From light to heavy nuclear systems, production and decay of fragments studied with powerful arrays

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For the **NUCL-EX FAZIA** collaboration

UNIVERSITAS IAGELLONICA CRACOVIENSIS

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II International Symposium on Applied Nuclear Physics and Innovative Technologies

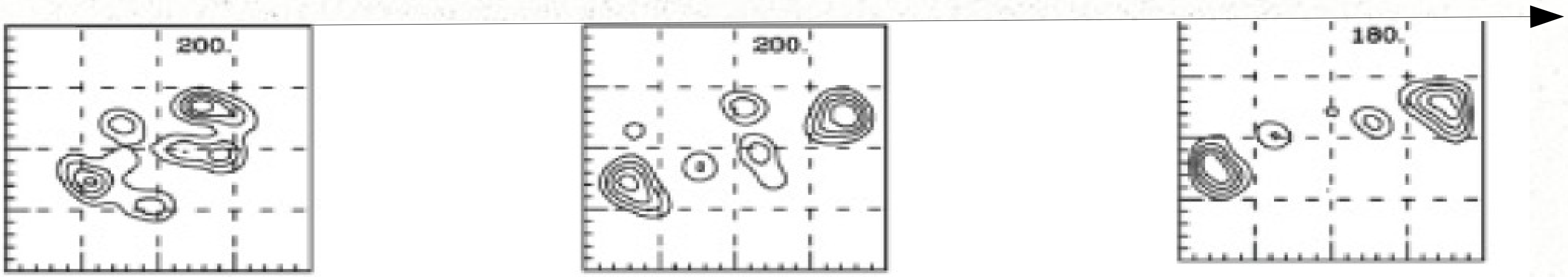
outline

- fragments in nuclear collisions
- links with other fields: from stellar explosions to medicine
- mechanisms of fragment production in ion collisions
- powerful detectors at work: **FAZIA** and **GARFIELD**
- two examples of our recent activity within the **FAZIA** (heavy systems) and **NUCL-EX** (light systems) collaborations

FRAGMENTS in nuclear collisions

In nuclear collisions, fragments or clusters can originate together with simpler particles (n,p,d,t). Their sources and characteristics are different depending on the bombarding energy, the sizes of the system and the impact parameter

Central collisions Semi Central collisions



b=2fm V. Baran PRC 85 2012 Sn+Sn 50MeV/u b=6fm

SMF calculations

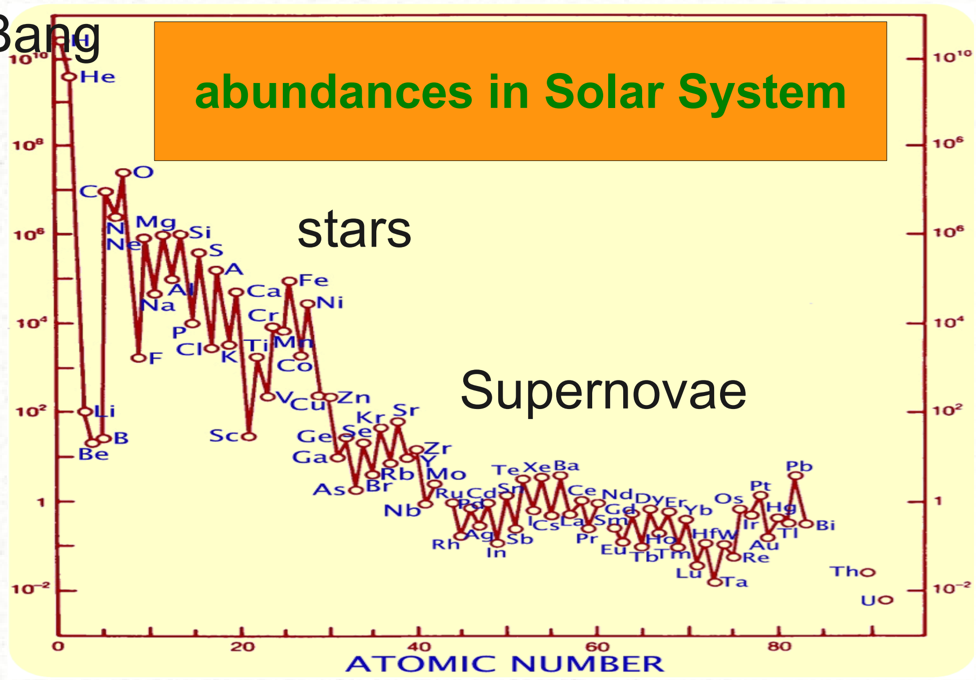
Facilities for exotic nuclei are under development and they have favoured a renewed interest

FRAGMENTS in the Cosmos

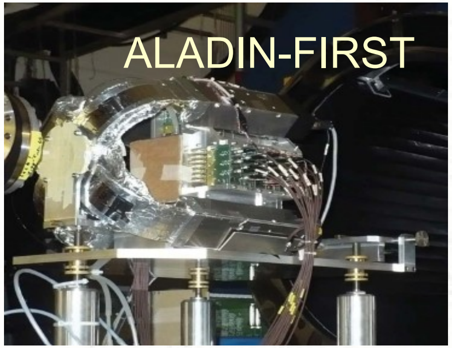
Many nuclei heavier than iron are produced in Core-Collapse Supernovae (r-process)

The environment of exploding stars is modeled through the nuclear EOS which gives the energy density vs. macroscopic parameters

$E=E(\rho,\delta)$



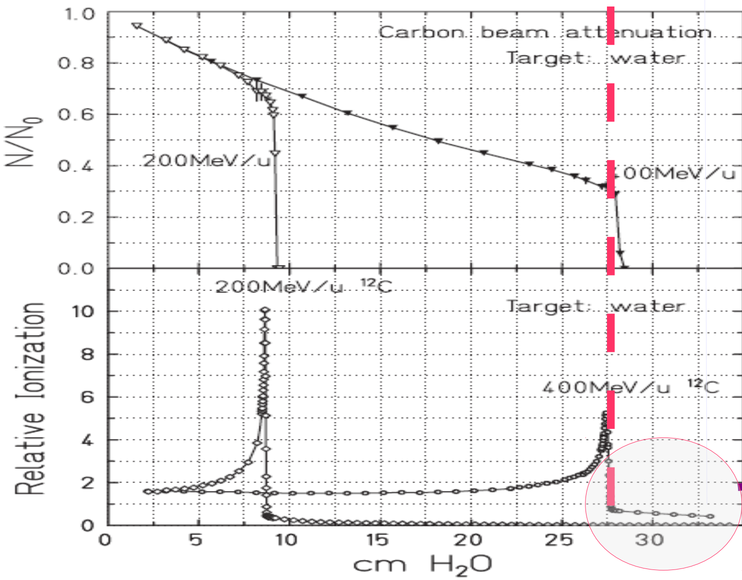
We can use nuclear reactions in order to approach the conditions supposed to be present in the astrophysical objects where fragments are produced in exotic conditions ($T,\rho,N/Z$, electron densities)

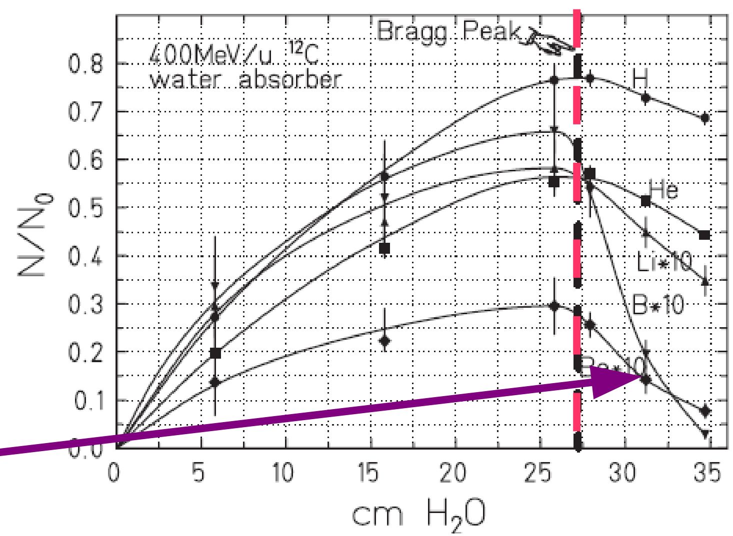


FRAGMENTS in radiotherapy

Fragments of Interest in medicine:
hadron RADIOTHERAPY

Fragmentation in Ne,C energetic radiotherapy beams is responsible for dose delivery after the Bragg Peak (BP).
Li,B,Be indeed contribute beyond the BP



