Inverse kinematics experiments with the PRISMA spectrometer

E. Fioretto

INFN – Laboratori Nazionali di Legnaro

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Outline

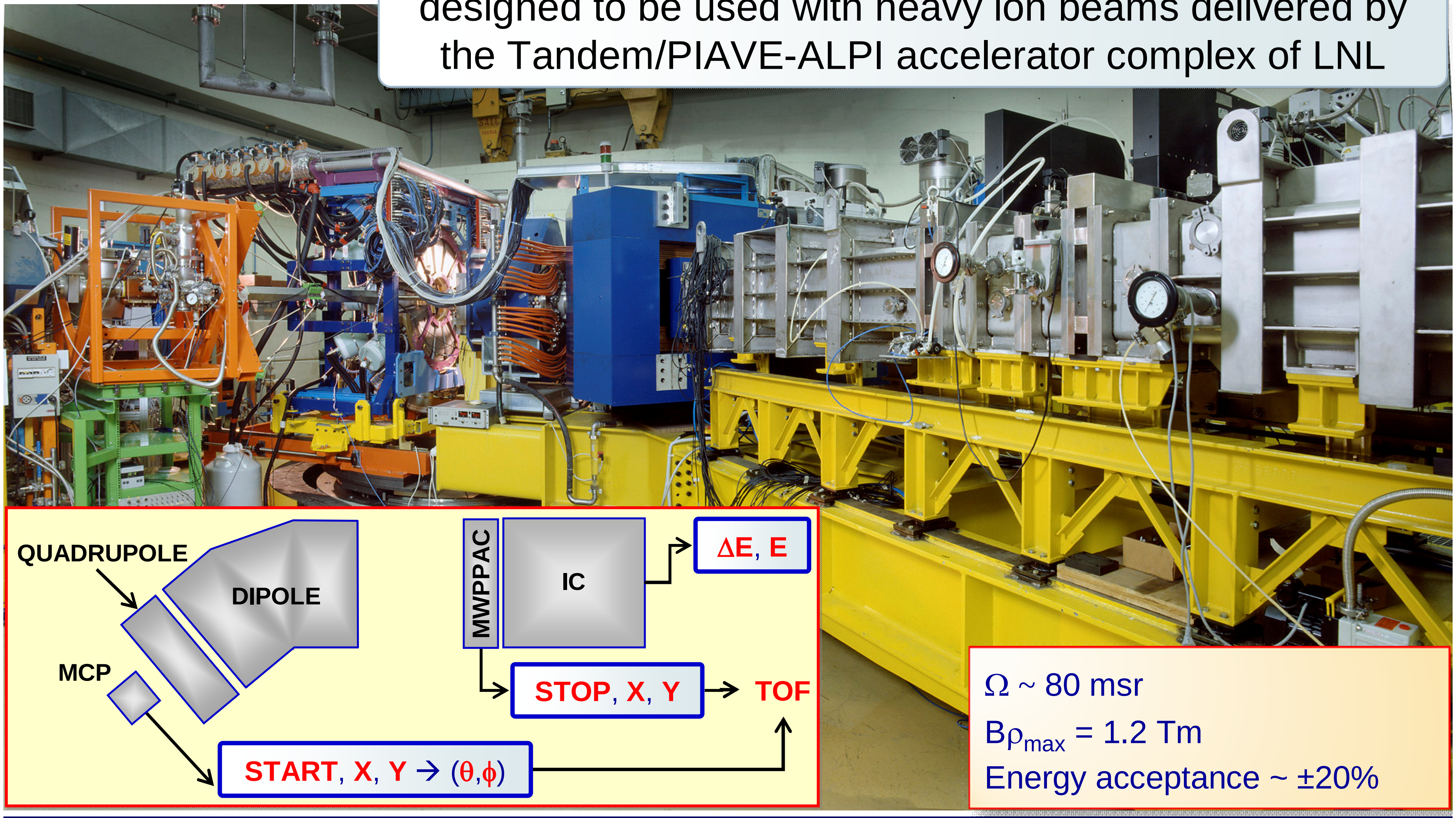
- **The large solid angle magnetic spectrometer PRISMA**

- **Inverse kinematics experiments with the large acceptance magnetic spectrometer PRISMA**
  - **Transfer reactions at sub-barrier energies**
    - $^{96}Zr+^{40}Ca$ (closed shell nuclei)
    - $^{116}Sn+^{60}Ni$ (superfluid nuclei)
  - **Population of neutron-rich nuclei via multinucleon transfer reactions**
    - Neutron rich nuclei at N=82 and N=126
    - How to explore the neutron rich heavy region of the nuclear chart via multinucleon transfer reactions (MNT)
    - The LNL test experiment: $^{197}Au+^{130}Te$

- **Summary**

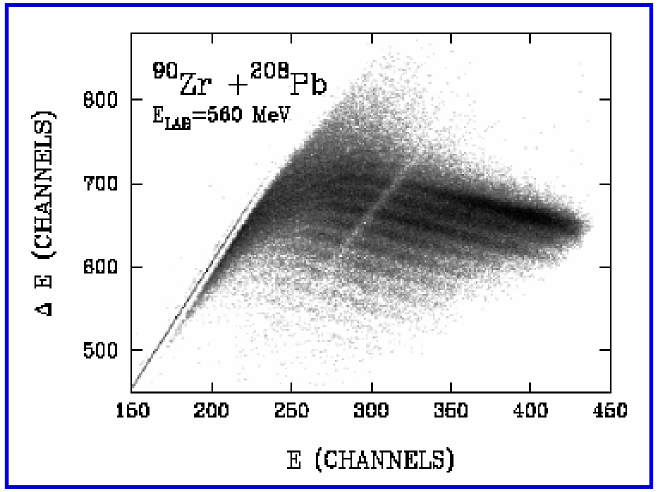
The PRISMA spectrometer

PRISMA : a large acceptance spectrometer
designed to be used with heavy ion beams delivered by the Tandem/PIAVE-ALPI accelerator complex of LNL

