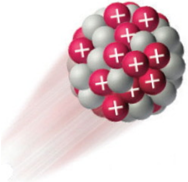
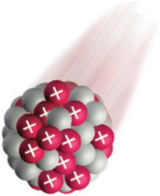
Simone Valdré
Grand Accélérateur National
d'Ions Lourds

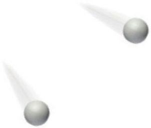


Open questions on heavy-ion reactions: from fusion to deep inelastic collisions



Celebration for Prof. Ricci's
90th Birthday

Laboratori Nazionali di Legnaro
July 5th, 2017



Outlook

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    - A century of discoveries

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    - EoS, asyEoS and isospin transport
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- Conclusions

History

1919 Rutherford perform the **first nuclear reaction** (using a α source) at University of Manchester:

- $\alpha + {}^{14}\mathrm{N} \longrightarrow {}^{16}\mathrm{O} + \mathrm{p}$

1929 Van de Graaf builds his **first high voltage generator**

1932 Cockroft and Walton build their high voltage generator

1932 Cockroft and Walton at Cambridge University use their generator to accelerate protons and perform the first **fully artificial** nuclear reaction:

- $\mathrm{p} + {}^{7}\mathrm{Li} \longrightarrow \alpha + \alpha$

History

1934	Lawrence designs the **first cyclotron**
1935	Weizsäcker writes the **semi-empirical mass formula**
1938	Hahn and Straßmann observe the **first nuclear fission**
1939	N. Bohr and Wheeler modelize the nuclear fission
1940	Weisskopf and Ewing modelize the decay of a **compound nucleus**
1952	Hauser and Feshbach refine the theory of the particle **evaporation** from a compound nucleus

History

1977 Bass **fusion** cross-section formula based on experimental systematics

- R. Bass, Phys. Rev. Lett. **39**, 265 (1977)

1984 Gupta **total** reaction cross-section formula

- S. K. Gupta *et al.*, Z. Phys. A **317**, 75 (1984)

1985 Viola systematics for **fission** fragment relative kinetic energy

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Prof. Ricci's research lines **FUFI-DEEP** and **FUFI-EVA** developed in this period

History

Pre-equilibrium

History

Pre-equilibrium

Dynamical fission

History

Pre-equilibrium

Liquid-gas phase transition

Dynamical fission

History

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asyEoS

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Physics cases

Nuclear matter

Ideal homogeneous and infinite system
made of protons and neutrons

- Excited nuclei produced in nuclear reactions
- Neutron stars

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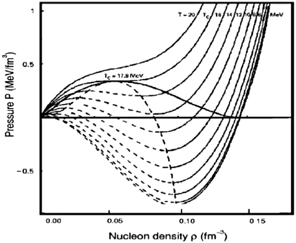
Applications

- Explore the phase diagram of nuclear systems



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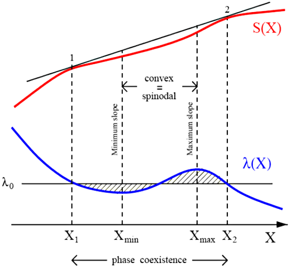

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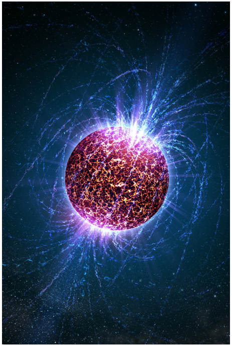


Applications

- Explore the phase diagram of nuclear systems
- Study the finite system phase transitions
- Understand supernovae and neutron stars

Physics cases

Nuclear matter Equation of State (EoS)

- Nucleus treated as Fermi-Dirac statistical ensemble
- Describes the evolution of a system made of interacting nuclei
    - Mean field potential

$$\frac{E}{A} = \frac{3}{5}\varepsilon_F + \frac{\mathcal{A}}{2}\left(\frac{\rho}{\rho_0}\right) + \frac{\mathcal{B}}{\sigma+1}\left(\frac{\rho}{\rho_0}\right)^{\sigma}$$

$\mathcal{A} = -356\,\text{MeV}$ $\mathcal{B} = 303\,\text{MeV}$ $\sigma = 7/6$

Saturation density

$\rho = \rho_0$ density of non-excited nuclear matter

asyEoS

Asymmetric nuclear matter Equation of State (EoS) (*asy*EoS)

- Symmetry energy term depending on proton and neutron densities:

$$\frac{E}{A}(\rho, I) = \frac{E}{A}(\rho) + \frac{E_{\text{sym}}}{A}(\rho) I^2$$

Isospin parameter

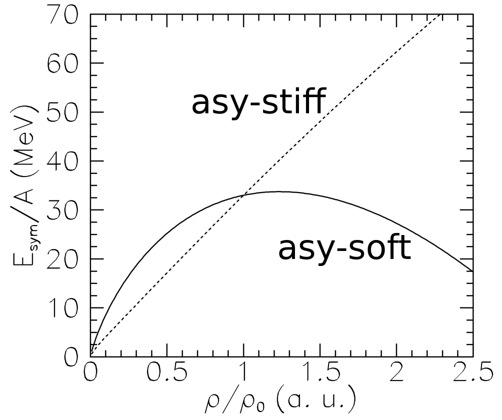
$$I = \frac{(\rho_n - \rho_p)}{\rho} = \frac{N - Z}{A}$$

E_{sym} behaviour is known only near ρ_0

asyEoS

Asymmetric *asy*EoS)