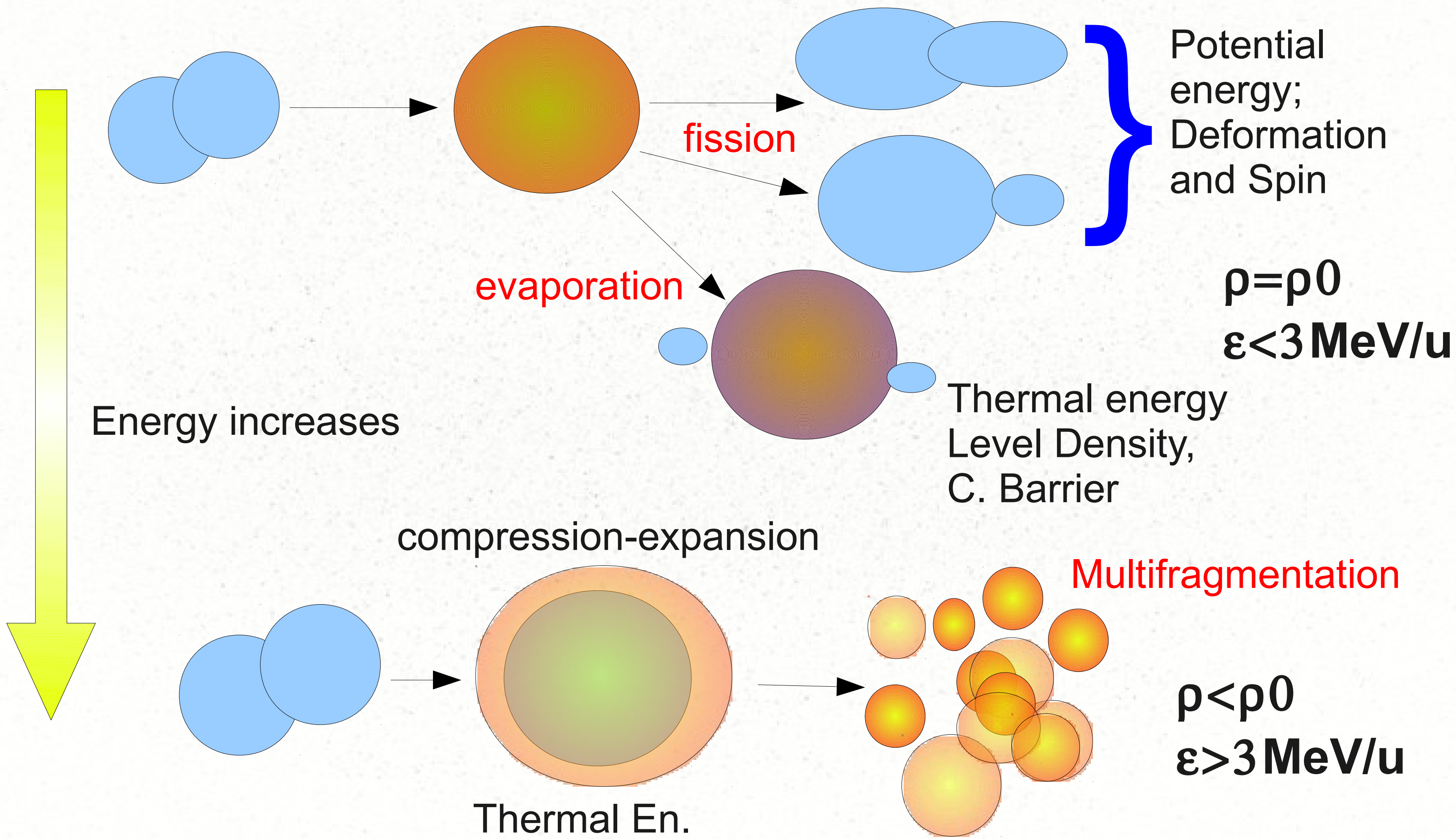


Recently: a new detector-collaboration ALADIN-FIRST at GSI on this subject

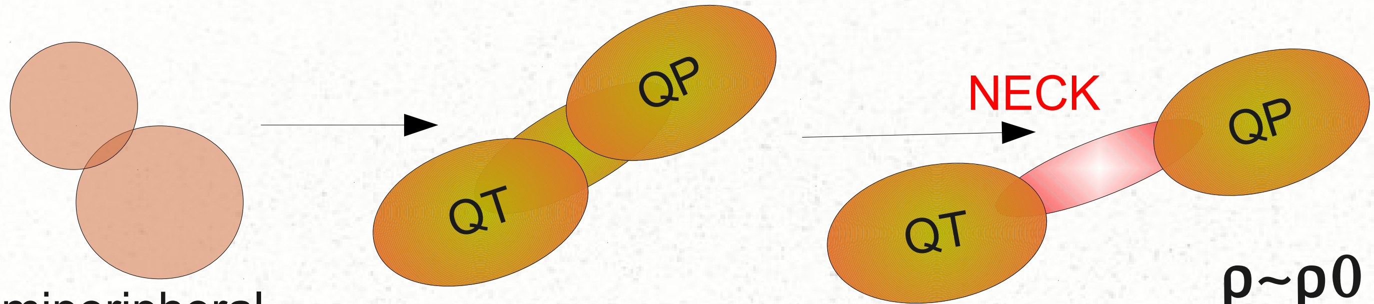
figures from **Haettner et al Rad.Prot.Dos 122 (2006)**

A look at (some) fragment production mechanisms

Origin of FRAGMENTS in ion collisions (1)



Origin of FRAGMENTS in ion collisions (2)



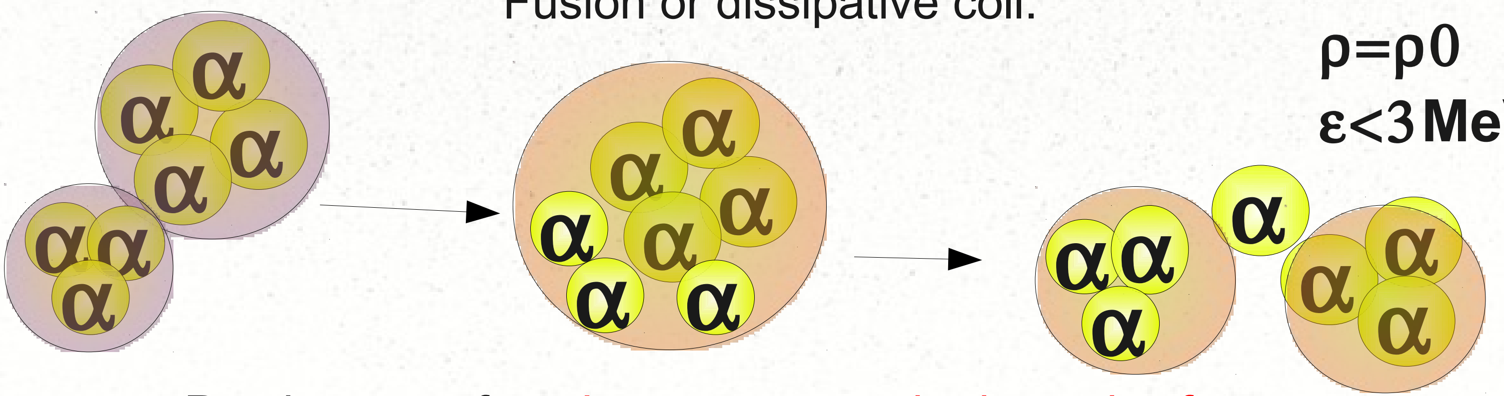
Semiperipheral
Energetic Collisions

Kinetic to Potential:
Deformation and Surface Energy;
Spin and isospin contributions