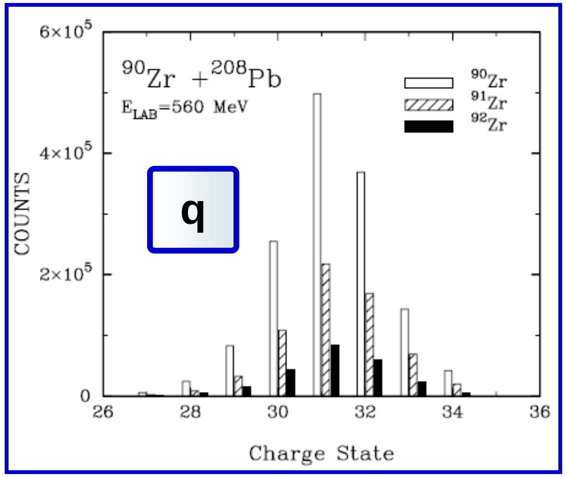


$\Omega \sim 80$ msr
$B\rho_{max} = 1.2$ Tm
Energy acceptance ~ ±20%

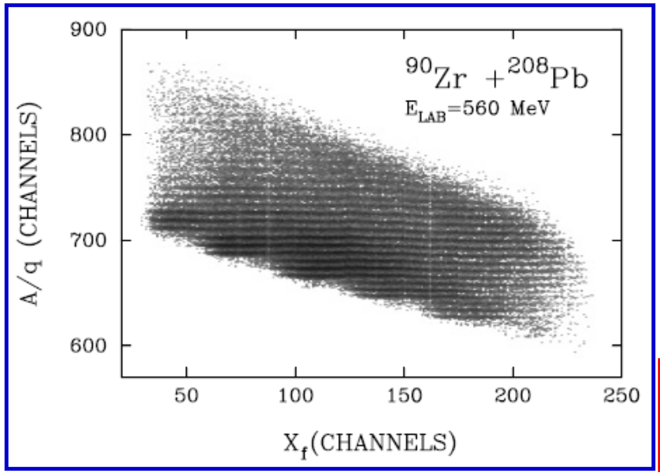
The PRISMA spectrometer



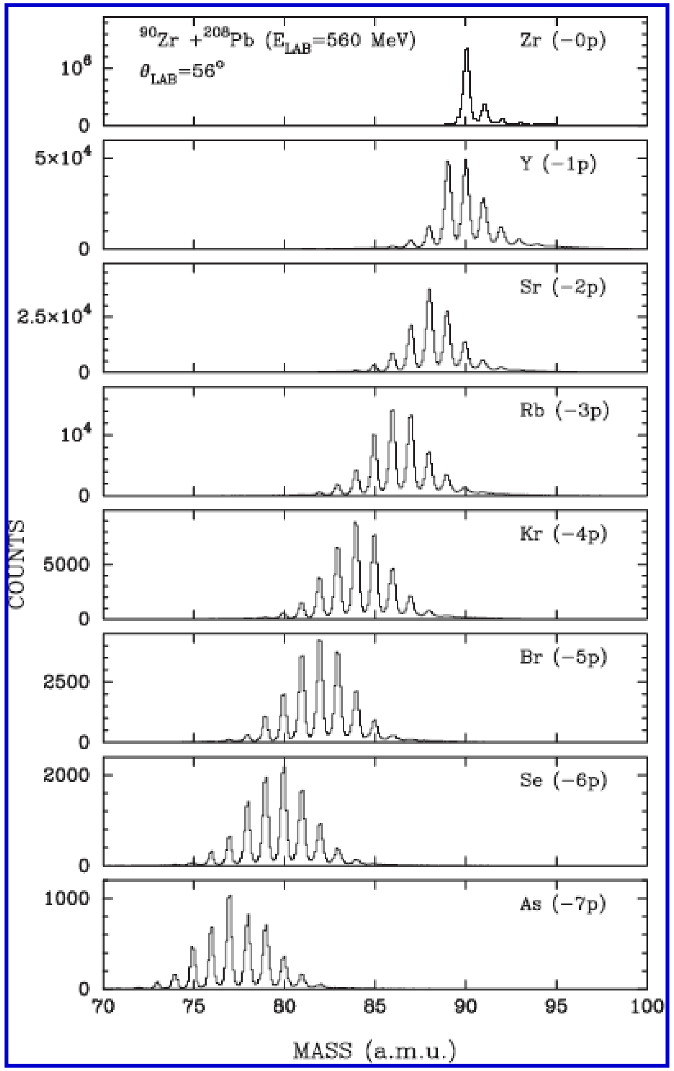
ΔZ/Z~1/60



$$\frac{E\,\tau_{TOF}}{B\rho\,L} \Rightarrow q$$



$$\frac{B\rho\,\tau_{TOF}}{L} \Rightarrow \frac{A}{q}$$



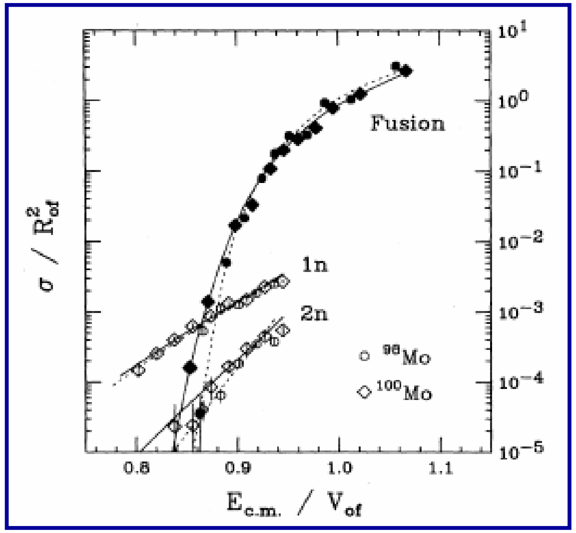
ΔA/A~1/200

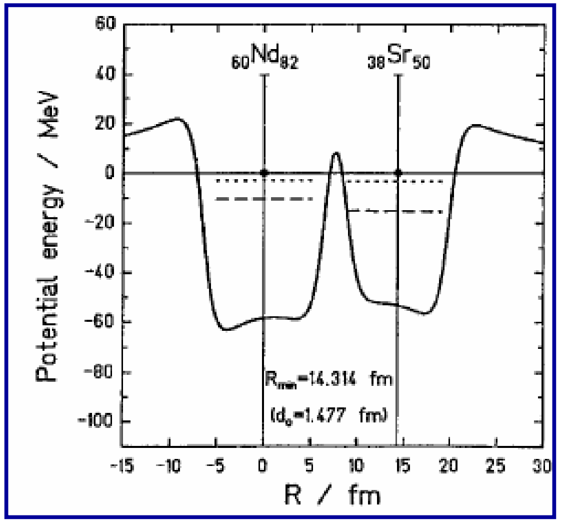
Transfer reactions at sub-barrier energies

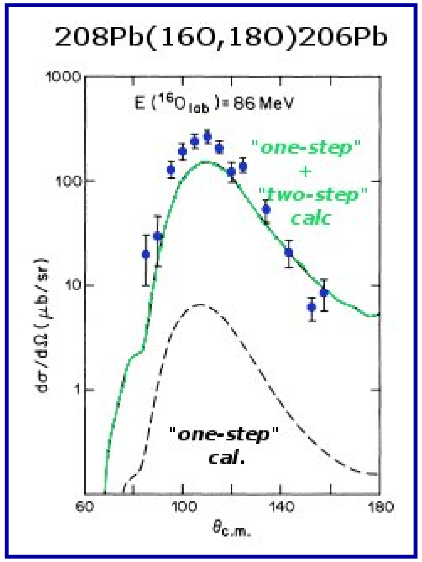
One probes transfer and fusion in an overlapping range of energies and angular momenta

One probes tunneling 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



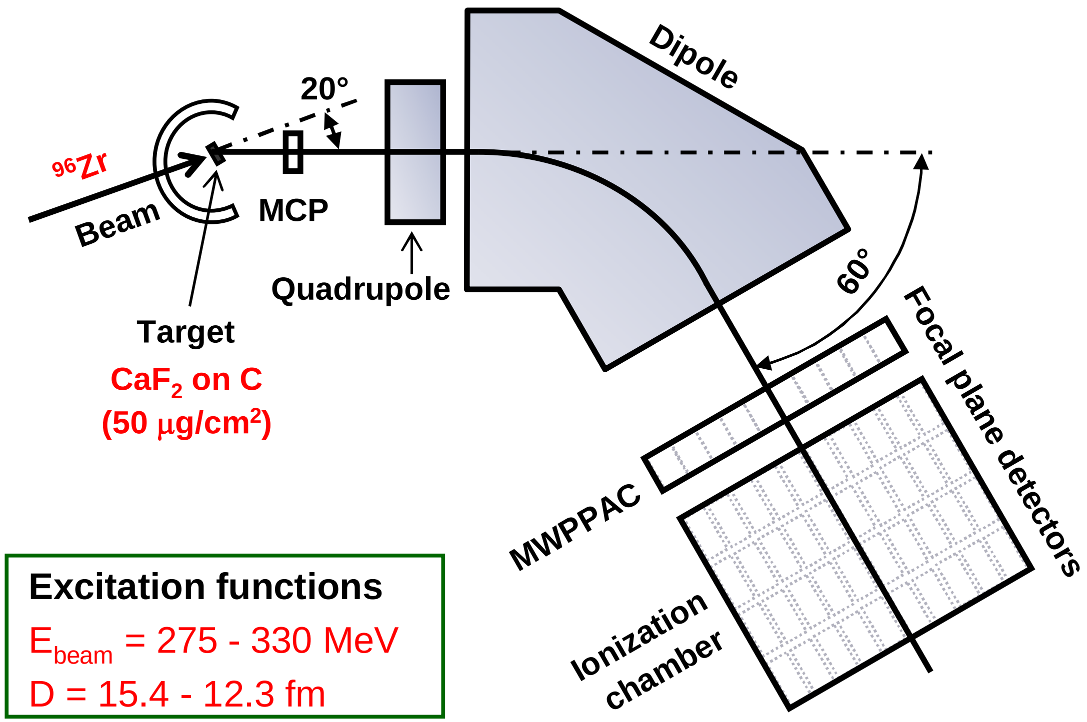




Theoretical advantages : few reaction channels, narrower Q-value distributions → one can probe nucleon correlation close to the g.s.

Experimental difficulties : Angular distributions are backward peaked and in direct kinematics projectile-like particles have low kinetic energy, cross sections get very small (need for high efficiency) → large solid angle magnetic spectrometers and inverse kinematics.

Sub-barrier transfer : $^{96}Zr+^{40}Ca$

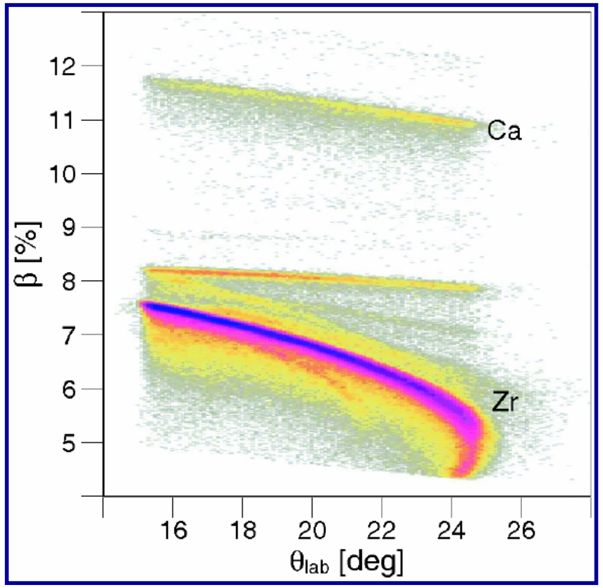


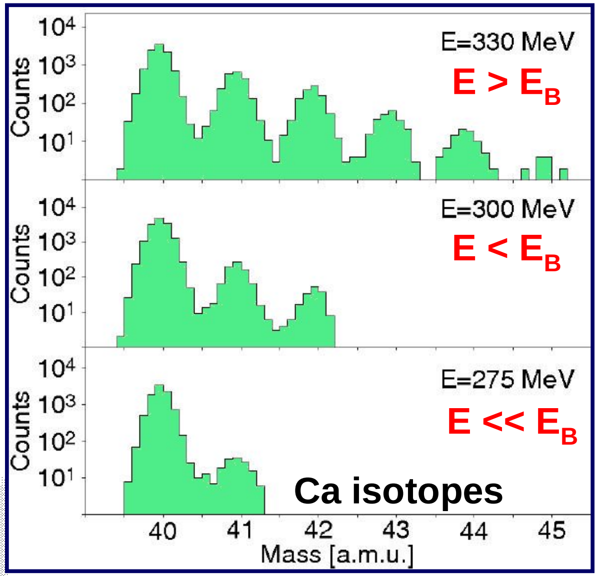
Target
CaF_2 on C
(50 $\mu g/cm^2$)

