Reaction mechanism at the Coulomb barrier

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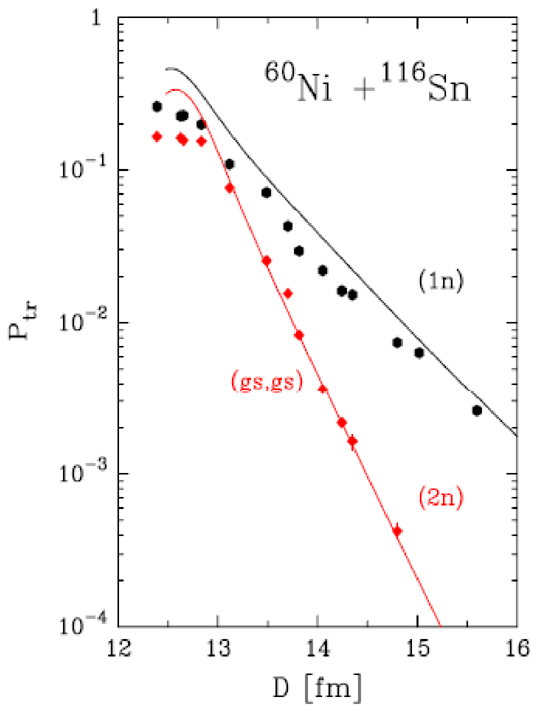
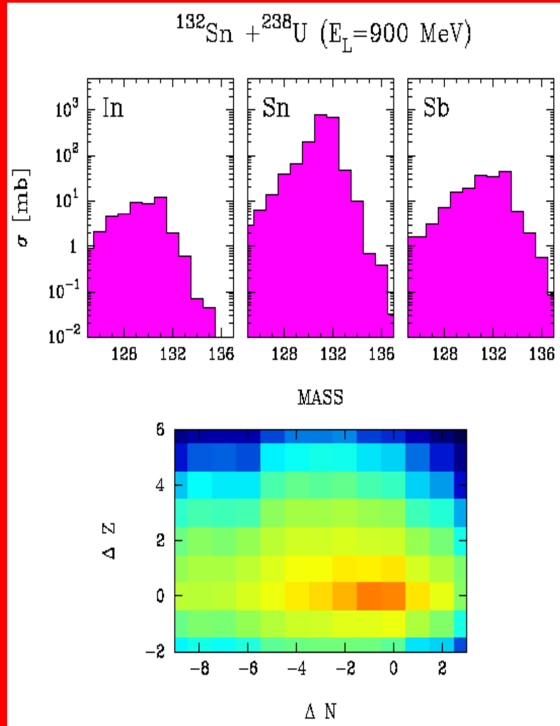
ECOS 2014, Orsay,
28-29/10/2014

Selected reaction mechanism issues for ECOS

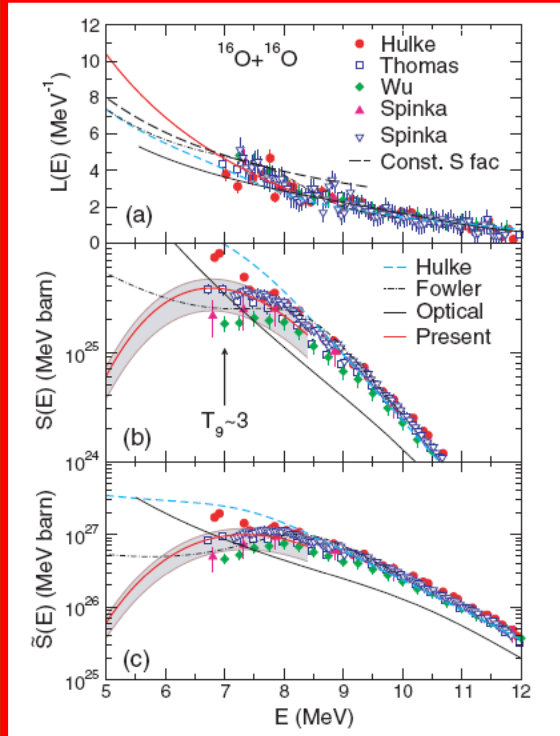
Sub barrier transfer reactions, study of nucleon-nucleon correlations



Heavy products produced via multinucleon transfer, study of secondary processes



Near and sub barrier fusion reactions, study of the hindrance phenomenon



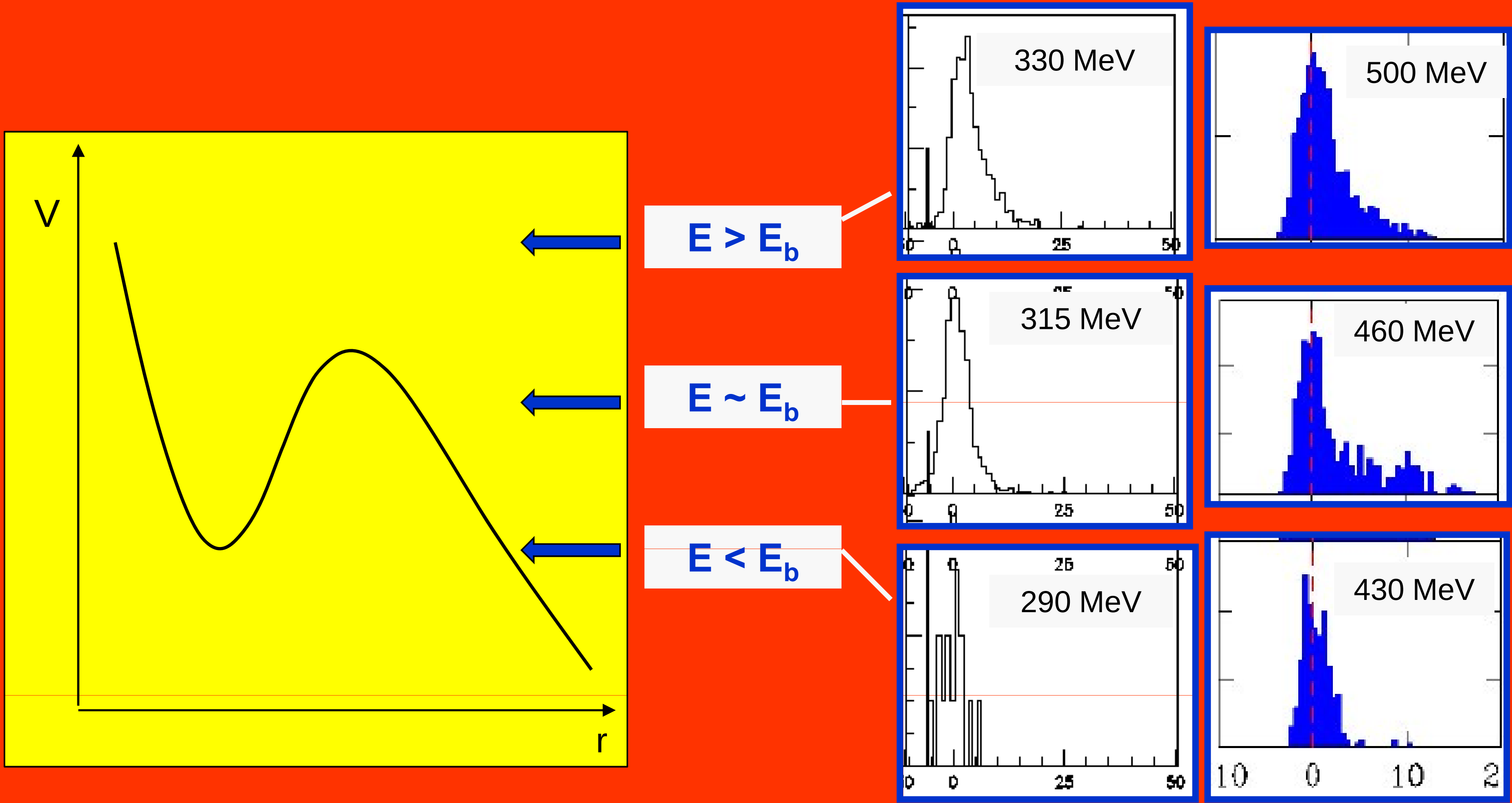
one could benefit from the use of high intensity beams (I_{beam} > 10 pμA)

Sub barrier transfer

A smooth transition between QE and DIC processes

$^{96}Zr(^{40}Ca,^{42}Ca)$ $Q_{gs} = +5.6$ MeV

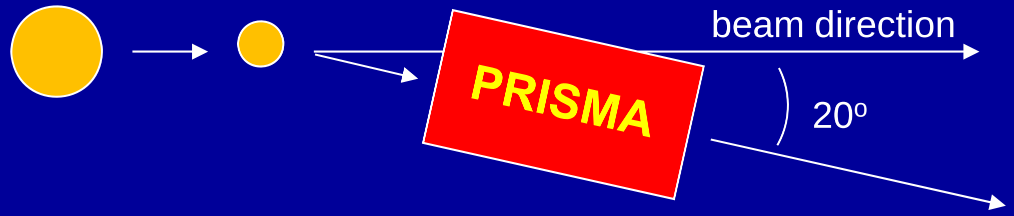
$^{116}Sn(^{60}Ni,^{62}Ni)$ $Q_{gs} = +1.3$ MeV



Below the barrier Q-values gets very narrow and without DIC components

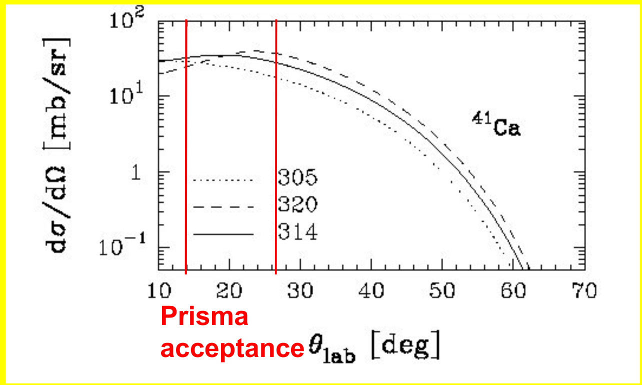
Detection of (light) target like ions in inverse kinematics with PRISMA

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

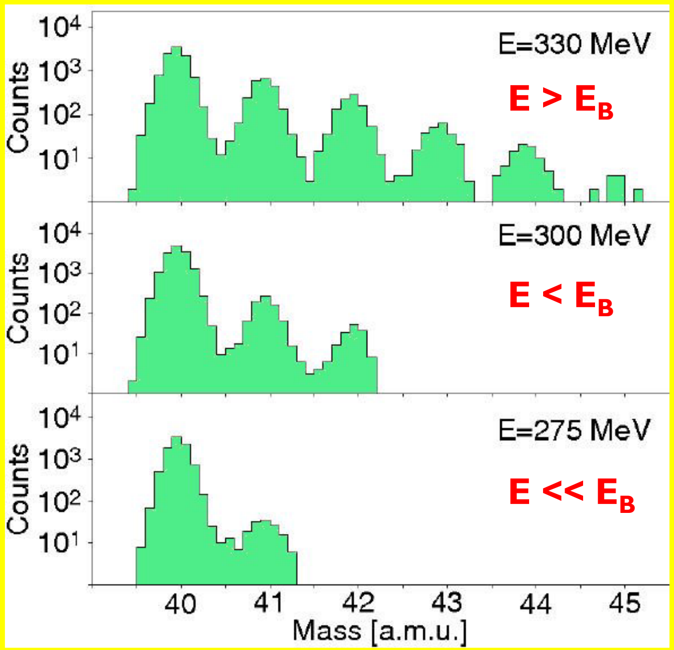


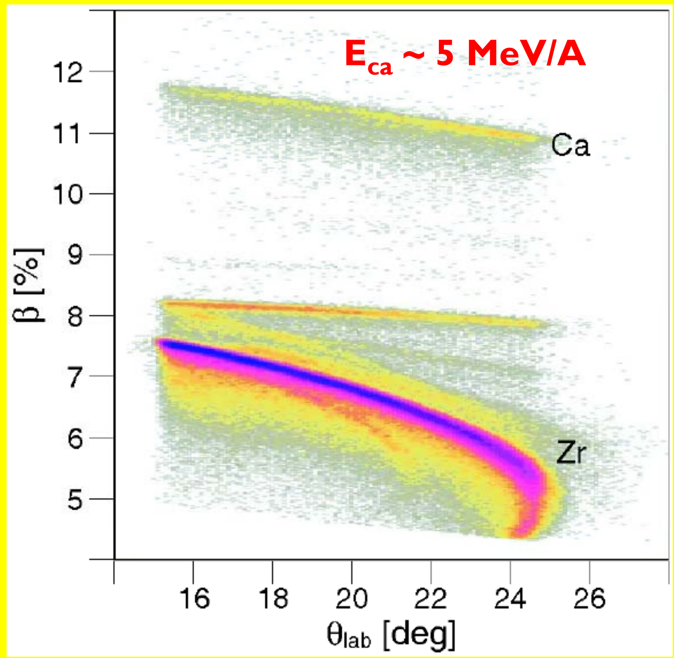
^{116}Sn ^{60}Ni **D.Montanari et al, PRL113(2014)052501**