$\rho \sim \rho 0$
$\varepsilon => 3$ MeV/u

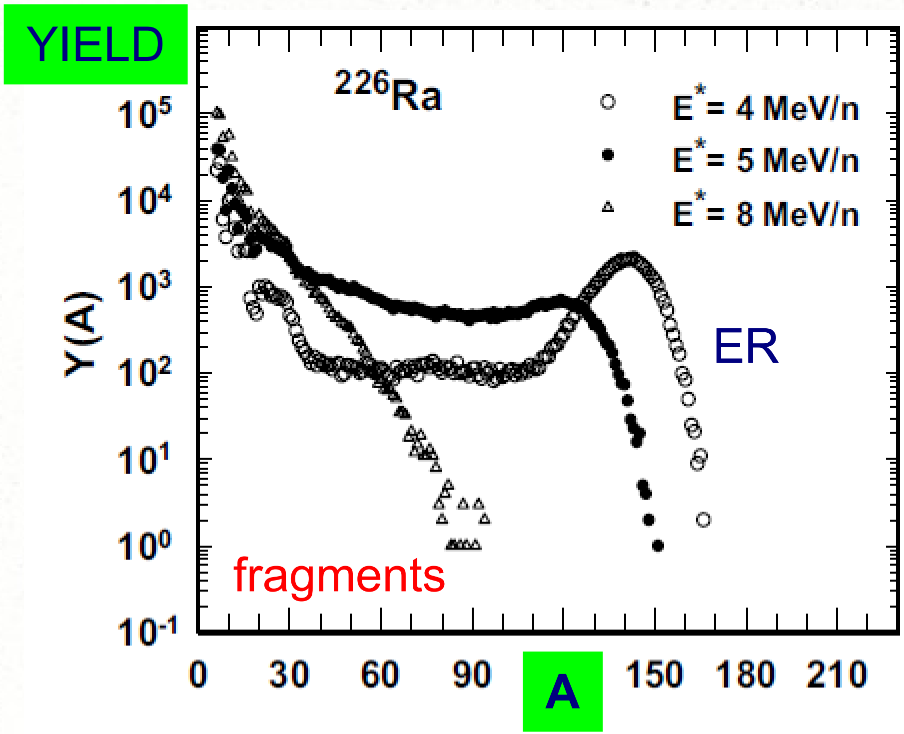
Fusion or dissipative coll.

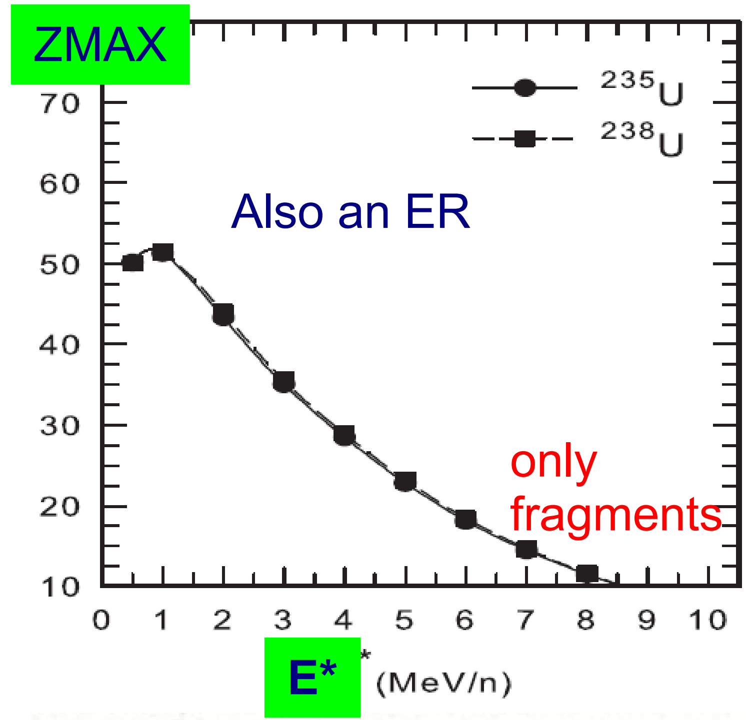
$\rho = \rho 0$
$\varepsilon < 3$ MeV/u



Persistence of α–cluster structure in dynamics features

FRAGMENTS from big sources

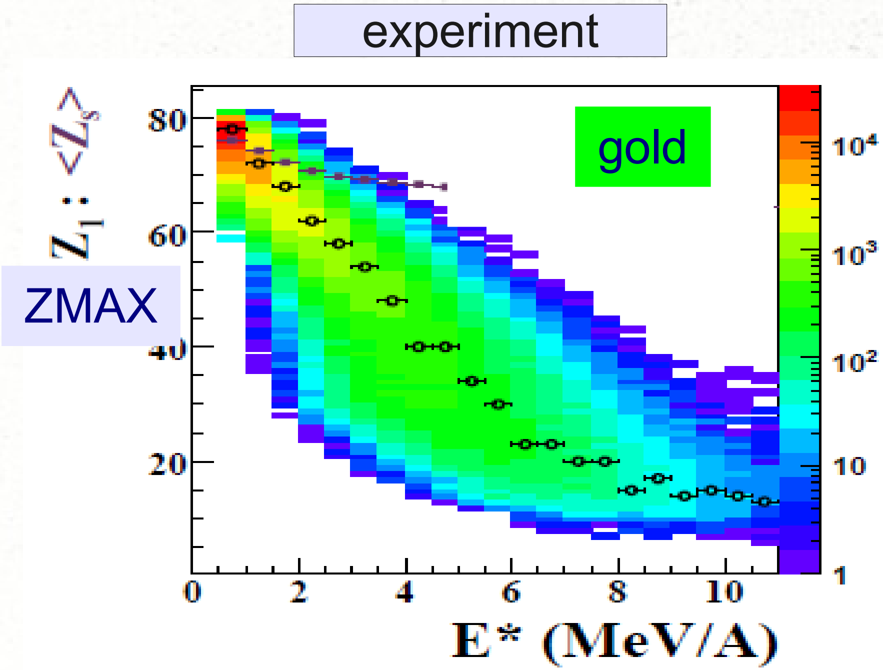


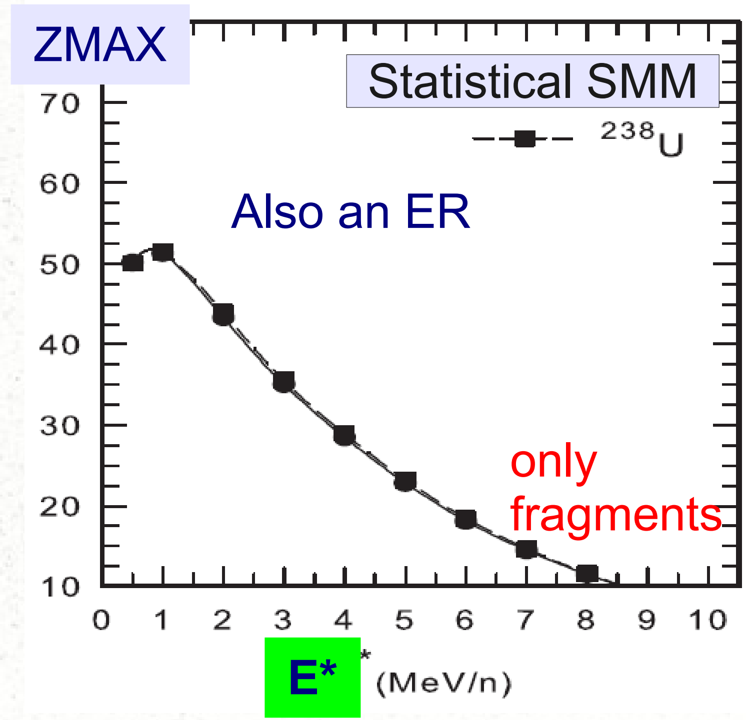


SMM Calculations Radon nuclei at various energy densities
N Eren et al. ArXiv nuclth-0706-2952v1

SMM Calculations Uranium isotopes: from fission to fragmentation vs. energy densities
N Eren et al. JoP Conf.Ser 436, 2013

FRAGMENTS from big sources





INDRA data Au+Au 100MeV/u
From F Gulminelli Proceedings Nobel Symposium 152, 2012 (ref. therein)