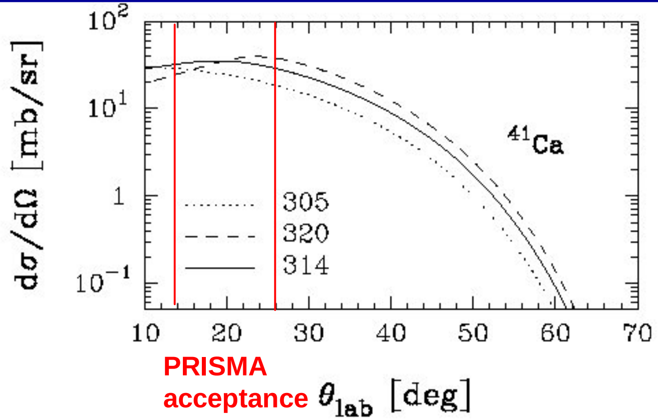
Excitation functions

E_{beam} = 275 - 330 MeV

D = 15.4 - 12.3 fm





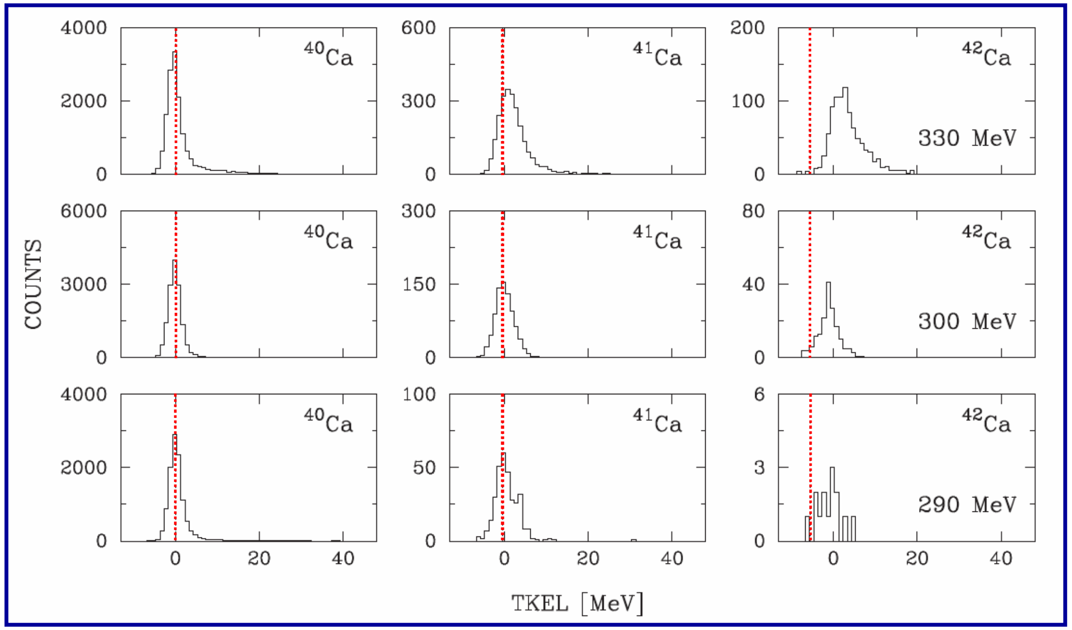


PRISMA acceptance

MNT channels from the Coulomb barrier to ~ 25 % below

L. Corradi et al., Phys. Rev. C 84 (2011) 034603

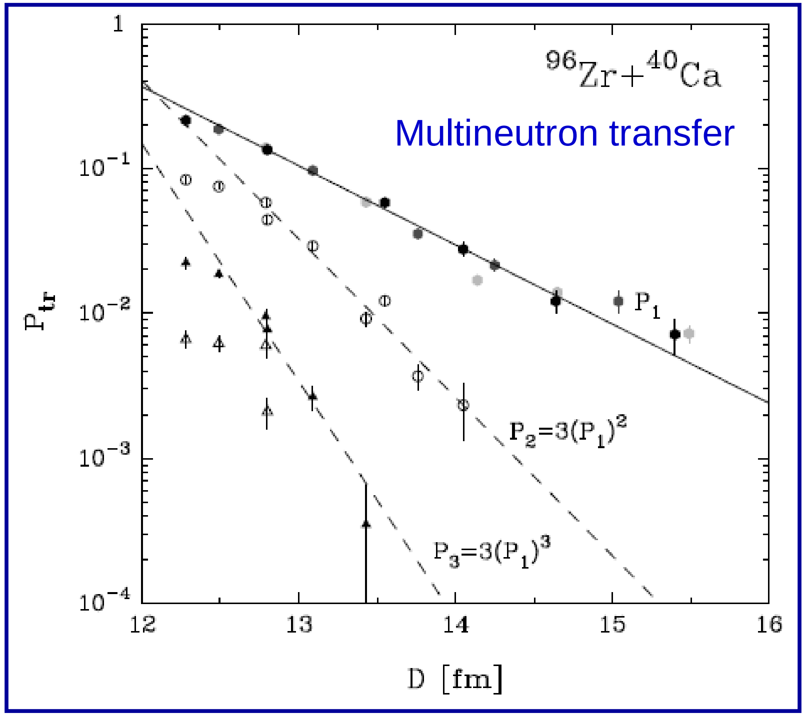
Sub-barrier transfer : $^{96}Zr+^{40}Ca$



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

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

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



	+1*n*	+2*n*	+3*n*	+4*n*
$^{96}Zr + ^{40}Ca$	+ 0.51	+ 5.53	+ 5.24	+ 9.64

g.s. Q-values

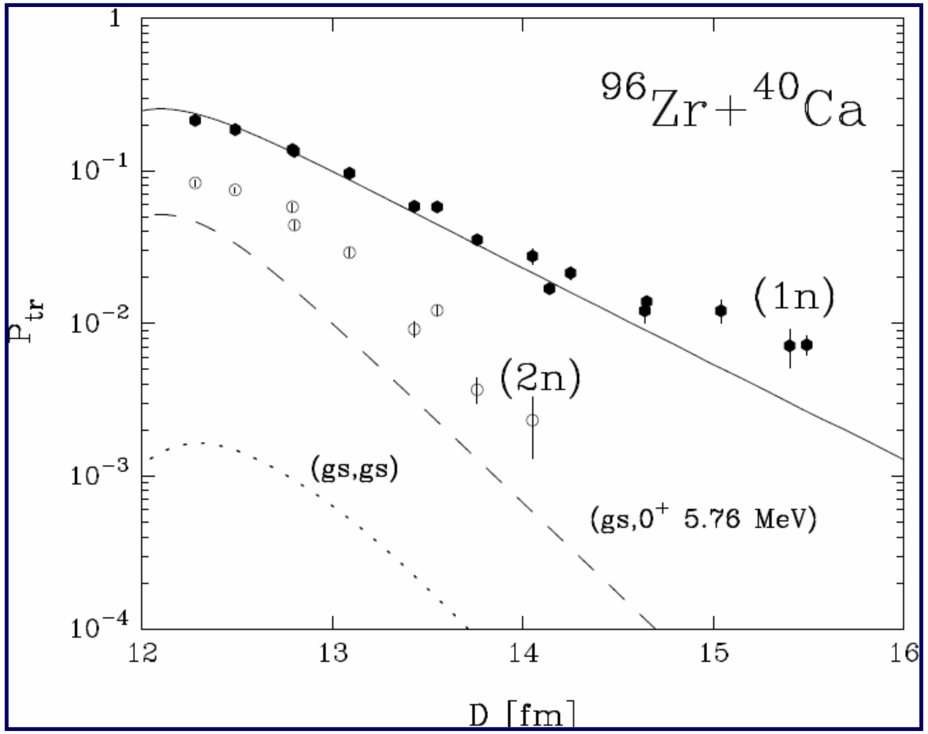
A bare phenomenological analysis shows an "enhanced" pair transfer: $P_{2n}\sim 3\,(P_{1n})^2$ and $P_{3n}\sim P_{1n}(P_{2n}) \sim 3\,(P_{1n})^3$

Slopes of P_{tr} vs D are as expected from the binding energies (tail of the form factor)

Transfer probabilities : $^{96}Zr+^{40}Ca$

Comparison between experimental data and microscopic calculations

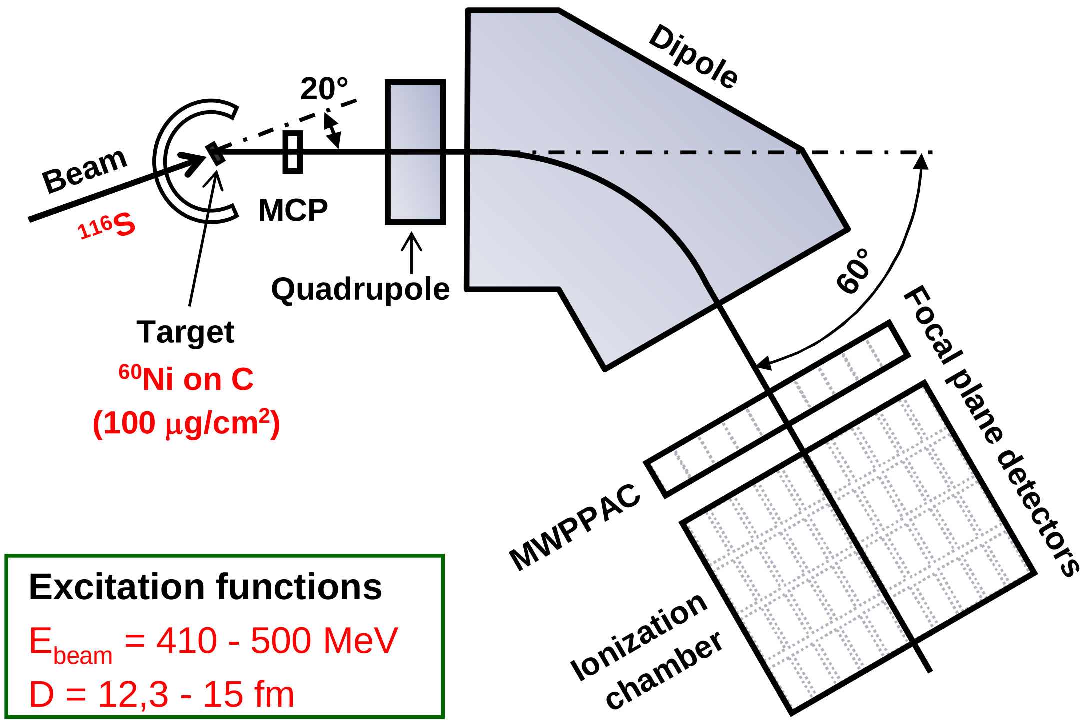
$Q_{g.s.}$ (for +2*n*) = + 5.5 MeV
far from Q_{opt} (~ 0 MeV)



L. Corradi et al., Phys. Rev. C 84 (2011) 034603

- **+1*n* well reproduced by theory in slope and absolute value**
- **Same slope of +2*n* between theory and experiment**
- **Considering only g.s. to g.s. transitions the transfer probability is underestimated by two orders of magnitude.**
- **An enhancement factor (~3) is needed for the transfer probability of two-neutron pickup channel also including 0^+ state transitions in ^{42}Ca**
- **Population of more complex states with higher angular momenta**

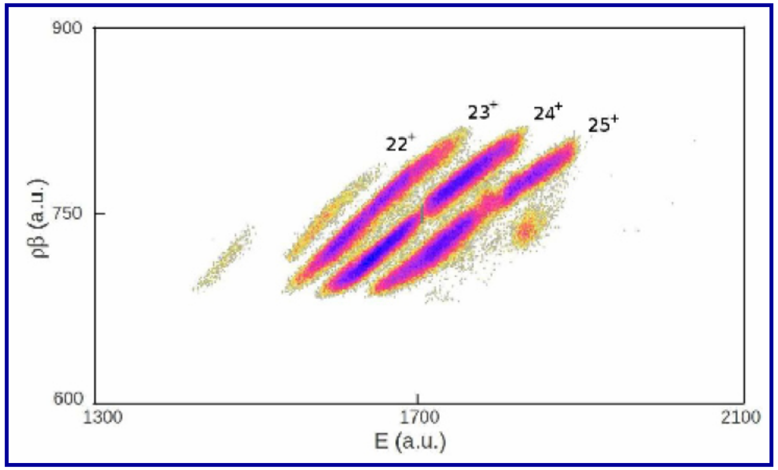
Sub-barrier transfer : $^{116}Sn+^{60}Ni$