^{92}Mo ^{54}Fe **S.Szilner et al, exp April 2013**

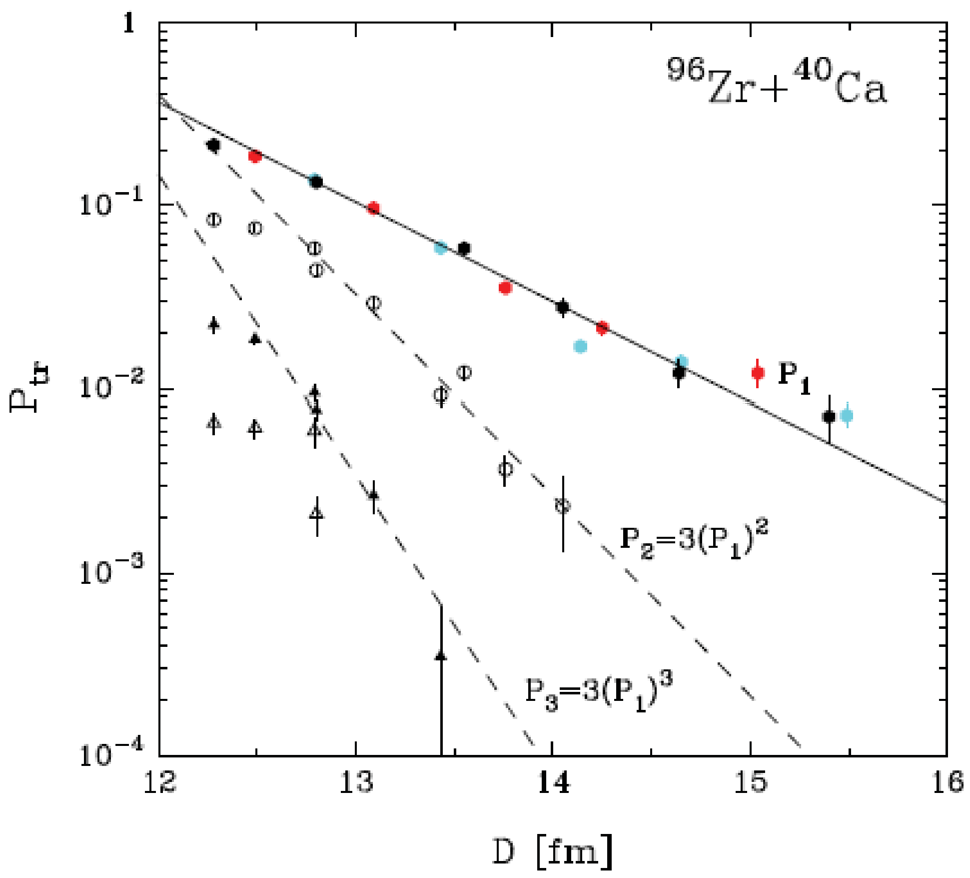


MNT channels have been measured down to 25 % below the Coulomb barrier





Experimental transfer probabilities



P_{tr} slope

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

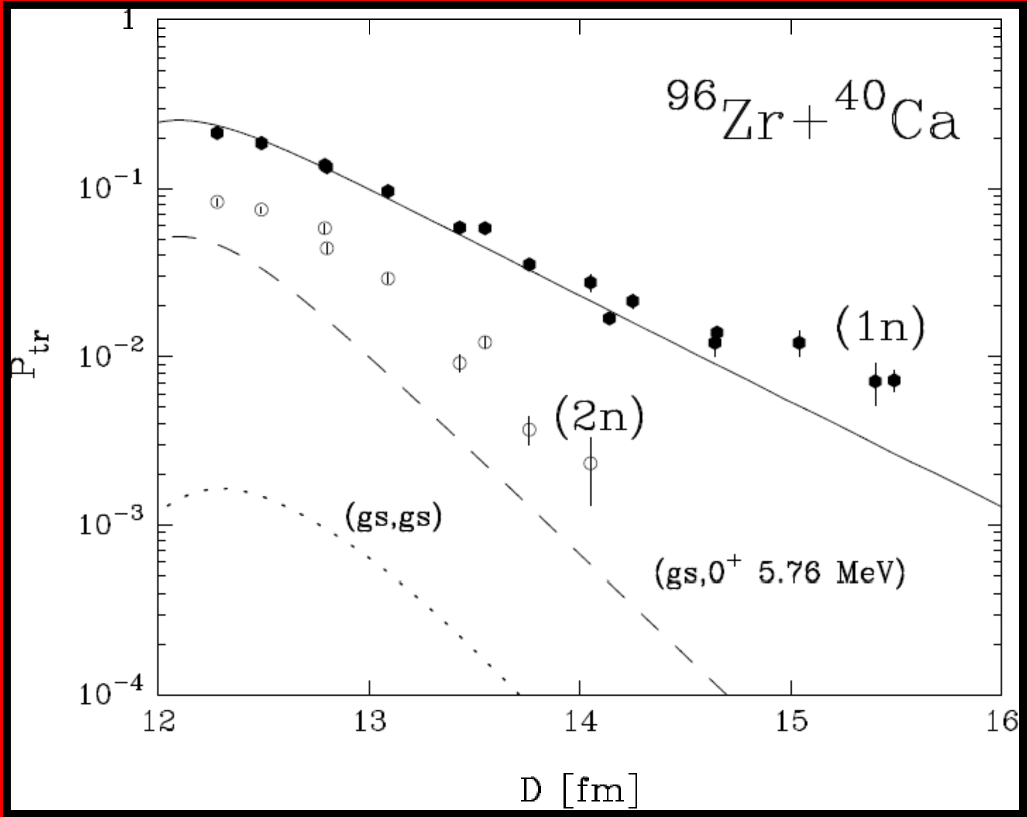
B → binding energy

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

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

L.Corradi et al, PRC84(2011)034603

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

Neutron pair transfer in $^{60}Ni + ^{116}Sn$ far below the Coulomb barrier

PRL **113,** 052501 (2014) PHYSICAL REVIEW LETTERS week ending 1 AUGUST 2014

Neutron Pair Transfer in $^{60}Ni + ^{116}Sn$ Far below the Coulomb Barrier

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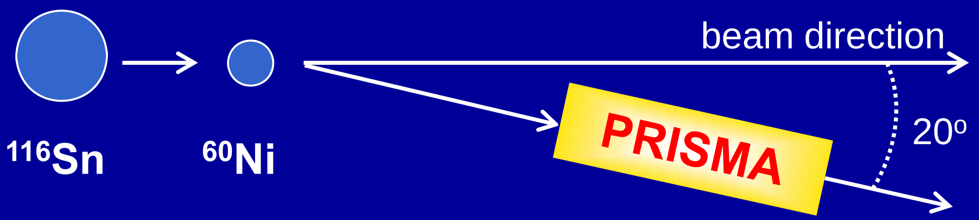
(Received 27 March 2014; published 29 July 2014)

An excitation function of one- and two-neutron transfer channels for the $^{60}Ni + ^{116}Sn$ system has been measured with the magnetic spectrometer PRISMA in a wide energy range, from the Coulomb barrier to far below it. The experimental transfer probabilities are well reproduced, for the first time with heavy ions, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon pairing correlations.

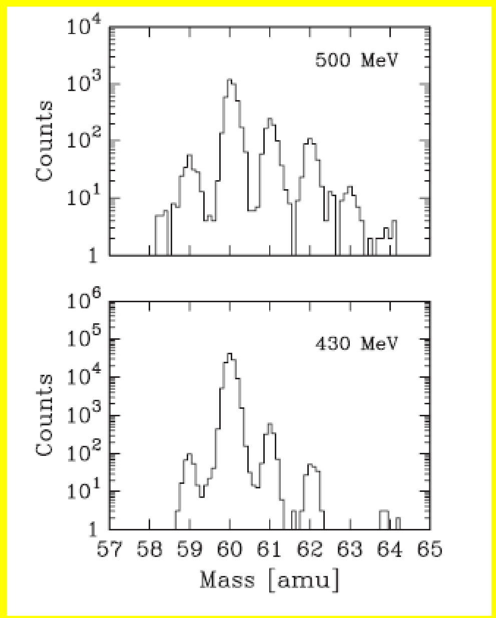
Detection of (light) target like ions in inverse kinematics with PRISMA

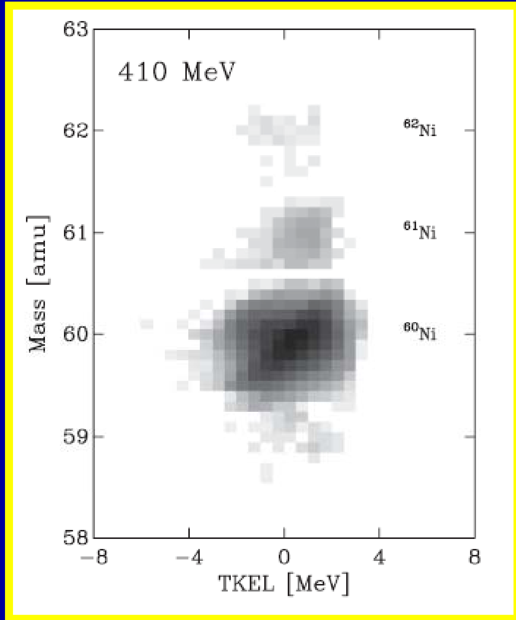


Excitation function

E_{beam} = 410 MeV – 500 MeV

(D ~ 12.3 to 15.0 fm)





Excellent mass resolution at energies below the Coulomb barrier

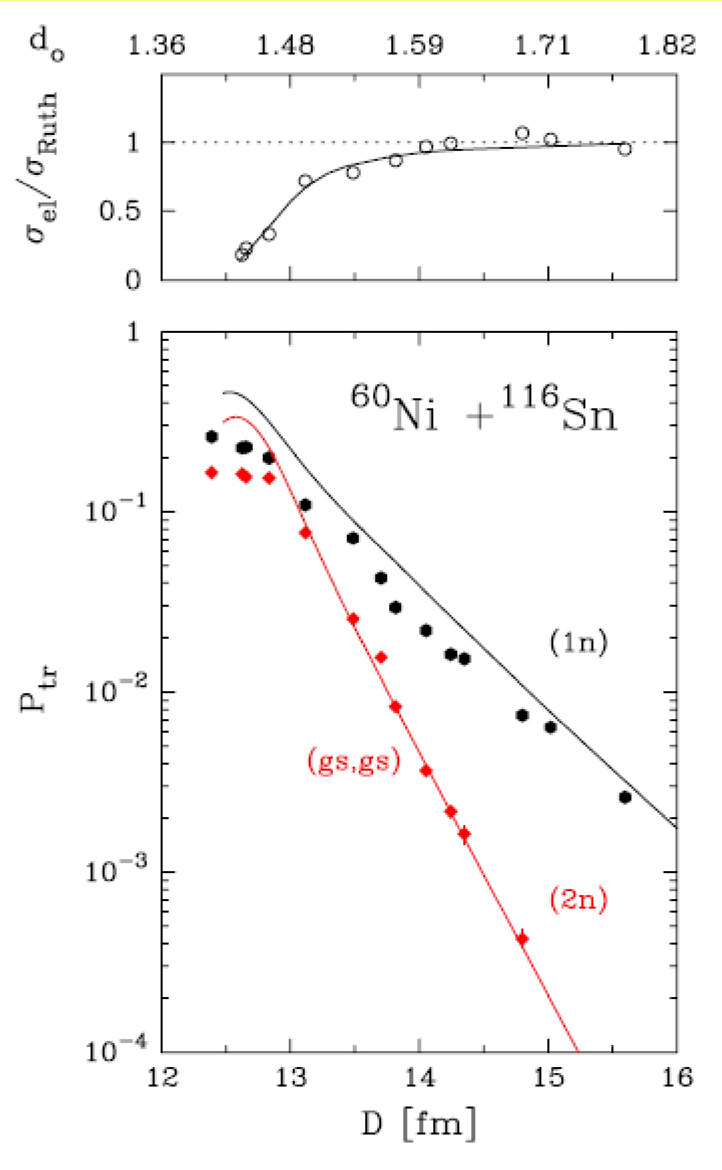
Excellent channel separation at D ~ 15 fm

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

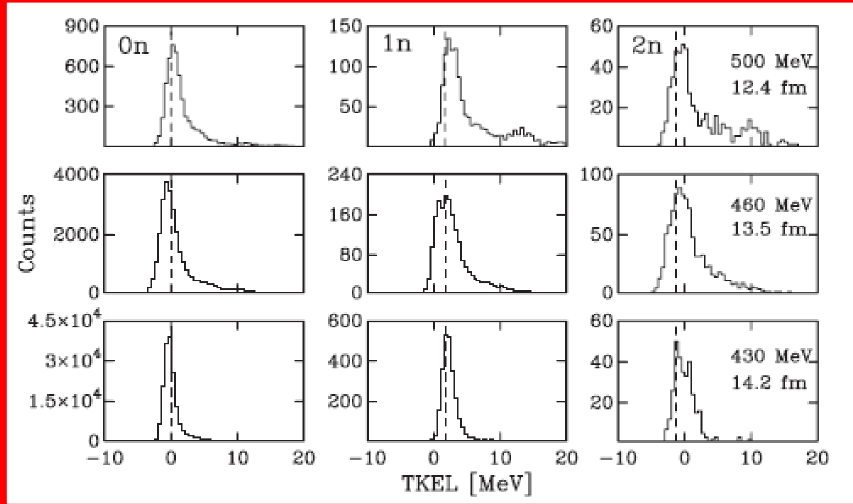
Q_{gs} much closer to Q_{opt} for $^{116}Sn+^{60}Ni$

D.Montanari et al., INPC2013 and PRL2014

Neutron pair transfer in $^{60}Ni+^{116}Sn$ far below the Coulomb barrier



Transfer strength very close to the g.s. to g.s. transitions



The experimental transfer probabilities are well reproduced, for the first time with heavy ion reactions, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon pairing correlations

