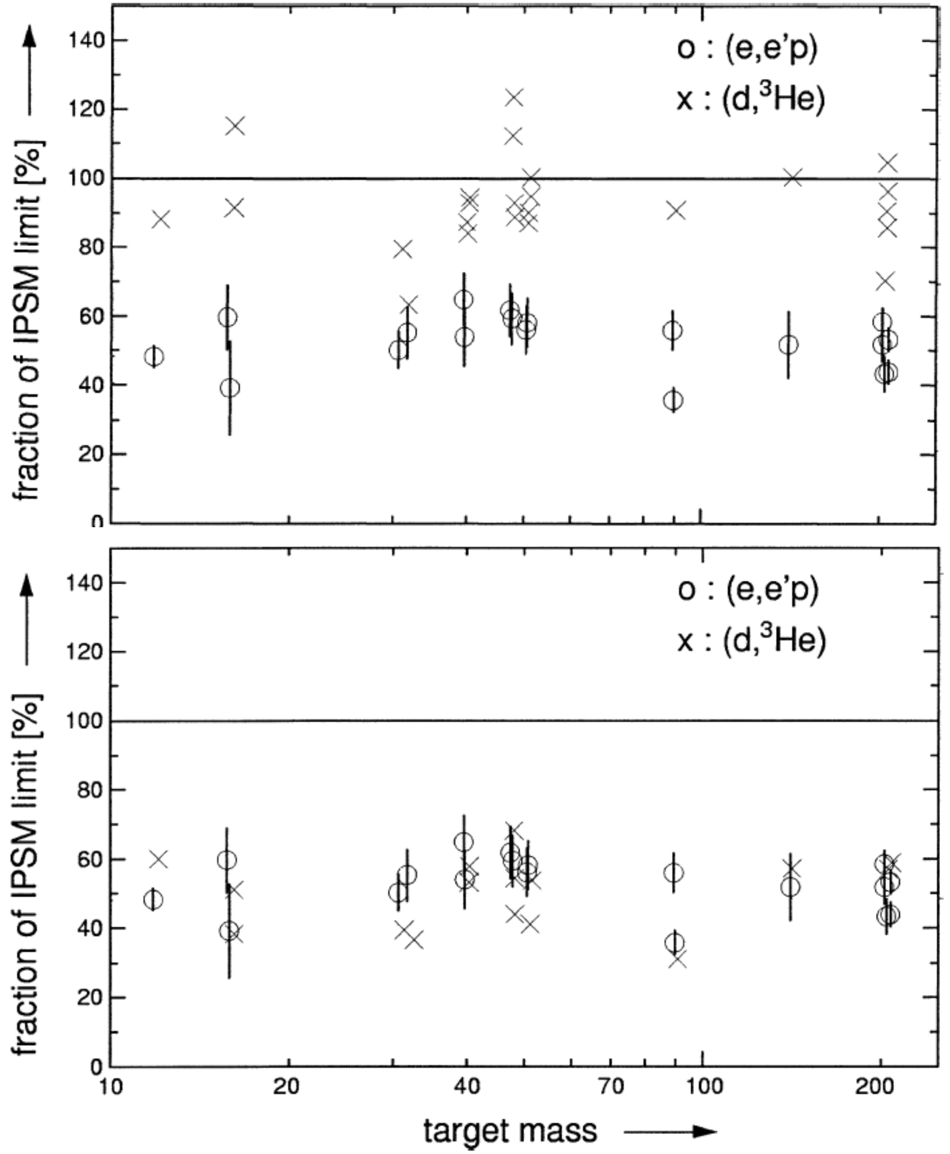




reaction	Beam intensity (pps)	Target thickness(mg/cm^2)	Counts/hour 1 level
^{56}Ni (p,^{3}He)	10^5	10	31
^{56}Ni(d,α)	10^5	10	14
^{48}Cr(p,^{3}He)	10^5	20	31
^{48}Cr(d,α)	10^5	10	14

M.Assie et al, GANIL PAC Proposal (Approved) Nov. 2011

Spectroscopic factors : electron scattering vs low energy transfer reactions

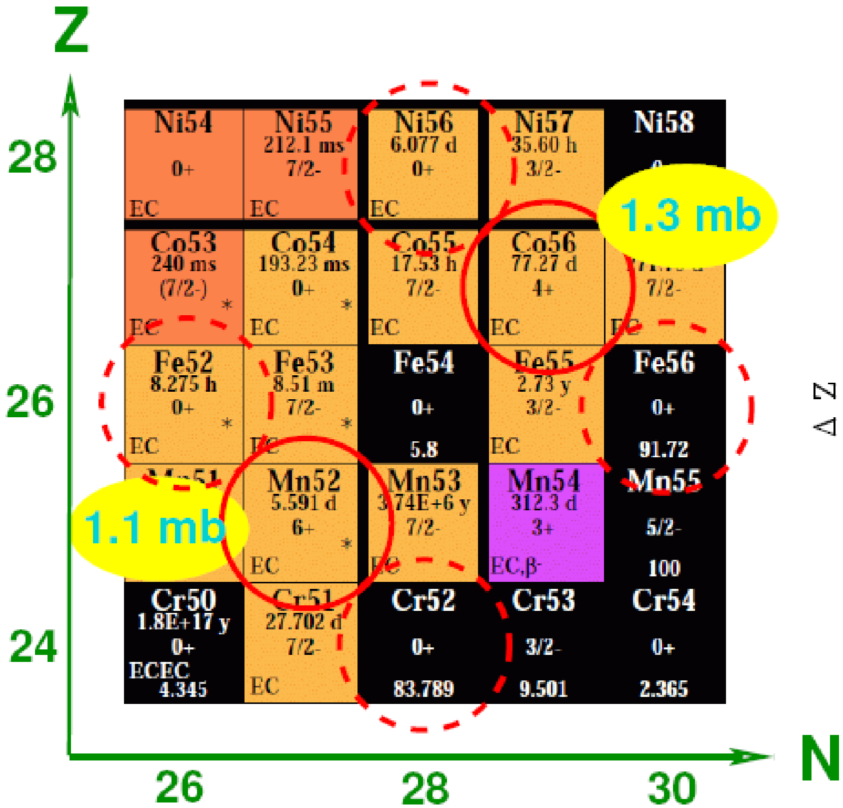


while (e,e'p) reactions are sensitive to the whole radial region in transfer reactions one probes the tail of the bound state wavefunctions

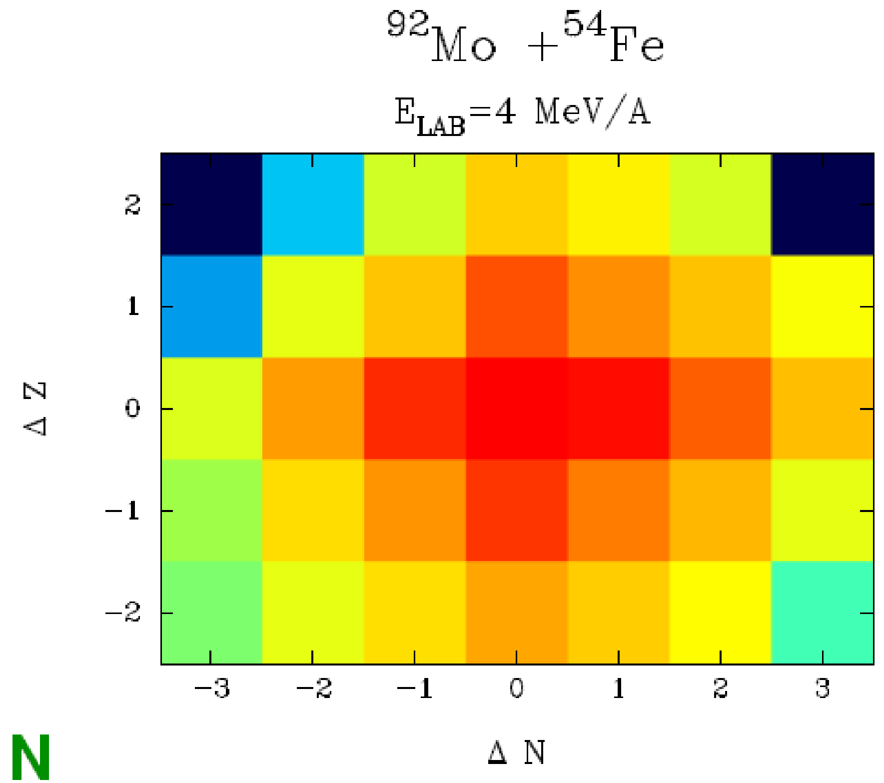
to reconcile transfer reactions with electron scattering one needs to include non-locality, finite range corrections and using bound state wavefunctions from (e,e'p) data

G.J.Kramer et al, NPA679(2001)267

Probing nucleon-nucleon correlations via transfer of (nn), (pp) and (np) pairs at sub-barrier energies in $^{92}Mo+^{54}Fe$ PRISMA



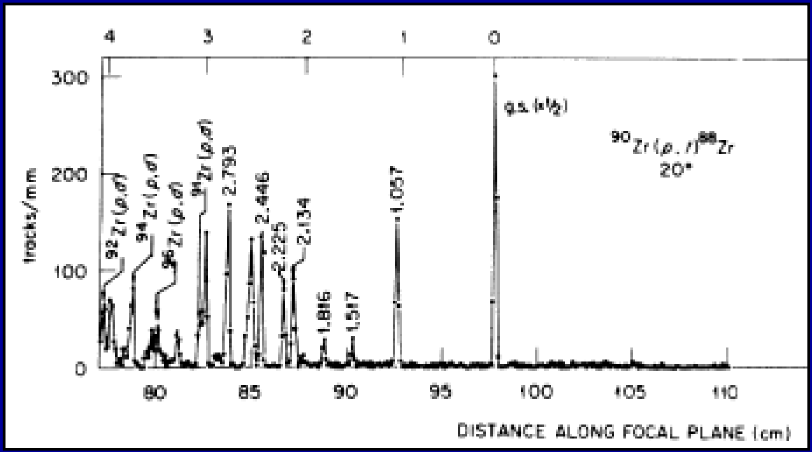
Grazing code calculations



S.Szilner, L.Corradi et al, May 2012 LNL PAC Proposal (approved)

light ion reactions

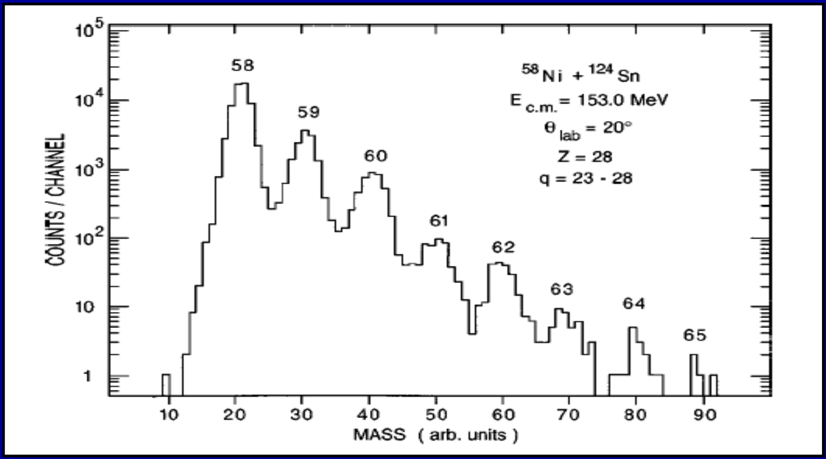
- probe single particle properties (spectroscopic factors, shell model)
- highly selective in energy and angular momentum transfer
- test for pairing and cluster properties



- radioactive beams in inverse kinematics

heavy ion reactions

- interplay between single particle and (multiple) pair transfer degrees of freedom
- simultaneous comparison of observables for nn/pp/np pairs
- optimum Q-value windows



- high intensity stable beams as well as radioactive beams

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

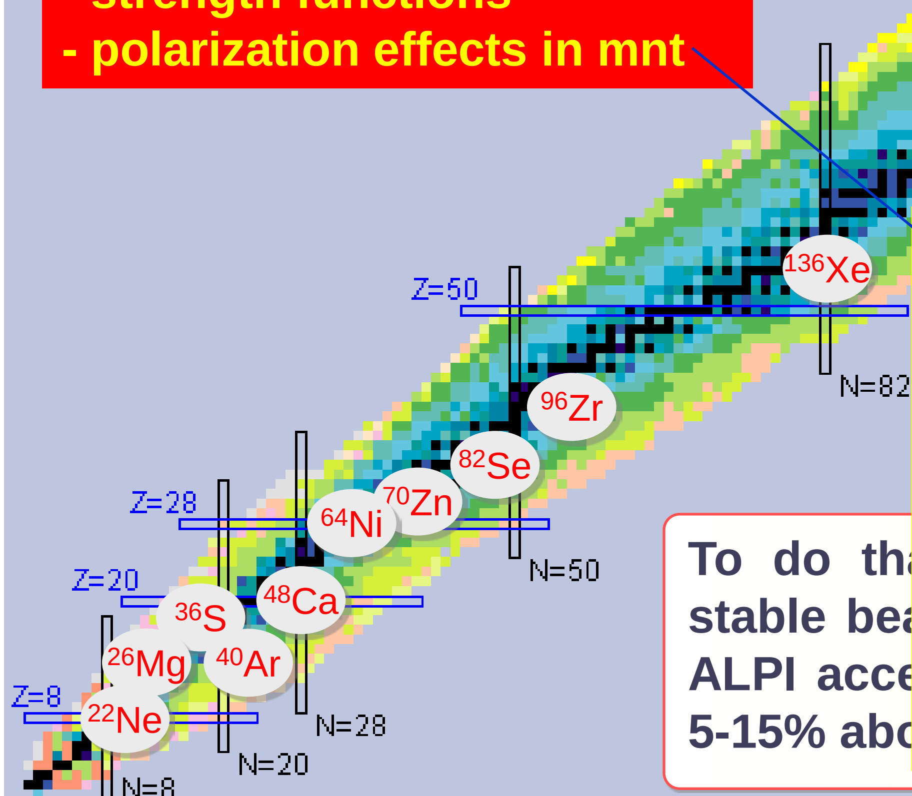
$\Delta A/A \sim 1/200$

Energy acceptance $\sim \pm 20\%$

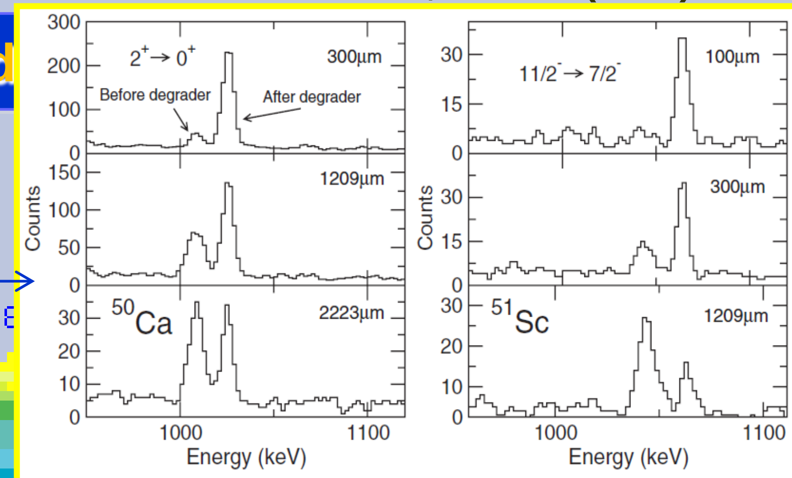
THE PRISMA + CLARA/AGATA CAMPAIGN

Grazing reactions as a tool to stud

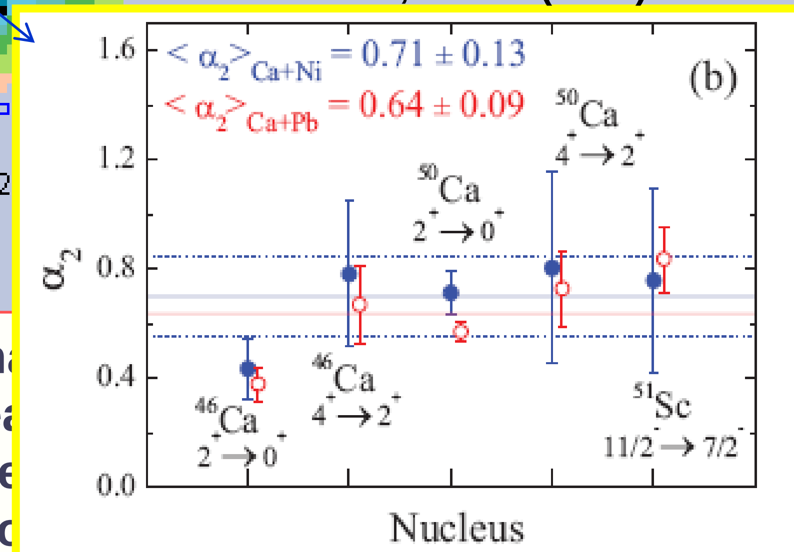
- evolution of shell structures
- lifetime measurements
- strength functions
- polarization effects in mnt