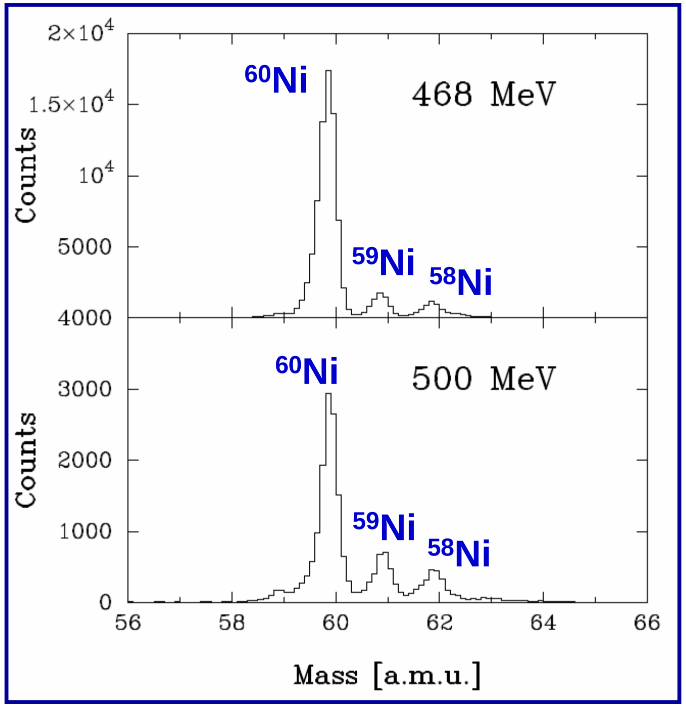


Excitation functions

E_{beam} = 410 - 500 MeV

D = 12,3 - 15 fm

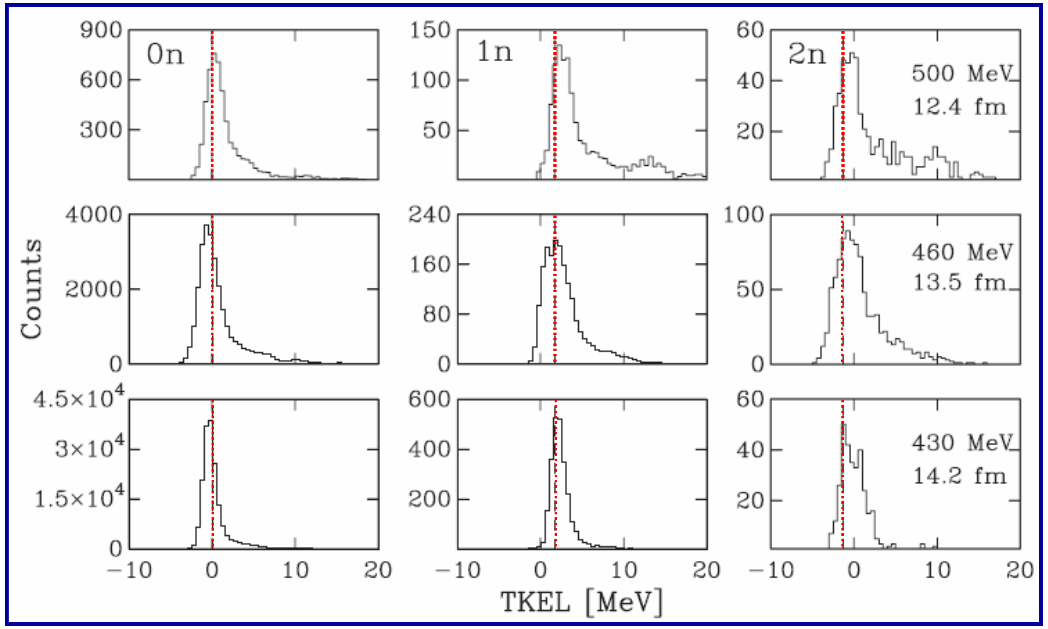




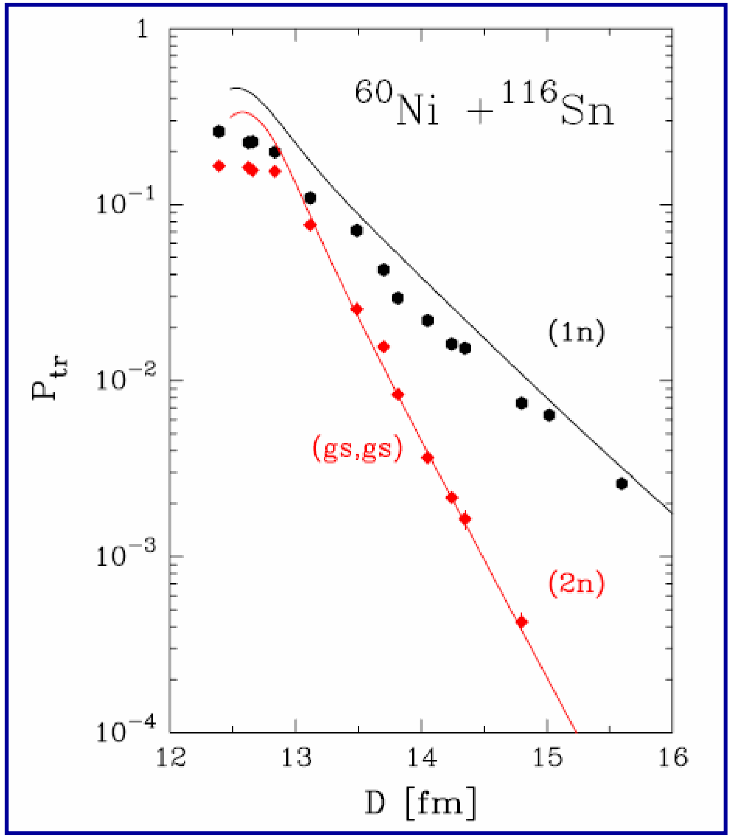
MNT channels from the Coulomb barrier to ~ 25 % below

D. Montanari et al., Phys. Rev. Lett. 113 (2014) 052501

Transfer probabilities : $^{116}Sn+^{60}Mo$



Exp. data vs microscopic calculations

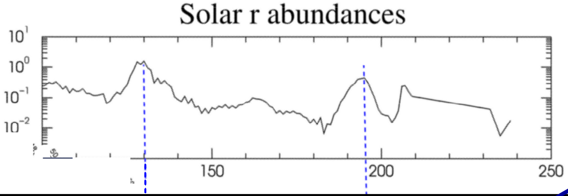


- $Q_{g.s.}$ for +2*n* very close to Q_{opt} (~ 0 MeV)
- Transfer strength very close to the g.s. to g.s. transitions
- The experimental transfer probabilities are well reproduced, for the first time with heavy ion reactions, in absolute values and in slope by microscopic calculations which incorporate nucleon-nucleon correlations

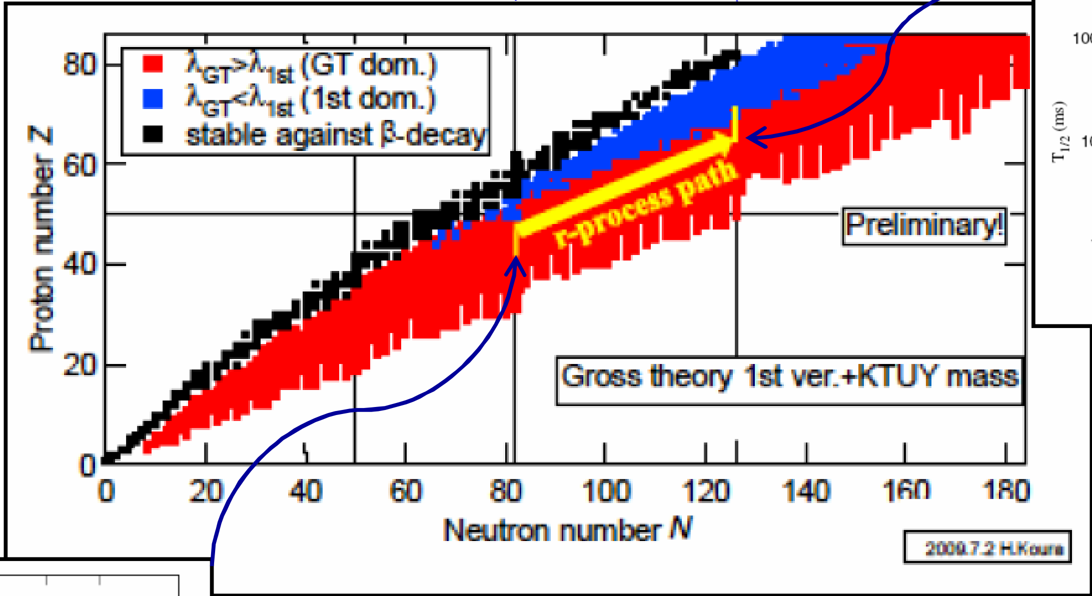
g.s. Q-values	+1*n*	+2*n*	+3*n*	+4*n*
$^{96}Zr + ^{40}Ca$	+ 0.51	+ 5.53	+ 5.24	+ 9.64
$^{116}Sn + ^{60}Ni$	- 1.74	+ 1.31	- 2.15	- 0.24

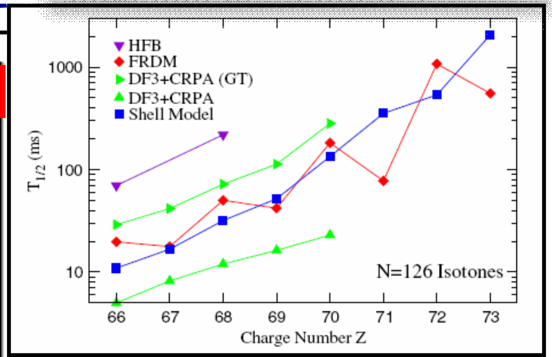
Neutron rich nuclei at N=82 and N=126

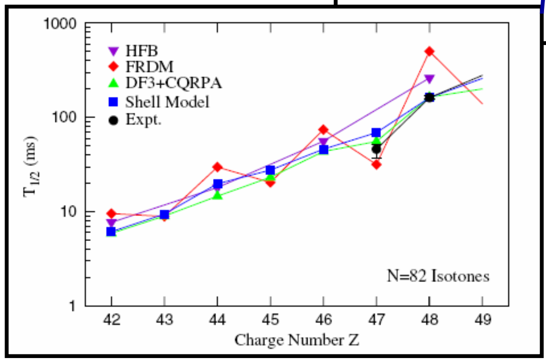
r-process and the importance of N = 82,126 shells