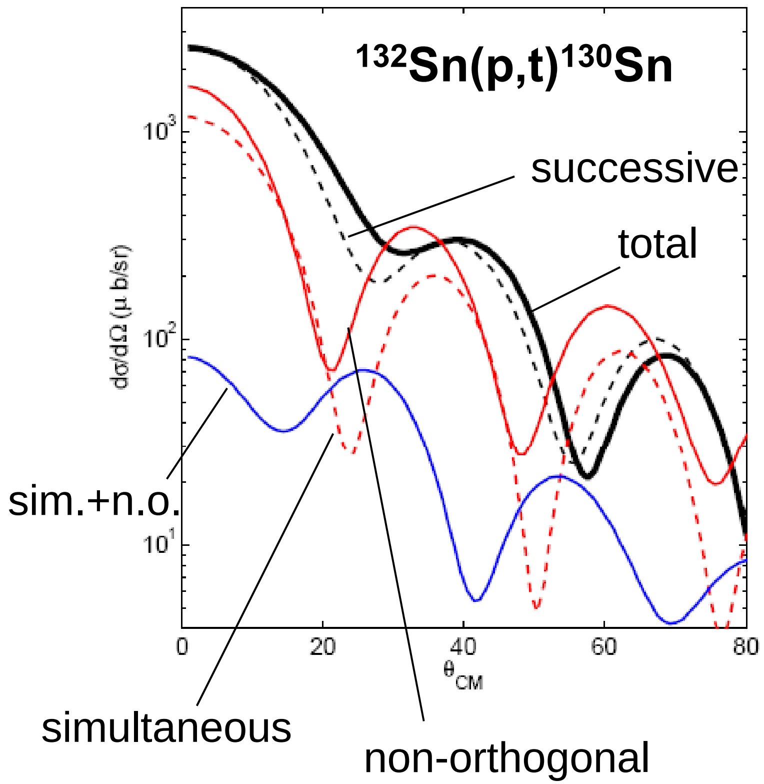
D.Montanari et al., PRL113(2014)052501

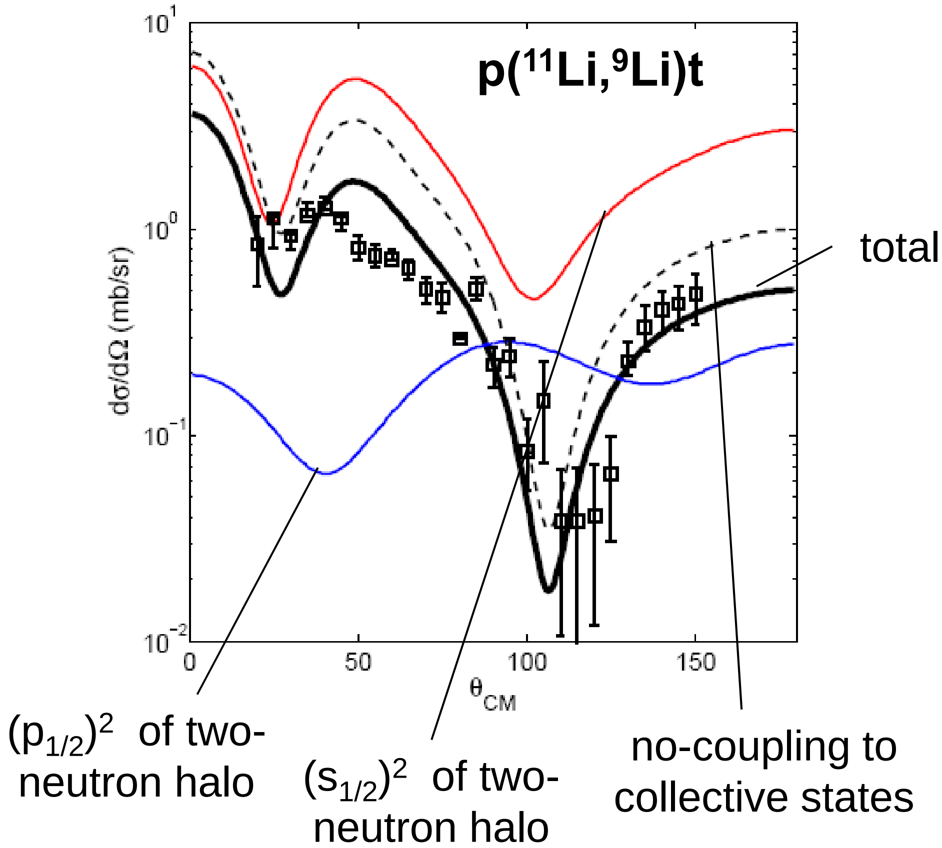
Pairing interaction in transfer reactions with light nuclei

calculations based on similar theory used for heavy ions

the successive term dominates

evidence of phonon mediated pairing interaction

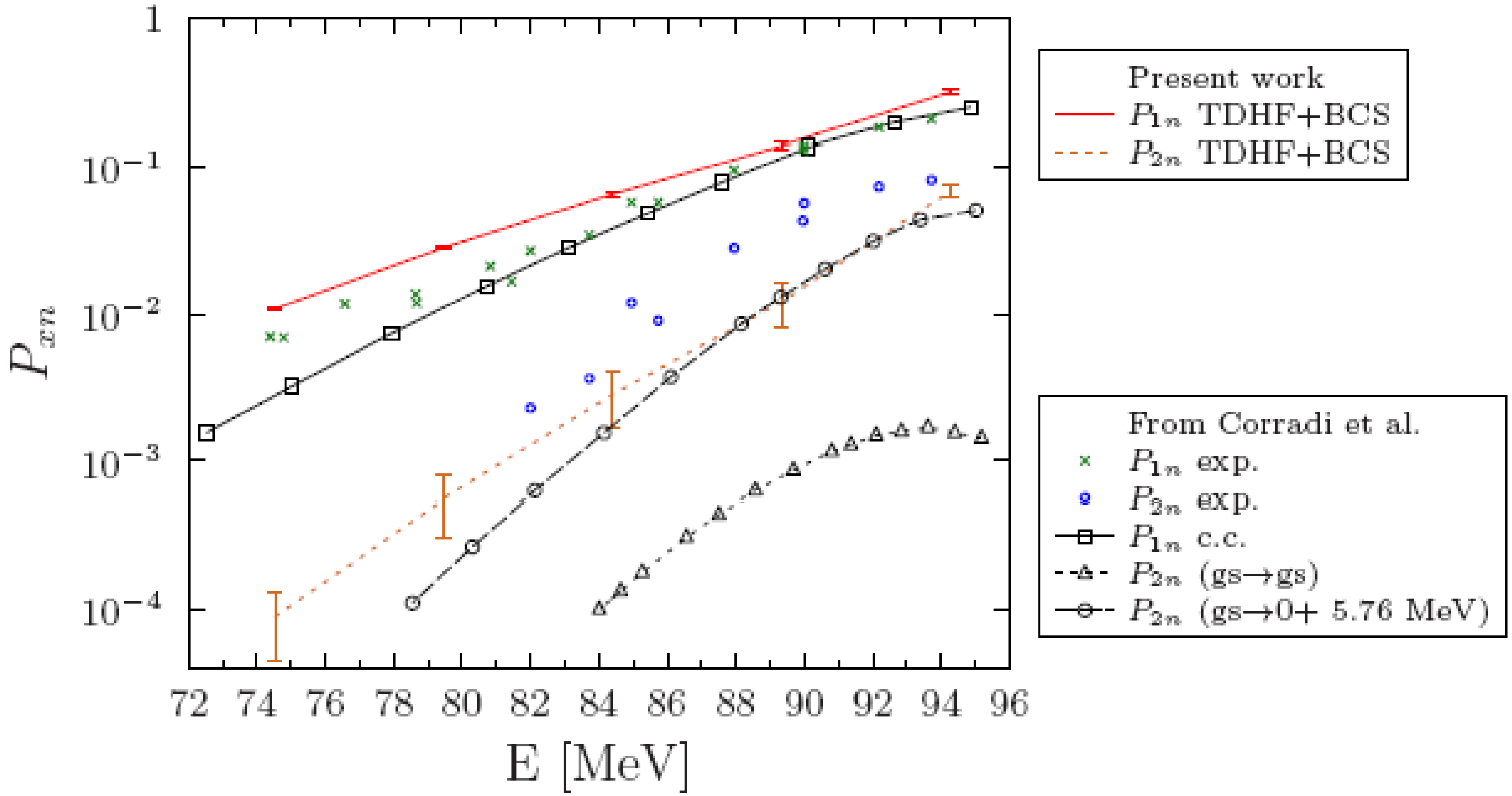




G.Potel et al, Fusion11 St.Malo' and PRL105(2010)172502

Sub-barrier transfer : TDHF+BCS

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



G.Scamps et al., ECT* Ws on Low Energy Dynamics and Exotic Nuclei – Trento, May 26-30, 2014

Sub-barrier transfer : where one could benefit from the use of high intensity beams

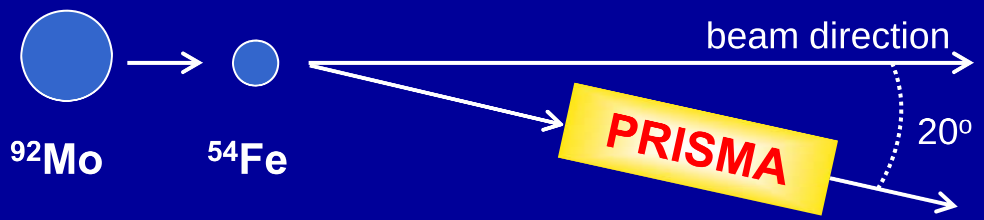
gamma-particle coincidences

multiple neutron pair transfer

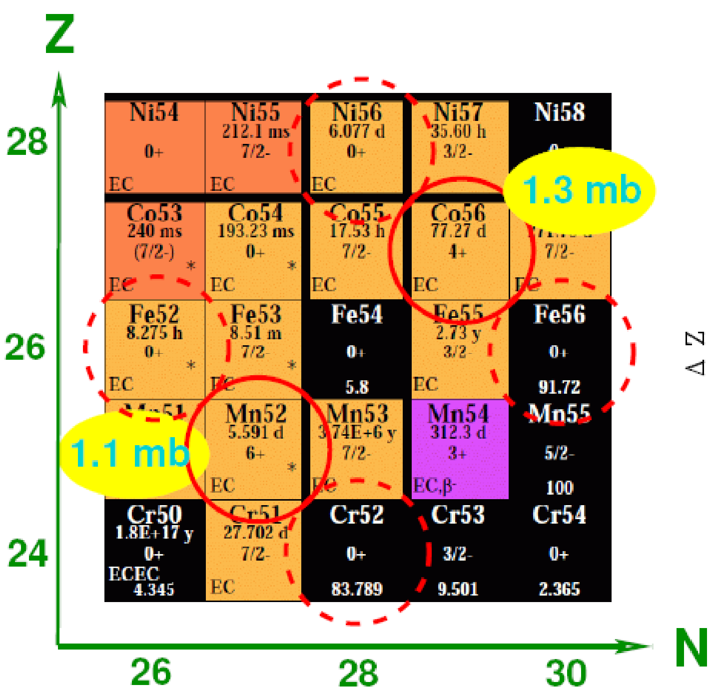
proton transfer channels at large D

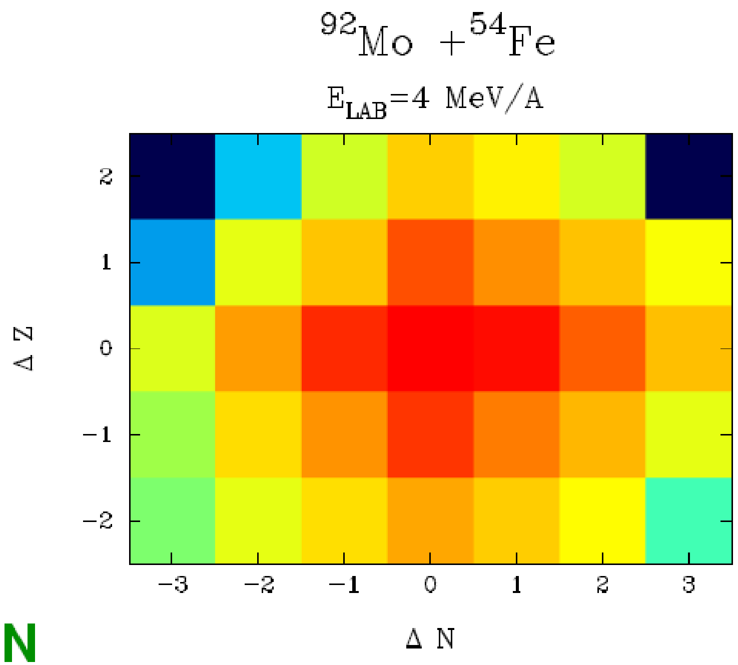
np transfer channels

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, T.Mijatovic et al, LNL exp April 2013