J.J.Valiente-Dobon et al, PRL102(2009)242502

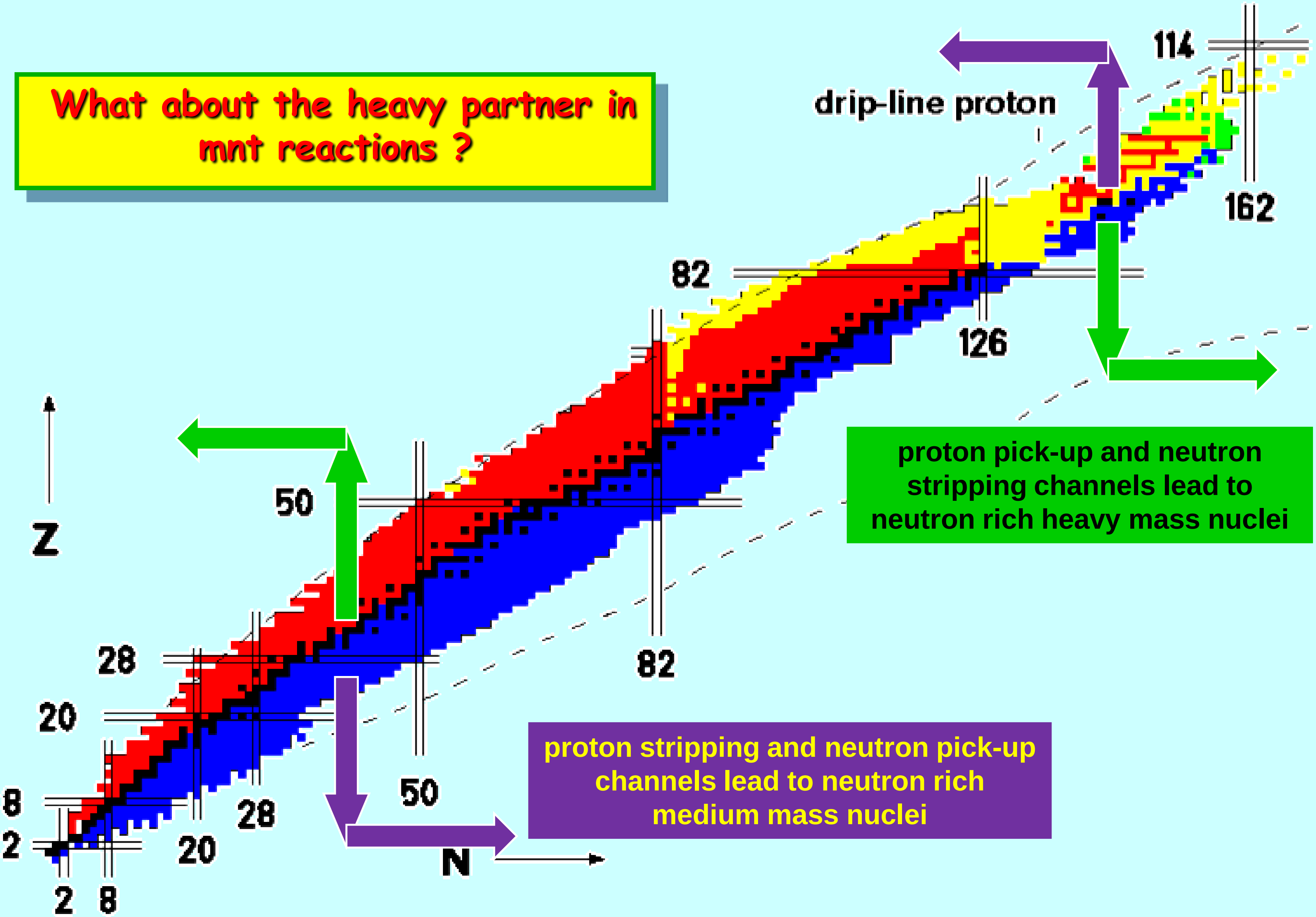


D.Montanari et al, PRC85(2012)044301



To do tha ... h
stable bea ... E-
ALPI acce ... s
5-15% abo

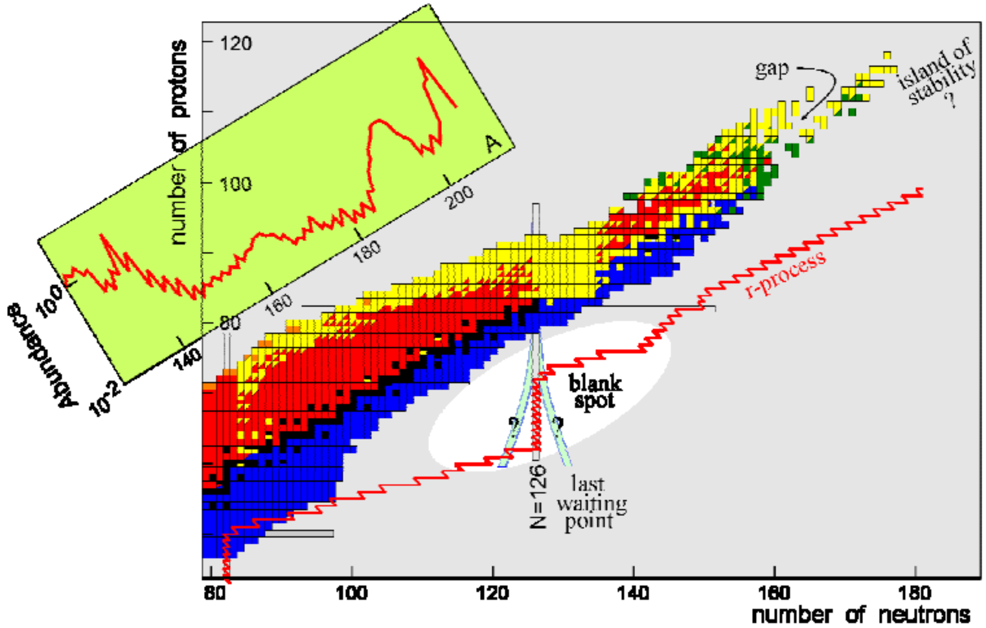
What about the heavy partner in mnt reactions ?



proton pick-up and neutron stripping channels lead to neutron rich heavy mass nuclei

proton stripping and neutron pick-up channels lead to neutron rich medium mass nuclei

Exploring the north-east part of the nuclear chart via multinucleon transfer



high primary cross sections of mnt channels (mb-μb range)

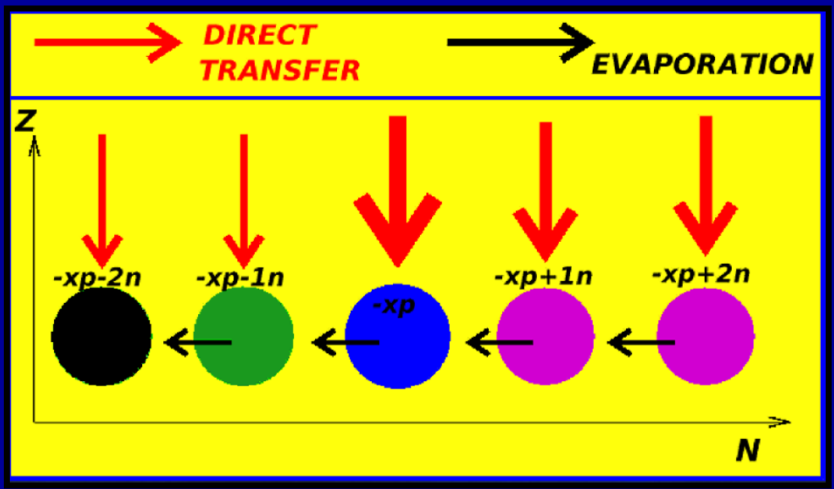
processes lowering final yield : evaporation and transfer induced fission

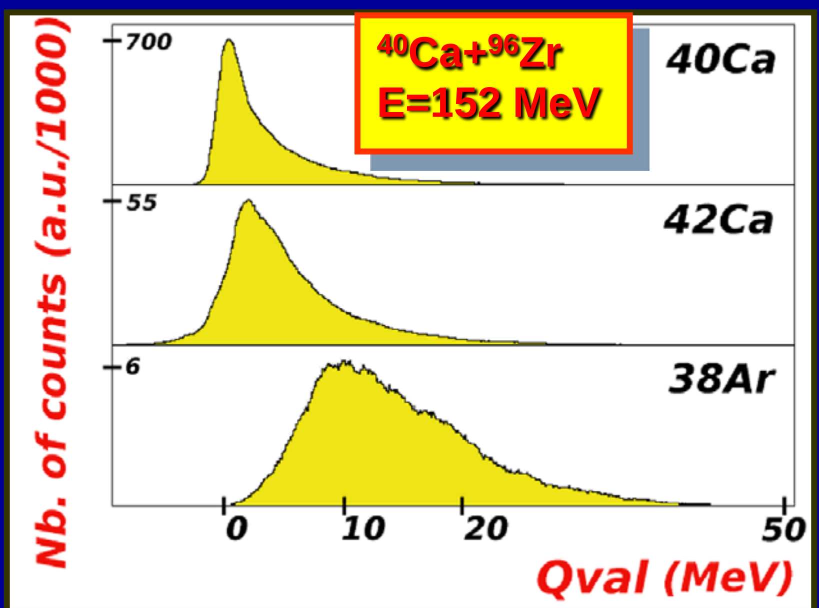
TWO KIND OF EXPERIMENTS NEED TO BE DONE

gamma-particle coincidences : tagging of light partner with high resolution spectrometers and detecting coincident gamma rays Doppler corrected for the heavy partner

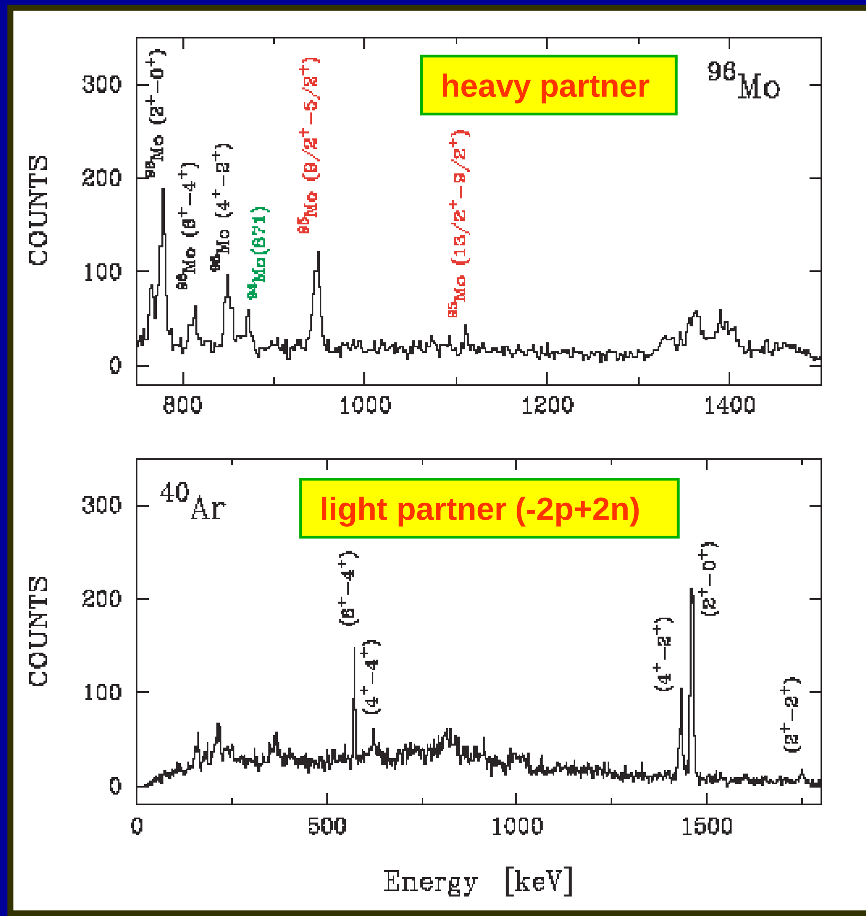
high resolution kinematic coincidences between binary partners : study of transfer induced fission (both mechanism and spectroscopy)

Evaporation processes in multinucleon transfer reactions : an example of gamma-particle coincidences



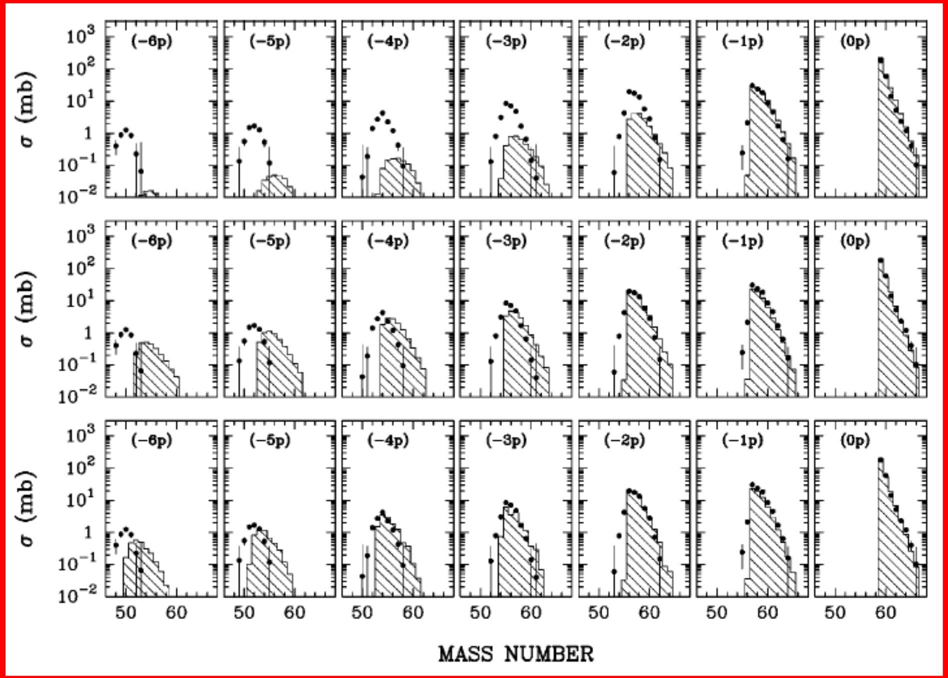


Direct identification with PRISMA+CLARA



S.Szilner et al, Phys.Rev.C76(2007)024604

An example of simultaneous detection light and heavy transfer products for transfer induced fission studies



ind. part. tr. only

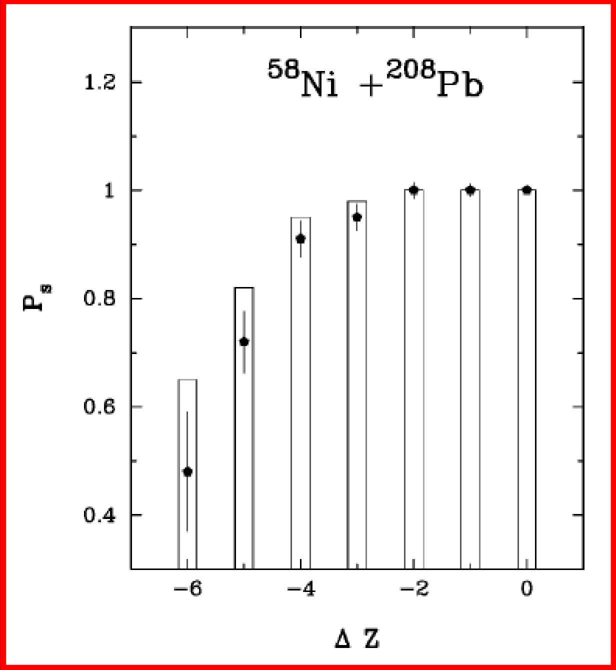
+ pair mode

+ evap

light reaction products fully identified via a time of flight system in $^{58}Ni+^{208}Pb$

points : exp. data

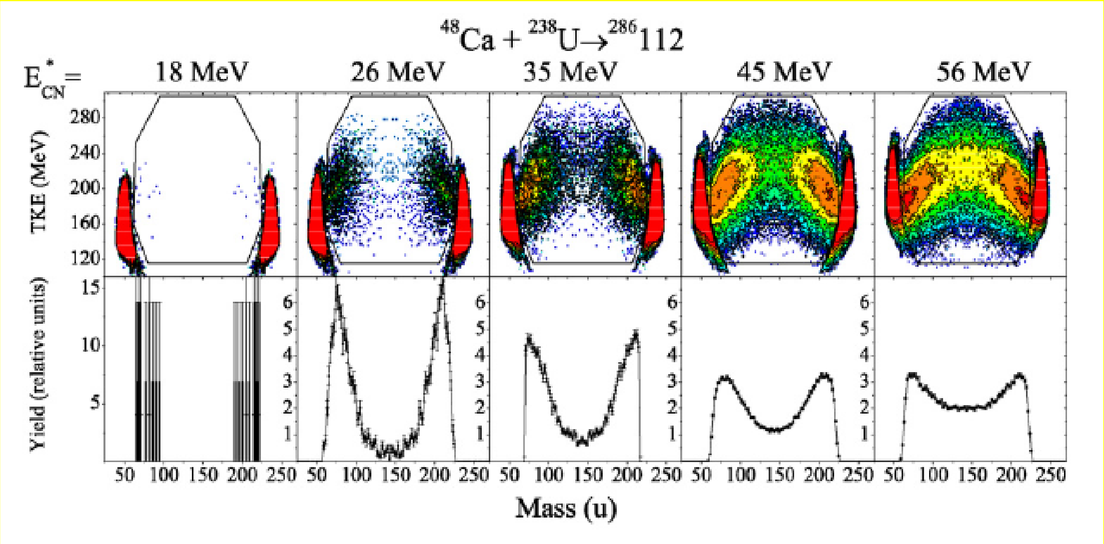
histograms : GRAZING calculations



fission probability of associated heavy partners determined as function of Z,A (light partner) and Q-value of the reaction via a high resolution kinematic coincidence

L.Corradi et al, Phys.Rev.C66(2002)024606

Quasi-fission processes



integral measurements presently studied to understand the production of heavy and superheavy elements

WITH HIGH INTENSITY BEAMS

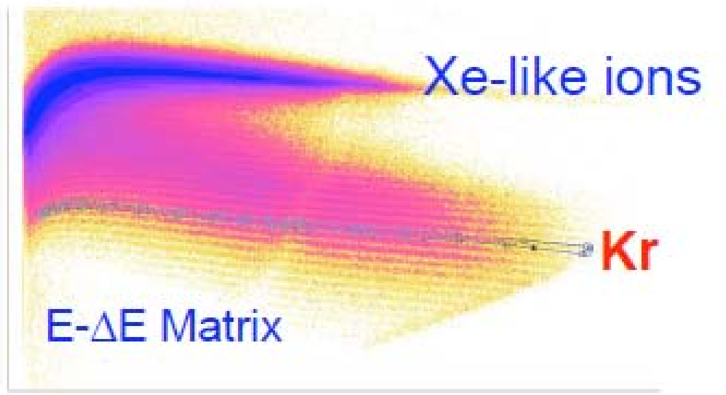
employing magnetic spectrometers one can make high resolution studies (details of Z,A,Q-value distributions)

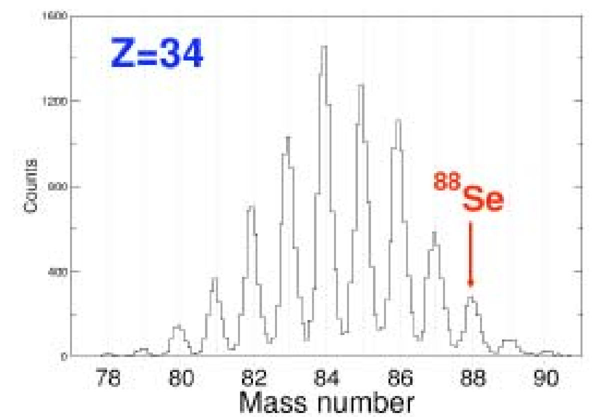
one can use "cold fission" mechanisms to populate very neutron rich nuclei (via transfer induced fission or quasi-fission)