H.Grawe et al., Rep. Prog. Phys. 70 (2007) 1525





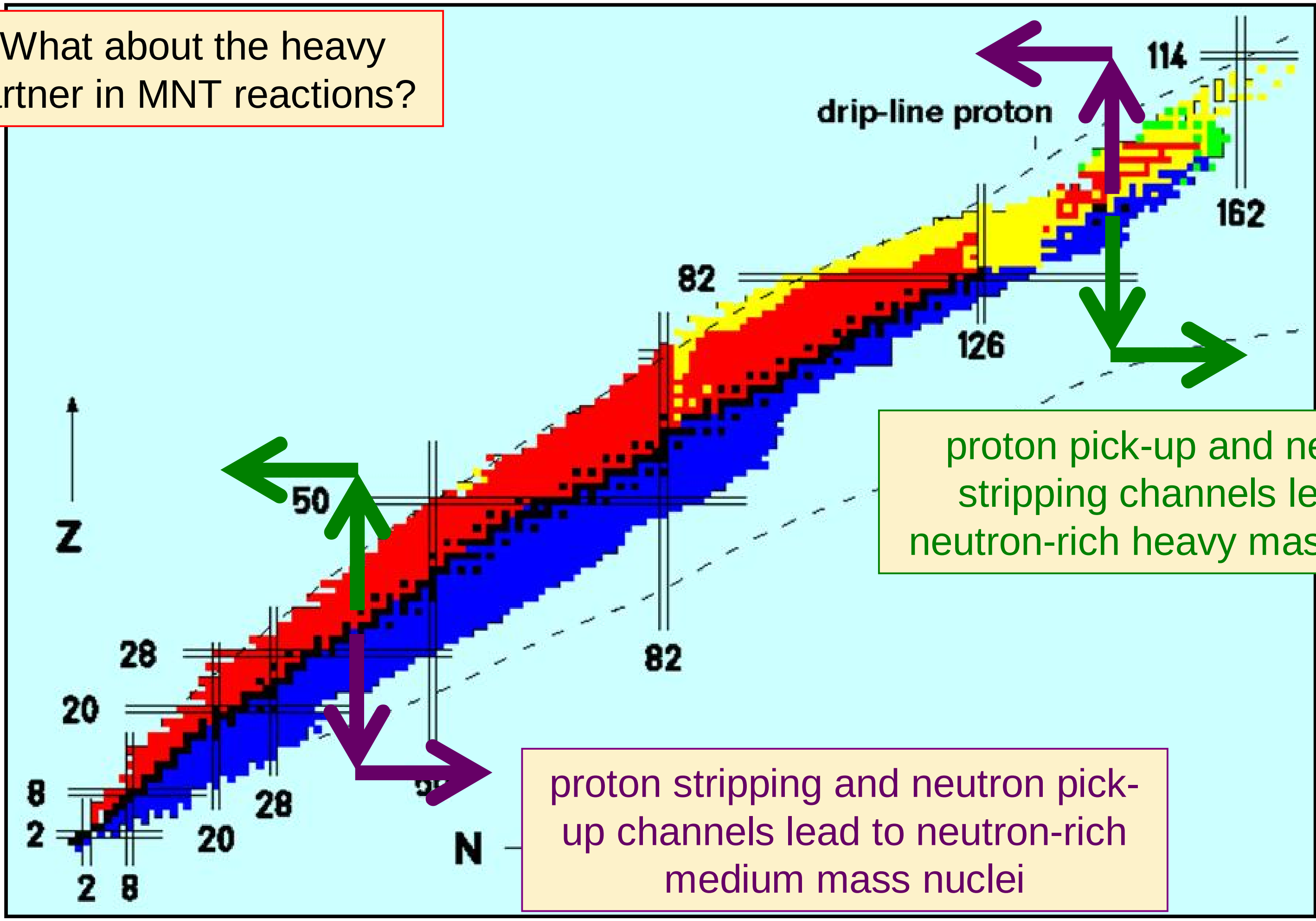


For nuclei with **N=82** on the r-process path the allowed **Gamow-Teller** (GT) **transitions are dominant**.

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.

Population of neutron rich heavy nuclei via MNT

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

Certain regions of the nuclear chart, like that below ^{208}Pb or in the actinides, can be hardly accessed by fragmentation or fission reactions, and multinucleon transfer represents a complementary mechanism to approach those neutron rich areas.

Exploring the neutron rich heavy region via MNT

Two kinds of experiments need to be done

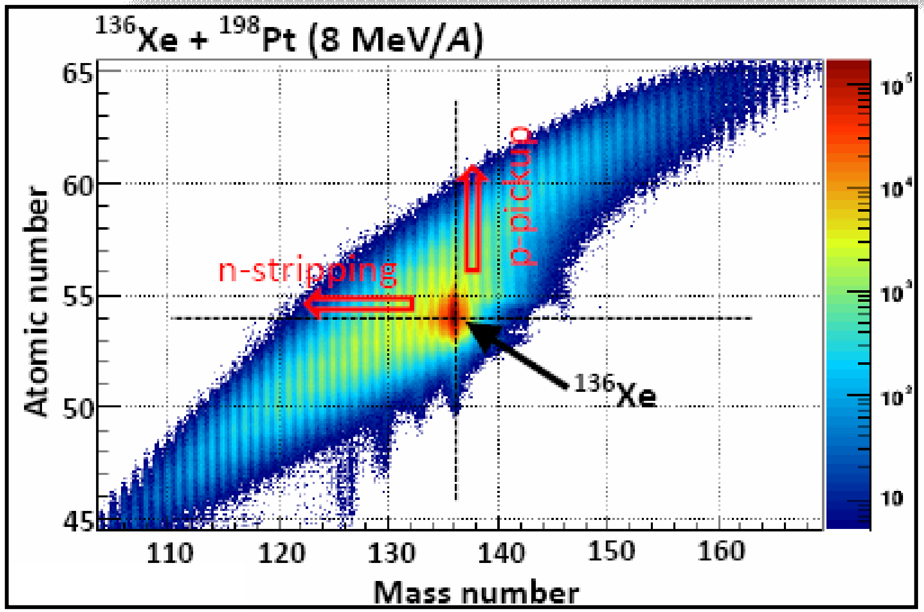
- **γ-particle coincidences**: tagging of the light partner with high resolution spectrometers and detecting coincident γ-rays Doppler corrected for the heavy partner
- **High resolution kinematic coincidences** between binary partners (direct or inverse kinematics)

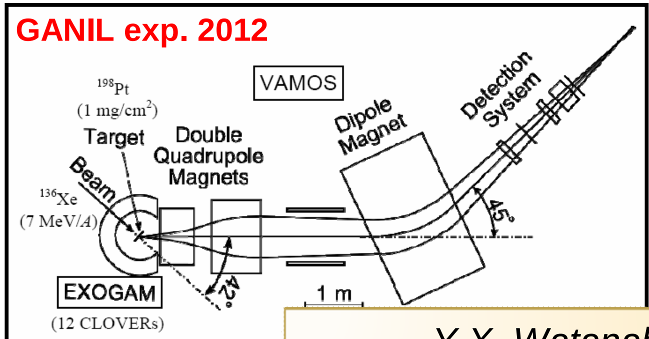
Onset of secondary processes

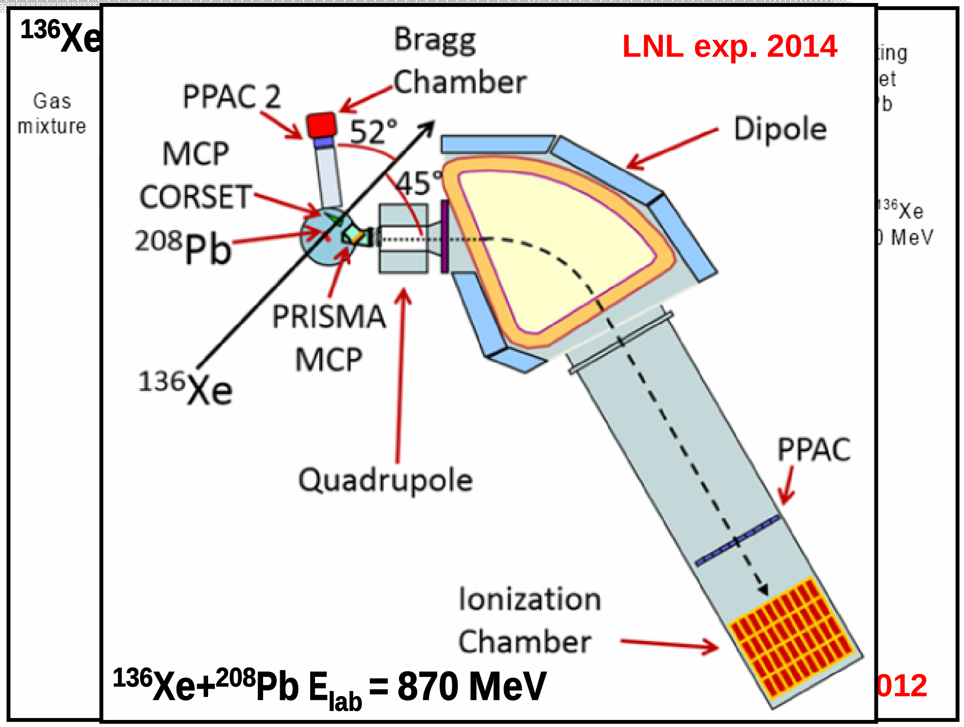
Evaporation and **transfer induced fission** shift the final yield to lower mass values. It is therefore extremely important to get quantitative information on the final yield distributions and compare them with theoretical predictions.

Exploring the N=126 region via MNT

Production of heavy neutron rich nuclei in the region of neutron closed shell N=126 populated via multinucleon transfer reactions







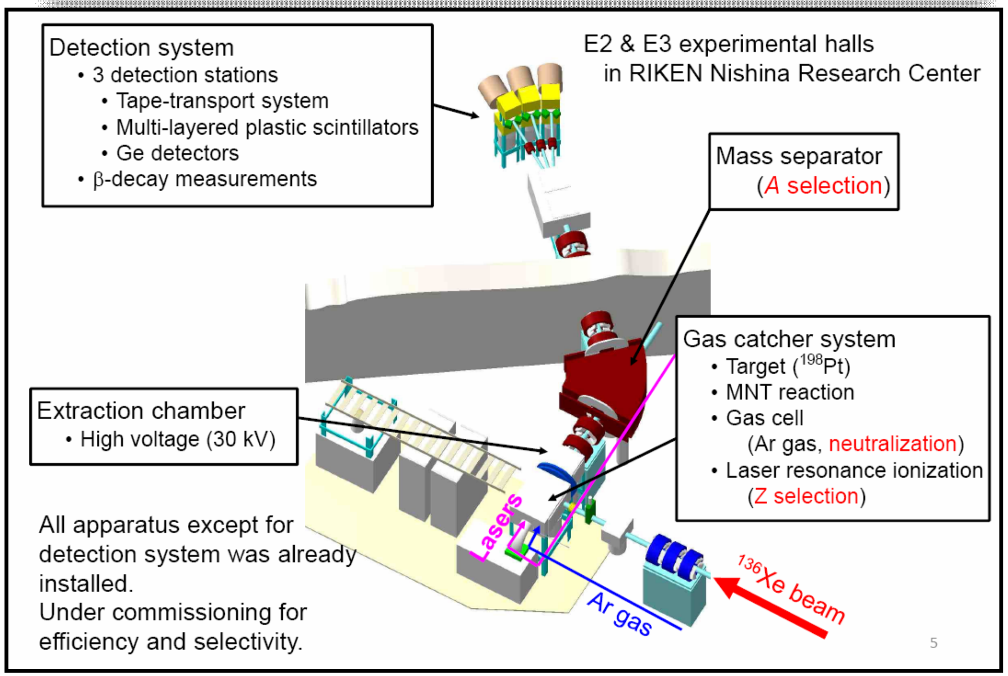
Kinematic coincidence measurement → heavy transfer reaction products below the Pb region
E.Kozulin, V. Zagrebaev et al.