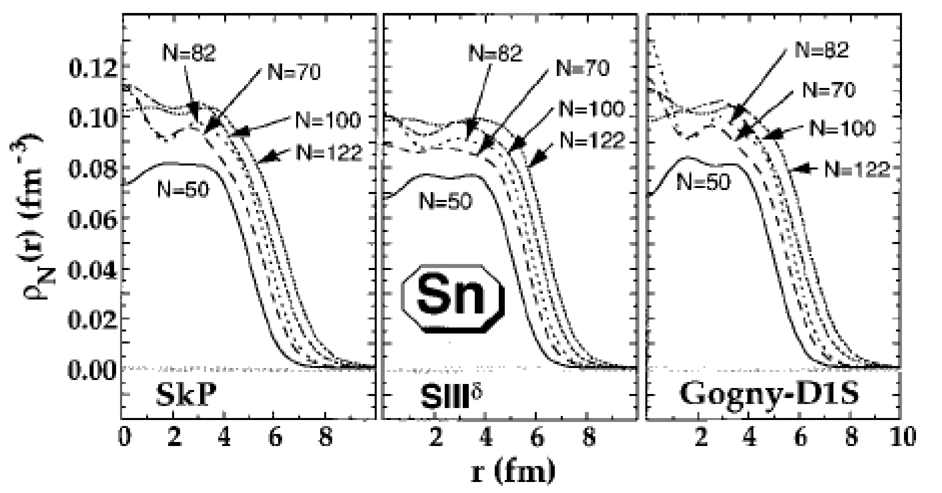
Sub-barrier transfer : neutron rich nuclei

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

- onset of density dependent forces

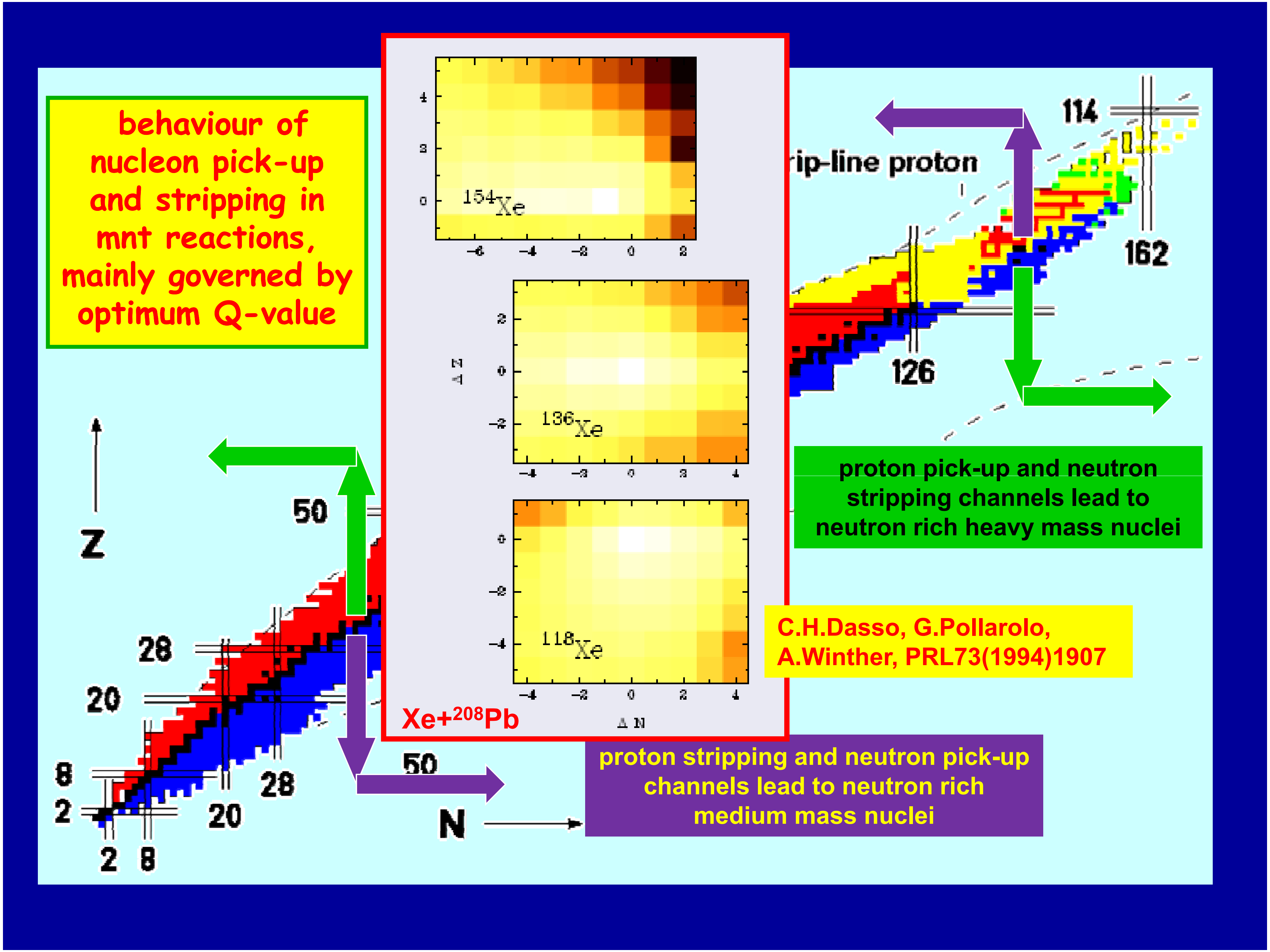
$$V_{eff} = \delta(\vec{r}_1 - \vec{r}_2)\Big(v_o + v_p\big(\frac{\rho((\vec{r}_1 + \vec{r}_2)/2)}{\rho_c}\big)^p\Big)$$

- neutron density profile



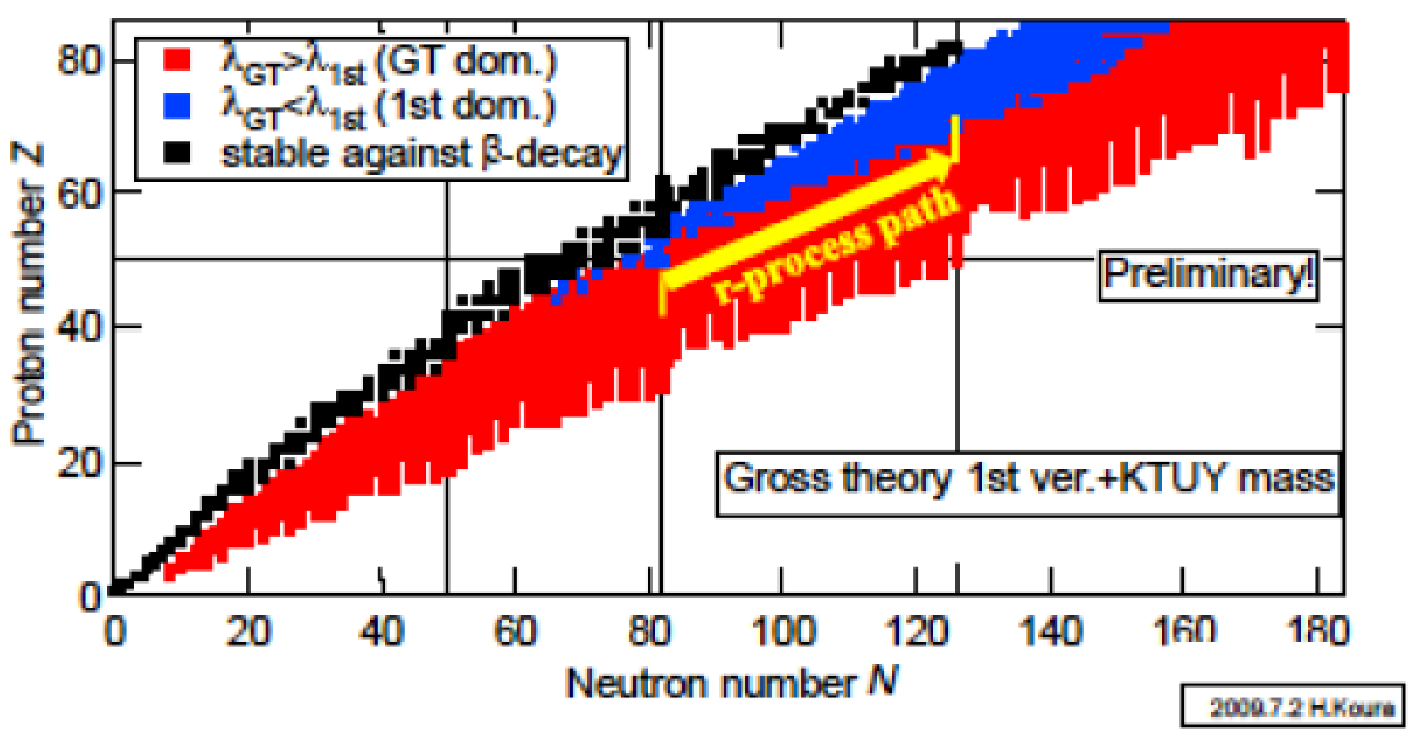
J.Dobaczewski et al., PRL72(1994)981

Study of "heavy partner" products



behaviour of nucleon pick-up and stripping in mnt reactions, mainly governed by optimum Q-value
154Xe
136Xe
118Xe
Δ Z
Δ N
Xe+208Pb
rip-line proton
114
162
126
50
28
20
8
2
proton pick-up and neutron stripping channels lead to neutron rich heavy mass nuclei
C.H.Dasso, G.Pollarolo, A.Winther, PRL73(1994)1907
proton stripping and neutron pick-up channels lead to neutron rich medium mass nuclei
Z
N

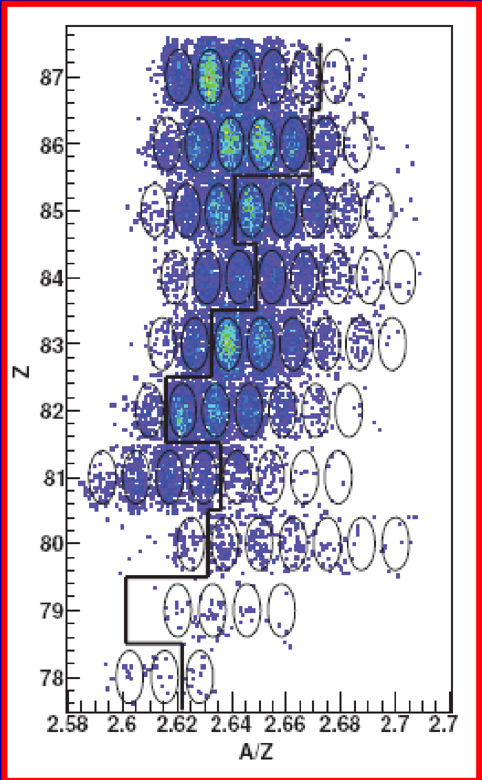
r-processes and the importance of N=50,82,126 shells

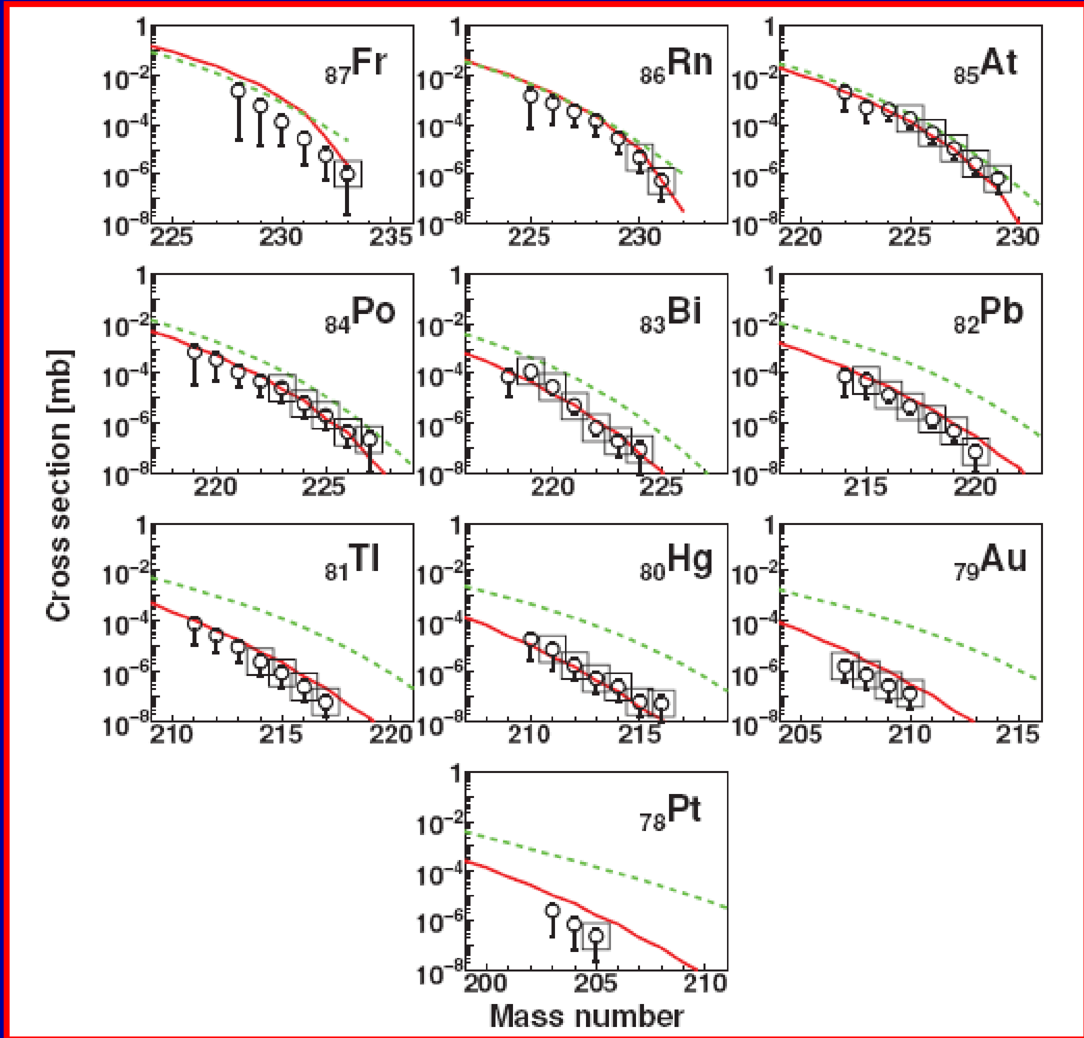


For nuclei with N=82 on the r-process path the allowed Gamow-Teller (GT) transitions are dominant