- Symmet neutron
densitie



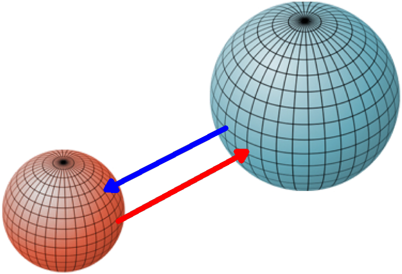
Isospin para

E_{sym} behaviour is known only near ρ_0

Isospin transport

Isospin diffusion

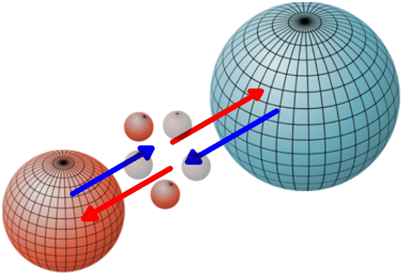
- Projectile and target isospins tend to **equilibrate** during interaction
- Isospin diffusion favoured by an **asy-soft** parametrization



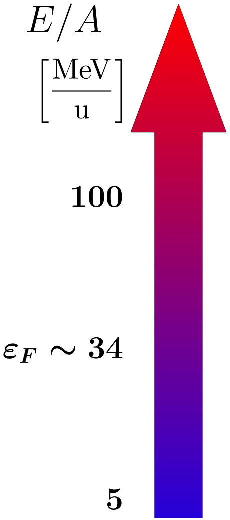
Isospin transport

Isospin drift

- Neutrons tend to migrate toward **low density** regions (neck)
- Isospin drift favoured by an **asy-stiff** parametrization



Heavy-ion collisions



E/A

$\left[\frac{\text{MeV}}{\text{u}}\right]$

$\mathbf{100}$

$\varepsilon_F \sim \mathbf{34}$

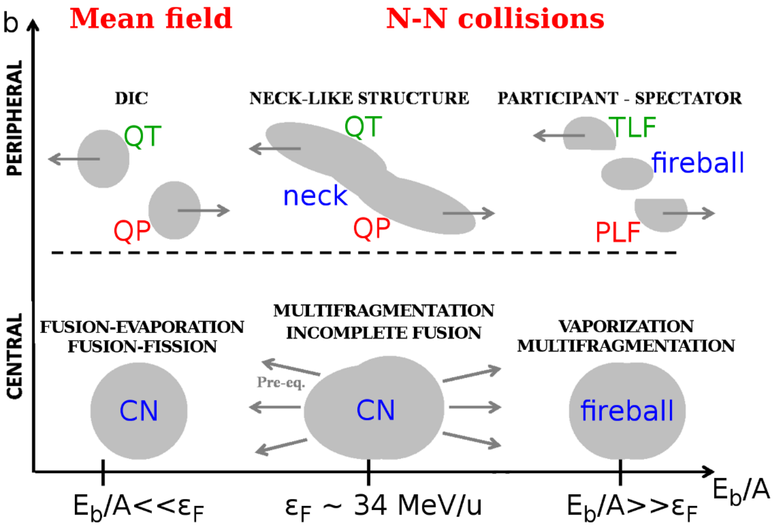
$\mathbf{5}$

Nuclear reactions

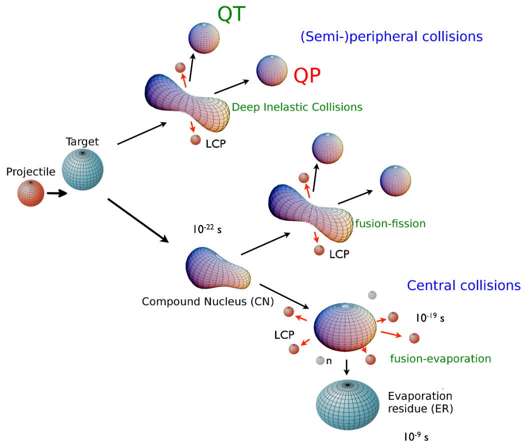
Most used method to reach the various regions of the phase diagram

- Ultrarelativistic regime
  - Gasous state
- Fermi energy region
  - Multifragmentation
  - Phase transition
- Coulomb barrier region
  - Compound Nucleus formation
  - Binary reactions and DIC
  - Liquid state

Reaction mechanisms

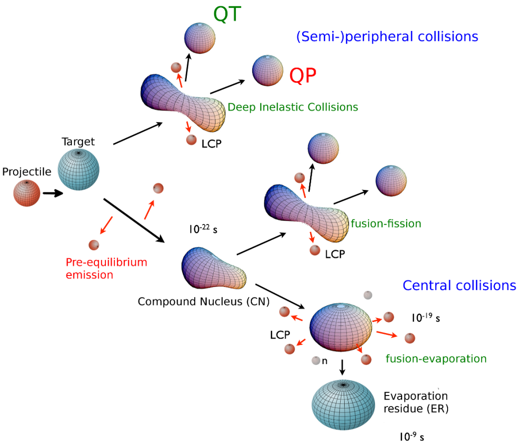


Pre-equilibrium emission



Pre-equilibrium emission

When energy increases, compound nucleus formation and decay phases tend to **overlap**



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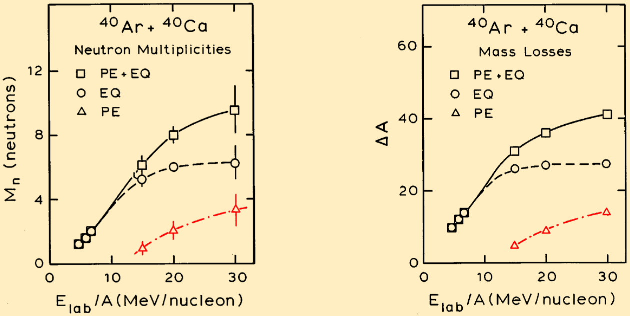
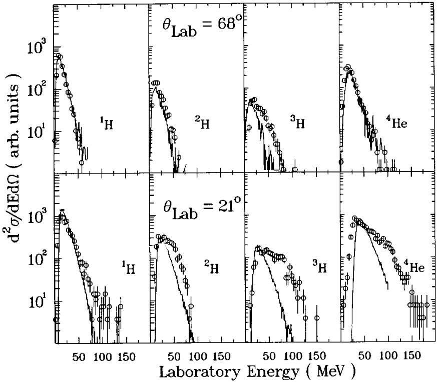