Y.X. Watanabe et al., Phys. Rev. Lett 115 (2015) 172503

E. Kozulin et al., LNL Annual Report 2014

Exploring the N=126 region via MNT

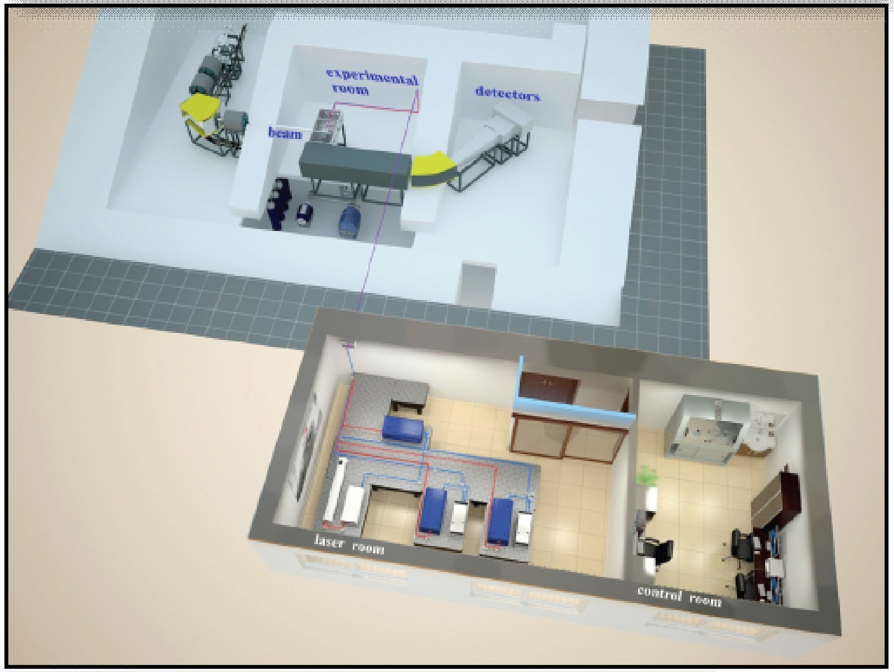
KEK Isotope Separator System (KISS) for β-decay spectroscopy of neutron rich nuclei with A~200 and N~126



KEK Laboratory, Tsukuba (J)

Y.X. Watanabe et al., 16th ASRC Intern. Workshop 18-20 March 2014 ,Tokai (J)

Gas cell and Laser ion & Separation (GaLS) setup for β spectroscopy of neutron rich nuclei at N~126



Flerov Laboratory, DUBNA (RUS)

S. Zemlyanoy et al., FUSION14 ,24-28 February 2014, New Delhi (IND)

The LNL test experiment: ^{197}Au+^{130}Te

^{197}Au+^{130}Te E_{lab}=1070 MeV

Goal: to 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 (-2*p*+4*n*) channel from ^{130}Te would lead to the benchmark nucleus ^{132}Sn

Via proton pick-up and neutron stripping one gets neutron rich nuclei around A~200.
In particular, the (+3*p*-4*n*) channel from ^{130}Te would lead to ^{198}Os and beyond

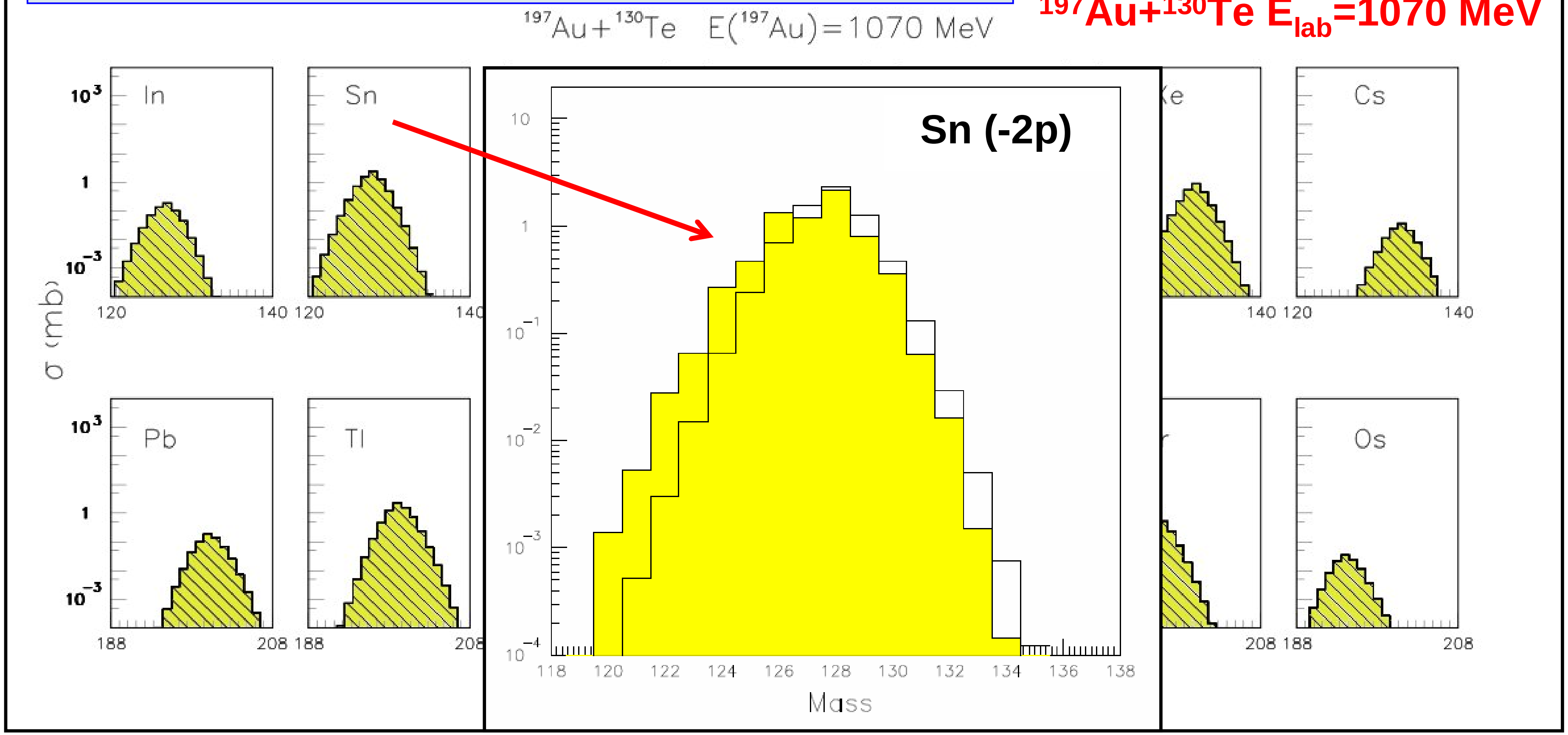
L.Corradi, E. Fioretto, S.Szilner et al., PRISMA exp.

GRAZING code calculations

$^{197}Au+^{130}Te$: theoretical total cross sections for the light and heavy transfer products

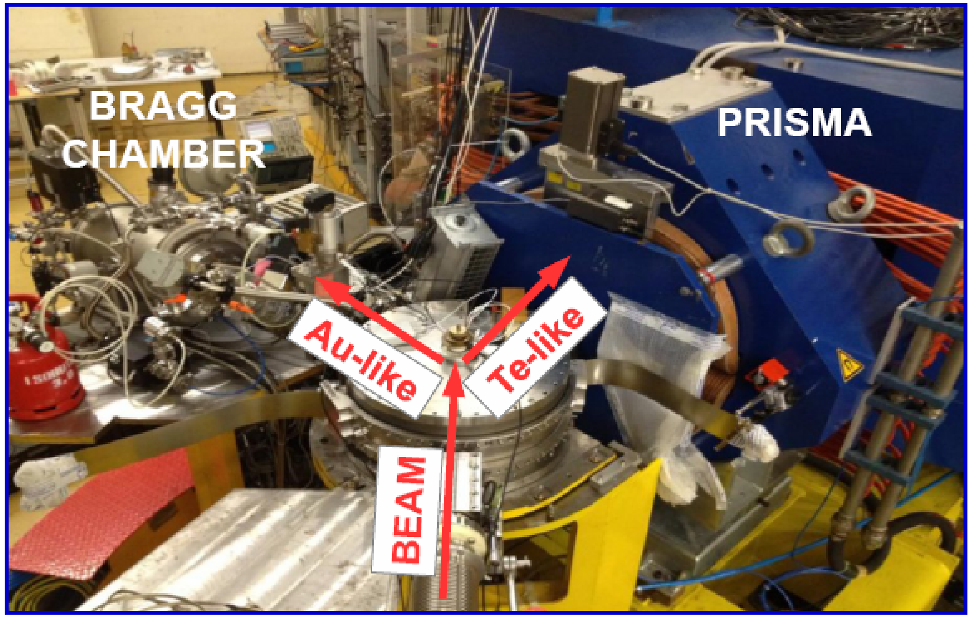
The yields of light and heavy reaction products can be directly compared

$^{197}Au+^{130}Te$ E_{lab}=1070 MeV



The second arm of PRISMA

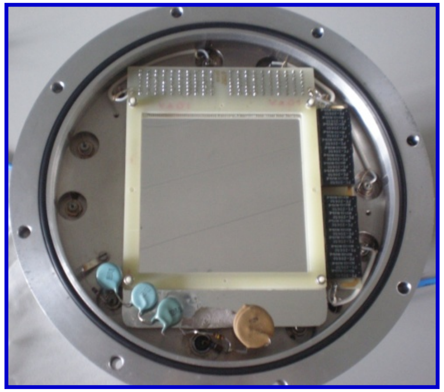
Kinematic coincidence measurements



Axial field IC

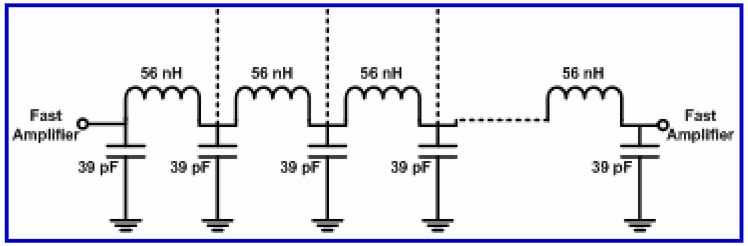
$d_{cathode\text{-}FG}$ = 32 cm
Gas : CF_4