SMM Calculations Uranium isotopes: from fission to fragmentation vs. energy densities
N Eren et al. JoP Conf.Ser 436, 2013

Isotopic separation of fragments

Information on the EOS can be extracted from isotopic yields of fragments. They are produced HOT but are measured COLD

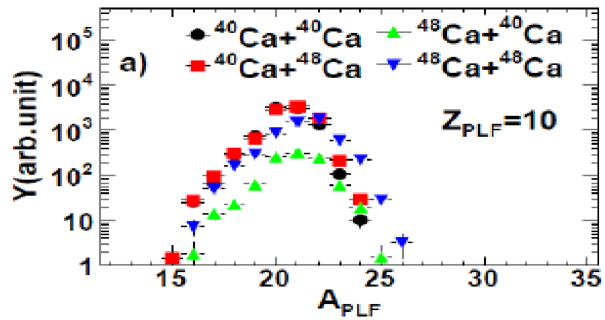
For instance concerning the Symmetry Energy **C(Z)** of the EOS we can use isoscaling

Isoscaling is based on the ratio of isotopic production yield Y(N,Z) and need the measurement of two systems with different N/Z

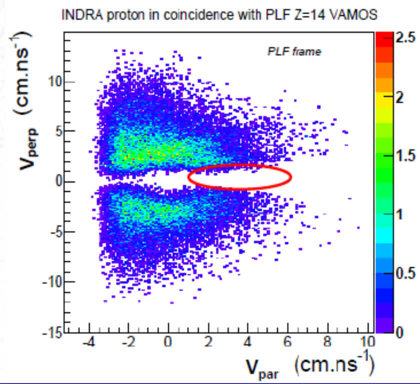
$$Y_2(N,Z)/Y_1(N,Z) \propto e^{\alpha N+\beta Z}$$

$$\frac{\alpha}{[Z/\overline{A}_1(Z)]^2-[Z/\overline{A}_2(Z)]^2} = 4C(Z)/T$$

INDRA VAMOS exp



Ca reactions at 35MeV/u



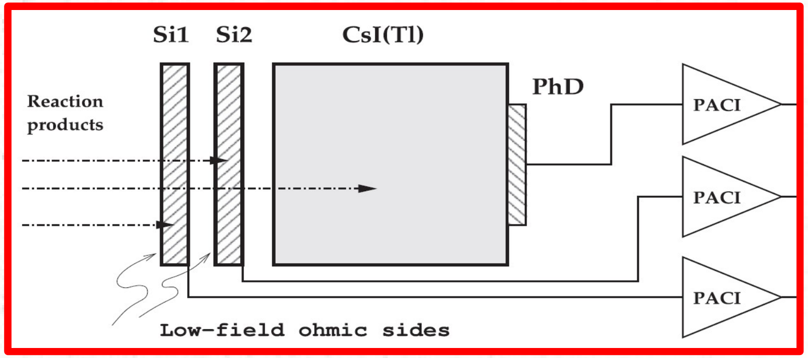
Detect all particles in coincidence with a given QP to access primary quantities......

The FAZIA experiment

GOAL: improve ion identification capabilities of Si-based telescopes while keeping energy thresholds low

METHOD

- Improving **silicon and CsI** properties and features
- Optimizing **digital sampling electronics**
- Looking for best identification **algorithms** and variables
- Push at the limits **$\Delta E - E$ and Pulse shape analysis (PSA)** techniques



Silicons
20x20mm2
nTD type
ρ~3-4000 ohm*cm
300 and 500 μm
7deg cut off <100>

CsI(Tl)
20x20mm2 tapered
1500-2000ppm Tl-doping
Uniform doping
10 cm thick

PHASES

- **R&D** on materials, mounting configuration, digital methods 2006-2012
- **Construction** of a versatile multidetector (2013-2015)

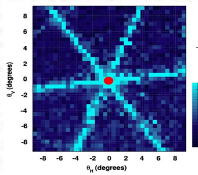
The FAZIA experiment

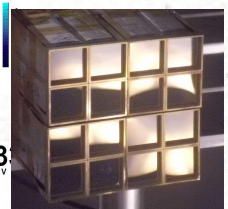
- **R&D on Si and CsI(Tl), mounting configuration, digital methods**
- **Strong improvements on Digital Pulse shape analysis and ΔE–E**
- **FAZIA 'recipe' for Silicons: concerns silicon doping homogeneity: crystal orientation, metal deposition.**

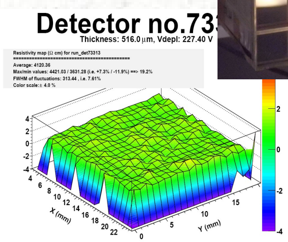
Avoid channeling

Specific Al deposition (20-30 nm) no passivation

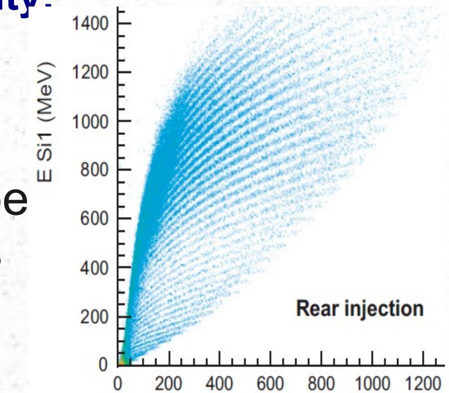
Selecting homogenous (doping) bulk



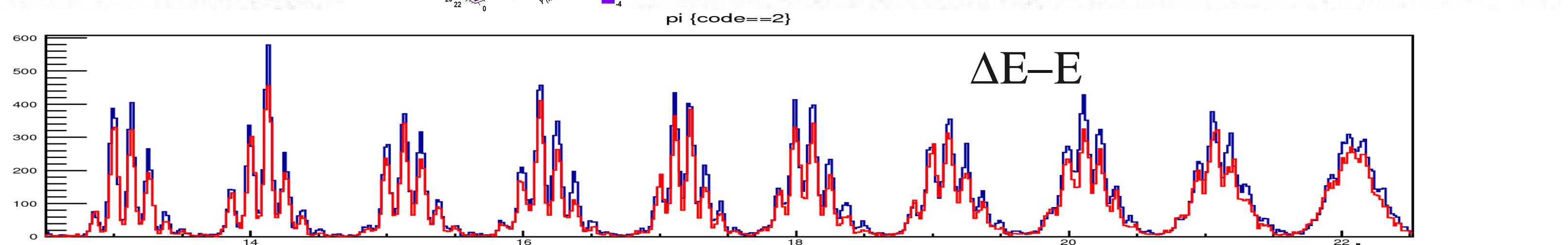




Reducing signal shape fluctuations



PULSE SHAPE ANALYSIS



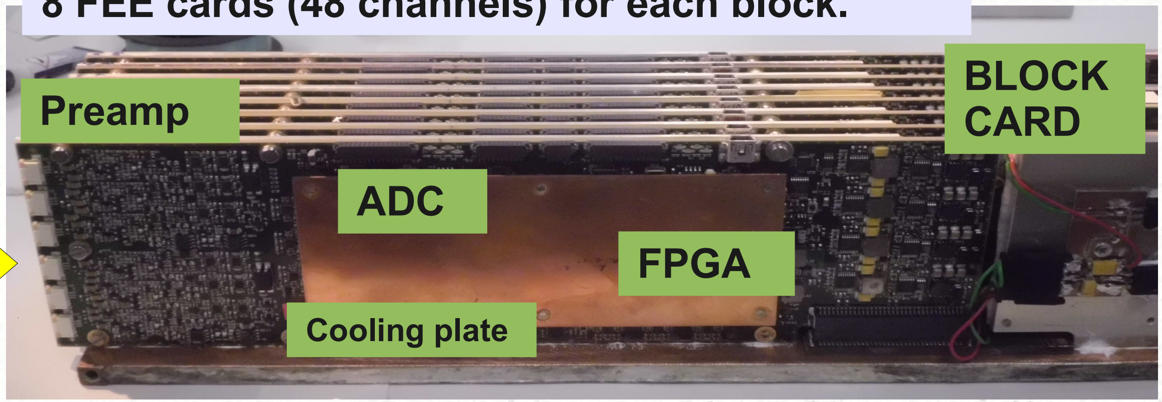
13 20 charge

An innovative Front End electronics

IPN Orsay
INFN Naples, Florence

8 FEE cards (48 channels) for each block.

detectors



Optical fiber

To DAQ boards

- Stage 1 (silicon 300 µm)
  - Charge 250 MeV full scale 250 Ms/s 14 bit
  - Charge 4 GeV full scale 100 Ms/s 14 bit
  - Current 250 Ms/s 14 bit
- Stage 2 (silicon 500 µm)
  - Charge 4 GeV full scale 100 Ms/s 14 bit
  - Current 250 Ms/s 14 bit
- Stage 3 (CsI + photodiode)
  - Charge 4 GeV full scale 100 Ms/s 14 bit