From literature: pre-equilibrium emission from 10–15 MeV/u

L. Lassen *et al.*, Phys. Rev. C **55**, 1900 (1997)

Pre-equilibrium emission



- **Fusion** channel
- ^{40}Ar + ^{nat}Ag
- $E_b = 27$ MeV/u

Energy spectra may give indication of pre-equilibrium effects via **deformations** with respect to statistical trend

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M. T. Magda *et al.*, Phys. Rev. C **53**, R1473 (1996)

Clustering

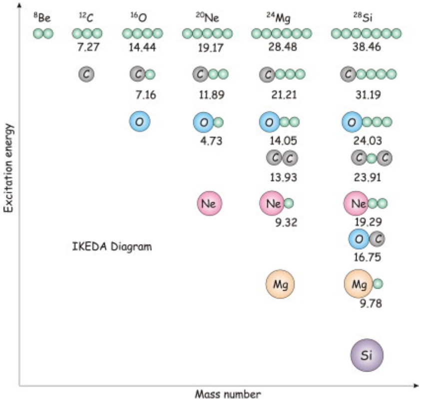
- Pre-equilibrium emission could give information on cluster structure[1]

---

[1] D. Fabris *et al.*, Acta Physica Polonica B **46** (2015)

Clustering

- Pre-equilibrium emission could give information on cluster structure[1]
- Ikeda diagram[2]



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[1] D. Fabris *et al.*, Acta Physica Polonica B **46** (2015)

[2] K. Ikeda *et al.*, Prog. Theor. Phys. E**68**, 464 (1968)

Apparatuses for heavy-ion collisions

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4π arrays

INDRA **CHIMERA** **8πLP** **GARFIELD**

Apparatuses for heavy-ion collisions

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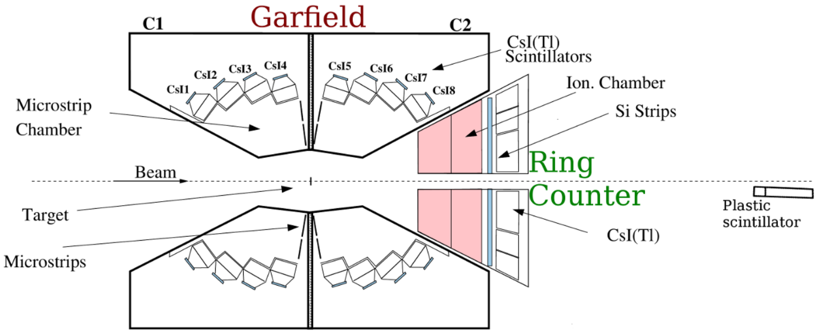
Others

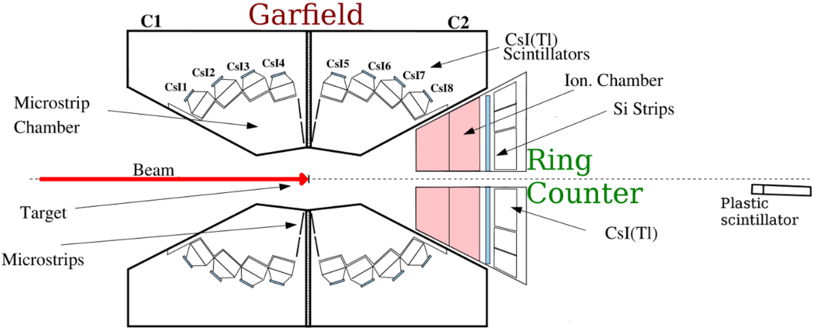
FAZIA **ACTAR**

Garfield @ LNL



- Lateral view in section
- Cylindrical symmetry

Garfield @ LNL



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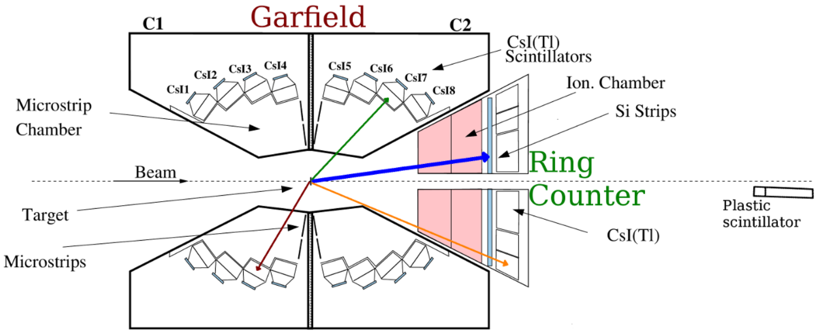

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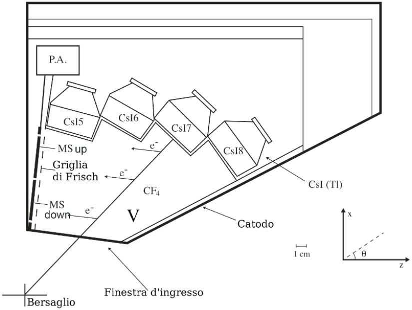
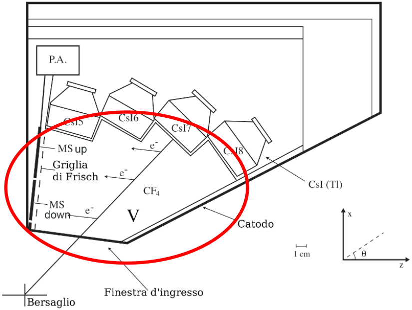