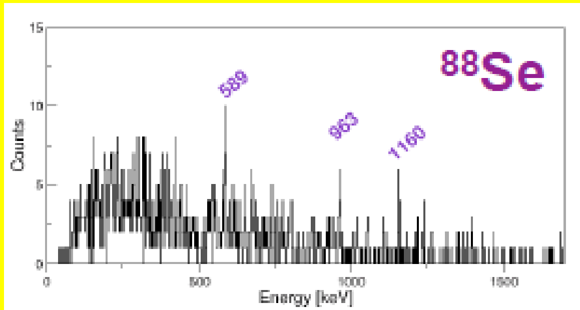
E.Kozulin et al, PLB686(2010)227

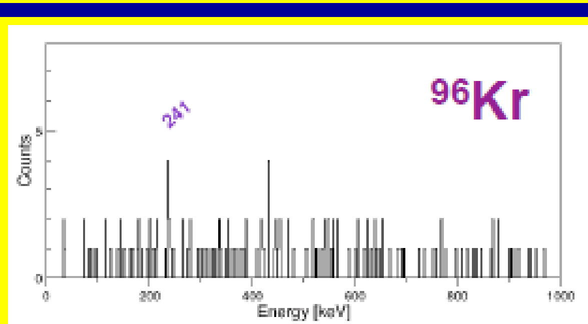
M.Itkis et al

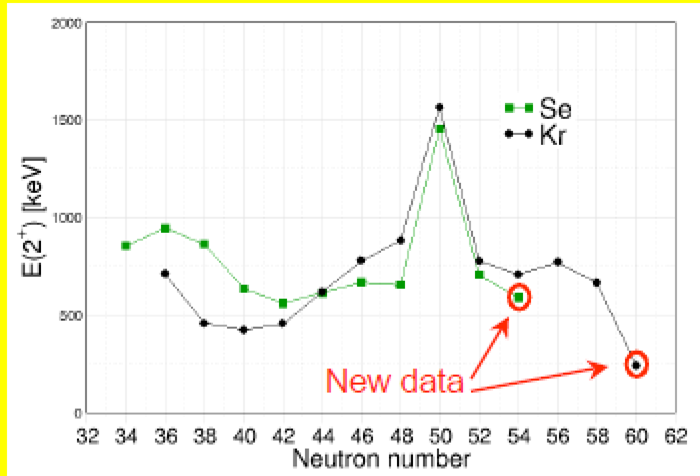
Neutron rich nuclei produced in the fission of ^{238}U in $^{136}Xe+^{238}U$ at E_{lab}=990 MeV











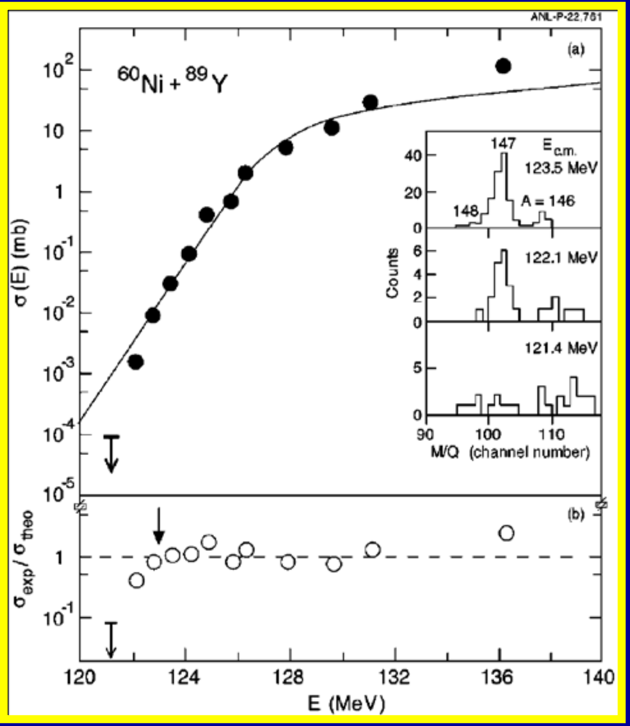
N.Marginean et al., Phys. Rev. C80(2009)021301(R)

Sub-barrier fusion reactions

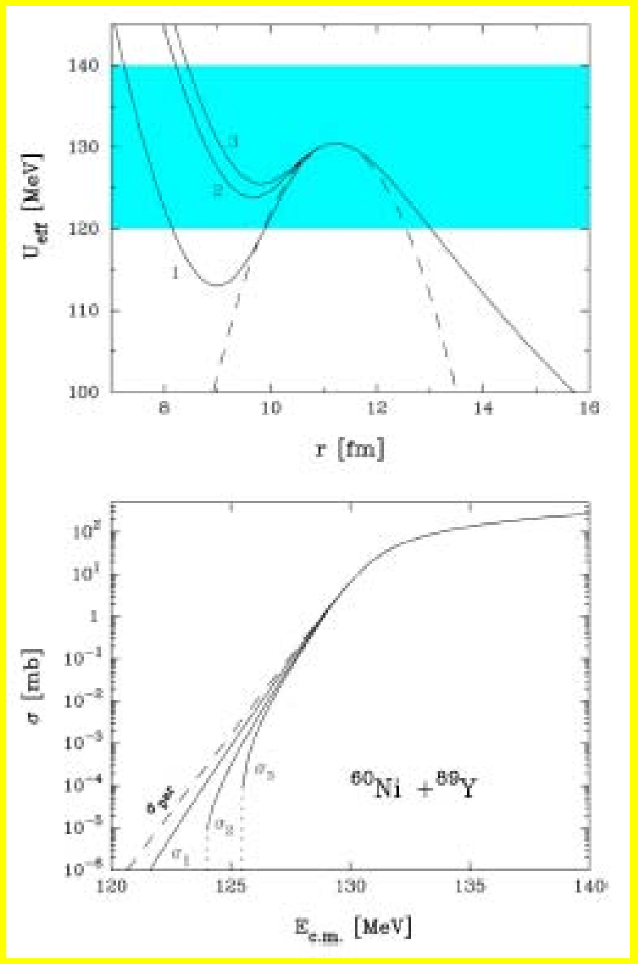
Hindrance phenomenon in heavy ion fusion reactions

unexpected behaviour of heavy-ion fusion cross sections at extreme sub-barrier energies

possibility to learn about the inner shape of the nucleus-nucleus interaction



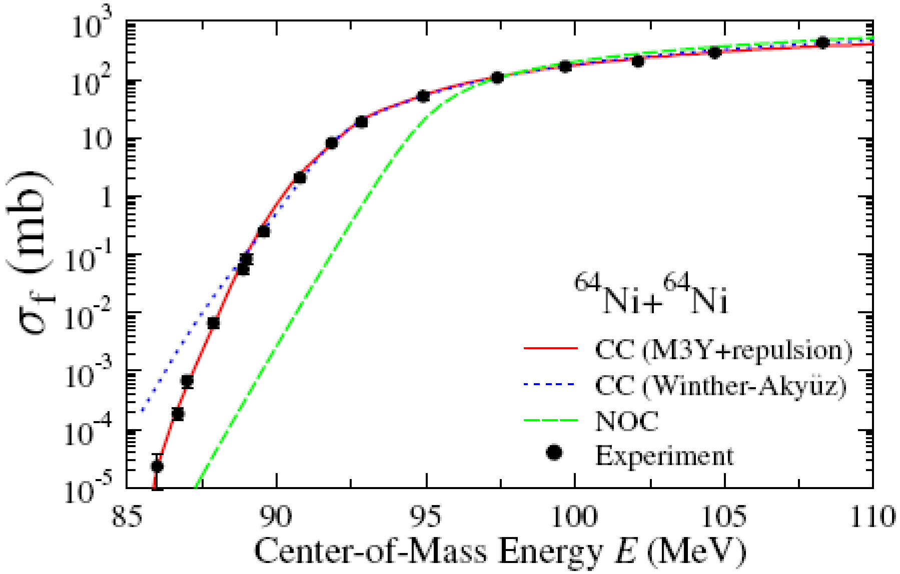
C.L.Jiang et al, PRL89(2002)052701

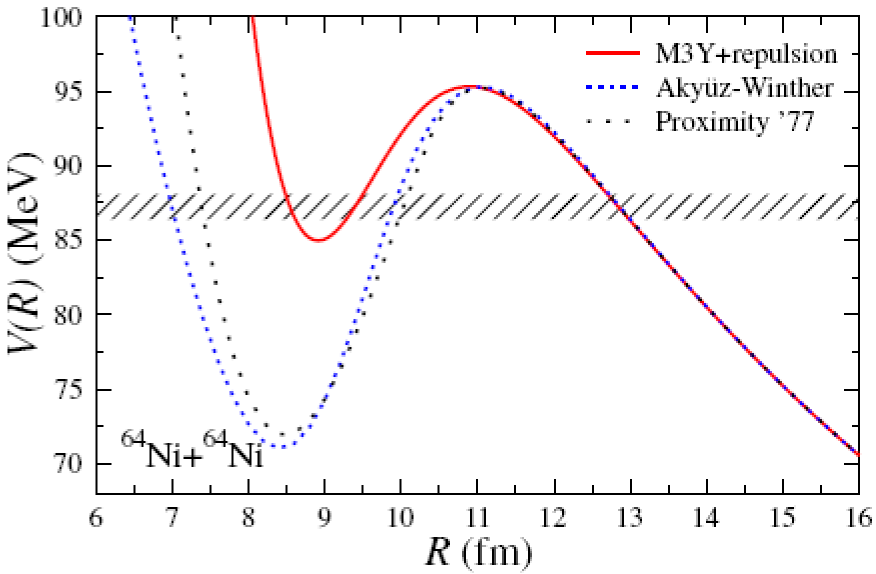


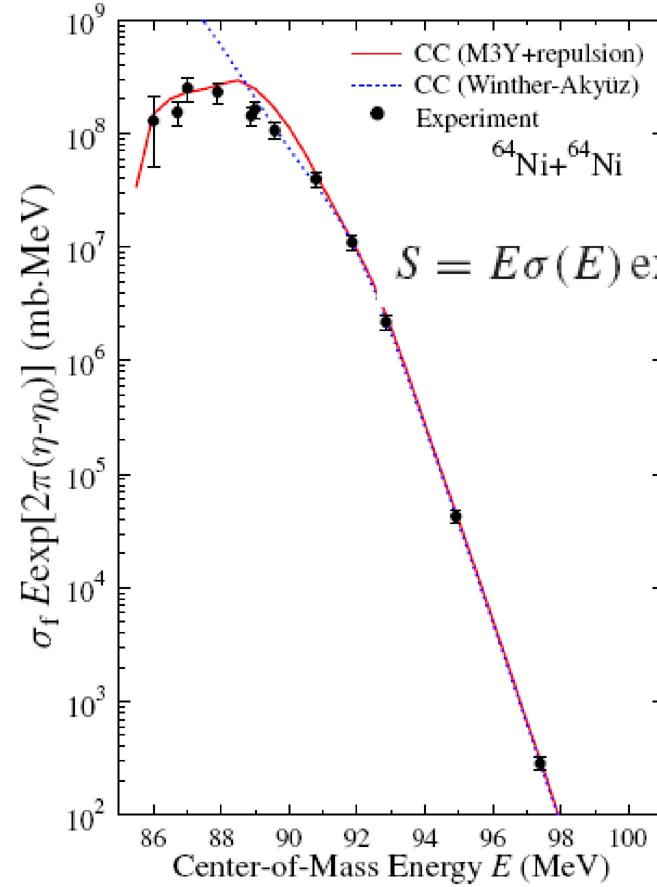
C.H.Dasso and G.Pollarolo, PRC68(2003)054604

Hindrance in heavy ion fusion due to nuclear incompressibility

$$V(\boldsymbol{R}) = \int d\boldsymbol{r}_1 \int d\boldsymbol{r}_2 \rho_1(\boldsymbol{r}_1)\rho_2(\boldsymbol{r}_2) v(\boldsymbol{r}_{12}, \rho_1, \rho_2)$$



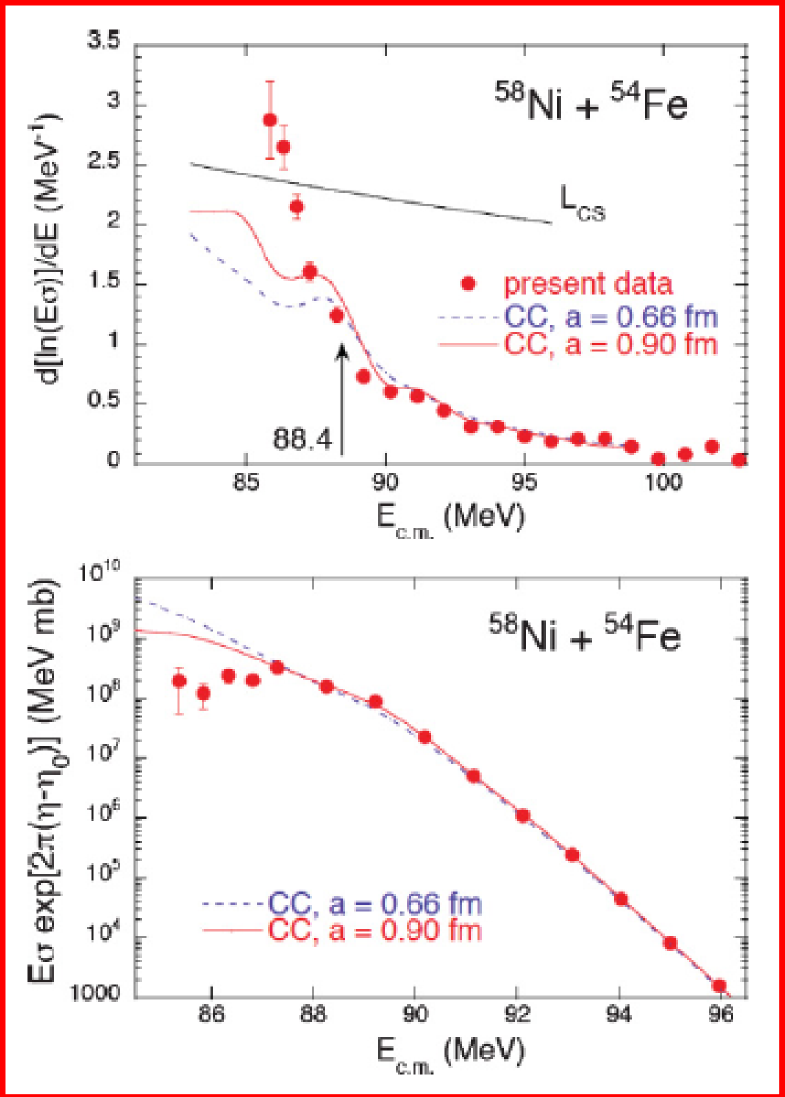




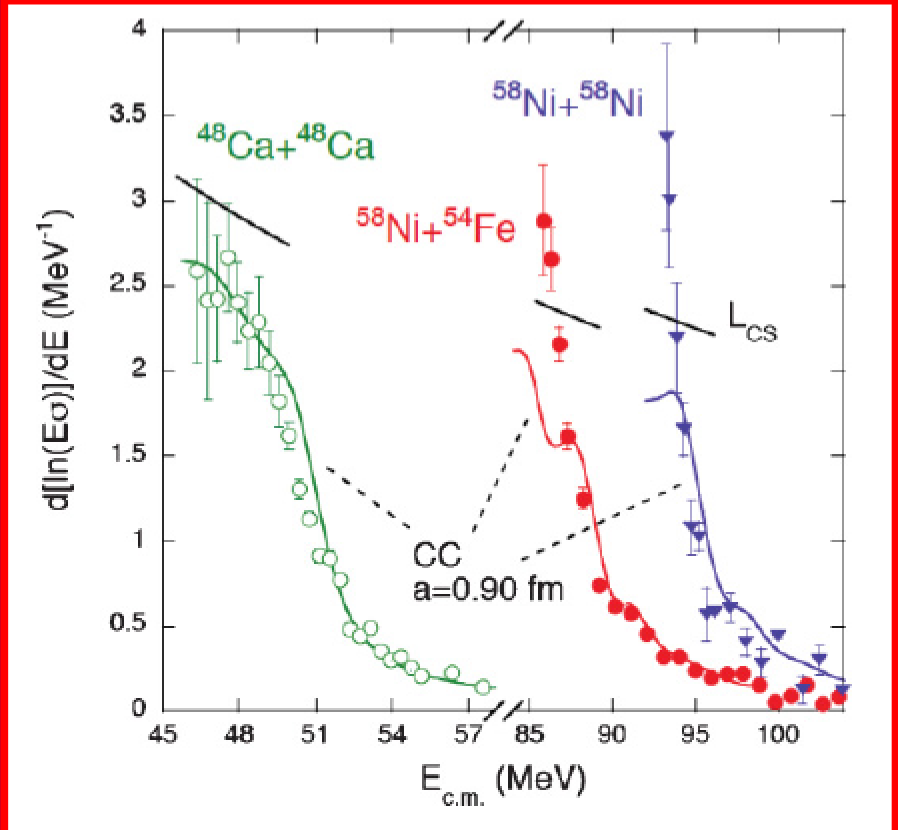
$$S = E\sigma(E)\exp(2\pi\eta)$$

S.Misicu and H.Esbensen, PRL96(2006)112701

Nuclear structure dependence of the hindrance phenomenon in medium mass systems

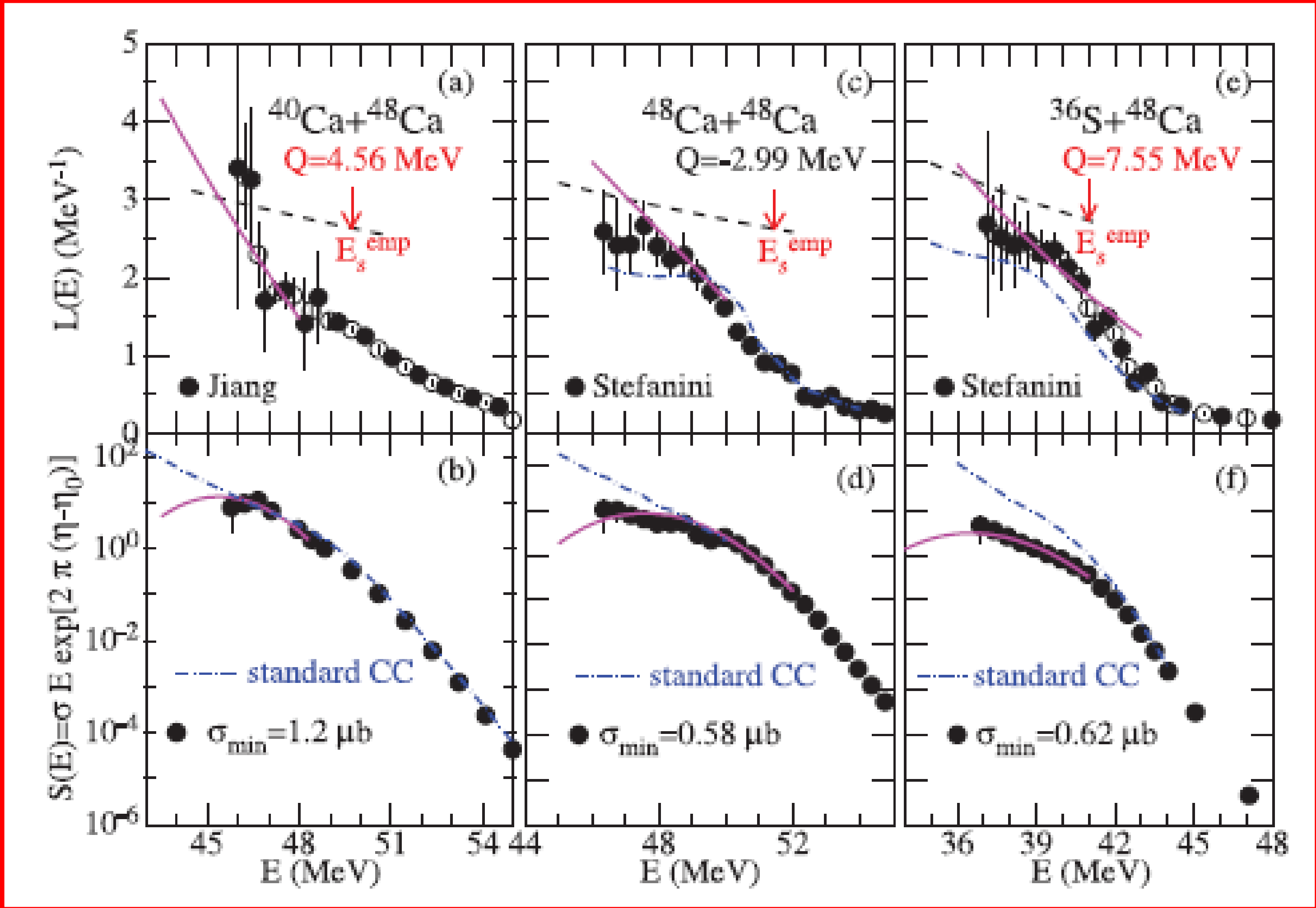


the very regular increase of slope for the ^{58}Ni+^{54}Fe contrasts with the behaviour of ^{48}Ca+^{48}Ca