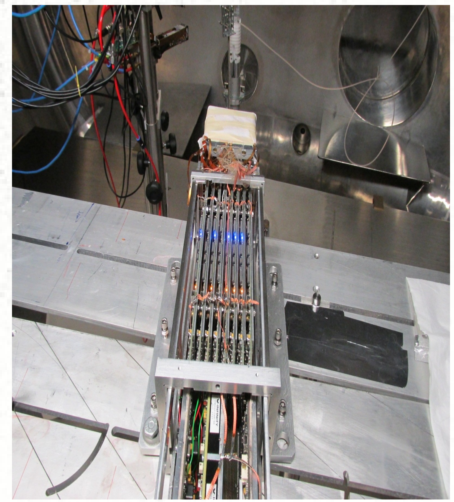
Embedded Logics

- Trigger
- Memories & buffers
- Communication

Embedded functions

- Pulser to all chan
- Generation and regulation of bias V

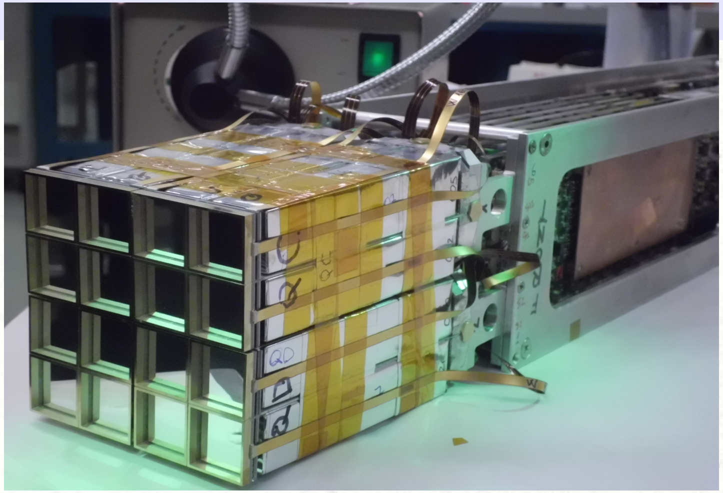
Pulser to all chan
Generation and
regulation of bias V



Under vacuum operation!

Building the FAZIA array

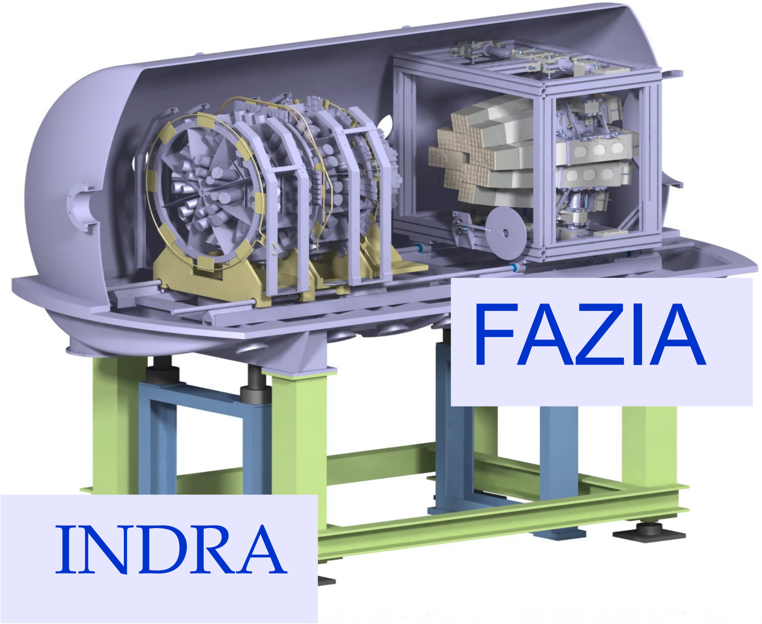
A block of 16 telescopes



Blocks at 100cm distance
Each block: 6.4msr solid angle

- Next year experiments with 4 blocks
- >2017 12 blocks coupled with INDRA

192 telescopes
12 Blocks
16 telescopes /block
48 channels /block



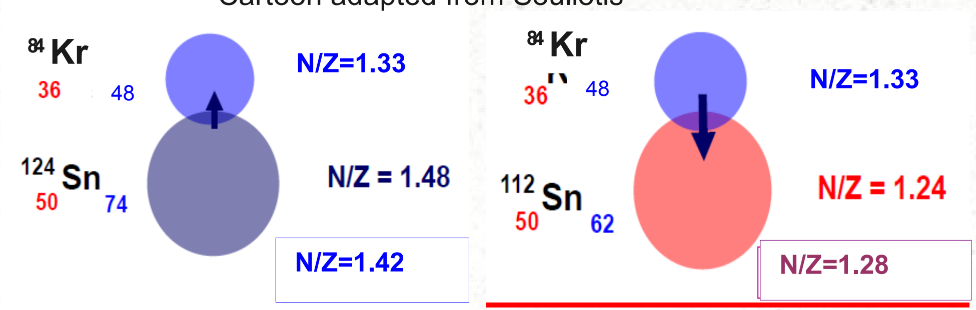
Isospin related phenomena in semi-central nuclear collisions

Barlini et al C 87, 054607 (2013)

$^{84}Kr + ^{112,124}Sn$
35MeV/u @LNS

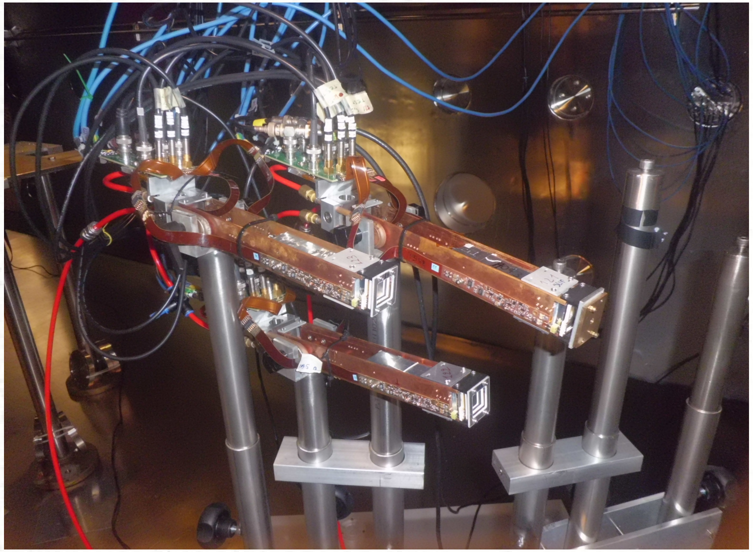
Comparing neutron content of fragments from the QuasiProj (QP)

Cartoon adapted from Souliotis



NZ of QP increas

N/Z of QP decreases



Si-Si-CsI(TI) Telescopes of the FAZIA collaboration

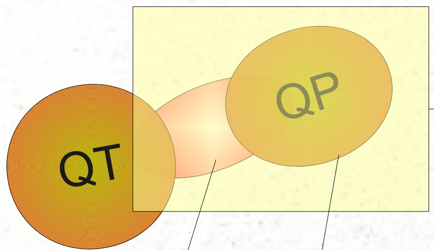
Quasi-projectiles and intermediate mass fragments (IMF)