Two-stage telescopes

- 2 drift chambers (CF_4 gas at 50 mbar) segmented in 24 sectors
- 4 CsI(Tl) scintillator crystals per sector per chamber

Garfield



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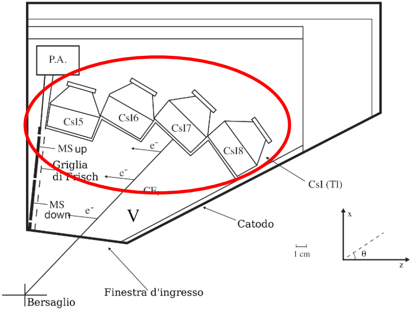

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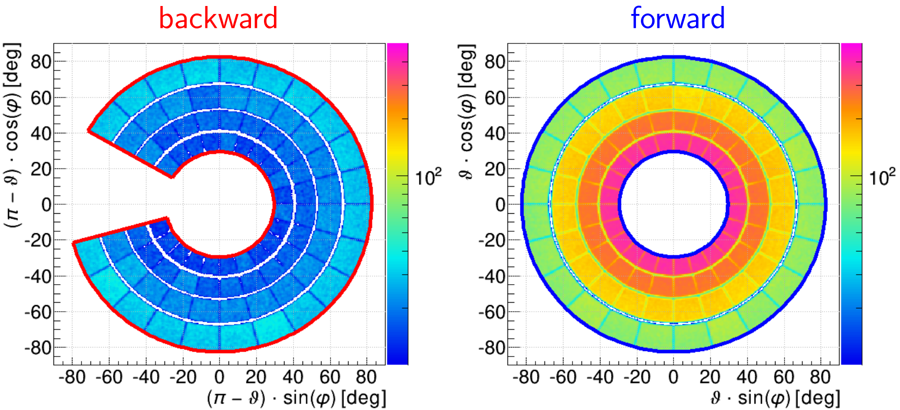

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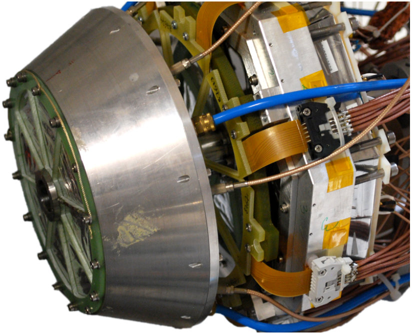
Ring Counter (RCo)



Three-stage telescopes

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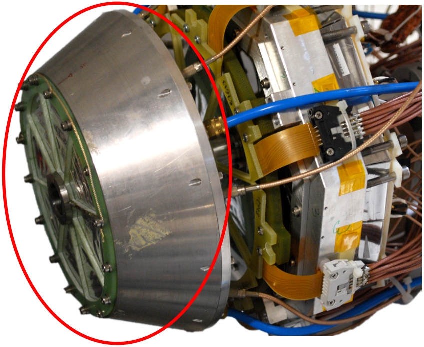

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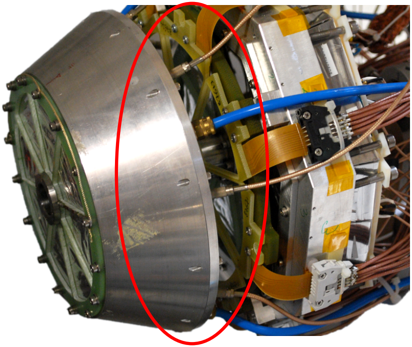

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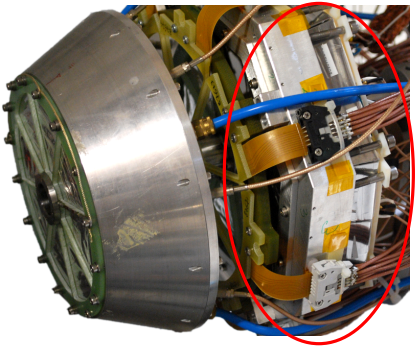

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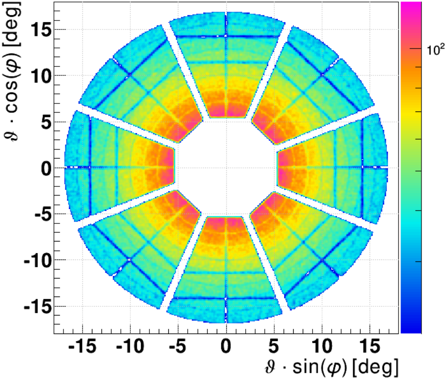

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FAZIA @ LNS

The telescope stages

1. 300 µm reverse-mounted Si detector;
2. 500 µm reverse-mounted Si detector;
3. 10 cm CsI(TI) cristal read by a photodiode.

To achieve the best possible energy resolution and A *and* Z *identification Si detectors come from a nTD ingot cut at random angle to avoid channeling effects.*

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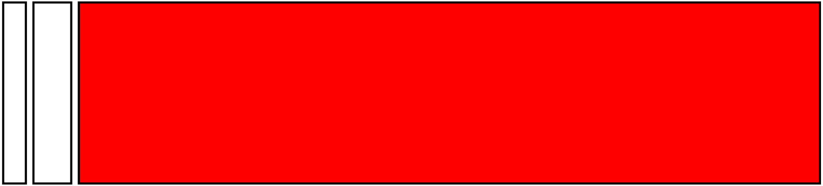
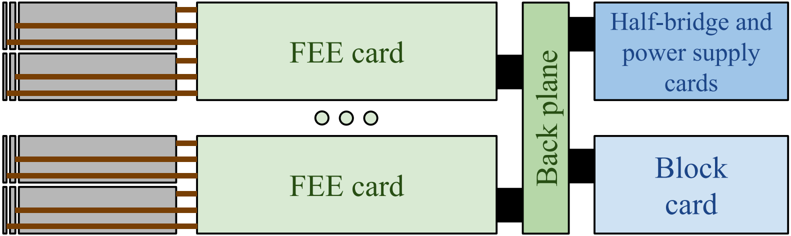