In the neutron shell closure N=126 the first forbidden transitions compete with the allowed transitions, therefore the β-decay lifetimes are difficult to predict since normal GT transitions are suppressed

Fragmentation reactions of ^{238}U at 1 A GeV on Be targets

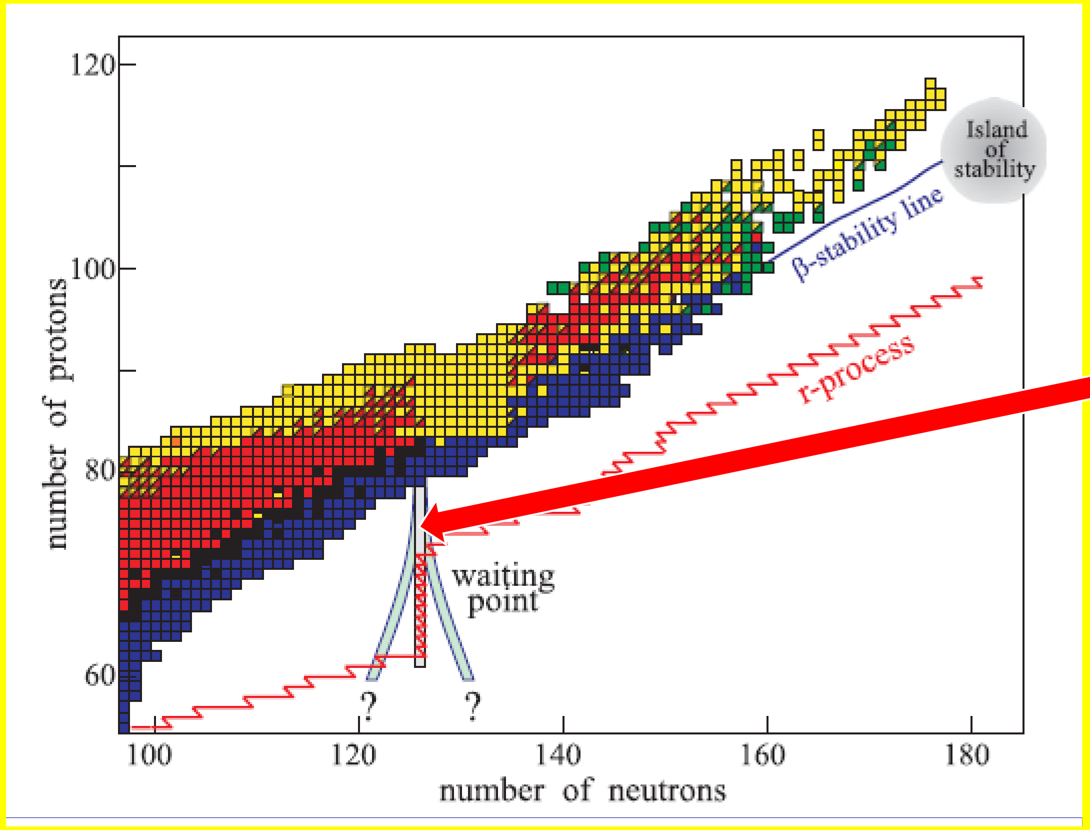




In fragmentation reactions on light targets one could produce very neutron rich nuclei in the "northeast" region, with cross sections down to 100 pb

H.Alvarez-Pol et al, Phys.Rev.C82(2010)041602R

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



V.Zagrebaev and W.Greiner, PRC83(2011)044618

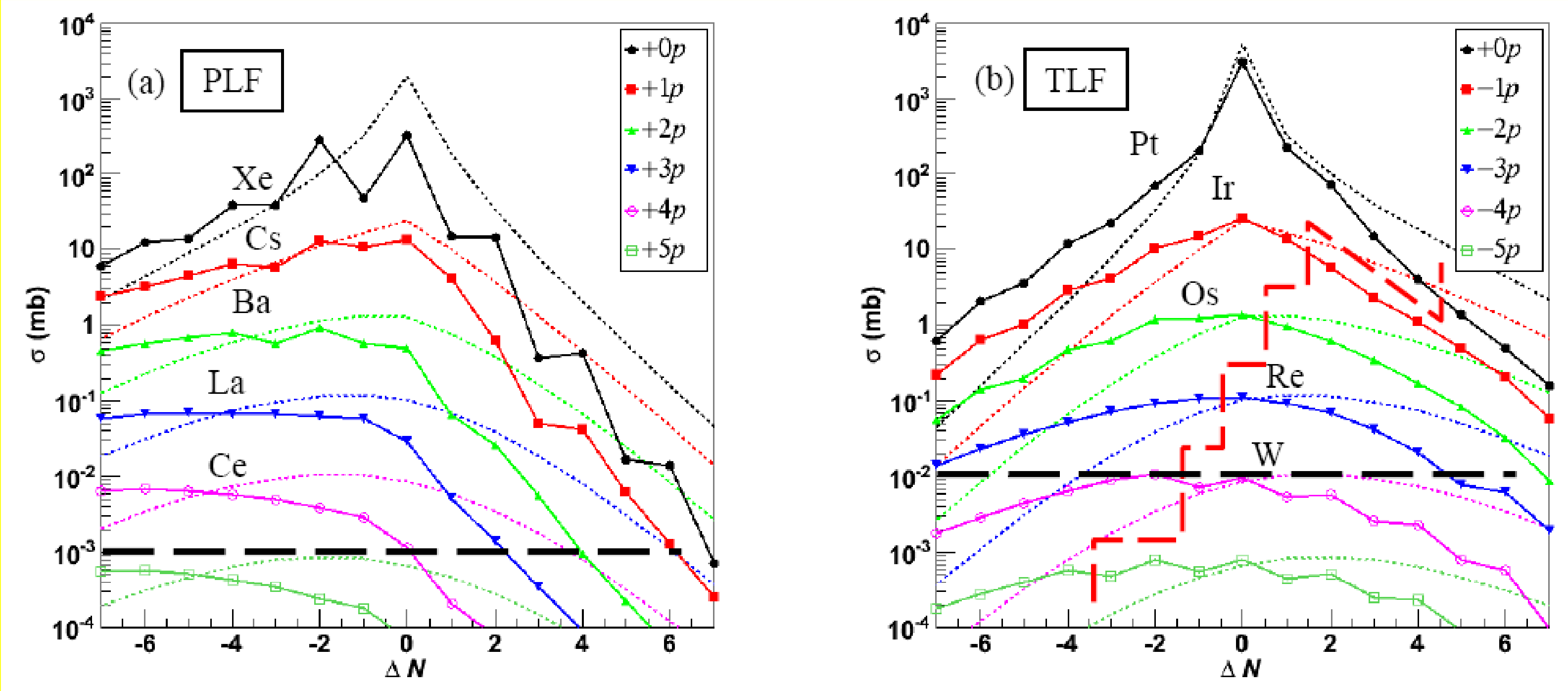
region below Pb not easily accessible via fragmentation or fission reactions, and suitable for multinucleon transfer

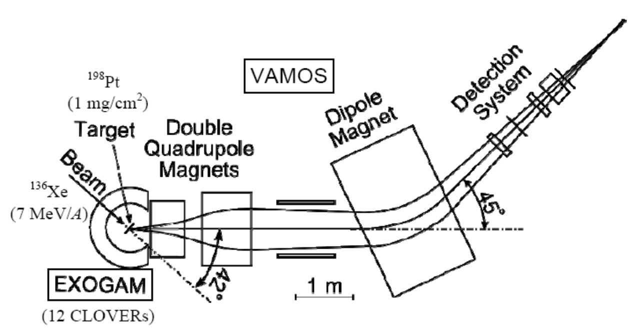
high primary cross sections of mnt channels (mb-μb range)

BUT there are processes lowering the final yield : evaporation and transfer induced fission

Production of heavy neutron rich nuclei by multinucleon transfer reactions in $^{136}Xe+^{198}Pt$ at 7 MeV/A

GRAZING code calculations



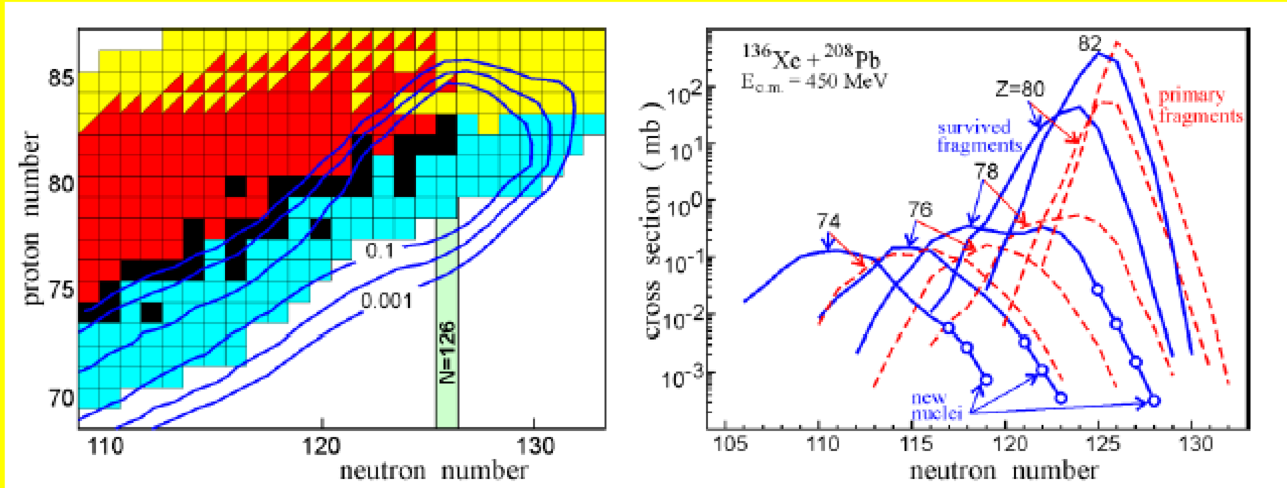


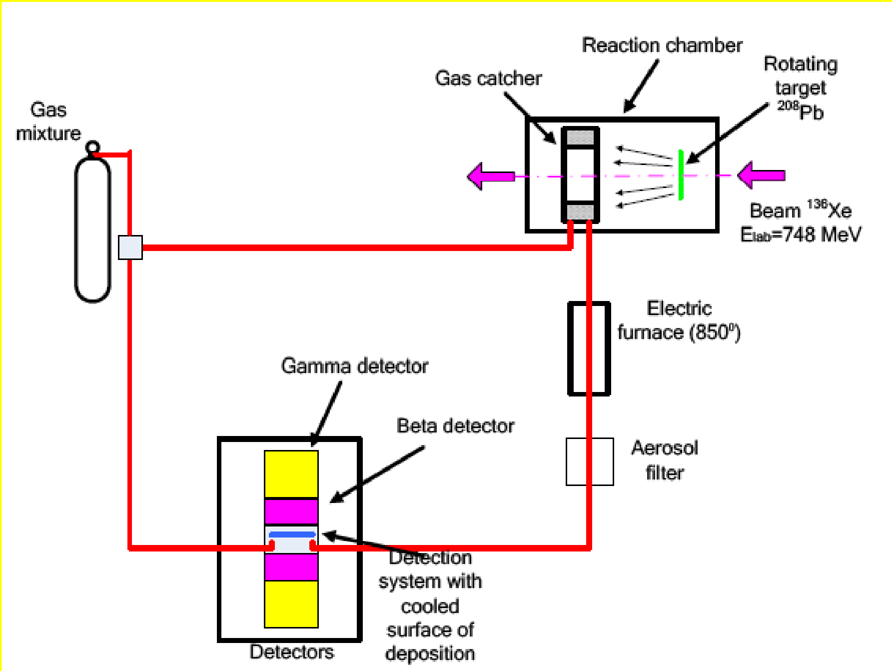
PLF nuclei detected with VAMOS, coincident gamma-rays (both PLF and TLF) detected with EXOGAM

GANIL exp 2012

Y.Watanabe et al, EMIS2012, Matsue (Jp)

Heavy neutron rich nuclei in the region of neutron closed shell N=126 populated via $^{136}Xe+^{208}Pb$ multinucleon transfer reaction