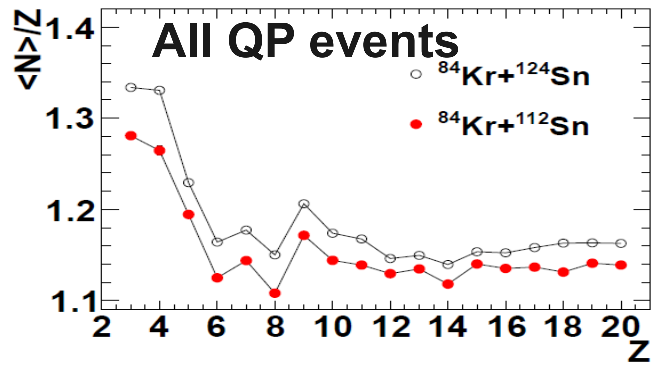
Isospin related phenomena in semi-central nuclear collisions

Barlini et al C 87, 054607 (2013)

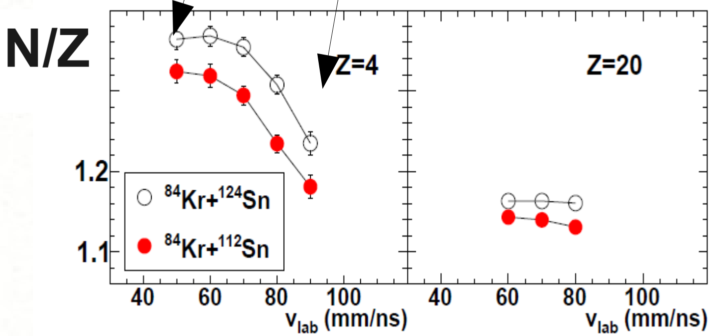
84Kr+ 112,124Sn 35MeV/u

Telescope angles select the QP phase-space





midvelocity forward



OBSERVATIONS

1) isospin diffusion between QP and QT (target effect)

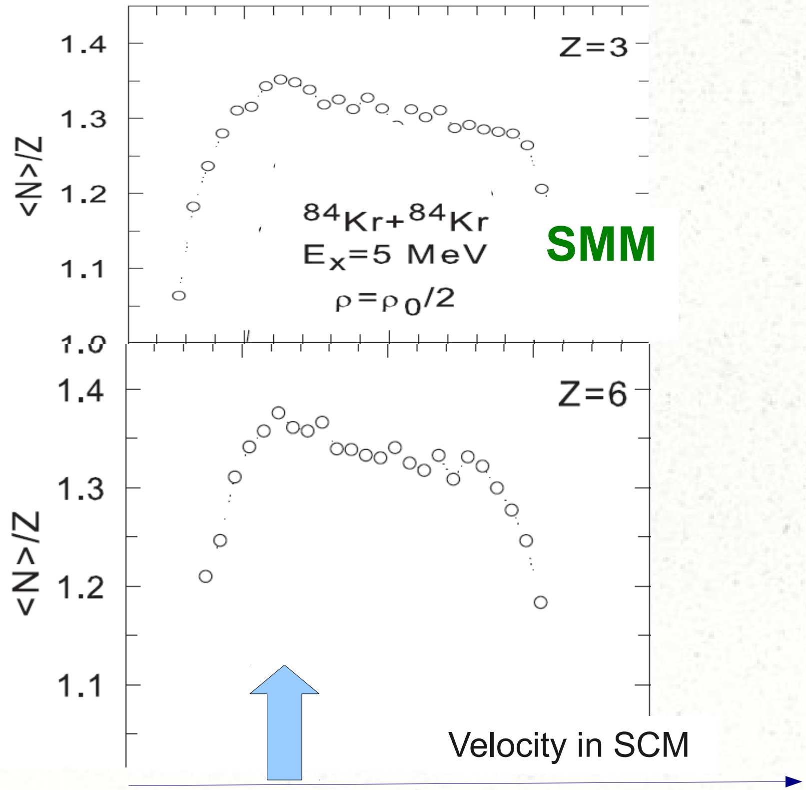
2) for IMF neutron content increases from QP to midvelocity (two origins of IMF)

3) the N/Z of big fragments is quite constant vs. velocity (QP fission)

Connections with E_{sym} in MODELS!

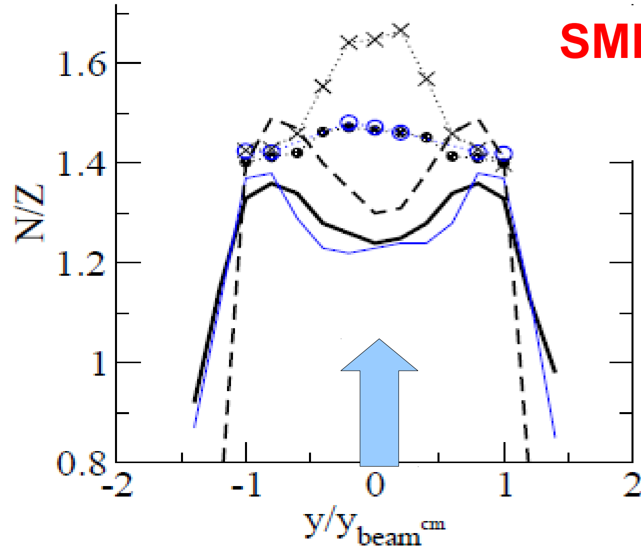
Statistical or dynamic interpretation of N/Z increase at midvelocity