The FAZIA block

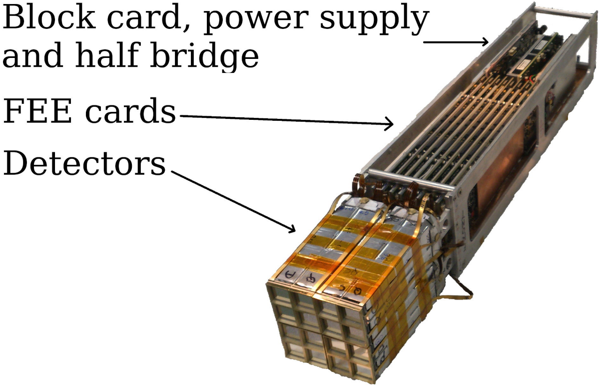
2 telescopes are connected to a FEE card.

The FAZIA block



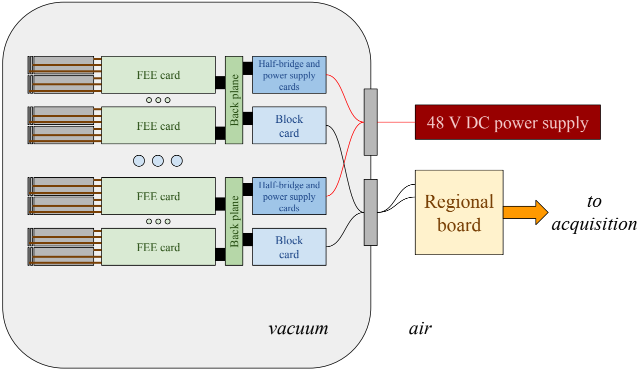
8 FEE cards are connected to a block card via a back plane.

The FAZIA block



Block is mounted on a copper base in which water flows to provide cooling

The FAZIA block



up to 36 block cards are connected to a regional board via a full duplex 3 Gb/s *optical link*

FAZIA innovative features

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  - minimization of signal distortion
  - data reduction at the source

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- Despite its compact design, energy resolution and quality of isotopic identification (up to $Z \sim 25$) of FAZIA block are excellent.

Reaction simulation

Dynamical models

- They simulate the **evolution** in time of the system
  - inelastic binary collisions (DIC)
  - pre-equilibrium emission

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Statistical models

- They simulate the decay of excited nuclei **at equilibrium**
    - fission processes
    - evaporation of light particles

Dynamical models

Molecular dynamics models

They consider the evolution via the equations of motion of **single nucleons**, modeled as gaussian packets under the effect of a mean field and two-body interactions

AMD works better for Fermi energy reactions

Transport models

They consider the evolution of **nuclear matter** via transport equations including a mean field and residual interactions

SMF adapted to work also at $E_b \sim 20\,\mathrm{MeV/u}$

A. Ono *et al.*, Phys. Rev. C **59**, 853 (1999)

M. Colonna *et al.*, Nucl. Phys. A **642**, 449 (1998)

Statistical models

GEMINI++ code

GEMINI++ is one of the most acknowledged statistical codes in the field of heavy-ion collisions:

- **afterburner** to produce secondary particle distributions from primary fragments
  - secondary distributions has been compared with experimental data
- in the hypothesis of **full momentum transfer** to generate reference distributions for the estimate of non-statistical contributions

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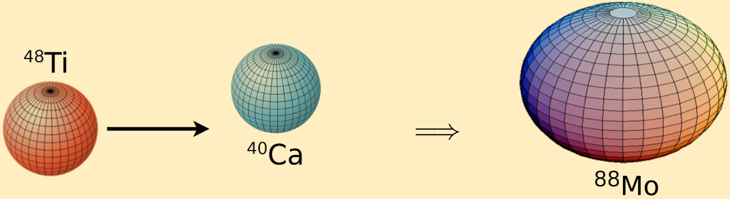
R. J. Charity, Phys. Rev. C **82**, 014610 (2010)

^{48}Ti + ^{40}Ca at 6.25, 9.38 and 12.5 MeV/u at LNL

The reaction



Why ^{88}Mo?

- large fission barrier up to **high spins**
- mass region not well explored in literature
- **GDR study** performed in Krakow
- light charged particles emission in **fusion-evaporation** channel

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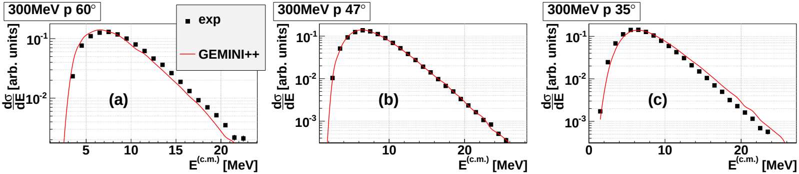
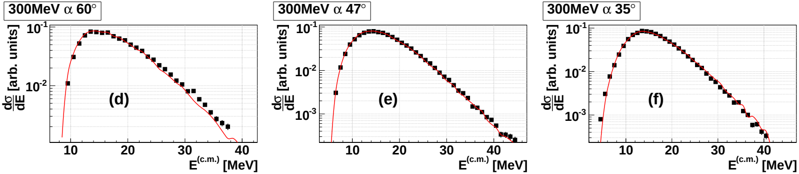
M. Ciemała *et al.*, Phys. Rev. C **91**,054313 (2015)
S. Valdré *et al.*, Phys. Rev. C **93**, 034617 (2016)