A.M.Stefanini et al, PRC82(2010)014614

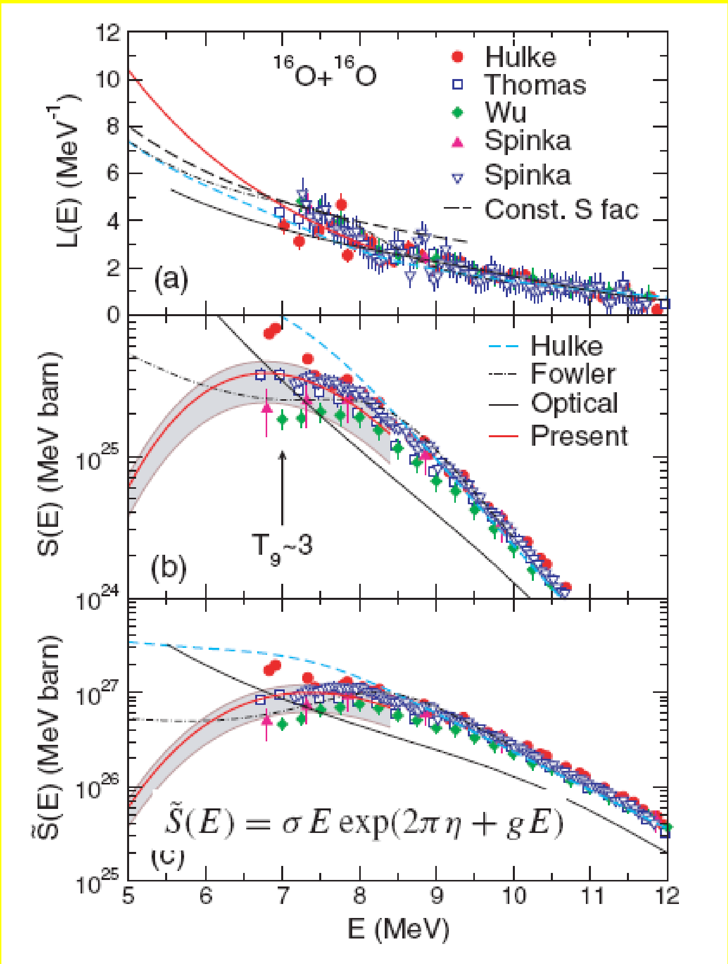
Nuclear structure dependence of the hindrance phenomenon in medium mass systems

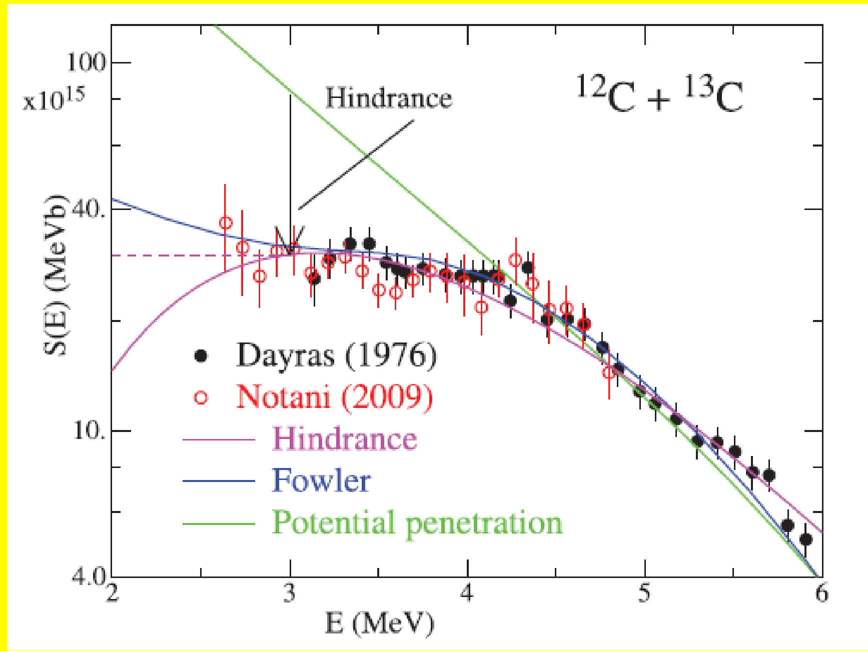


do we see any effect due to positive Q-values for fusion ?

Extrapolations in the relevant astrophysical energies

the hindrance phenomenon can cause large differences at T < T_9 , a range important for reactions occurring in the late evolution of massive stars and type-Ia supernova explosions



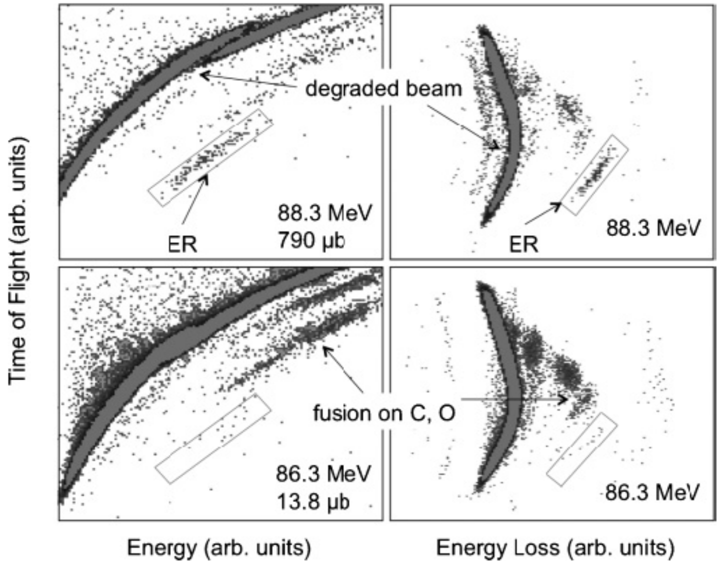


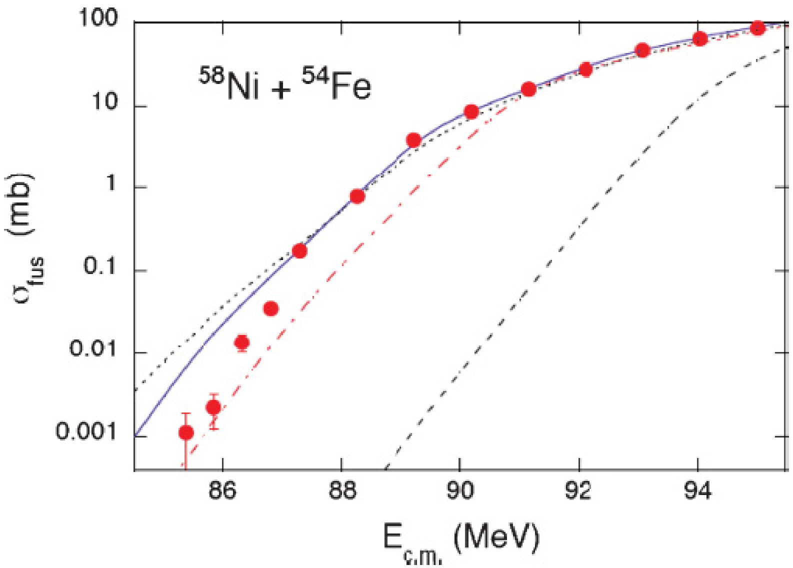
it is crucial to determine as better as possible extrapolations to energies of astrophysical interest

C.L.Jiang et al, PRC75(2007)015803

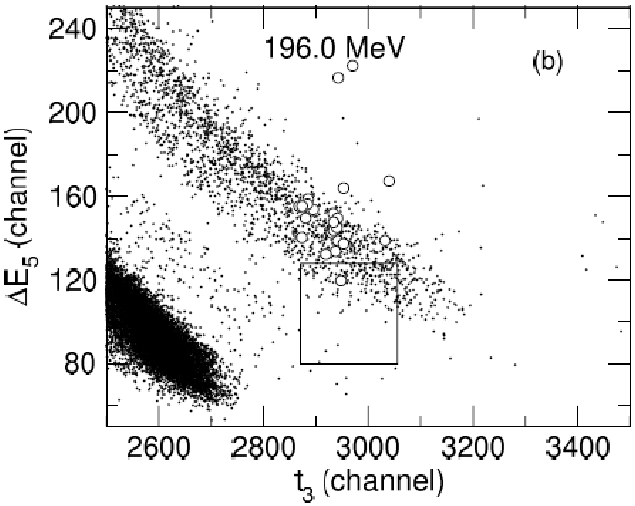
Experimental techniques : direct particle detection

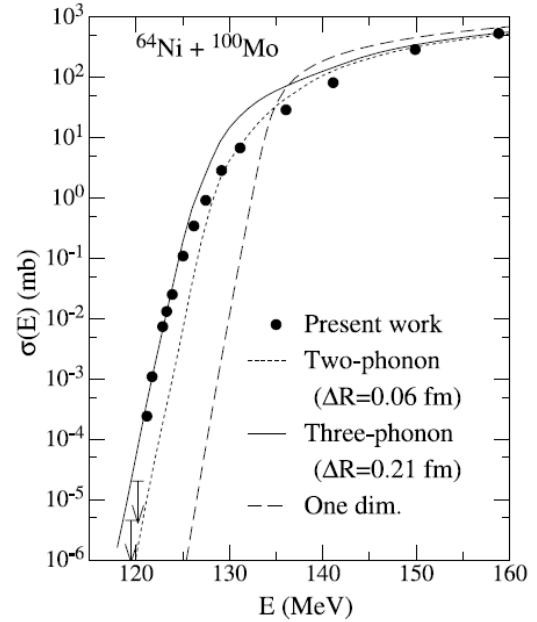
6 pnA - electrostatic separator



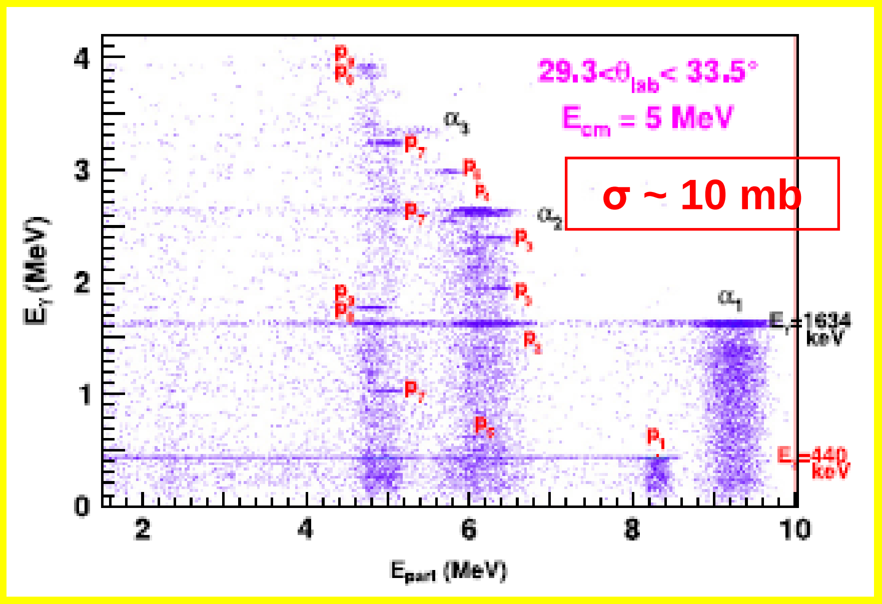


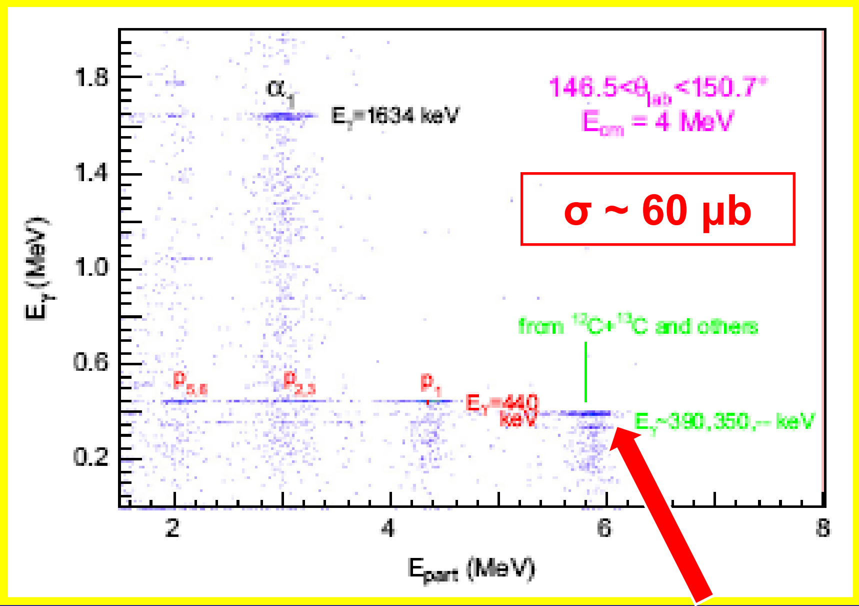
60 pnA - recoil mass spectrometer





Novel experimental techniques : GAMMASPHERE + DSSD detectors for $^{12}C+^{12}C$ fusion reactions studies at E_{cm}=5 MeV





main channels from $^{12}C(^{12}C,p)$ and $^{12}C(^{12}C,\alpha)$

contaminants from $^{13}C(^{12}C,\alpha)$ and $^{14}N(^{12}C,p)$ can be discriminated

by using efficient gamma detection in coincidence with efficient particle detectors one can reduce background effects and it appears possible to perform measurements with beam currents of ~ 100 pμA and σ ~ 10 pb

C.L.Jiang, K.E.Rehm et al, NIMA682(2012)12

Summary : studies where one can benefit from high intensity beams

- pair correlations (nn,pp,np channels) in transfer reactions at sub-barrier energies and large internuclear distances

- population of heavy partners in mnt reactions (neutron rich nuclei) and importance of transfer induced fission and quasi fission processes

- hindrance phenomenon in sub-barrier fusion reactions

- determination of S-factors in the astrophysical relevant energies

key physics issues

How can we selectively probe the relative role of single particle and pair or cluster transfer modes

How can we at best extract quantitative information on pair correlations (e.g. measurements at sub-barrier energies, gamma-particle coincidences) and how these correlations are modified with neutron-rich and proton-rich nuclei

Need for a correct evaluation of spectroscopic factors (from transfer and from knock-out reactions)

To what extent can we populate heavy neutron rich nuclei in mnt reactions (effects of transfer induced fission and quasi fission processes)

Hindrance phenomenon in sub-barrier fusion reactions : can we learn more on the inner side of the nuclear potential

Can we experimentally get access to S-factors in the astrophysical relevant energies