Adapted from
A.Ergan et al ArXiv 1408.2840v1



PROXIMITY and ANGULAR MOMENTUM effect

124Sn+124Sn@50MeV/u



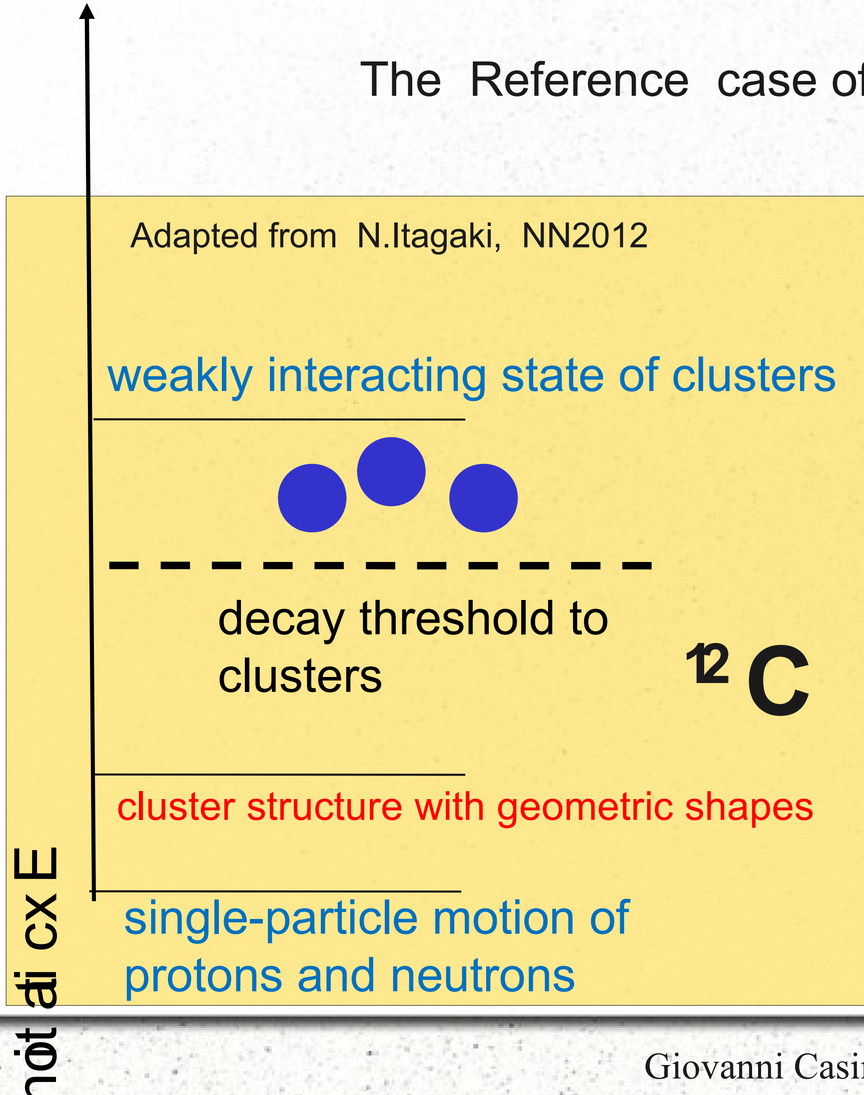
M.Colonna et al ArXiv 1209.1542v1

Sensitivity to Esym in the EOS

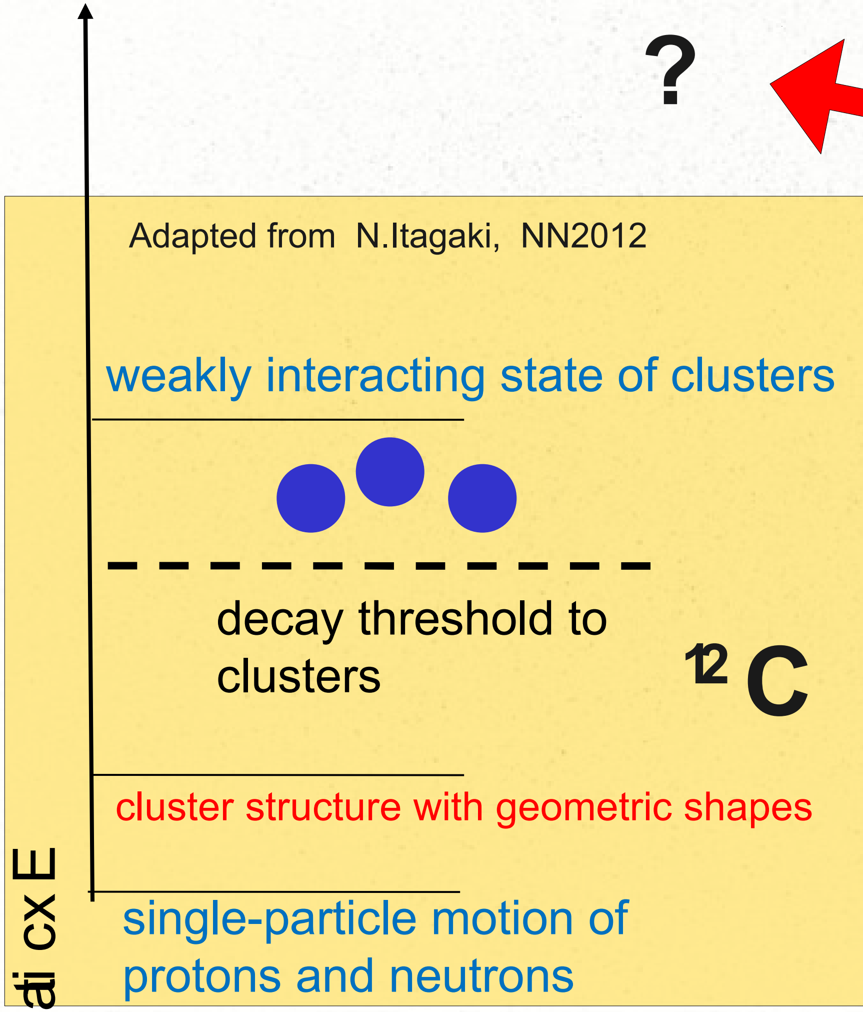
Indicates midvelocity region

looking for α–cluster effects at 'high' excitation

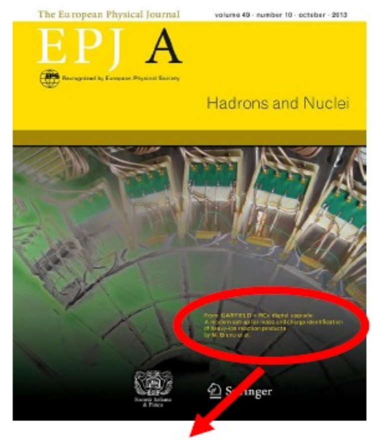
The Reference case of ^{12}C



looking for α–cluster effects at 'high' excitation



Is there persistence of α-cluster effects in N=Z systems going well above the threshold for particle emission?

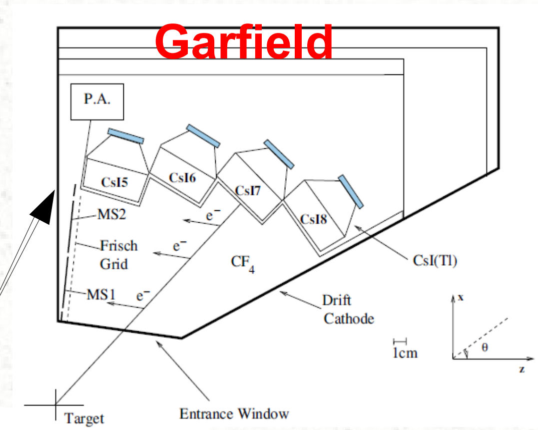


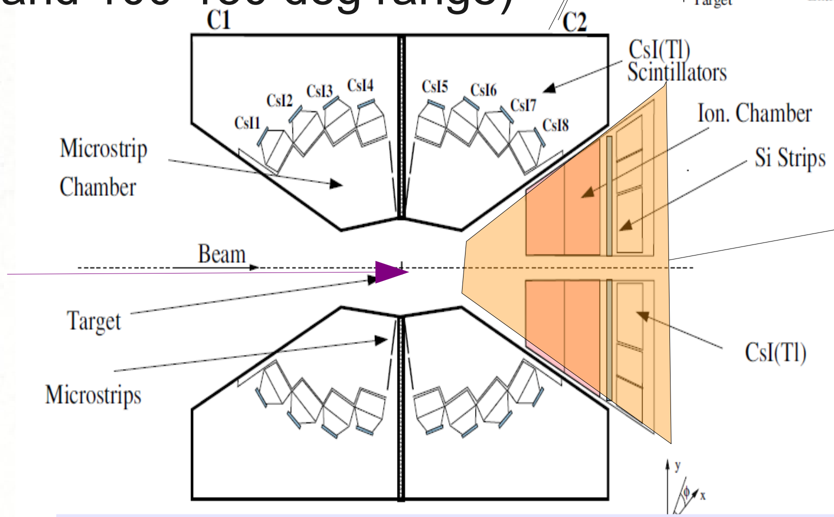
GARFIELD + RCo digital upgrade.....

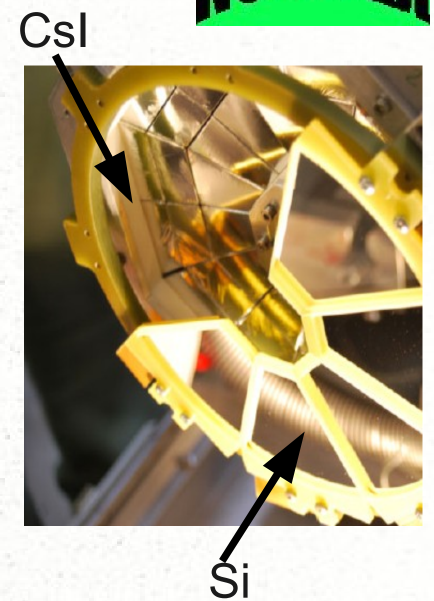
Let's use our apparatus at LNL (Padua, Italy)!