Comparison between experimental data and GEMINI++

proton energy spectra at 300 MeV

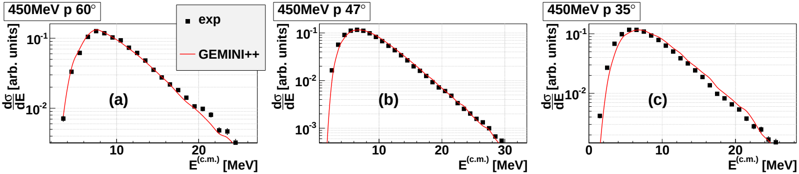


α-particle energy spectra at 300 MeV

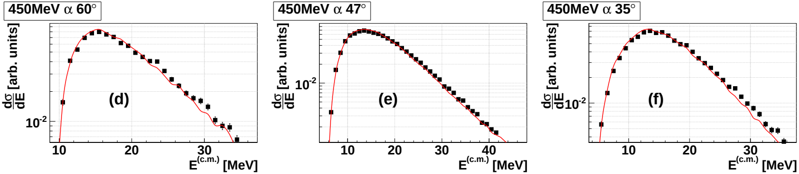


Comparison between experimental data and GEMINI++

proton energy spectra at 450 MeV

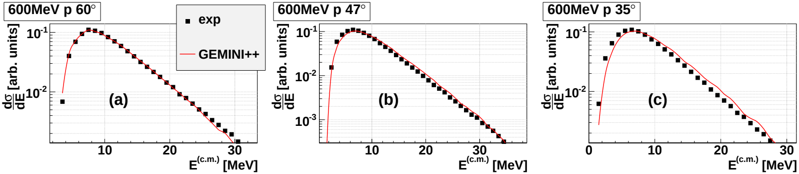


α-particle energy spectra at 450 MeV

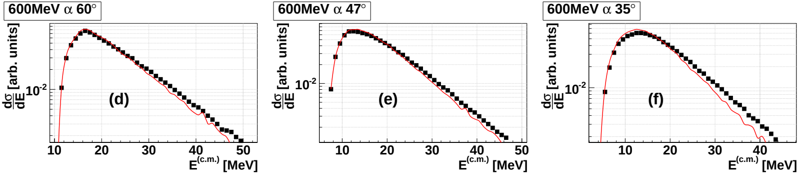


Comparison between experimental data and GEMINI++

proton energy spectra at 600 MeV

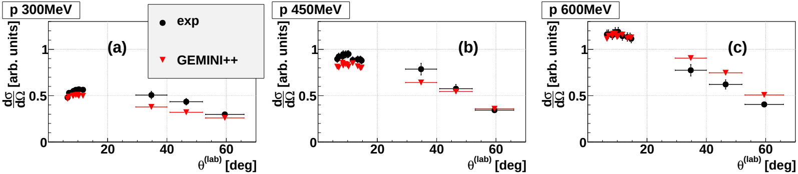


α-particle energy spectra at 600 MeV

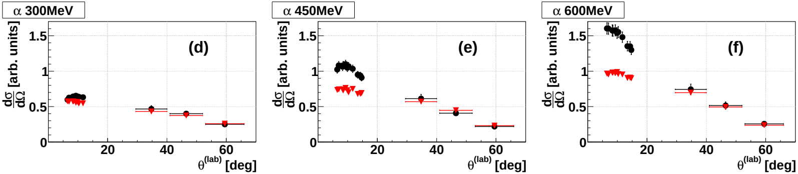


Comparison between experimental data and GEMINI++

proton angular distributions



α-particle angular distributions



Conclusions on ^{48}Ti + ^{40}Ca experiment

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- We found an α-particle yield excess, in particular at forward angles and increasing with energy.
- It's difficult to improve the agreement by tuning the model parameters; indication of the onset of minor **pre-equilibrium emission** or contamination from other processes.

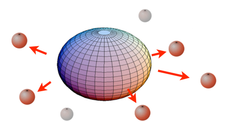
Csym experiment at LNL

Aim of this work

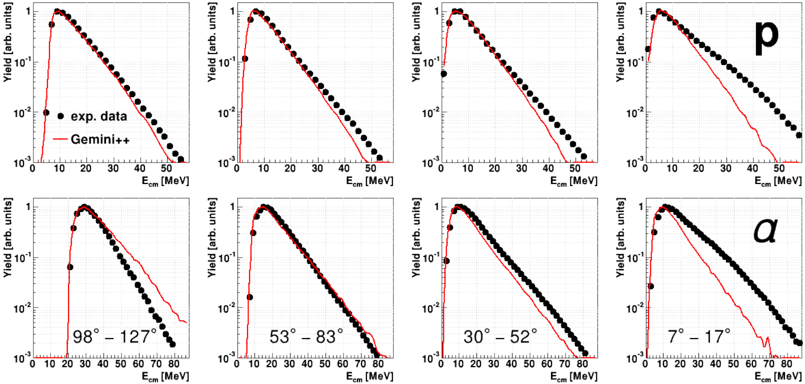
Study of ^{32}**S** + ^{40,48}**Ca** and ^{32}**S** + ^{48}**Ti** reactions at 17.7 MeV/u

- **Pre-equilibrium** emission in central collisions
- **Isospin transport** effects in binary collisions