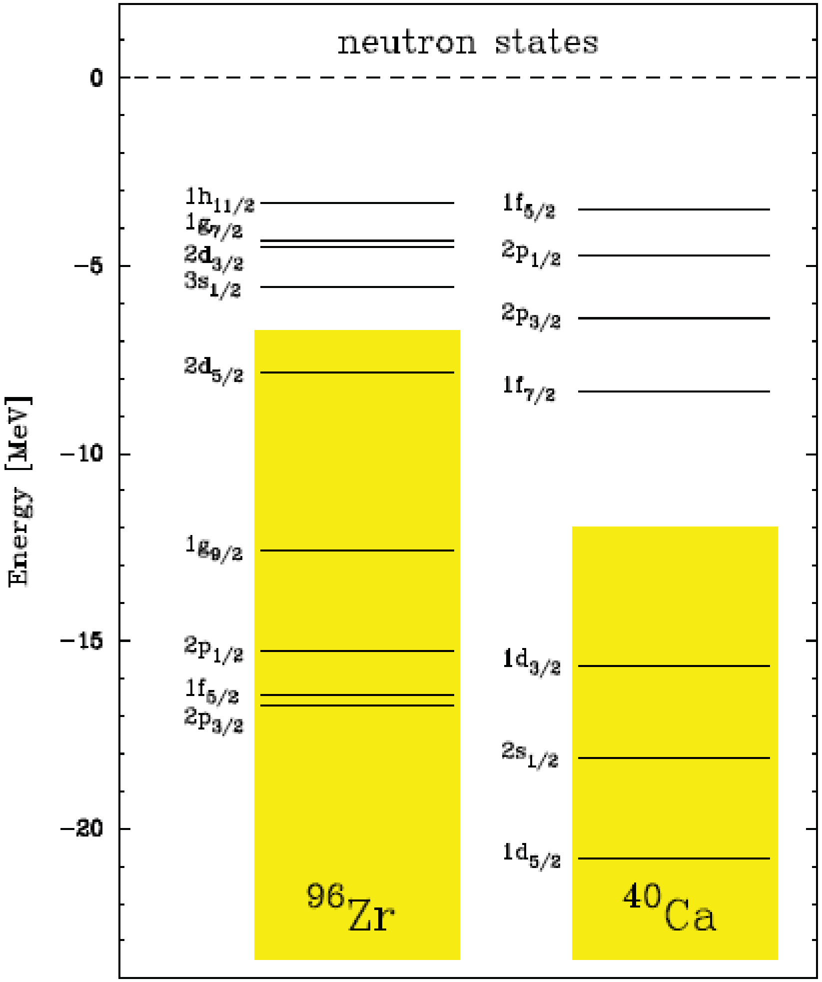
Issues on instrumentation

Improvements in the tracking reconstruction techniques and detector performances for large solid angle spectrometers (Prisma, Vamos…) to identify high mass nuclei

High rate capabilities of spectrometers to be used at very forward angles for peripheral and fusion reactions (e.g. gas-filled mode)

Coupling of magnetic spectrometers to large gamma-arrays (transfer) and large gamma-arrays to large particle detector arrays (sbt fusion)

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)

3 terms : simultaneous, orthogonal and successive

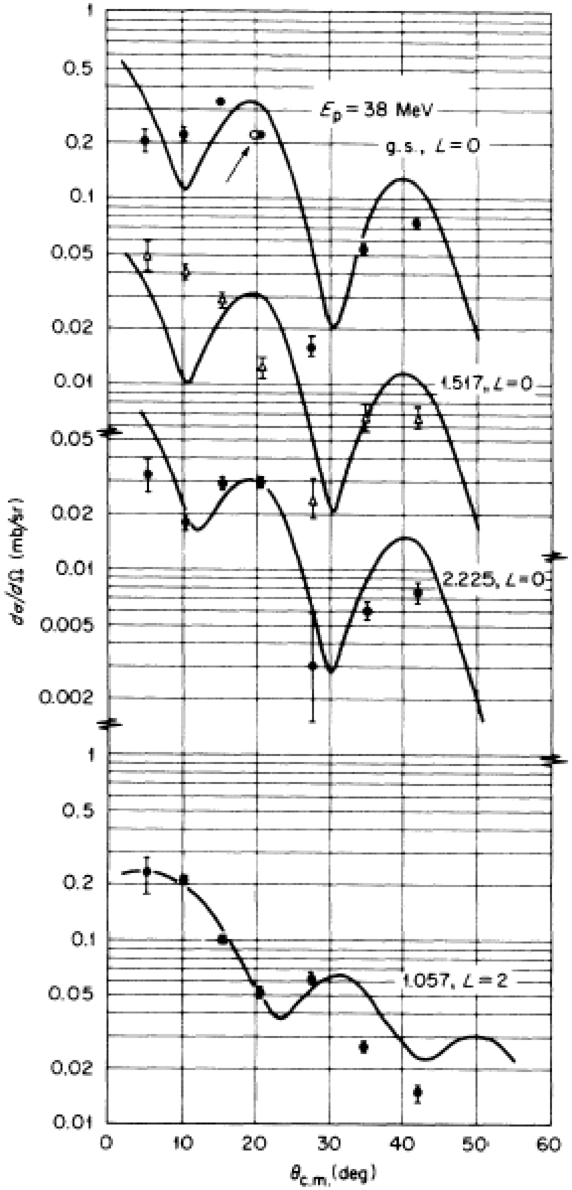
$$c_\beta(\ell) = (c_\beta)_{(1)} + (c_\beta)_{\mathrm{ort}} + (c_\beta)_{\mathrm{succ}}$$

only the successive term contributes to the transfer amplitude

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

$^{90}Zr(p,t)^{88}Zr$

From transfer reactions with light ions



$$\sigma = \varepsilon \, S_p \, S_T \, \sigma_{DWBA}$$

enhancement factor

spectroscopic factors

the enhancement factor ε has been used to compare the experimental cross sections with those calculated on the basis of specific assumptions about the nuclear wave functions involved and DWBA reaction models

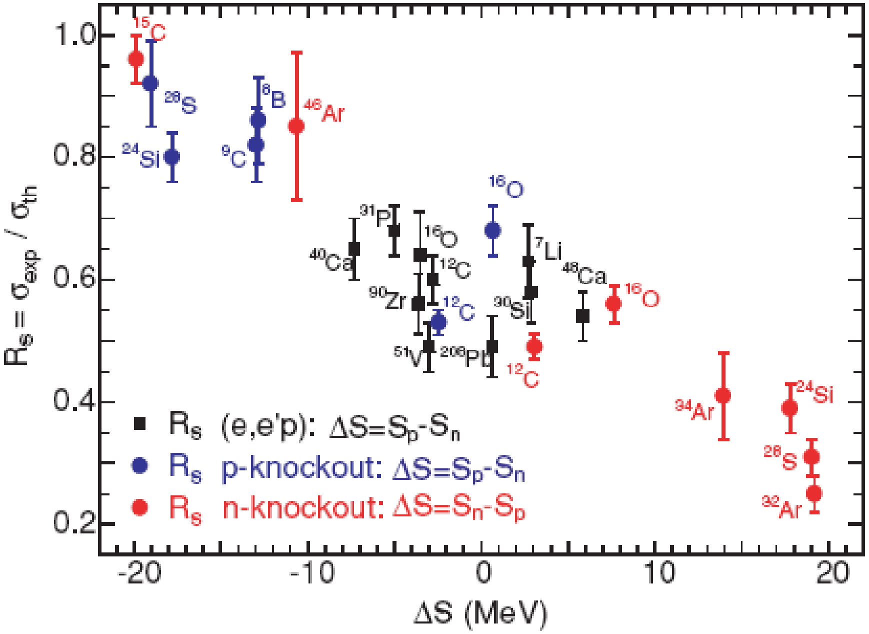
disagreement between theory and experiment is indicated by deviations of ε from unity.

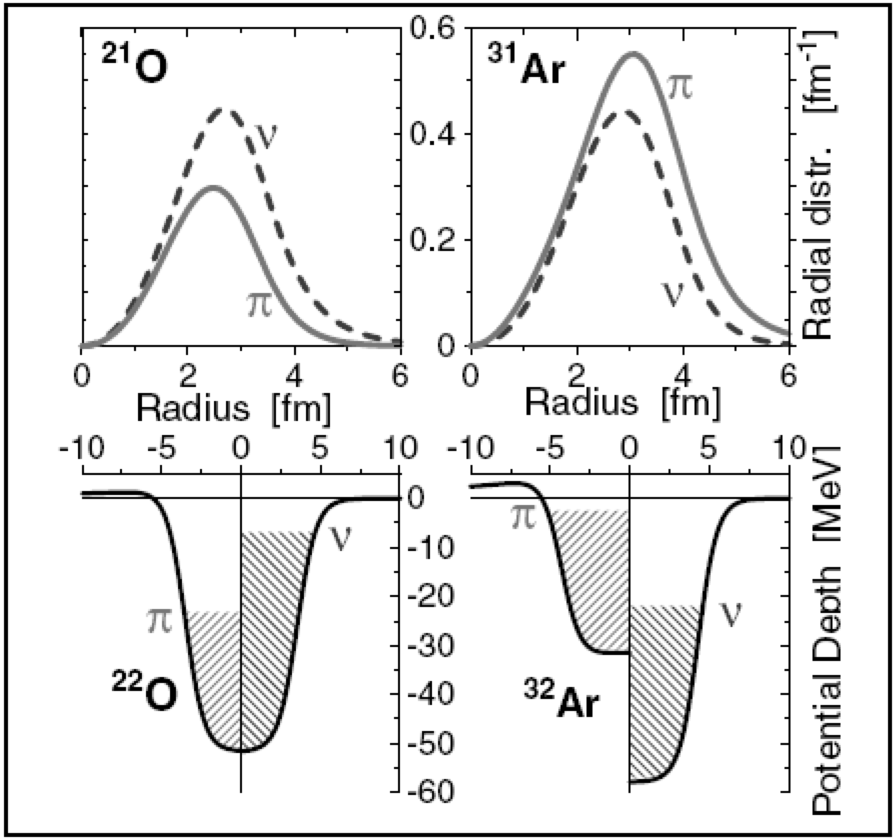
J.Ball et al., PRC4(1971)196

From knock-out reactions

trend of SF reduction factors suggest an enhancement of correlation effects experienced by strongly bound valence nucleons and weakened correlations of excess valence nucleons

$$\sigma(j^\pi) = \left(\frac{A}{A-1}\right)^2 C^2 S(j^\pi)\sigma_{sp}(j, S_N + E_x[j^\pi])$$



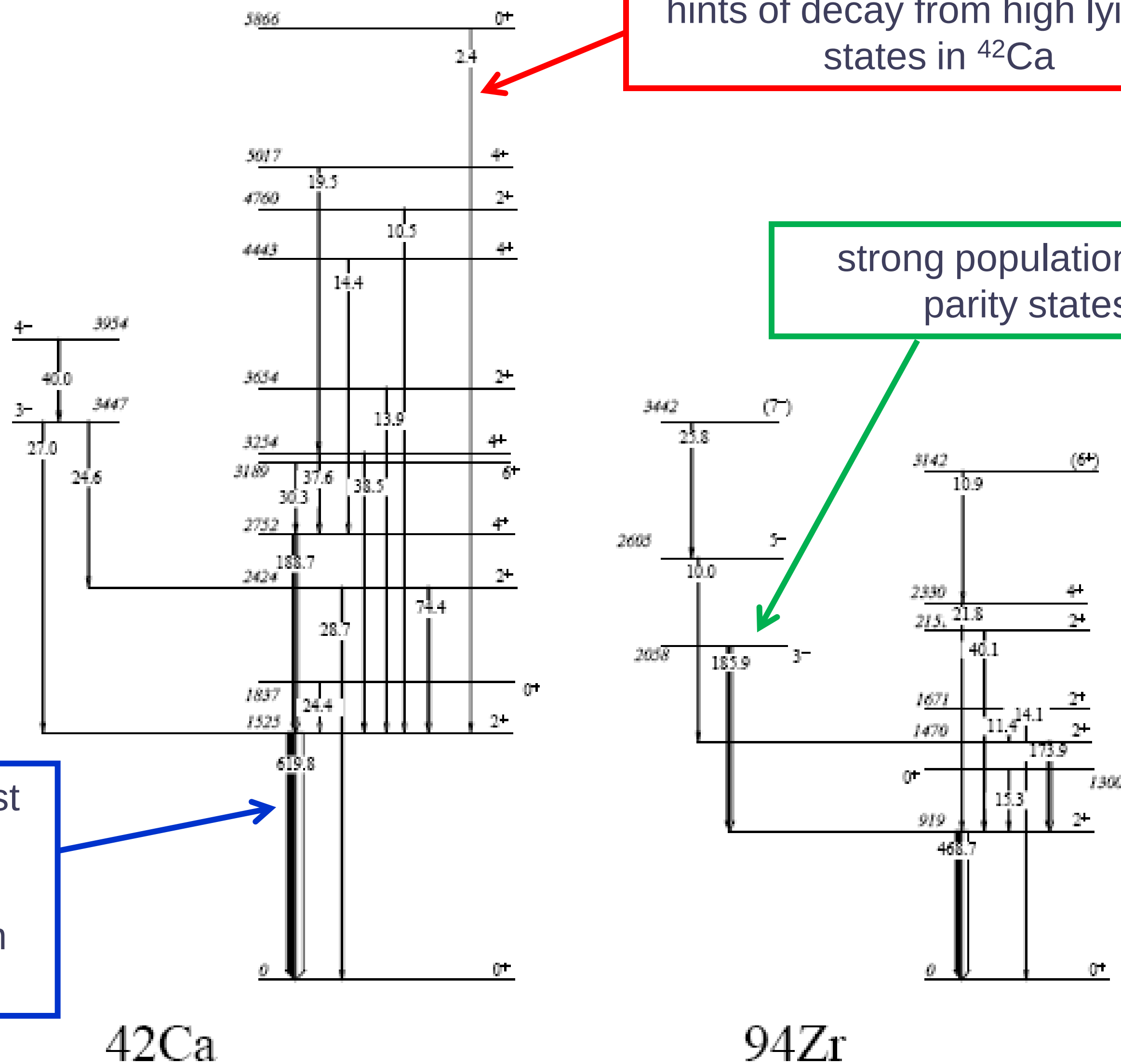


A.Gade et al, PRC77(2008)044306

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

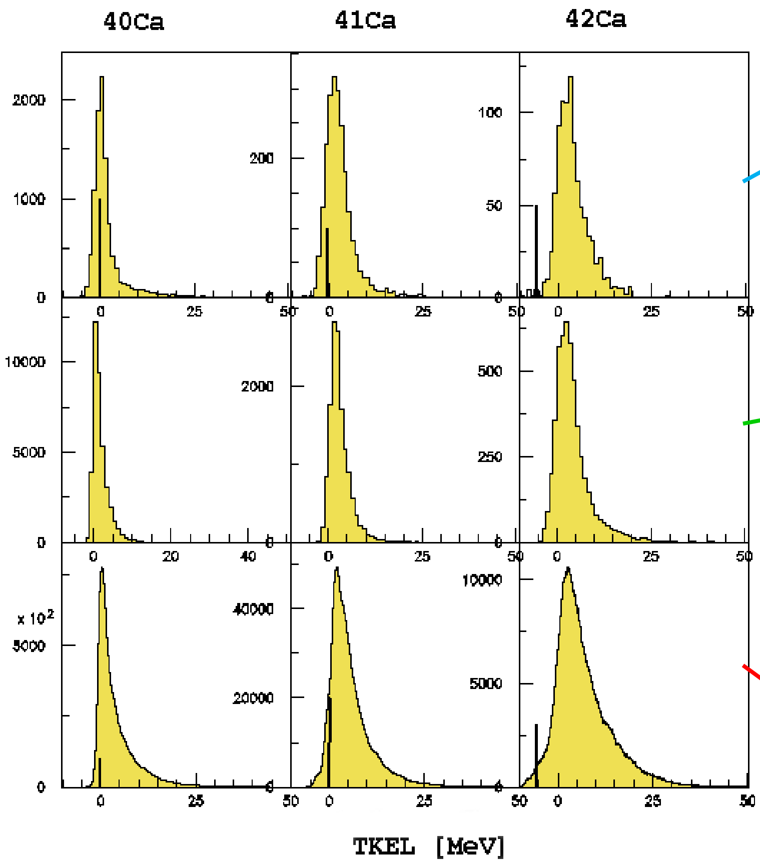
hints of decay from high lying 0^+ states in ^{42}Ca

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

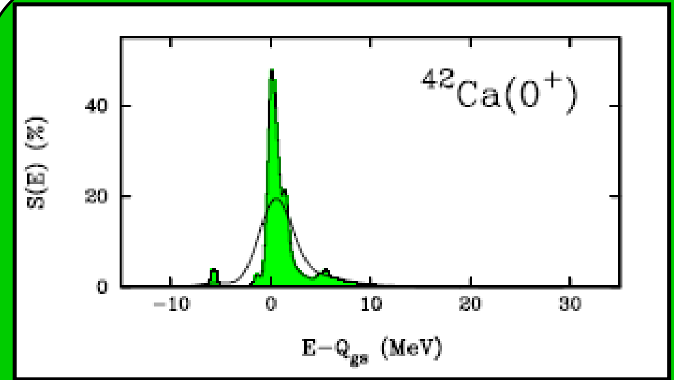


only 60% of the last 2^+ - 0^+ transition in ^{42}Ca can be accounted for from observed feeding

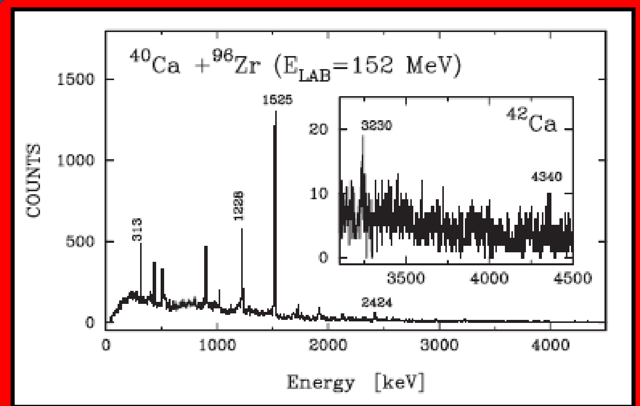
Total kinetic energy loss distributions



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



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

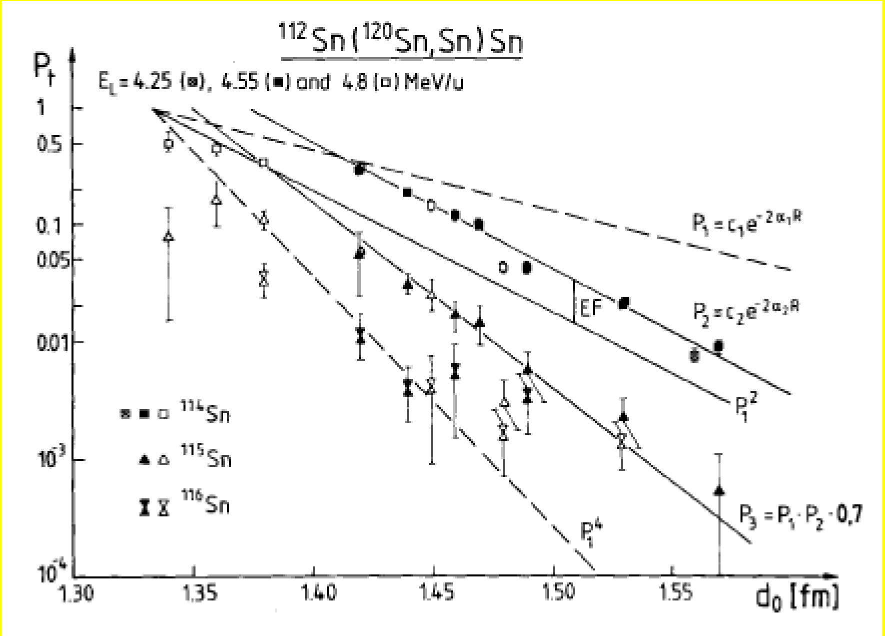


$^{40}Ca + ^{96}Zr$ 152 MeV – PRISMA+CLARA
S.Szilner et al, PRC7(2007)024604

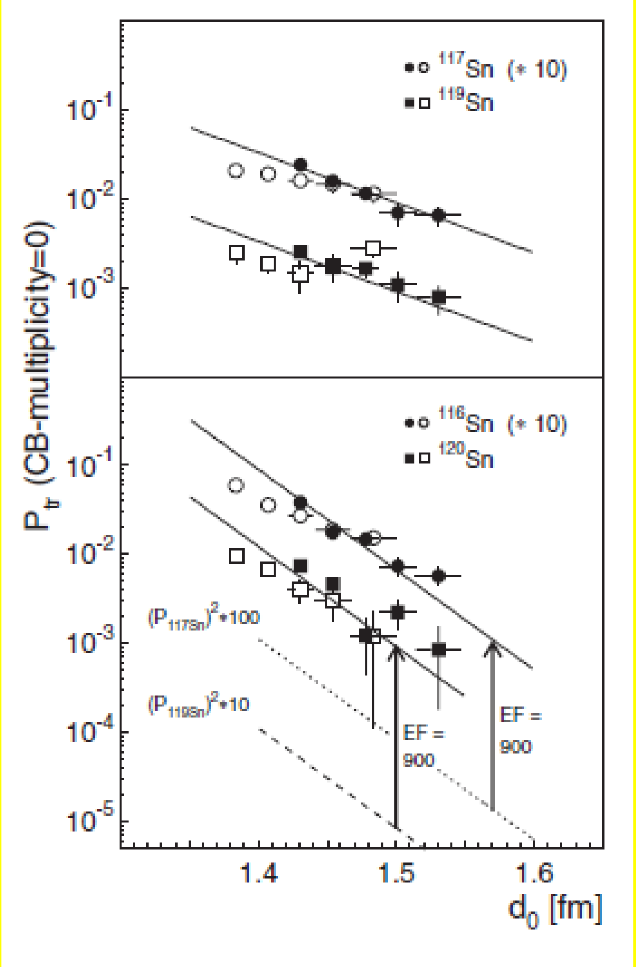
Enhancement factors in two nucleon transfer reactions