The Garfield+Rco detector at LNL (1)

- Two ΔE–E gas Chambers-CsI
- ΔE stage with gas multiplication
- Azimuthal symmetry: 48 sectors in PHI
- 8 rings in THETA (30-80 and 100-150 deg range)







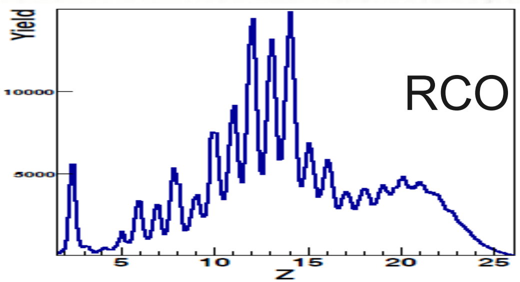
RCO

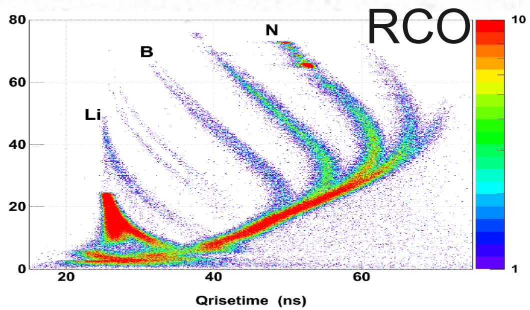
- Three layer ΔE–ΔE–E gas Chamber- Si-CsI telescopes
- Azimuthal symmetry
- Si-strips, 300μm, reverse mounted, nTD

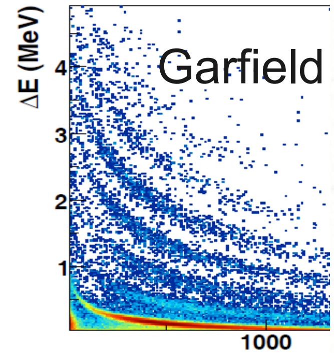
All channels with fast digital electronics

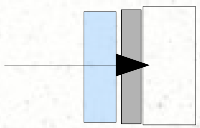
Bruno et al EPJ A 49, 2013

The Garfield+Rco detector at LNL (2)

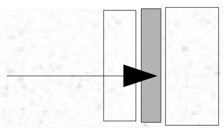




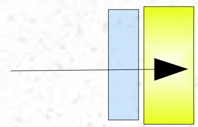




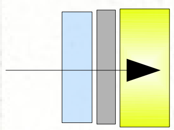
Slow/heavy ions
ΔE–E gas-Si

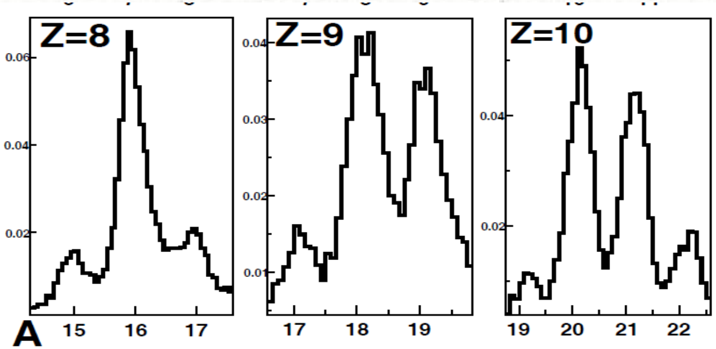


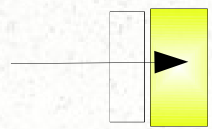
Ions stopped in Si
identified via PSA

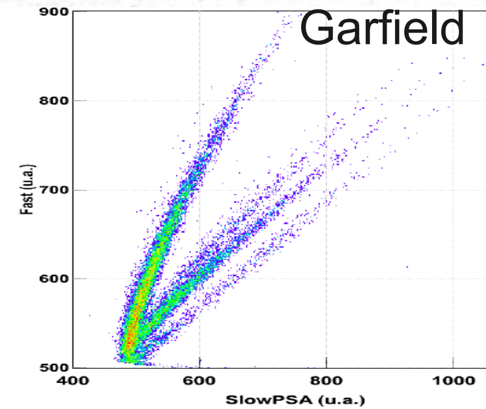


heavy fragments and
particles in ΔE–E gas-CsI









Isotopic separation for QP from Si-CsI

fragments and particles in
PSA in -CsI

looking for α-cluster effects at 'high' excitation

L.Morelli et al JoP G 41 2014 (2 papers)

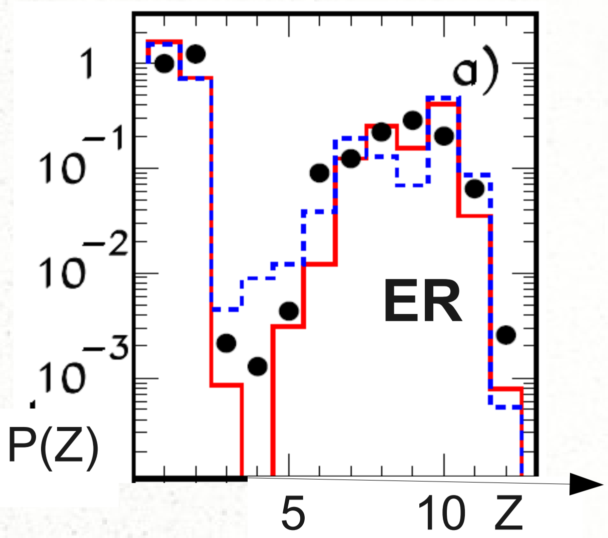
L.Morelli et al IWM2014 proc.

$^{12}C+^{12}C$ at 95MeV

$^{14}N+^{10}B$ at 82.5MeV

24Mg
2.6MeV/u

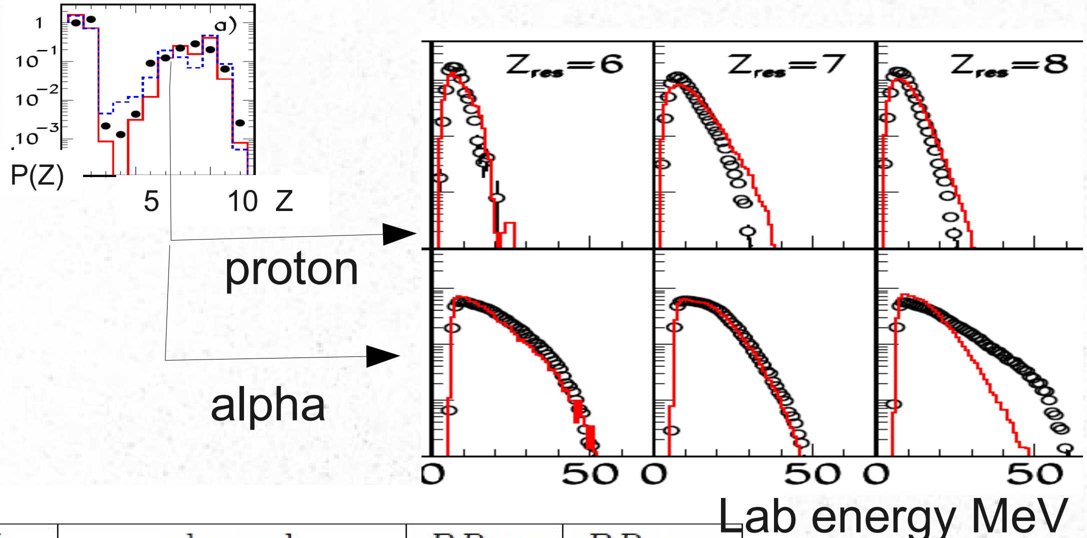
Select complete fusion (like) channel



24Mg produced at the same excitation energy (E*~2.6MeV/u) using two different channels, one with α-cluster nuclei the other with non α-cluster nuclei.

- **Compare data for each system with predictions of a refined Hauser-Feschbach decay code and with the widely used GEMINI code**
- **Compare experimental results from the two systems**

looking for a-cluster effects at 'high' excitation



12C+12C at 95MeV

- Complete events (Z=12)
- Evaporation chains studied for each Z
- Energy and angular distribution of LCP
- Calorimetry for each event and Branching Ratios estimate

Z_{res}	channel	BR_{HF}	BR_{EXP}
5	$^{11-xn}B+xn+p+3\alpha$	100%	99%
6	$^{12-xn}C+xn+3\alpha$	66%	98%
7	$^{15-xn}N+xn+p+2\alpha$	94%	91%
8	$^{16-xn}O+xn+2\alpha$	11%	63%
9	$^{19-xn}F+xn+p+\alpha$	87%	92%

L.Morelli et al JoP G 41 2014

- Extra-contribution of α emission in multiple α-channels (Z=6,8) emerges on top of statistical model predictions.
- persistence of cluster effects well above the Separation energies

Comparison between the two reactions in progress

conclusions

- Fragments emitted in heavy-ion collisions in different reaction conditions are a fundamental tool to explore nuclear systems, both their dynamics and structure
- Energy and sizes of fragments depend much on the emitting source
- Identification of charge and mass of fragments with low thresholds and with large acceptance is an important and challenging task
- this objective is at the basis of detector and electronics developments currently on going in different labs, in particular in the FAZIA and NUCL-EX collaborations