Fusion-evaporation events

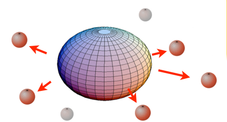


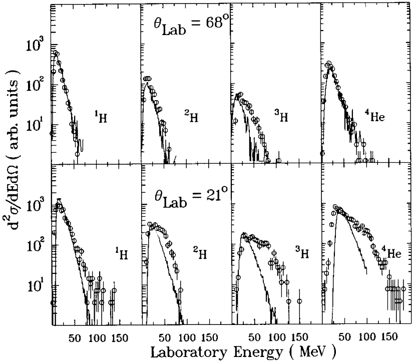
$^{32}S + {}^{48}Ca$



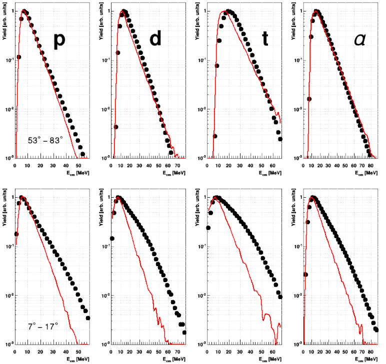
Spectra scaled by the maximum value to highlight shape differences

Fusion-evaporation events





^{40}Ar + ^{nat}Ag @ 27 MeV/u

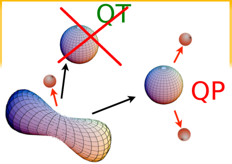


^{32}S + ^{48}Ca @ 18 MeV/u

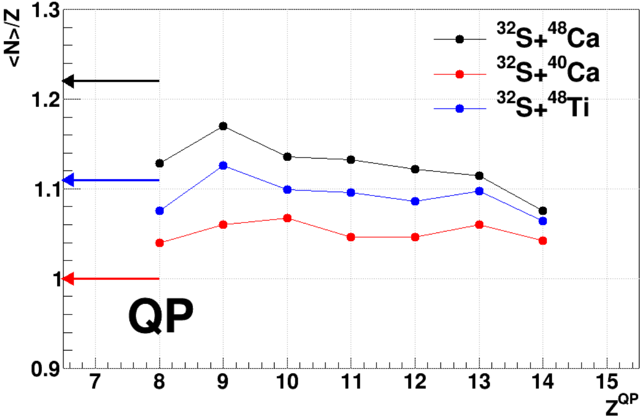
our data

M. T. Magda *et al.*, Phys. Rev. C **53**, R1473 (1996)

DIC events

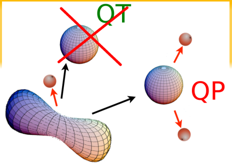


$\langle N \rangle / Z$ of QPs



S. Piantelli *et al.*, *submitted to* Phys. Rev. C (2017)

DIC events



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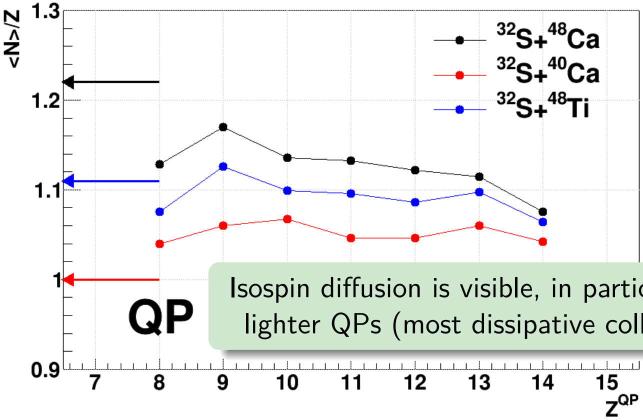
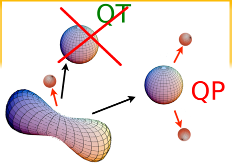


Isospin diffusion is visible, in particular for lighter QPs (most dissipative collisions)

S. Piantelli *et al.*, *submitted to* Phys. Rev. C (2017)

DIC events



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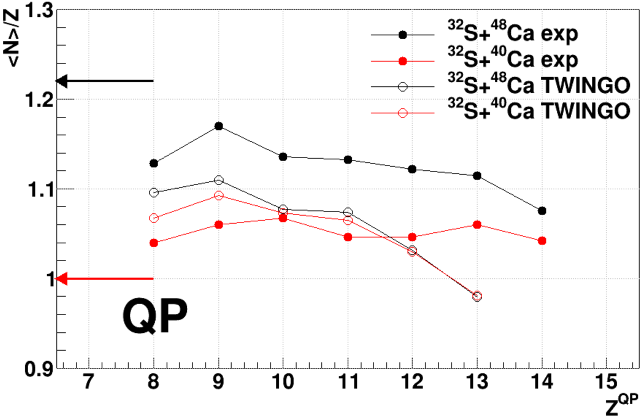

S. Piantelli *et al.*, *submitted to* Phys. Rev. C (2017)

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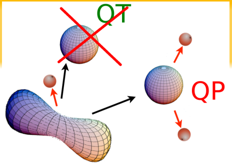

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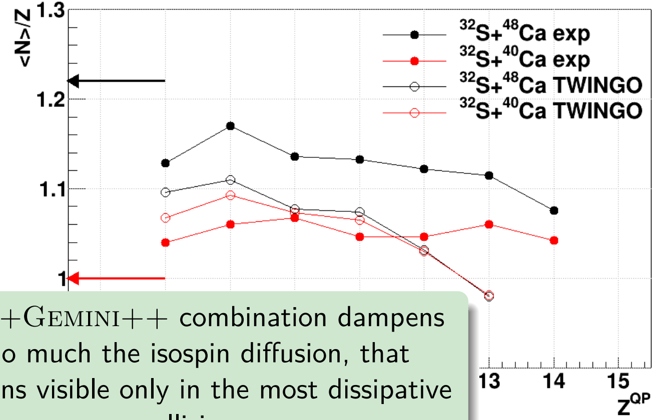

SMF+Gemini++ combination dampens too much the isospin diffusion, that remains visible only in the most dissipative collisions

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S. Piantelli *et al.*, *submitted to* Phys. Rev. C (2017)