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

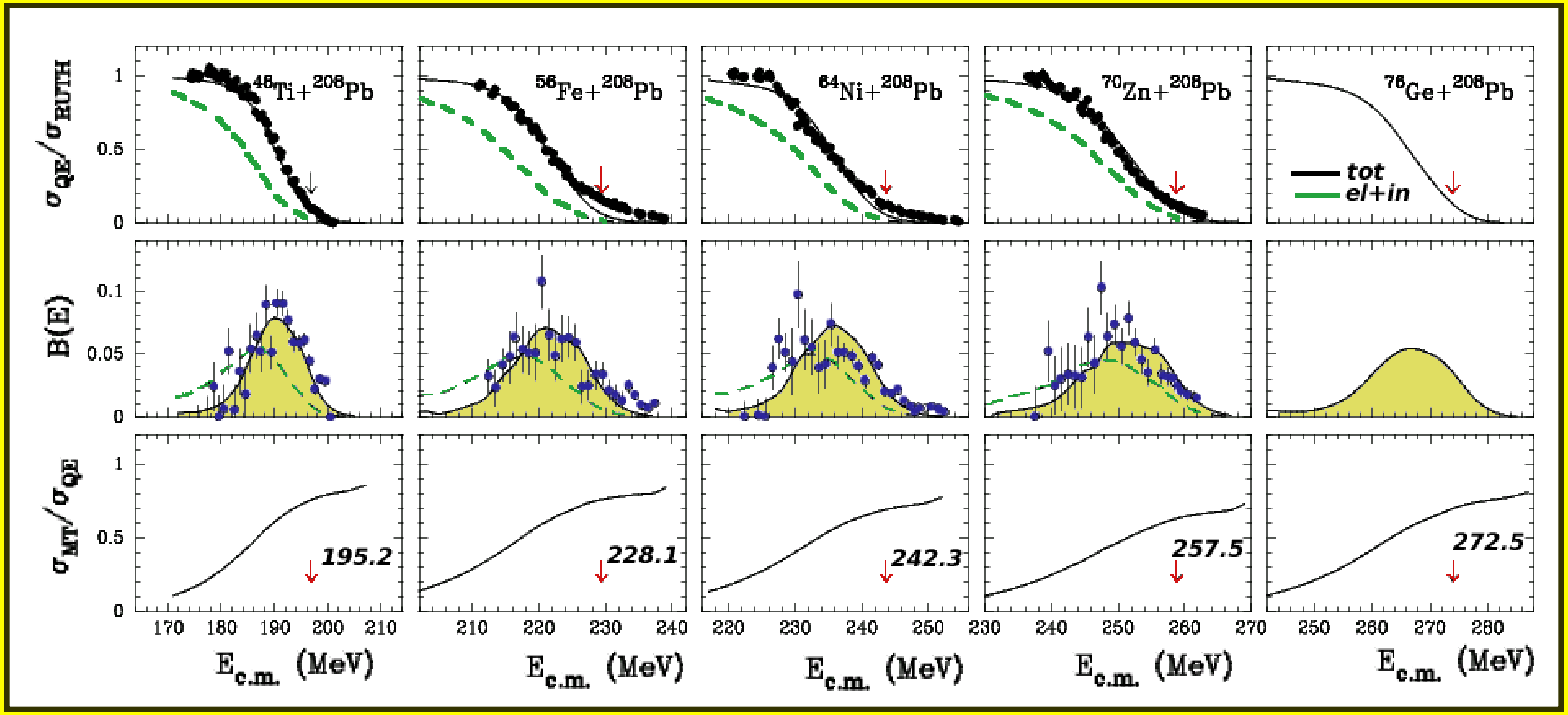


$^{206}Pb+^{116}Sn$ particle-γ data



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

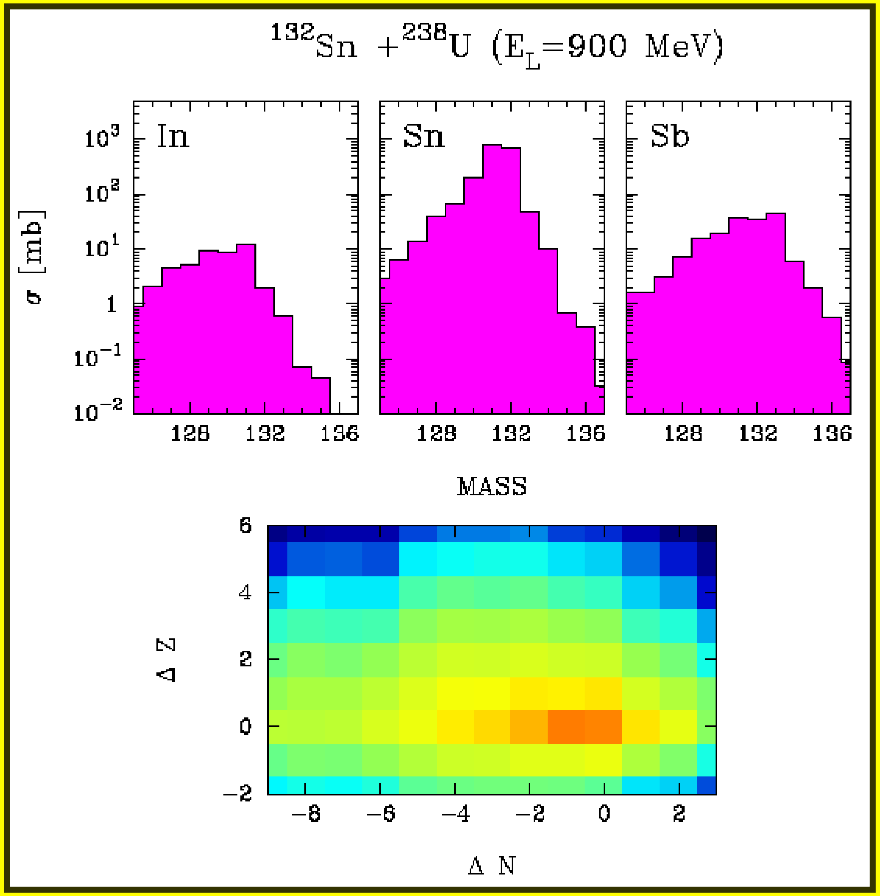
Quasielastic barrier distributions : role of particle transfer channels



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

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

Multinucleon transfer reactions with neutron-rich beams



GRAZING code calculations

possibility to populate nuclei via pick-up and stripping of both neutrons and protons

probing (nn), (pp) and (np) correlations. Important for studies on pairing vibrations/rotations, nuclear superfluidity

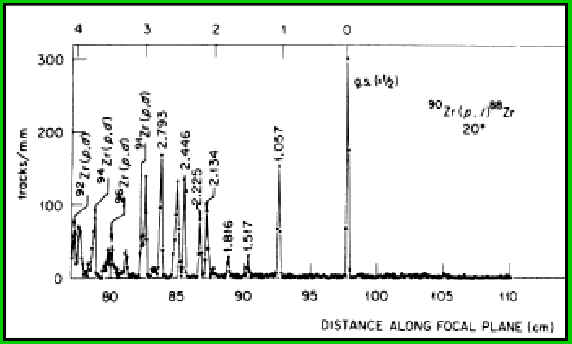
production of neutron rich isotopes

C.H.Dasso, G.Pollarolo, A.Winther, PRL73(1994)1907

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)

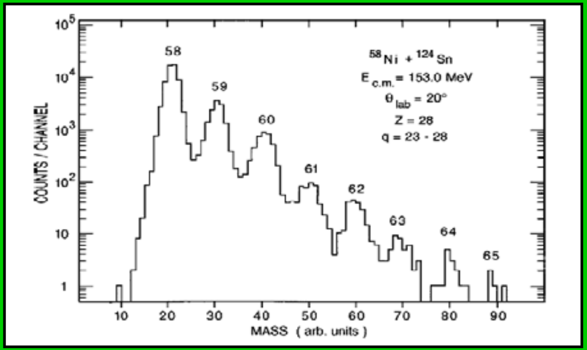


single particle levels (shell model)

nucleon-nucleon correlations (pair transfer)

3-5 msr

80's - 90's — Heavy ions spectrometers



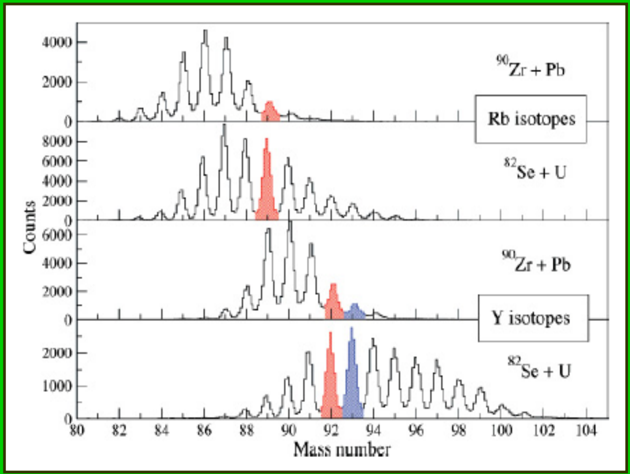
A,Z yields

cross sections

Q-value distributions

5-10 msr

recent years — Tracking spectrometers

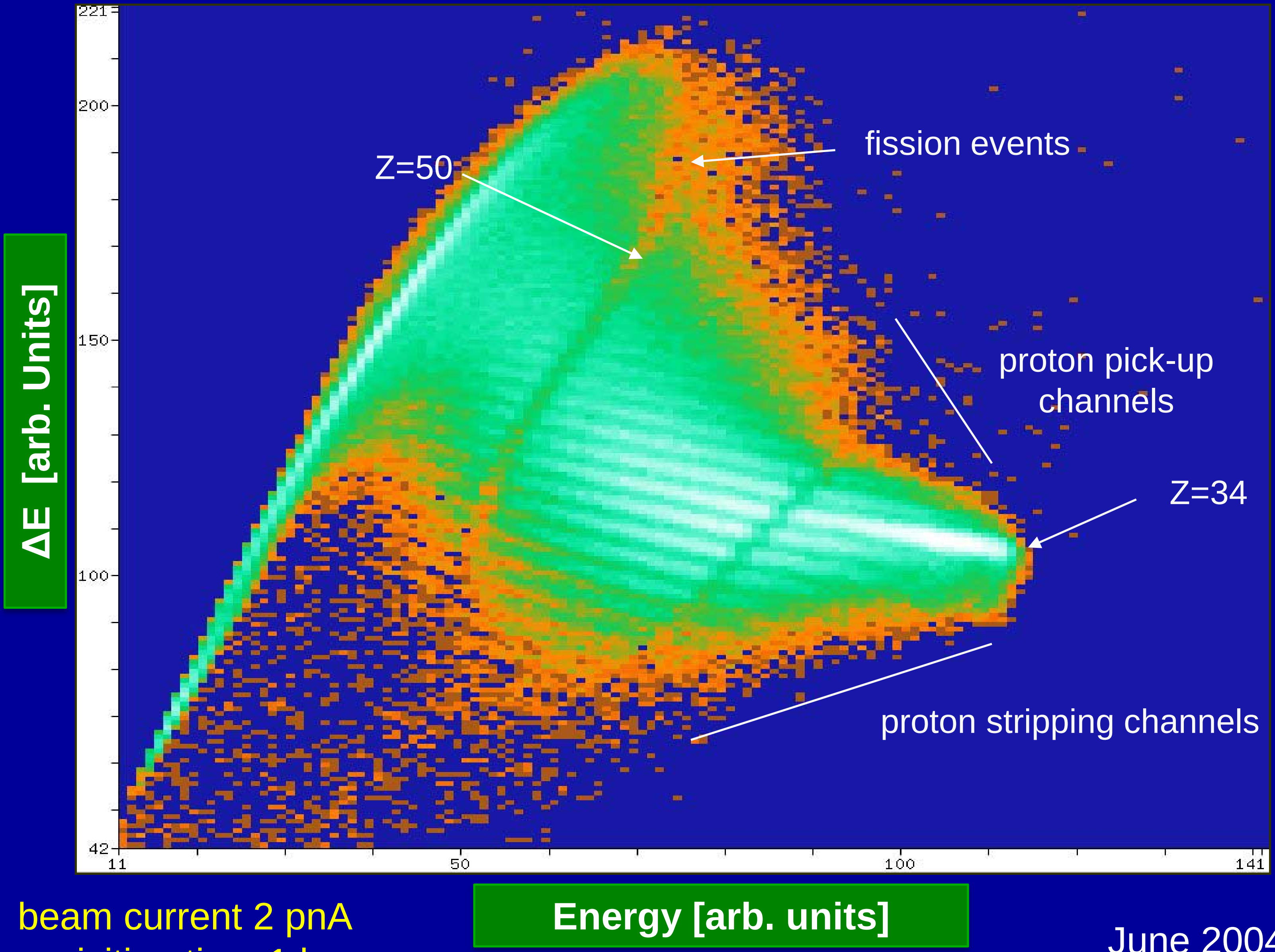


Reaction mechanism

Gamma spectroscopy

80-100 msr

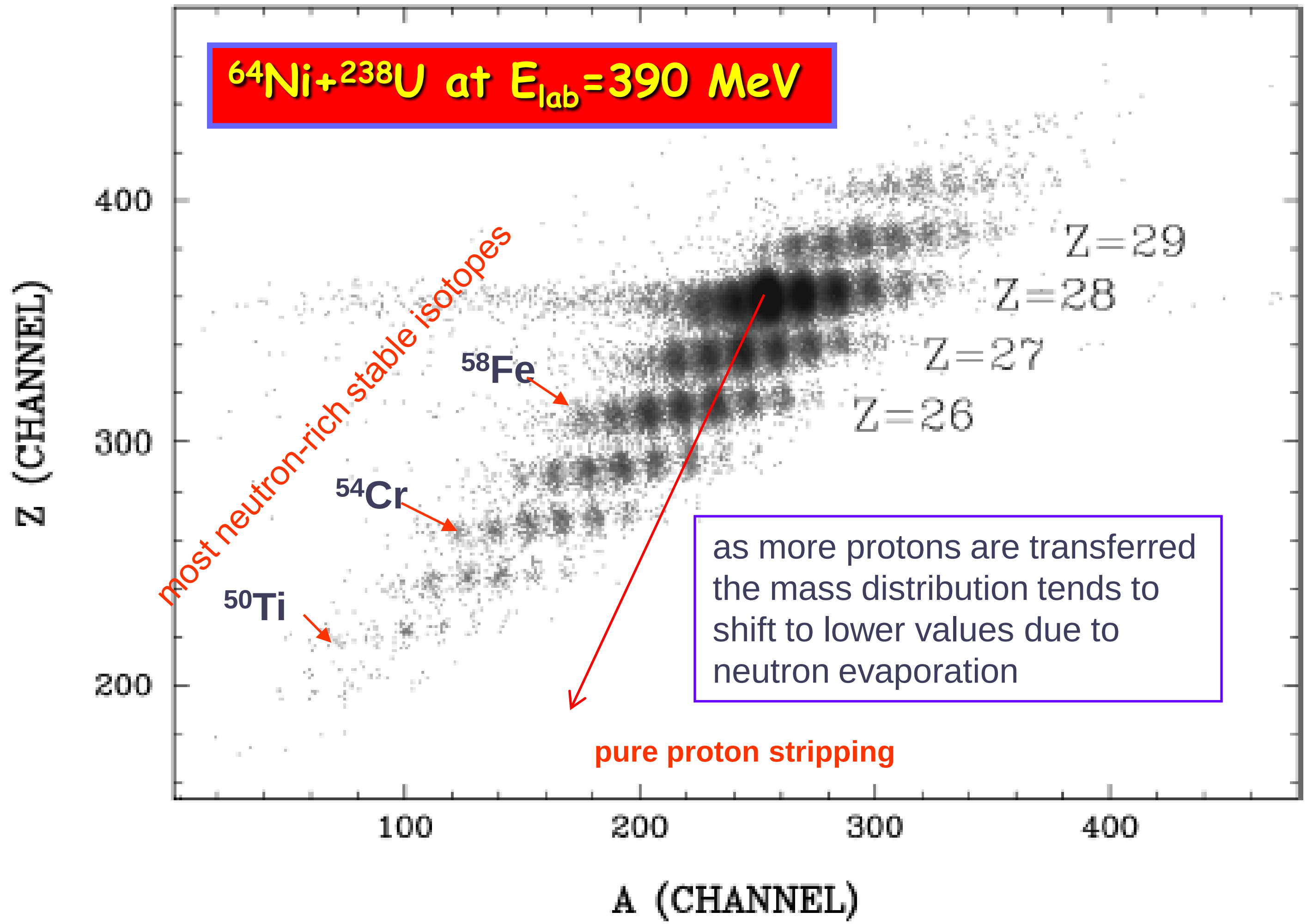
DE – E matrix in $^{82}Se+^{238}U$ at E_{lab}=505 MeV, θ_{lab} = 64°