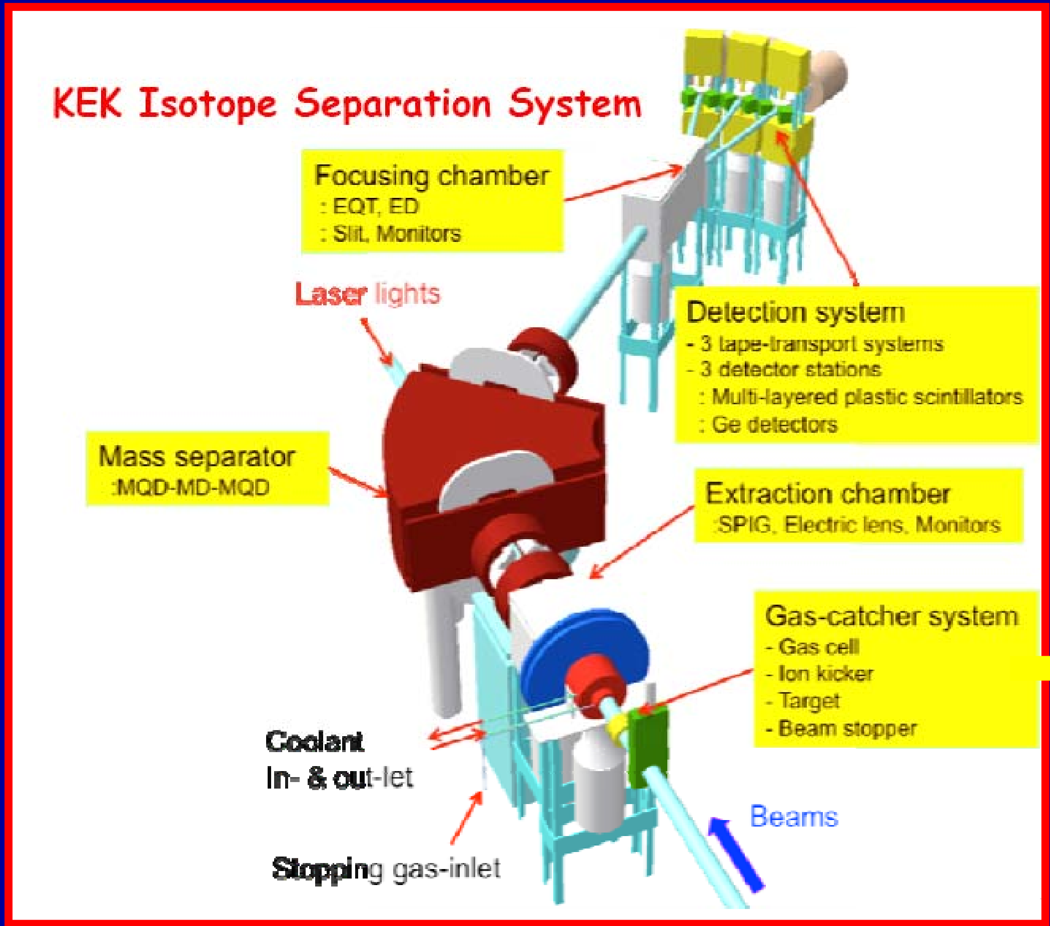
Integral measurement to detect heavy transfer reaction products below the Pb region

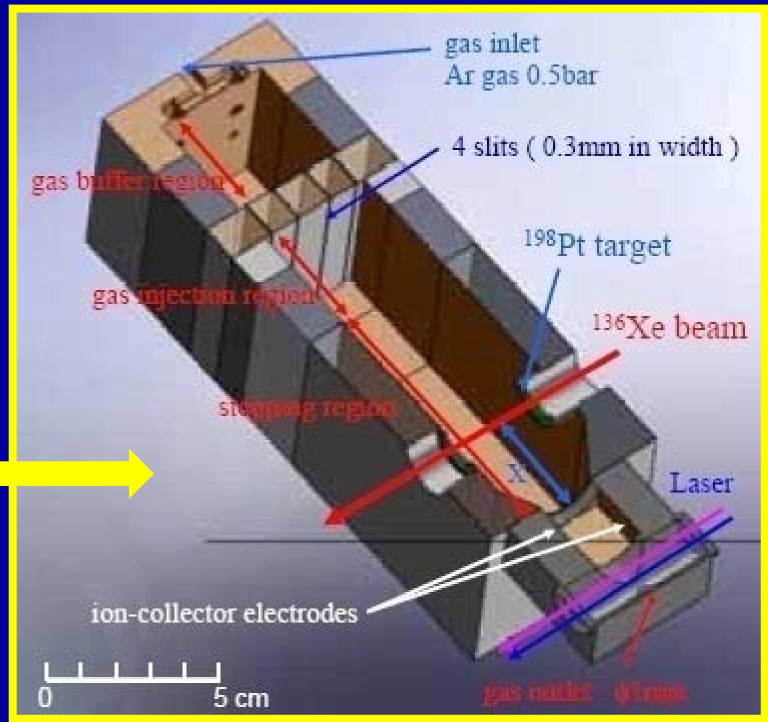
Possibility to study beta-gamma decays properties

Jyväskylä exp 2012

E.Kozulin, V.Zagrebaev et al

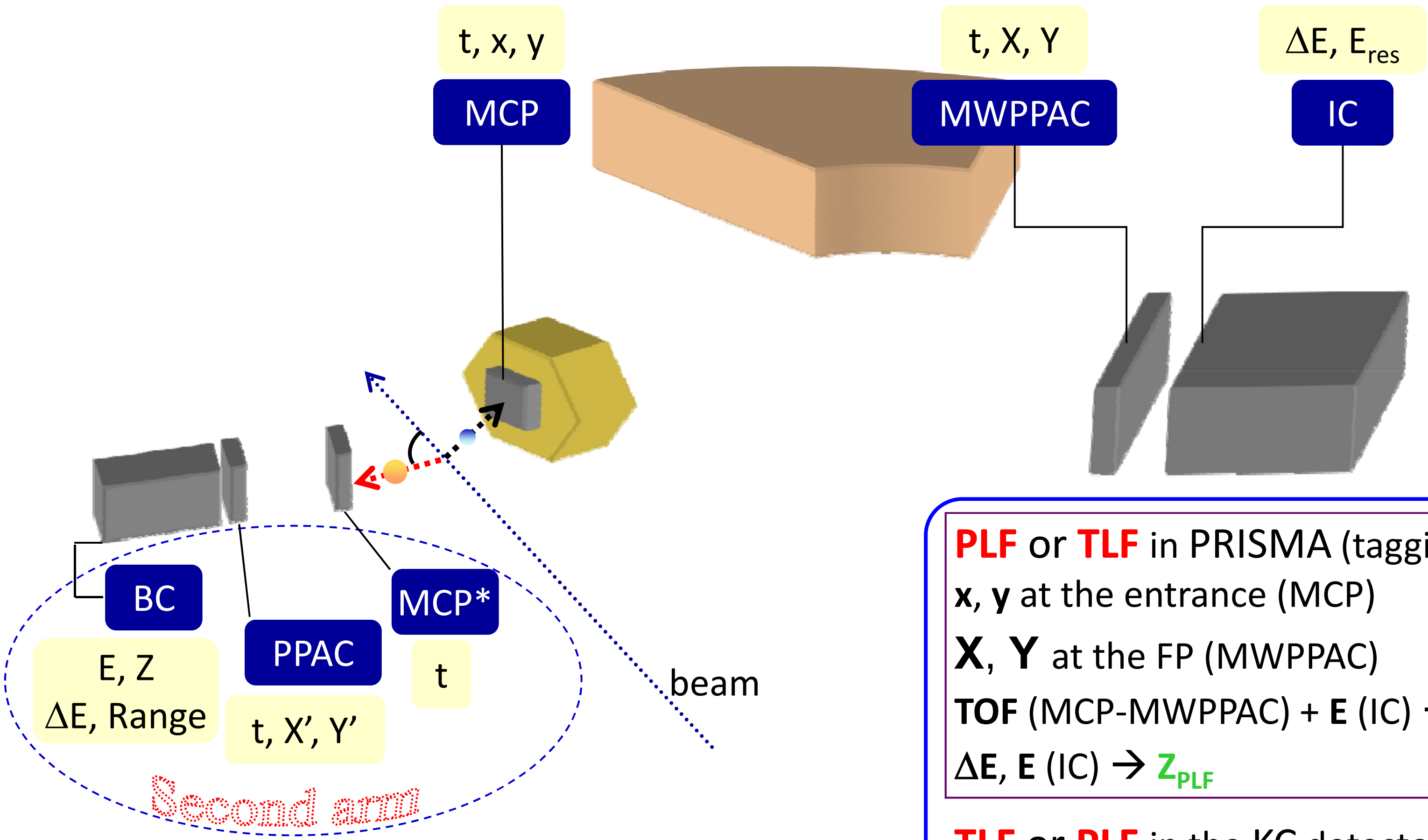
The KEK Isotope Separator System KISS for β-decay spectroscopy of neutron rich nuclei with A~200 and N~126 produced via $^{136}Xe+^{198}Pt$ multinucleon transfer reactions





S.Jeong et al, EMIS2012, Matsue (Jp)

High resolution kinematic coincidence between PRISMA and a second arm



Experimental parameters and fragment discrimination

PLF or **TLF** in PRISMA (tagging)

x, **y** at the entrance (MCP)
X, **Y** at the FP (MWPPAC) } **Trajec.**

TOF (MCP-MWPPAC) + **E** (IC) → A_{PLF}

ΔE, **E** (IC) → Z_{PLF}

PRISMA

TLF or **PLF** in the KC detector

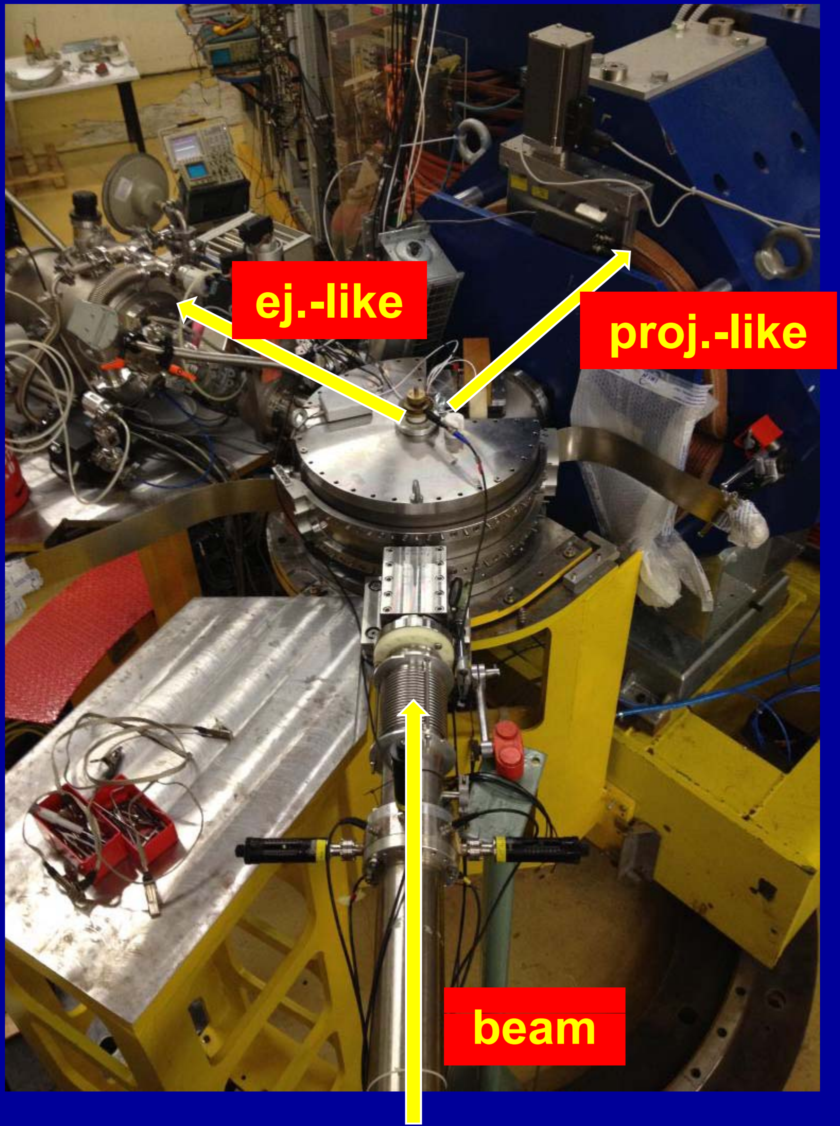
X', **Y'** at KC angle (PPAC) → (θ_{TLF}, ϕ_{TLF})

Δ**TOF** (MCP-MCP*), **TOF** (MCP*-PPAC)

E, **Z**, **Range**, **ΔE** (BC)

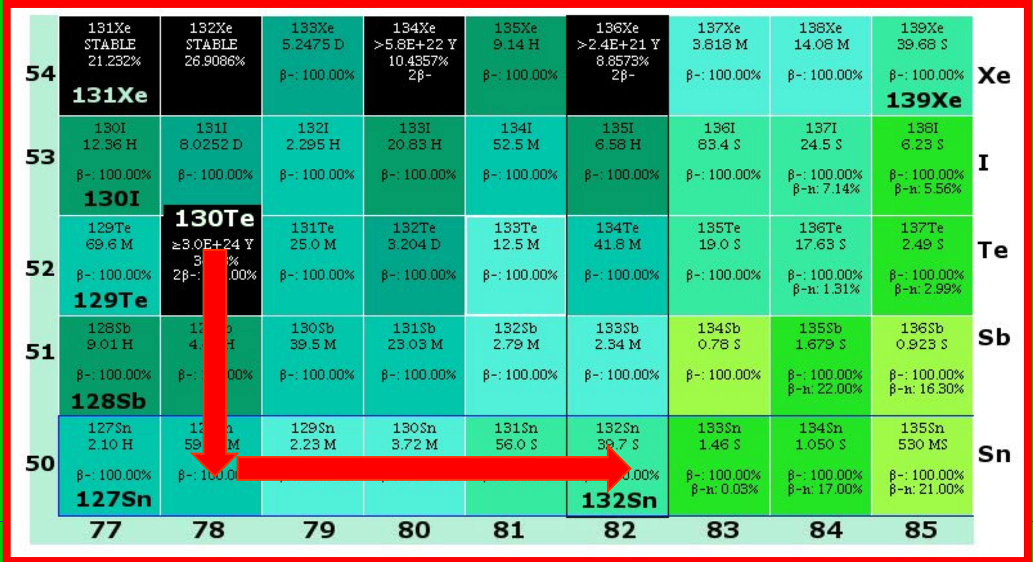
→ **PLF-TLF discrimination**

High resolution kinematic coincidence between PRISMA and a second arm



we recently performed a high resolution kinematic coincidence for the systems $^{197}Au+^{130}Te$ @ 1070 MeV and $^{136}Xe+^{208}Pb$ @ 870 MeV to study the population yields in the Pt-Os region