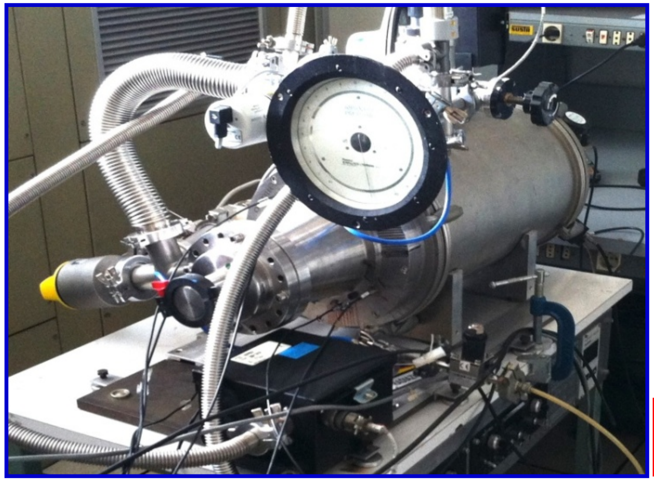
MWPPAC



$d_{cathode\text{-}anodes}$ = 2 mm
Gas : C_4H_{10}

X and Y anode wires
10 μm diameter - 1 mm
delay-line readout → 1ns

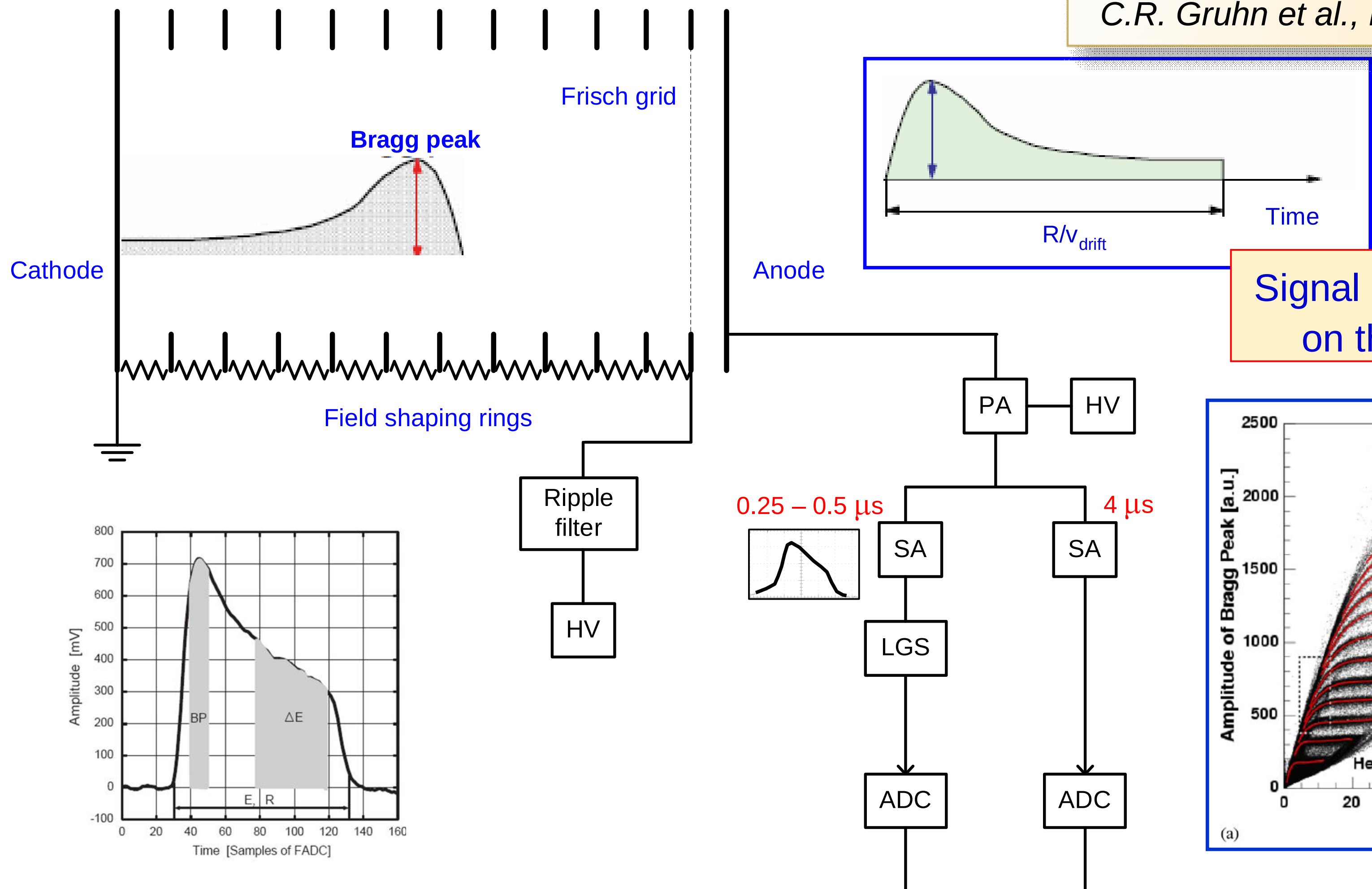




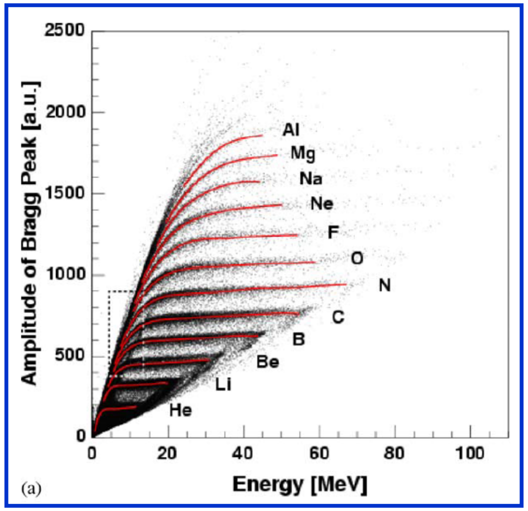
Second arm

Bragg Curve Spectroscopy

C.R. Gruhn et al., NIM 196 (1982) 33



Signal as collected on the anode



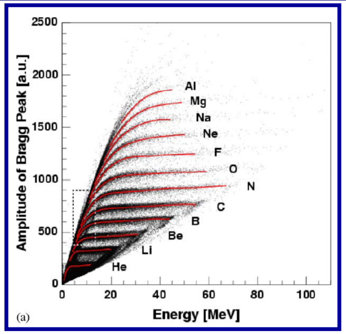
Atomic number *Z* of the fragments from the Bragg peak

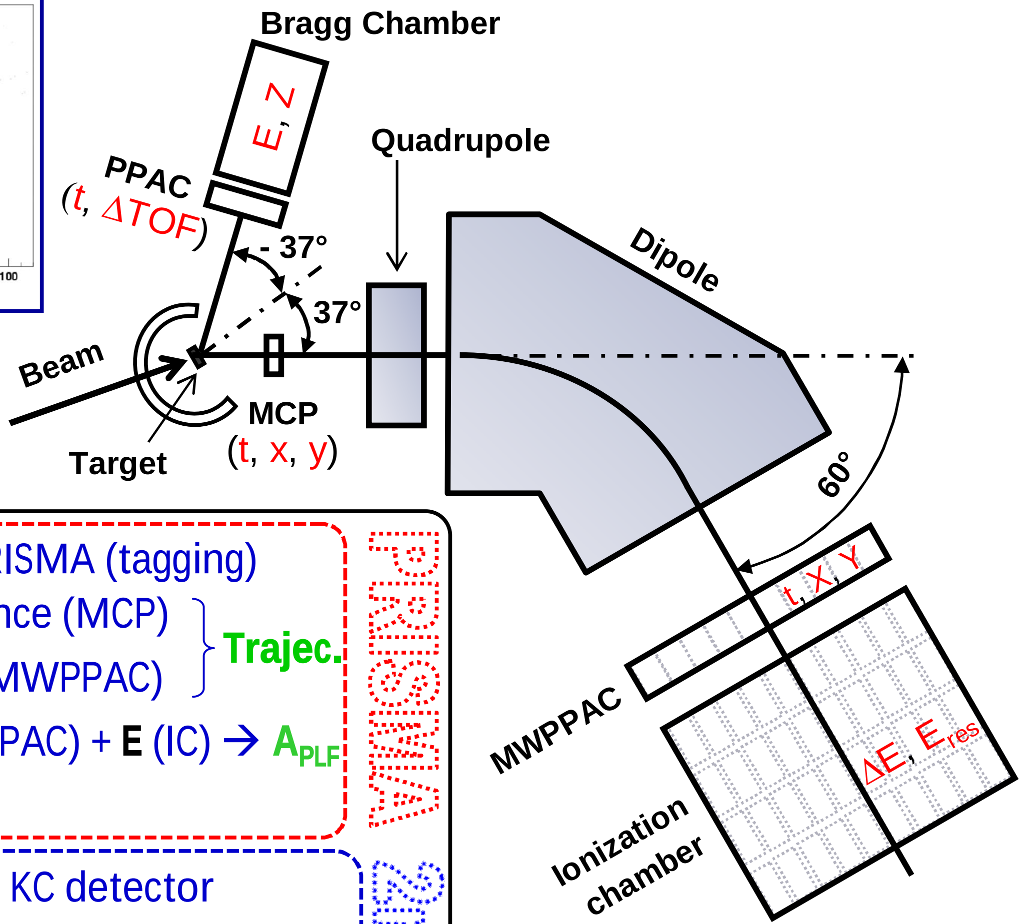
Z

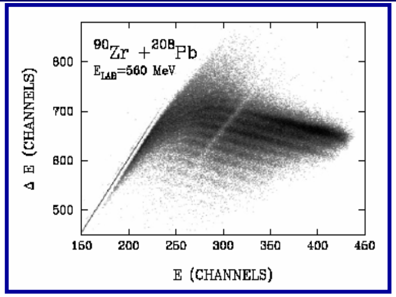
E

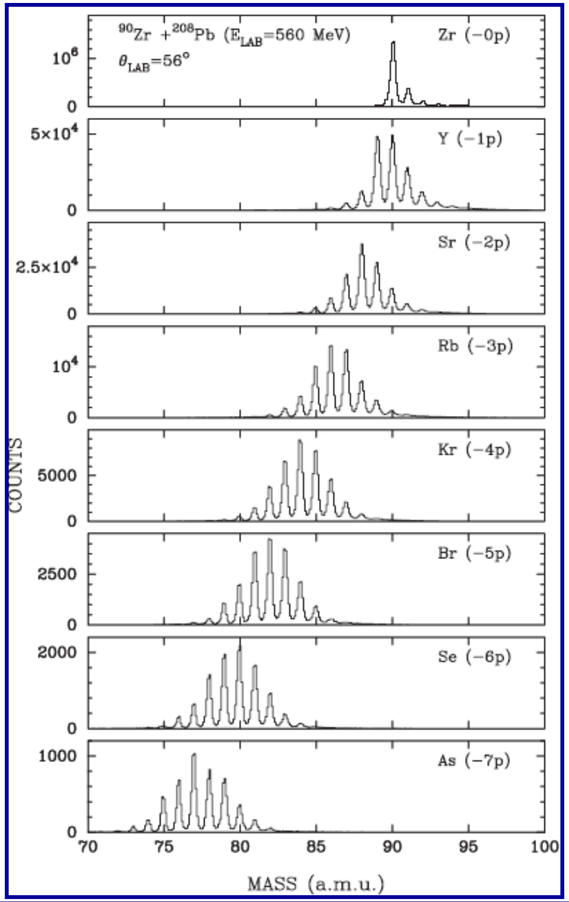
Energy *E* of the fragments from the integrated charge