beam current 2 pnA
acquisition time 1 hour

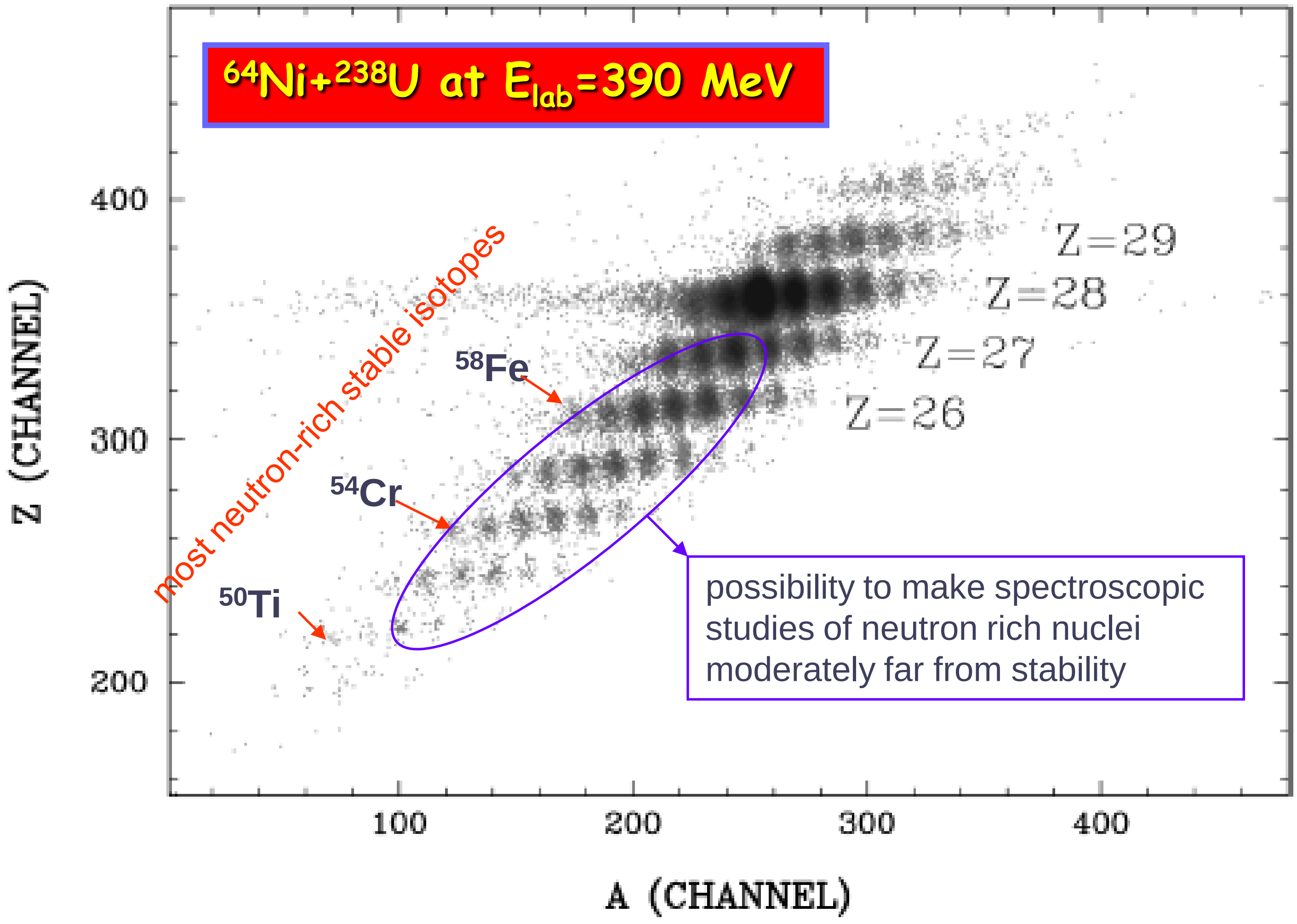
June 2004

Population of neutron rich nuclei : point of view of reaction mechanism



L.Corradi et al, Phys.Rev.C59(1999)261

Population of neutron rich nuclei : point of view of nuclear spectroscopy



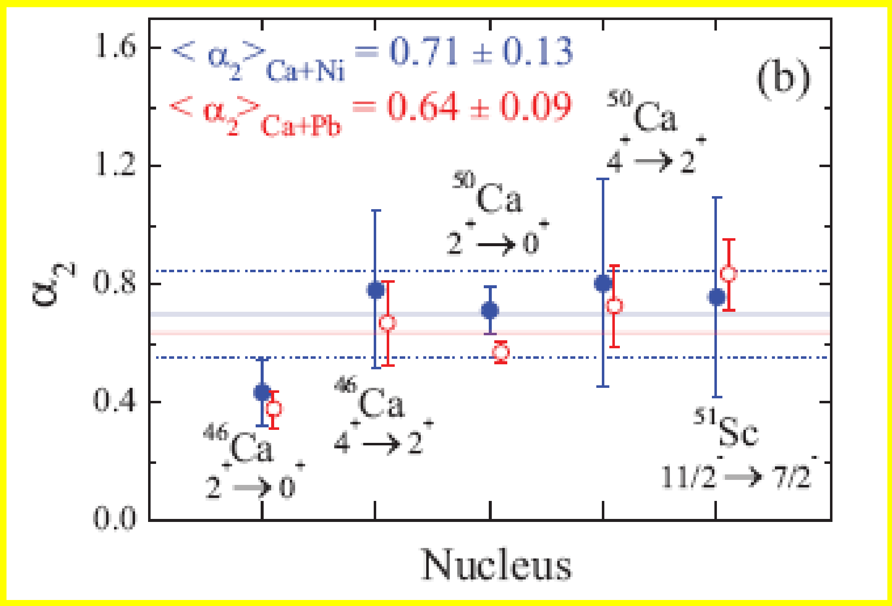
L.Corradi et al, Phys.Rev.C59(1999)261

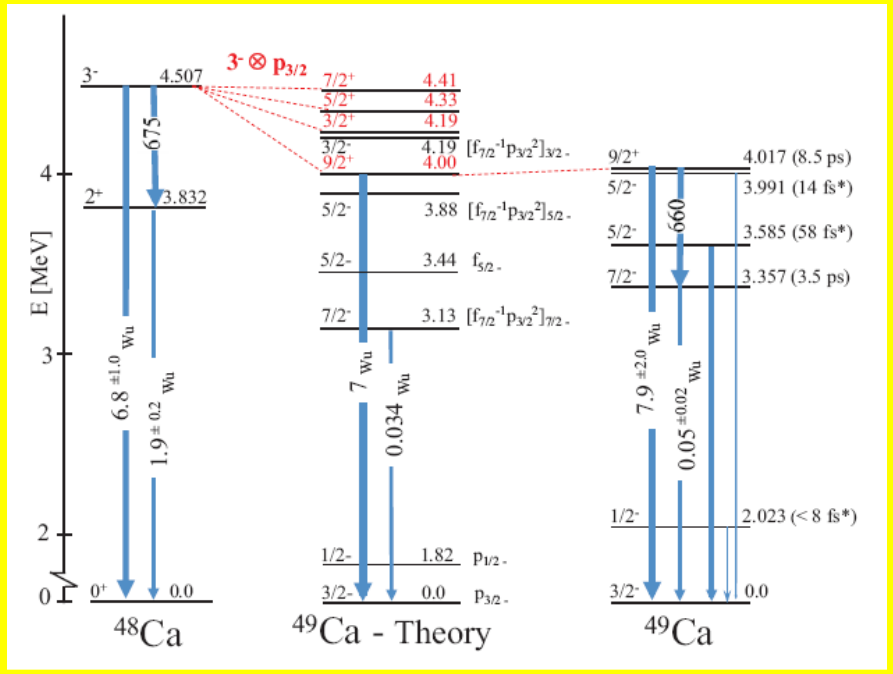
spin alignments in $^{48}Ca+^{64}Ni$ and $^{48}Ca+^{208}Pb$ mnt reactions

mnt reactions produce a large degree of spin alignment, which allows to study decay properties of populated states

positive parity states obtained within the particle-vibration model employing the SkX Skyrme interaction

fraction of full spin alignment

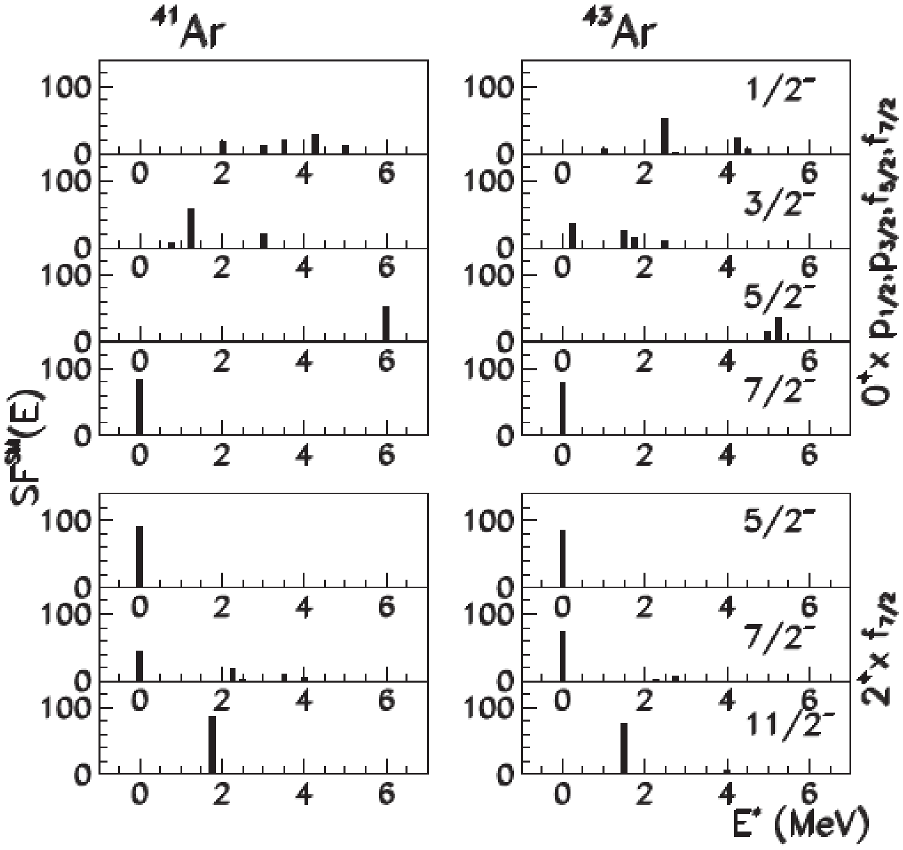




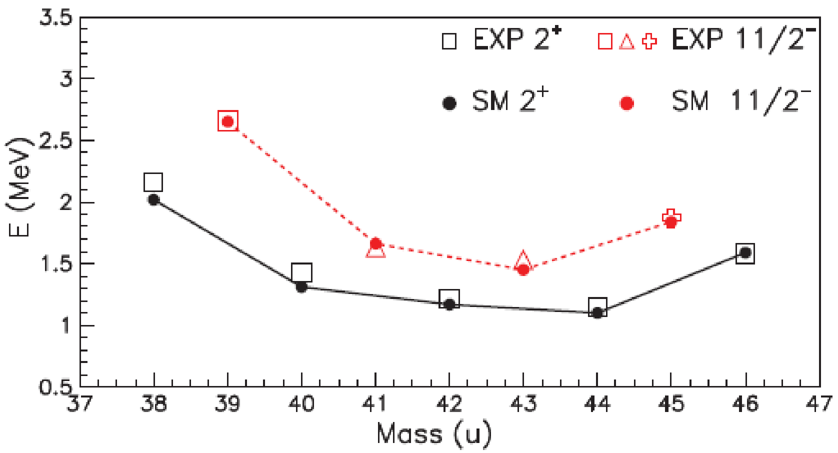
D.Montanari et al, PRC85(2012)044301

single particle and collective excitations studied in $^{40}Ar+^{208}Pb$ multinucleon transfer reactions

strength functions extracted from data and compared with SM calculations



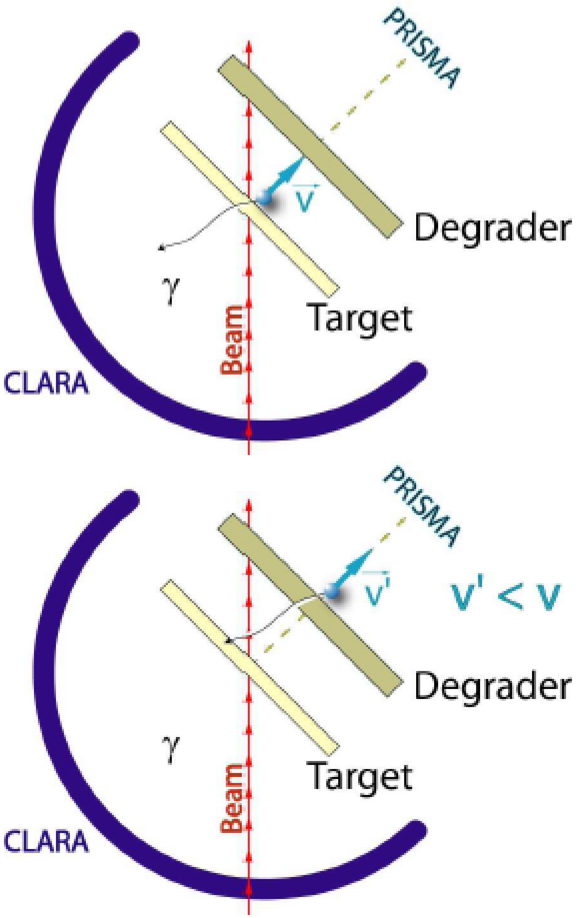
the structure of 11/2⁻ states in odd Ar isotopes matches a stretched configuration of the valence neutron coupled to the vibration quanta