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- To improve our knowledge on pre-equilibrium emission, **FAZIAPRE** experiment is scheduled in the next months
- We clearly highlighted **isospin diffusion** in DIC reactions by measuring $\langle N \rangle / Z$ of QP in function of the target isospin

ISOFAZIA experiment at LNS

Aim of this work

Study of **^{80}Kr + ^{40,48}Ca** reactions at 35 MeV/u

- **Multifragmentation** in central collisions
- Quasi-projectile **dynamical fission**
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G. Pastore *et al.*, Nuovo Cimento C **39**, 383 (2016)

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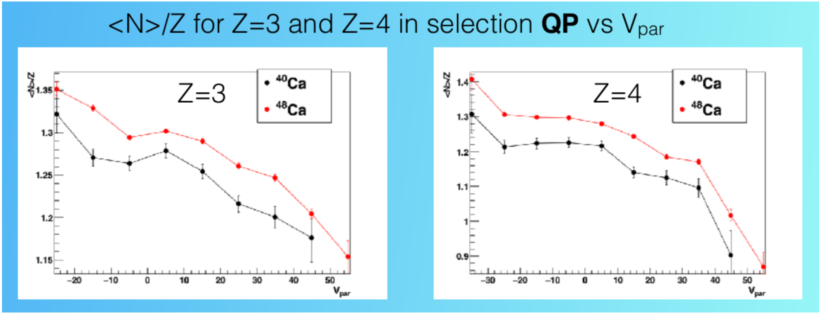
Preliminary results

G. Pastore *et al.*, Nuovo Cimento C **39**, 383 (2016)

ISOFAZIA experiment

Isospin drift effect is well evidenced



<N>/Z for Z=3 and Z=4 in selection **QP** vs V_{par}

Comparing many observables with the **AMD dynamical model** predictions an **asy-stiff** parametrization of the symmetry energy term of the EoS is favoured

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Courtesy of Dr. G. Pastore

Clustering and Hoyle State

Some excited states of nuclei may present a “cluster” structure

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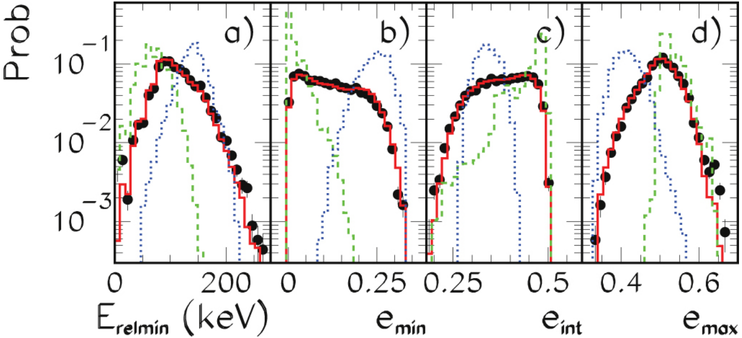
The Hoyle state of ^{12}C

- 7.65 MeV
- 3α cluster structure

Open debate on **sequential** or **direct** decay into 3α

QP decay in $^{12}C + ^{12}C$ at 7.92 MeV/u @ LNL

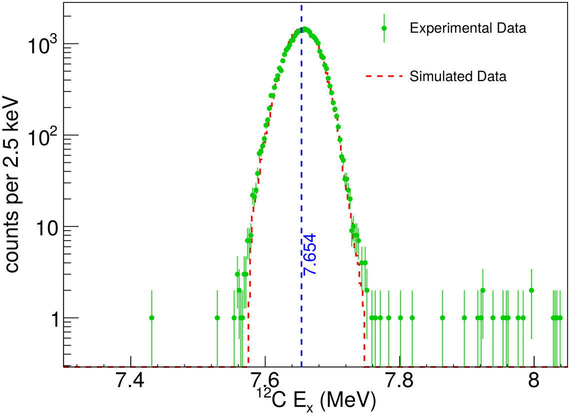


Direct decay contribution estimated around 1.1 %

L. Morelli *et al.*, J. Phys G **43**, 045110 (2016)

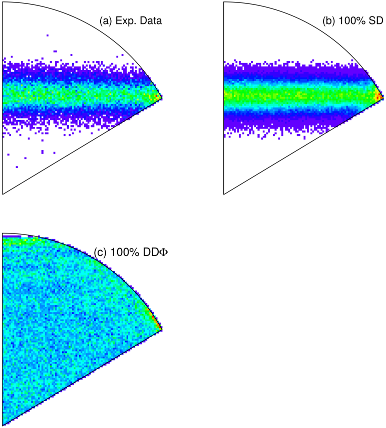
d + ^{14}N at 5.25 MeV/u @ LNS

^{14}N (d, α) ^{12}C direct reaction



Hoyle state selection with almost **zero background**

d + ^{14}N at 5.25 MeV/u @ LNS



Comparing **Dalitz plots** of experimental data and Monte Carlo simulations it's clear that the Hoyle state decay is **sequential**. Direct decay B.R. is evaluated **under** $0.04\,\%$

D. Dell'Aquila *et al.*, *accepted in* Phys. Rev. Lett., arXiv:1705.09196 (2017)

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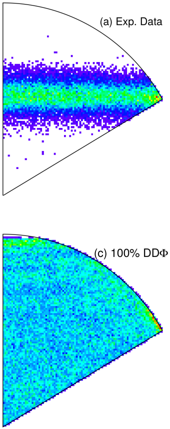

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Analysis of FAZIACOR experiment is going on to study also the Hoyle state formation and decay **in medium** at higher energies

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D. Dell'Aquila *et al.*, *accepted in* Phys. Rev. Lett., arXiv:1705.09196 (2017)

Conclusions and open questions

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Thanks for your attention and. . .

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Thanks for your attention and. . .

happy birthday Prof. Ricci