Kinematic coincidence measurements









PRISMA

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

x, **y** at the entrance (MCP) } **Trajec.**

X, **Y** at the FP (MWPPAC)

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

ΔE, **E** (IC) → Z_{PLF}

2nd arm

TLF or **PLF** in the KC detector

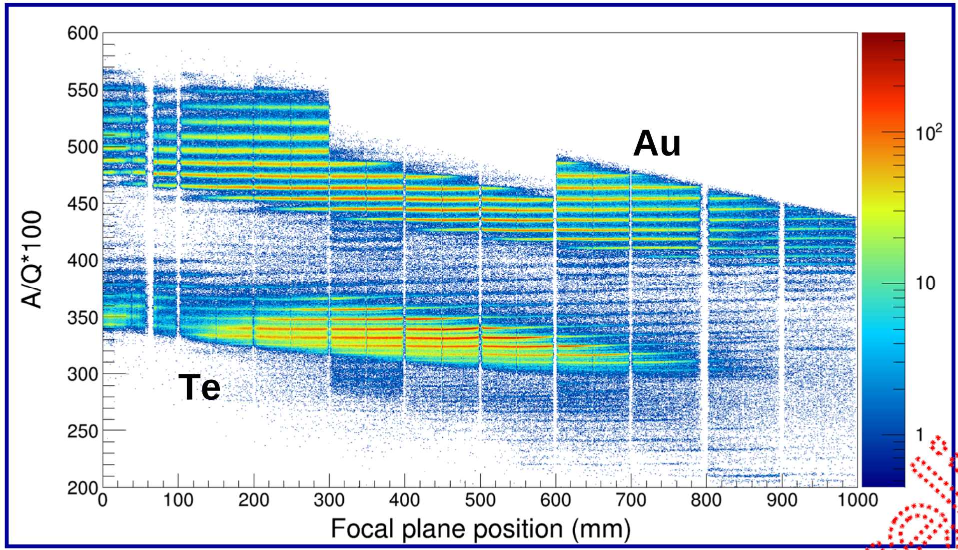
X', **Y'** at KC angle (PPAC) → θ_{TLF}, ϕ_{TLF}

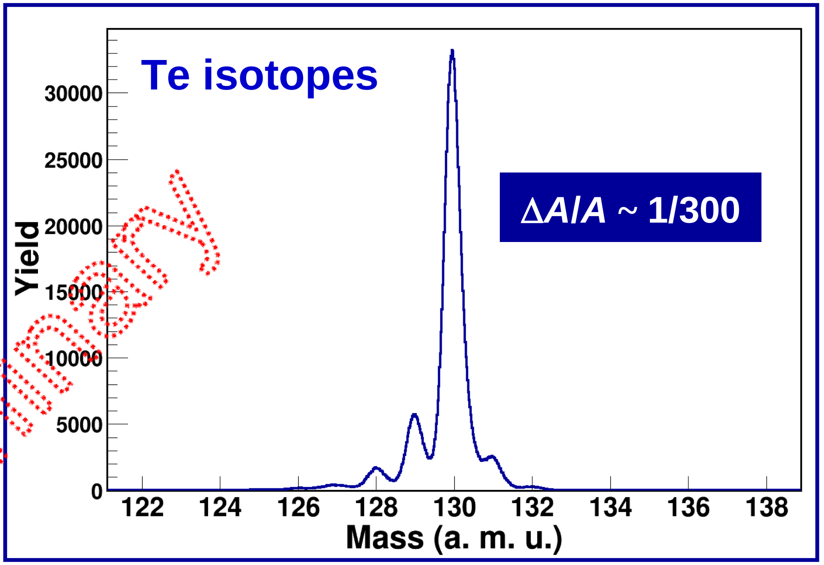
ΔTOF (MCP-PPAC)

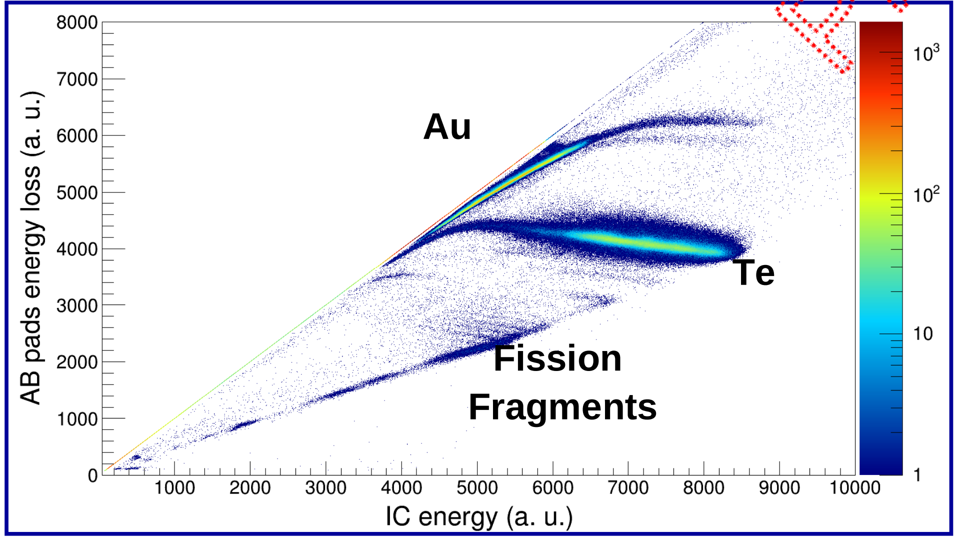
E, **Z** (BC)

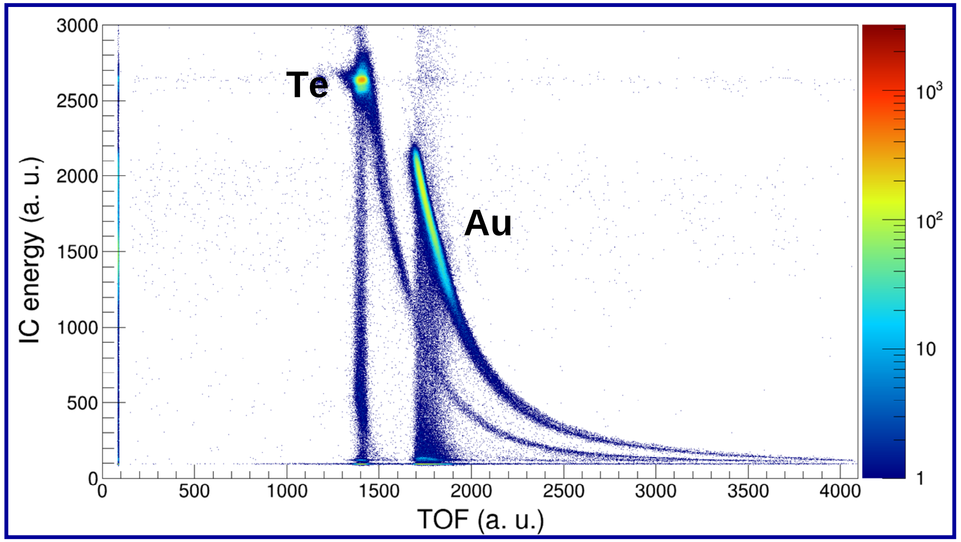
→ **PLF-TLF discrimination**

Preliminary results : $^{197}Au+^{130}Te$









Summary

- **Sub-barrier transfer**
  - **Inverse kinematics reactions have been studied with the magnetic spectrometer PRISMA at forward angles in order to have recoils with enough kinetic energy and good efficiency.**
    Transfer probabilities are well reproduced for the first time with heavy ions (in absolute values and in slope) by microscopic calculations which include nucleon-nucleon correlations.

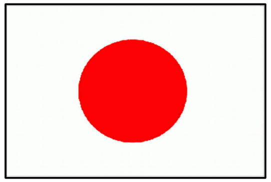
- **Population of neutron rich heavy nuclei via MNT reactions**
  - **A test experiment has been carried out at LNL to populate neutron rich nuclei close to A ~ 130 and A ~ 200. To this end a second arm has been installed in target area of PRISMA for kinematic coincidence measurements.**
    Good quality data have been collected and the analysis of the heavy partner is still in progress.
  - **In-beam tests of the BC coupled to digital electronics have been carried out in order to extract additional parameters such as the range *R*. Algorithms are being developed in order to improve the *Z* resolving power.**

Collaborations

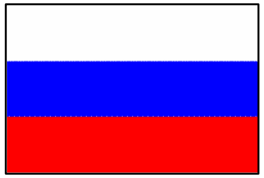
E. Fioretto, L. Corradi, S. Szilner, D. Montanari,
T. Marchi, G.Pollarolo, A.M. Stefanini, G. Montagnoli,
F. Scarlassara, S. Courtin, A. Goasduff, F. Haas,
D. Jelavic-Malenica, C. Michelagnoli, T. Mijatovic,
N. Soic, C. Ur, J.J. Valiente-Dobon

INFN – Laboratori Nazionali di Legnaro, Italy
Università di Padova and INFN, Italy
Ruđer Bošković Institute, Zagreb, Croatia
Università di Torino and INFN, Italy
IPHC, Strasbourg, France
IFIN-HH, Bucharest, Romania

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



KEK -Tsukuba



FLNR - Dubna