^{197}Au+^{130}Te : one can populate neutron rich nuclei close to A ~ 130 and A ~ 200

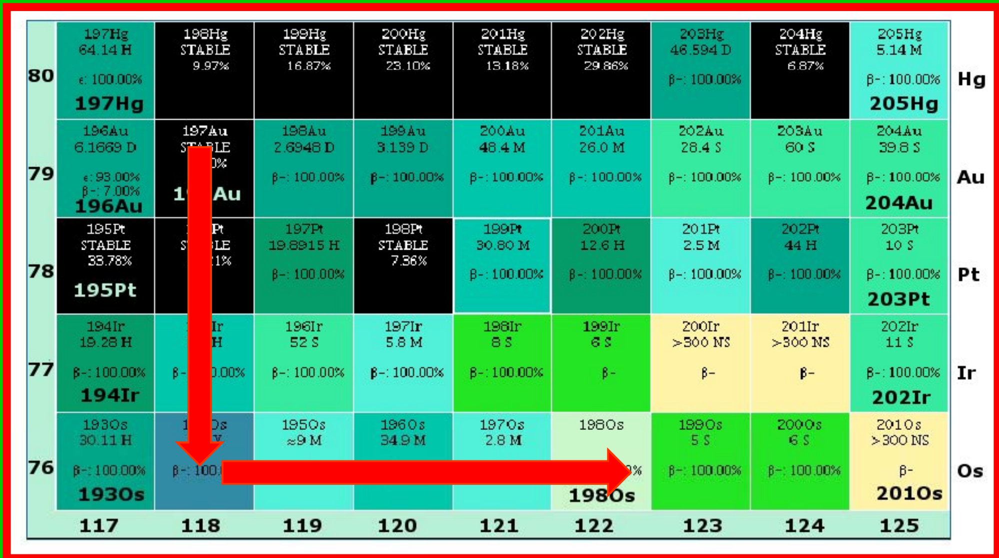


via proton stripping and neutron pick-up one gets neutron rich nuclei around A~130

in particular, the (-2p+4n) channel from 130Te would lead to the benchmark nucleus 132Sn

via proton pick-up and neutron stripping one gets neutron rich nuclei around A~200

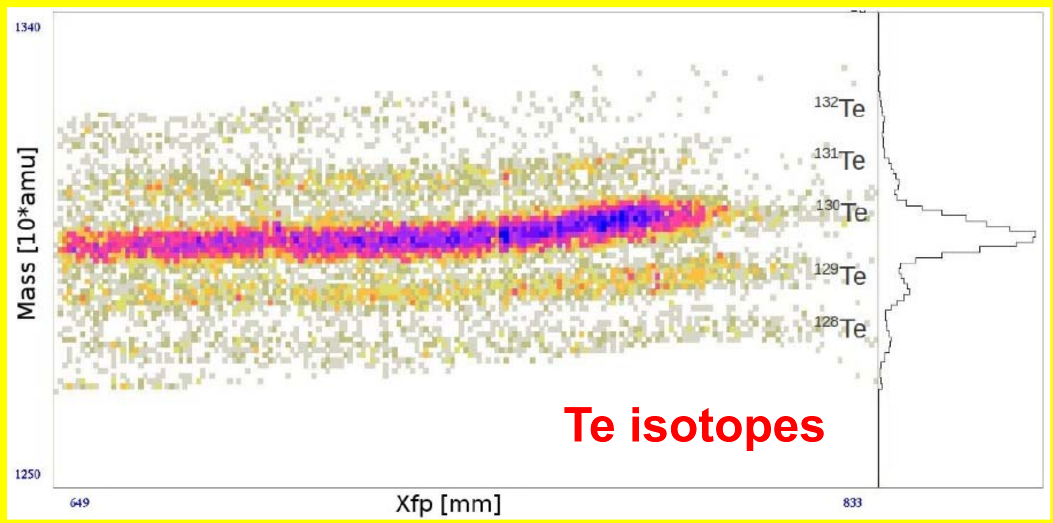
in particular, the (+3p-4n) channel from 130Te would lead to 198Os and beyond



L.Corradi, S.Szilner, D.Montanari et al.,

PRISMA exp May 2013

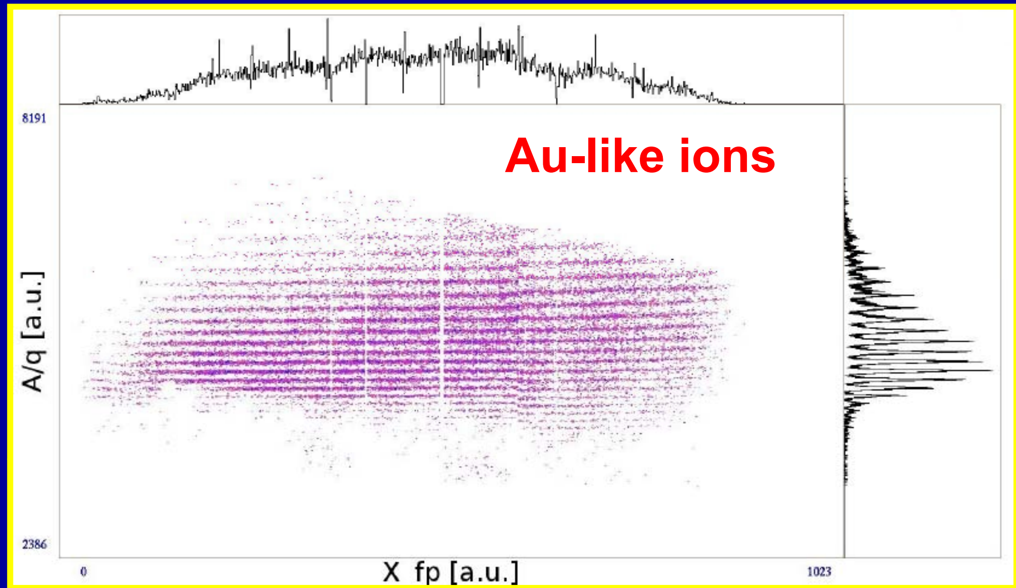
^{197}Au+^{130}Te in inverse kinematics at E_{lab}=1070 MeV and θ_{lab}=37°



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

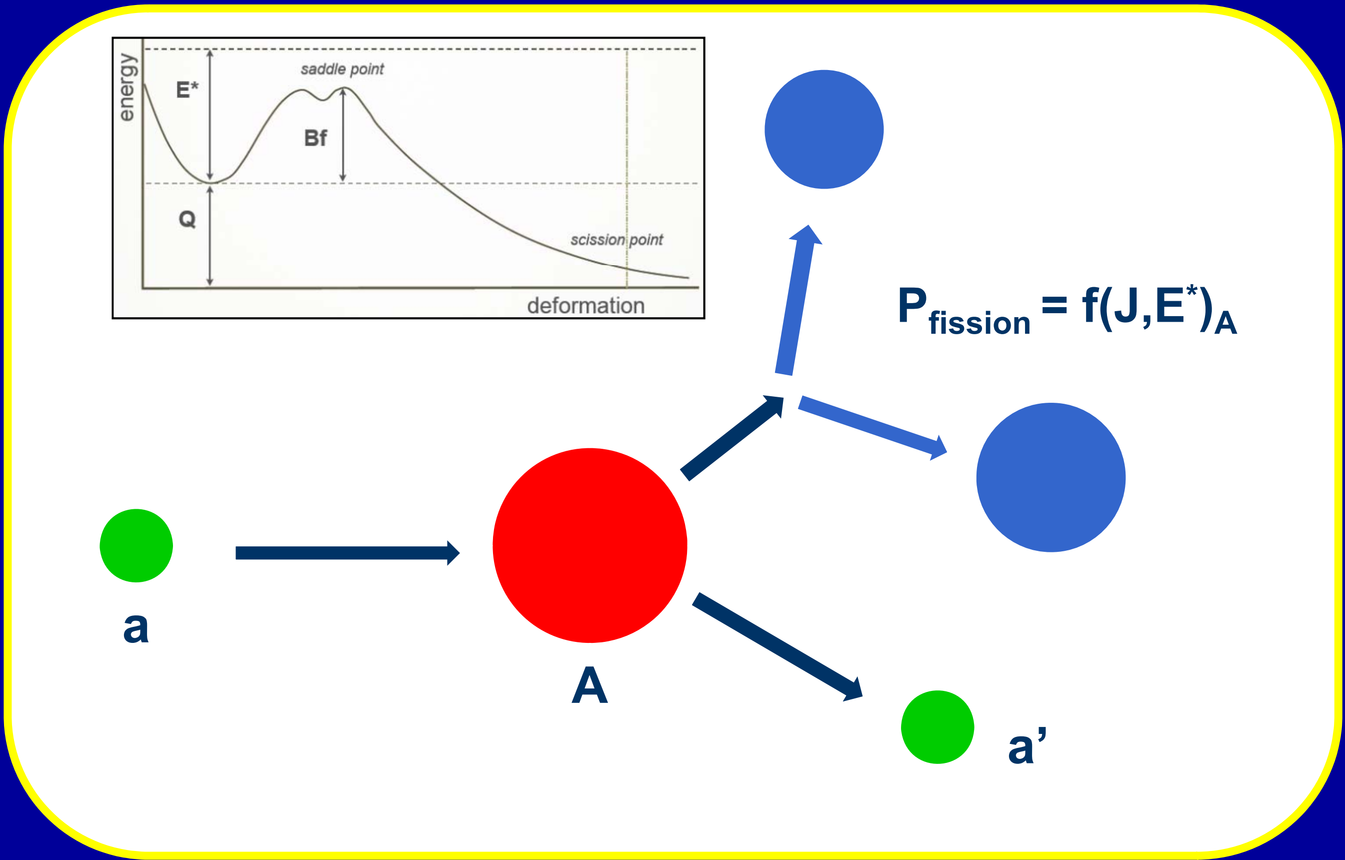
Mass vs position at the focal plane displays the good separation for Te isotopes

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



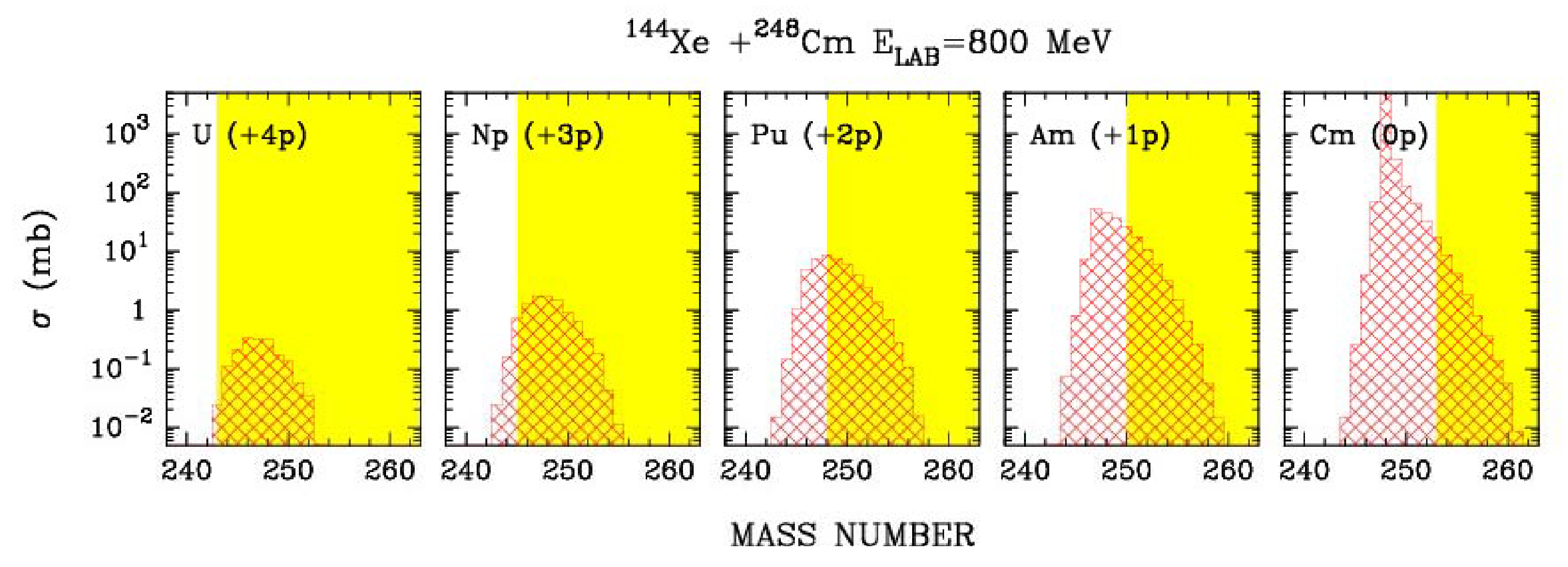
**For the heavy parntner we obtained excellent A/q resolution.
The present problem is to get atomic charge states discrimination to uniquely identify final A**