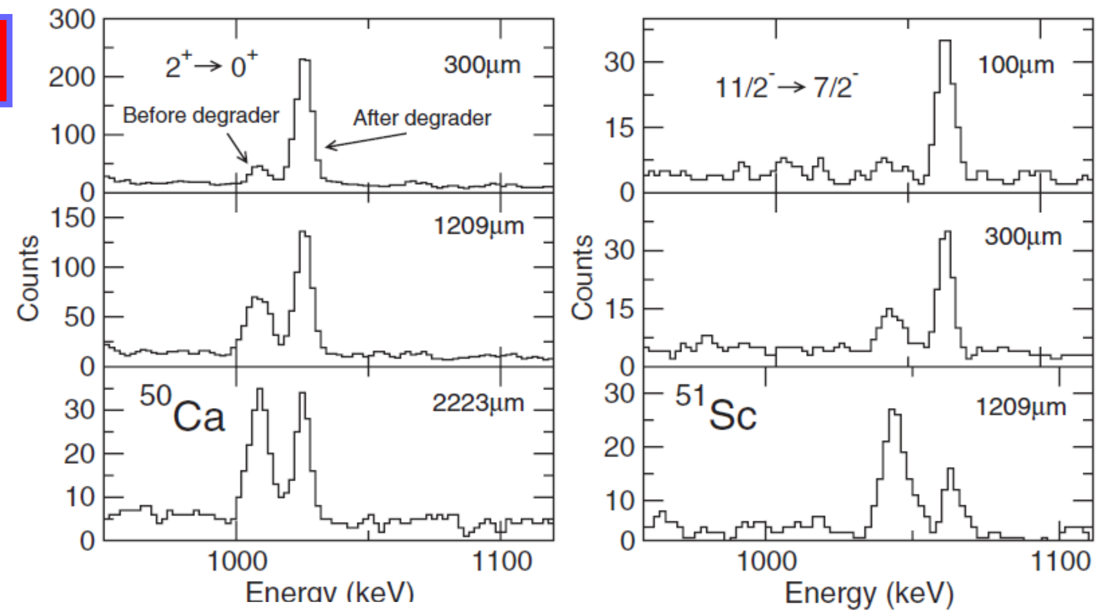


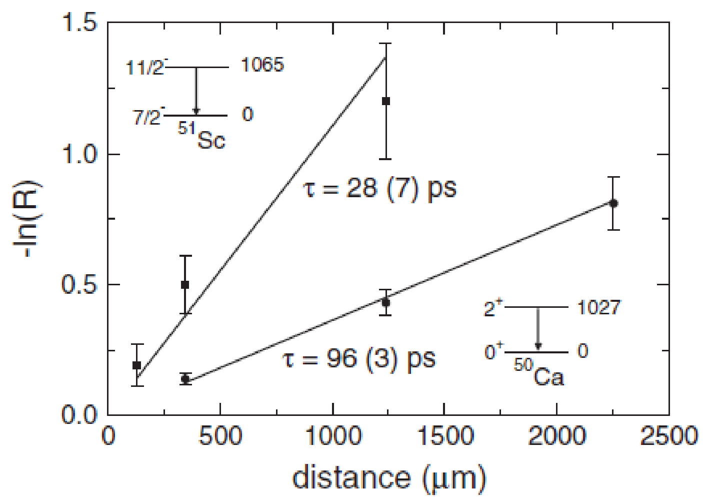
S.Szilner et al, PRC84(2011)014325

Lifetimes measurements in $^{48}Ca+^{208}Pb$ at E_{lab}=310 MeV

Differential Plunger Method



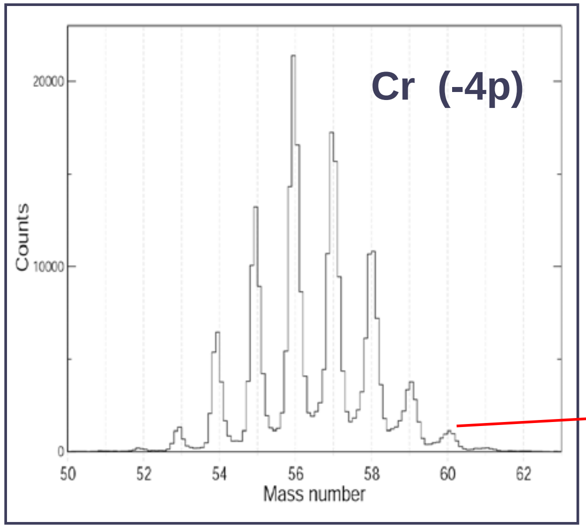


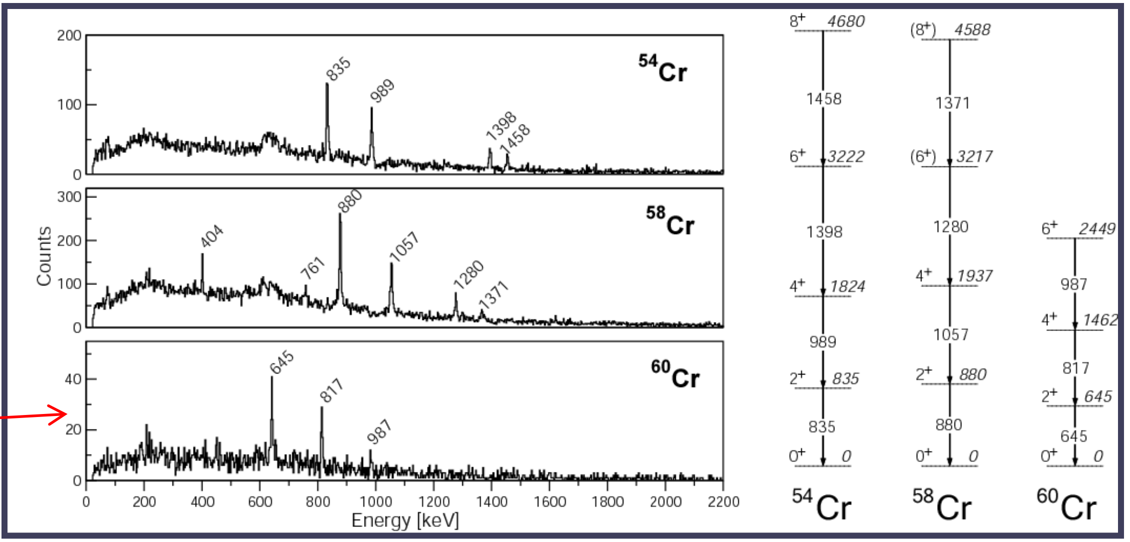


comparison of deduced B(E2) with large scale shell model calculations

J.J.Valiente-Dobon et al, PRL102(2009)242502

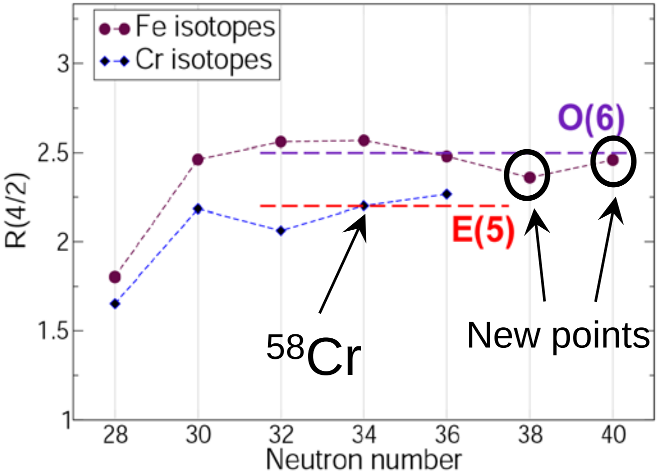
Gamma softness in heavy Cr and Fe isotopes populated in $^{64}Ni+^{238}U$ at E_{lab}=404 MeV





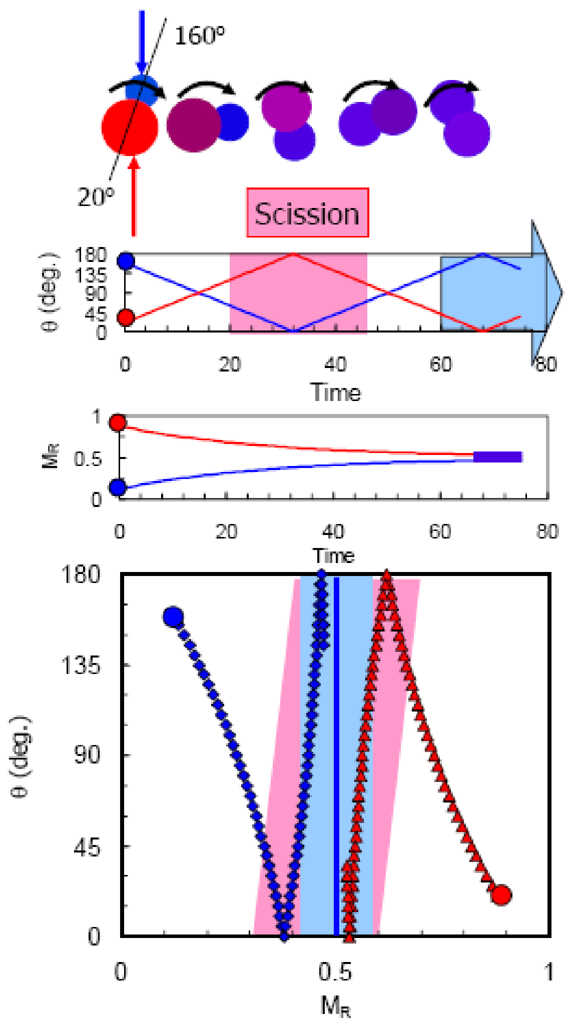
N.Marginean et al., Phys. Lett. B 633(2006)696

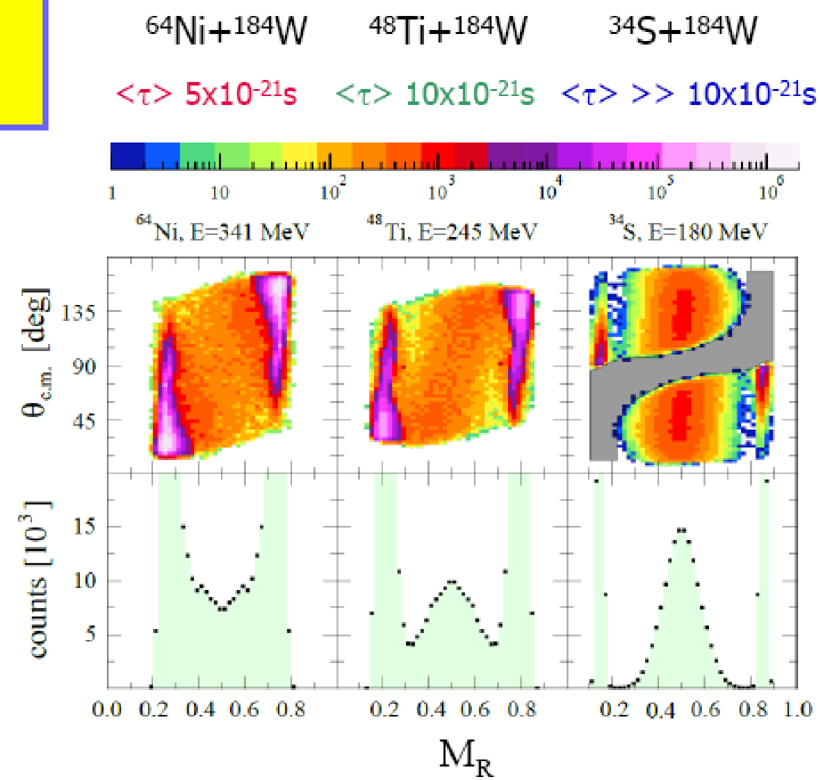
dynamical symmetries

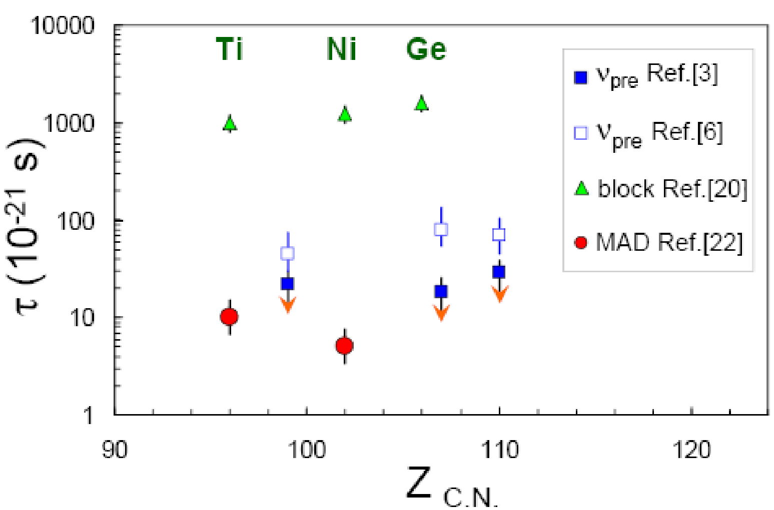


- The R(E_4/E_2) ratio for the heavy Fe isotopes is very close to the 2.50 value characteristic of γ-soft rotors
- The value for the heavier Cr isotopes is also close to the same limit
- ^{58}Cr lies exactly at the 2.20 value predicted for the E(5) dynamical symmetry. The energies of the yrast band are in good agreement with the predictions of this symmetry. Transition probabilities are essential to decide whether ^{58}Cr lies or not at the E(5) critical point.

QF time scales derived from mass-angle correlation measurements

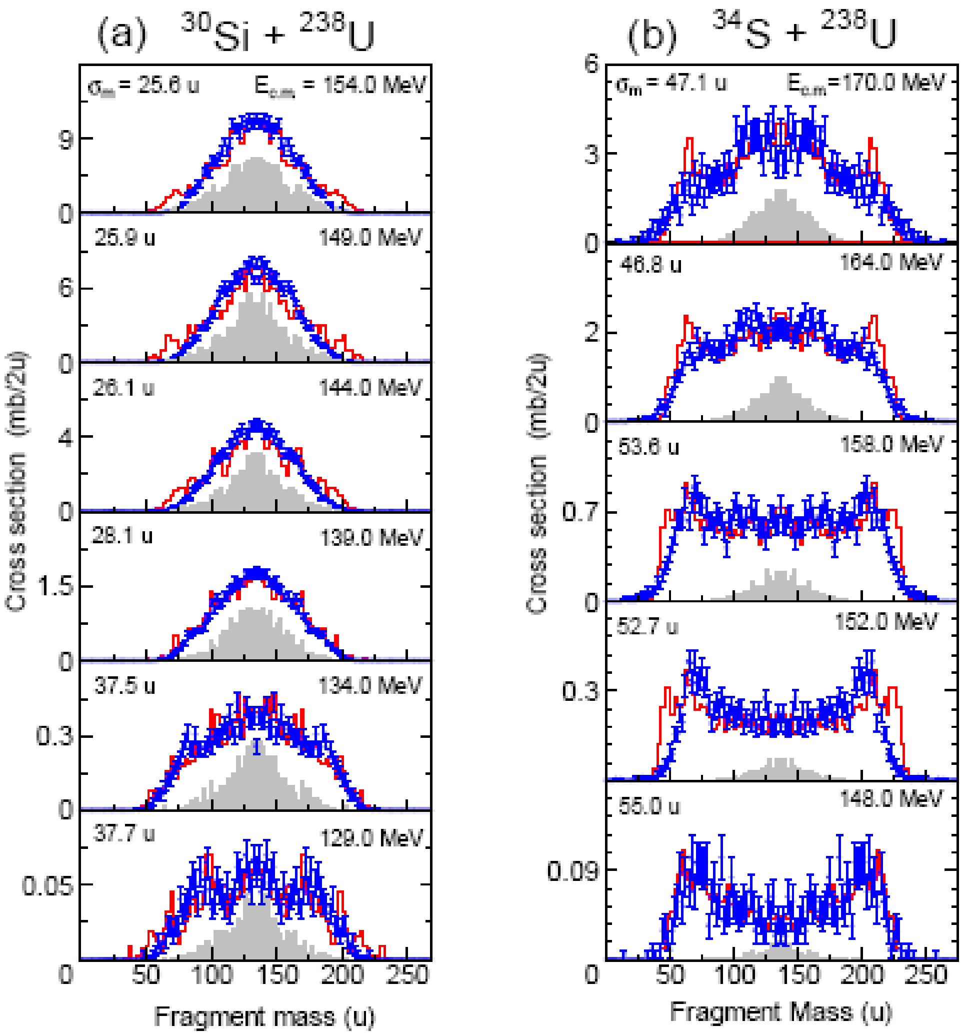


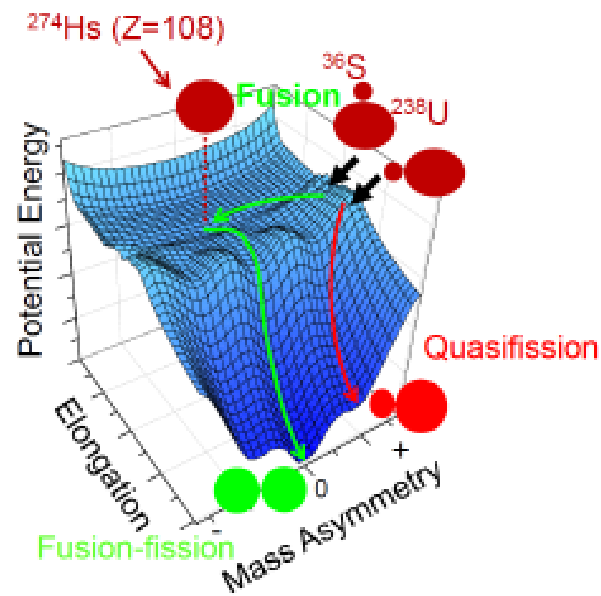




D.Hinde, Fusion11, St.Malo' 2011

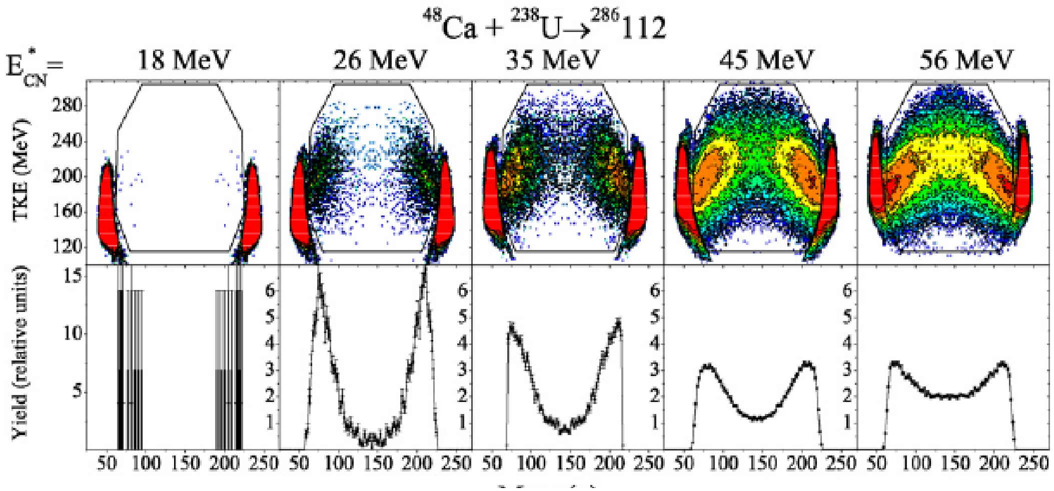
Energy dependence of quasi fission components in reactions with ^{238}U targets



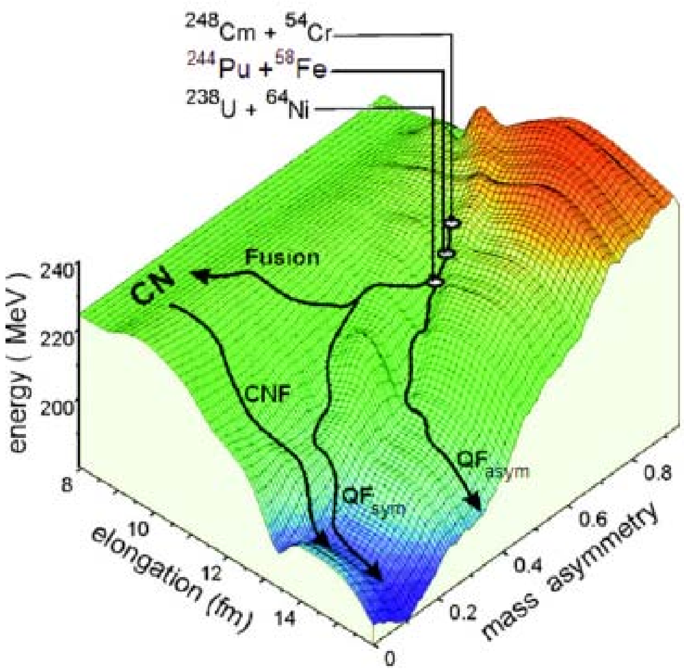


K.Nishio et al, Fusion11, St.Malo' 2011

Quasi-fission processes



integral measurements presently studied to understand the production of heavy and superheavy elements



E.Kozulin et al, PLB686(2010)227

WITH HIGH INTENSITY BEAMS

employing magnetic spectrometers one can make high resolution studies (details of Z,A,Q-value distributions)

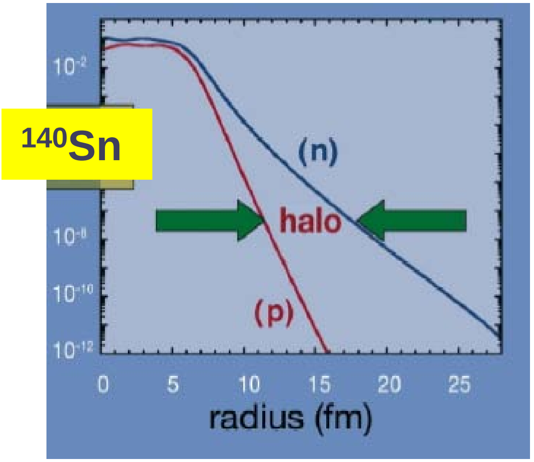
one can use “cold fission” mechanisms to populate very neutron rich nuclei (via transfer induced fission or quasi-fission)

Multinucleon transfer reactions with radioactive beams

Do the degrees of freedom and the corresponding matrix elements tested with stable beams hold with RIBs ?

Do the form factors for one and two particle transfer and their strength need to be modified with RIBs ?

modification of nn correlations (neutron rich nuclei)



neutron-proton correlations (proton rich nuclei)