Transfer induced fission



Exploiting the multinucleon transfer mechanism to get acces to yet unknown actinides and transactinides

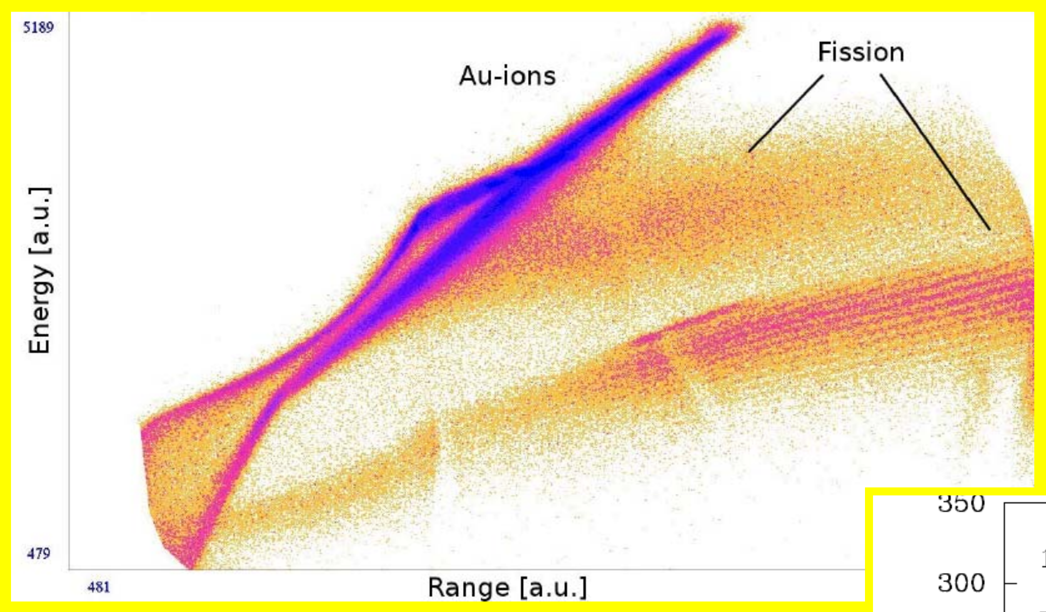
GRAZING code calculations



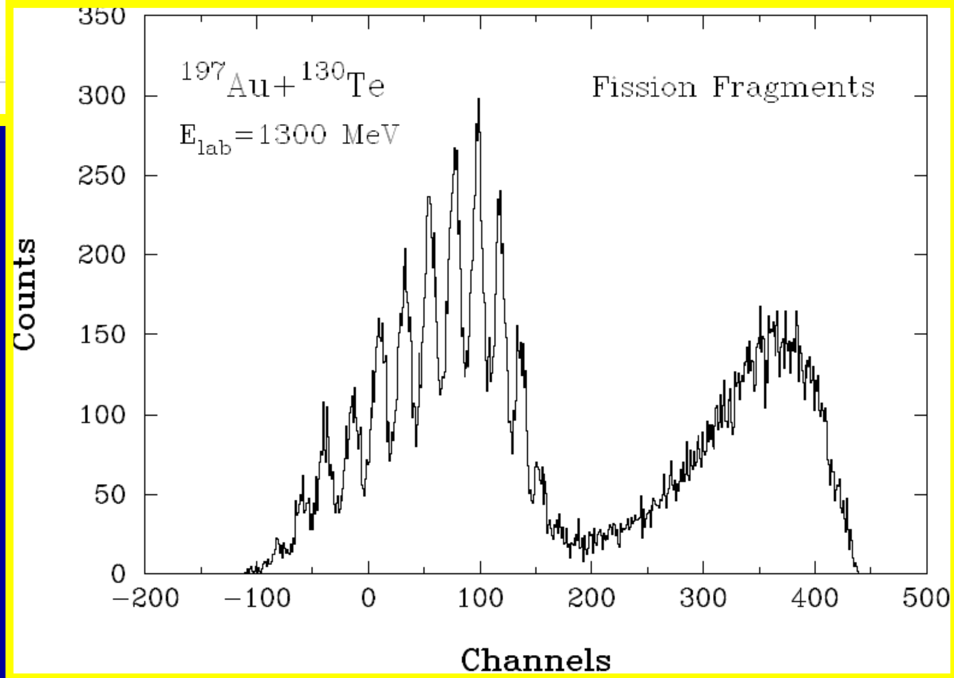
using very neutron rich projectiles, via proton pick-up and neutron stripping channels, one predicts very high primary cross sections for yet unknown transactinides. Therefore, it is important to study the fission probability of the heavy partner

Eurisol Project (key experiments) http://www.ganil.fr/eurisol/

$^{197}Au+^{130}Te$ in inverse kinematics at E_{lab}=1300 MeV and θ_{lab}=27°
PRISMA fields setted in order to detect fission fragments

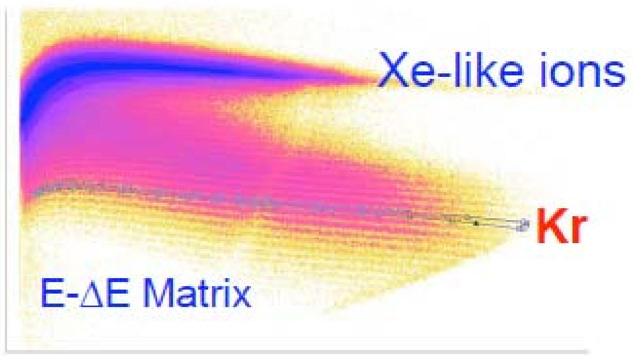


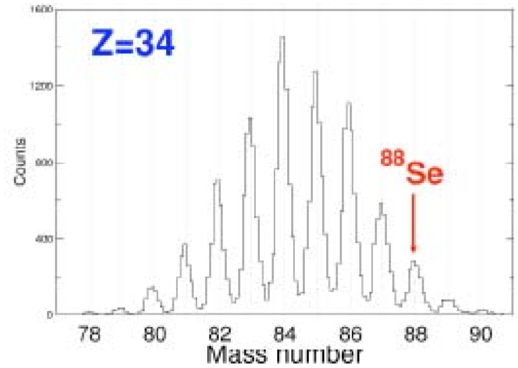
PRISMA focal plane detectors setted to optimize lighter fission fragments



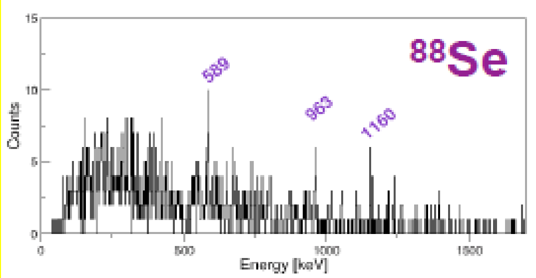
part of the detected yield should correspond to transfer induced fission, a mechanism suitable to produce more neutron rich nuclei

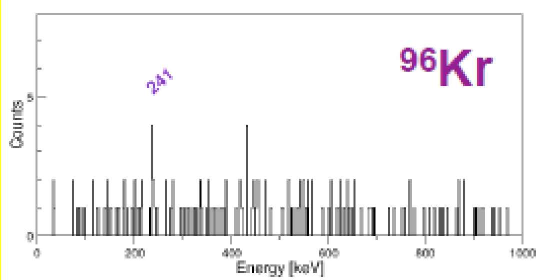
Neutron rich nuclei produced in the fission of ^{238}U in $^{136}Xe+^{238}U$ at E_{lab}=990 MeV



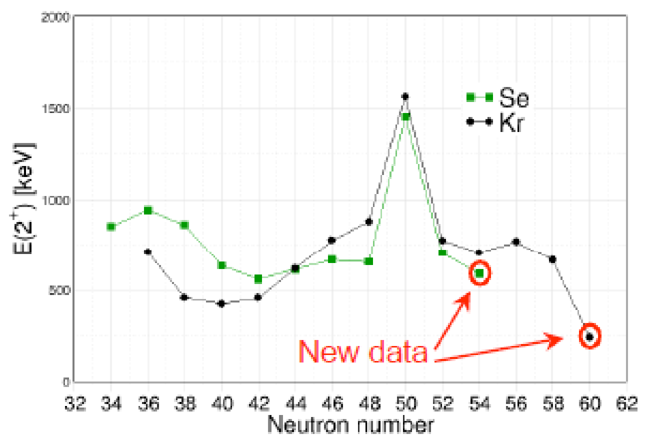


PRISMA setted in order to detect (lighter) fission fragments



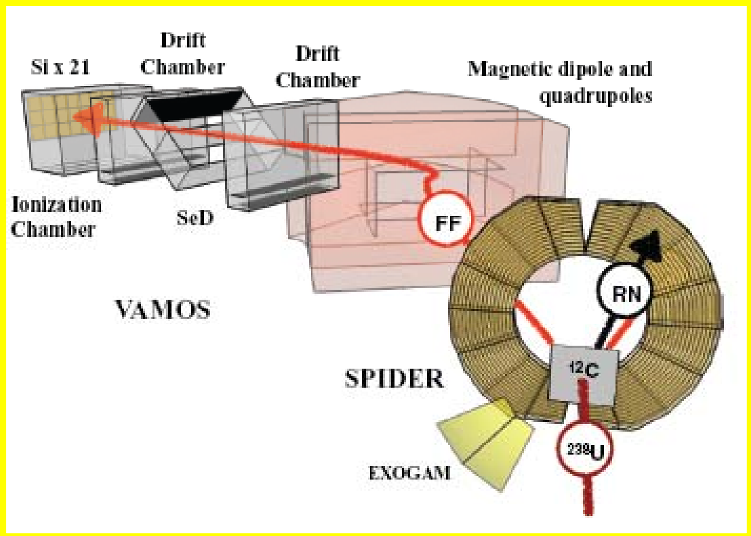


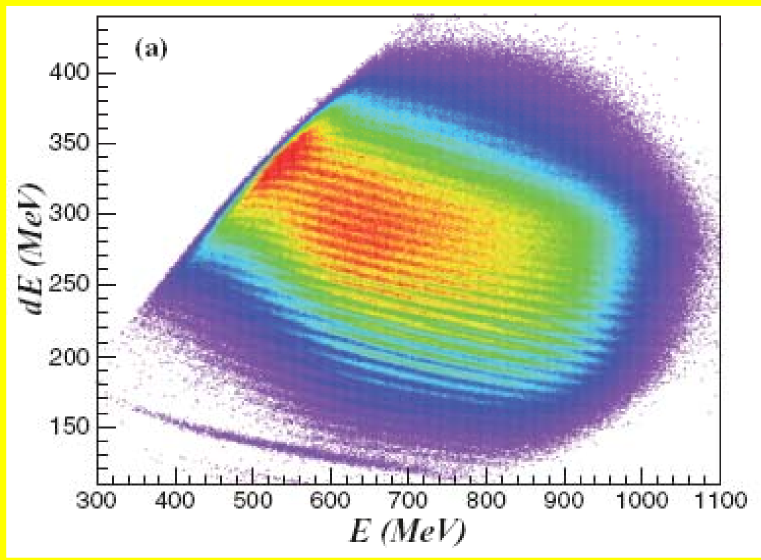
Extended the studies of the evolution of collectivity in n-rich Kr isotopes

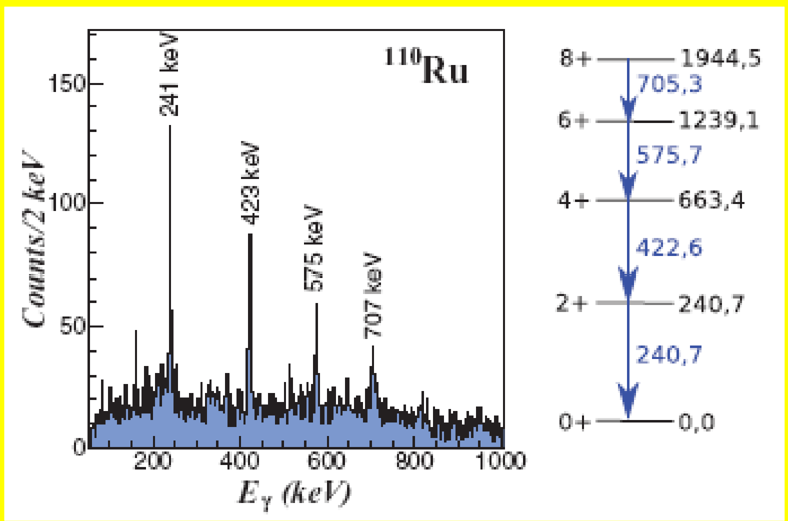


N.Marginean et al., Phys. Rev. C80(2009)021301(R)

Neutron rich nuclei produced in the fission of ^{238}U in $^{238}U+^{12}C$ at E = 6 MeV/A







Fission fragment identification with VAMOS+EXOGAM (GANIL)

M.Caamano et al., Phys.Rev.C88(2013)024605

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

L.Corradi[1], S.Szilner[3], D.Montanari[2], E.Fioretto[1], A.M.Stefanini[1], G.Montagnoli[2], F.Scarlassara[2], G.Pollarolo[4], S.Courtin[5], A.Goasduff[5], F.Haas[5], D.Jelavec-Malenica[3], C.Michelagnoli[2], T.Mijatovic[3], N.Soic[3], C.Ur[2,6], J.J.Valiente-Dobon[1], D.Ackermann[7]

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Very Recent experiments performed at LNL within Trans-EU International Collaborations

Argonne	KEK -Tsukuba	ANU - Canberra	Dubna