# INDRA a $4\pi$ detector for nuclear dynamics and thermodynamics studies

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# Nuclear dynamics and thermodynamics

1. Nuclear thermodynamics : study the properties of an equilibrated nuclear system
   - excited (temperature T >0)
   - compressed or diluted (density $\rho \neq \rho_0$)
   - with a high angular momentum
   - Nuclear interaction similar to Van der Waals forces for fluids : expected phase transition for nuclear systems. Nuclei (finite systems) show some specific behaviour in the transition region. Multifragmentation is seen as the manifestation of this phase transition.
2. Nuclear dynamics : transport properties of nuclear matter
   - energy : dissipation
   - linear momentum
   - nucleons : mass transfer, isospin (N/Z) diffusion
   - depend on the incident energy, the impact parameter, the target/projectile mass ratio
3. Goal : get the Equation of State (EOS) of nuclei (nuclear matter, neutron stars)

Physics context

Detectors - INDRA array

Some highlights

- Isospin transport (Nuclear Dynamics)
- Multifragmentation & Phase transition (Nuclear Thermodynamics)
- Level density parameters (Nuclear Thermodynamics)

Perspectives

# Tools

We work in the Fermi energy domain (E/A $\sim$ 10 - 100 MeV)

1. Experimental tools
   - Heavy ion nuclear collisions allow to drive nuclear systems towards extreme states in density, temperature, N/Z ... (GANIL, GSI, Catania ... )
   - Collection of products of nuclear collisions, that may have high multiplicities : to get the maximum information, need to cover the whole (phase)space
2. Theoretical tools
   - Microscopic transport models for dynamics (BUU, QMD families)
   - Statistical models for thermodynamics (SMM, MMM, MMMC, GEMINI)

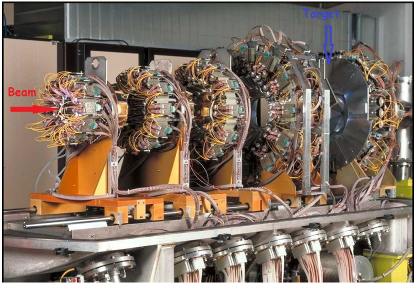
# $4\pi$ (multi)detectors

What are the necessary qualities of a $4\pi$ detector ?

- Large spatial coverage $(\Omega/4\pi) > 0.9)$
- Good granularity (number of detection modules) to avoid getting several particles in the same module
- Phase space coverage : not universal, designed to work in a given energy range.
- detect charged products (Z≥1), rarely neutrons

Among the working arrays : Miniball, INDRA, CHIMERA ...

# INDRA (1993 - 2013 . . . )

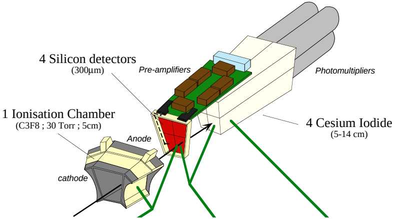



$\Omega/4\pi = 0.90$

640 detectors grouped in

**336 modules**

ChIo (5 cm $C_3F_8$)
Si 300 $\mu$m (2°-45°)
CsI(Tl) 14 - 5 cm




J. Pouthas *et al.* NIM A357 (1995)

**Identification**

$1 \leq Z \leq 80$
Z≥5-8 : A unknown
isotopes for H - Be, (B)

**designed for**

Incident energy range 10 - 100 AMeV
v/$c$ 0.15 - 0.45

# Phase space coverage

Should detect all products from any collision ($\sigma_{reaction}$) but …

**Total detected linear momentum**

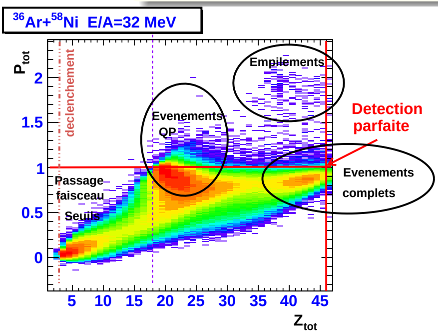
$P_{tot} = (\sum_i P_i)/P_{beam}$

**Phase space coverage**

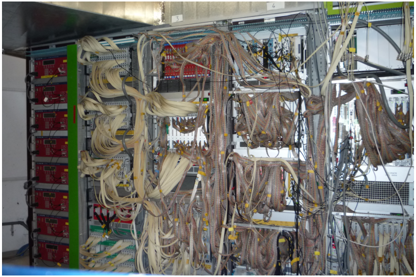
Angles : 2°-88°+92°-176°
Detected energies up to 4 GeV
Energy detection threshold : ~1 AMeV

**Total detected charge**

$Z_{tot} = \sum Z_i$



# A compact electronics



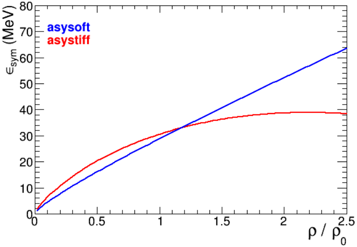
J. Pouthas *et al.* NIM A369 (1996)

- Integrated electronics :
  - VXI D cards for Discriminators (32 ch), Converters (32, 24 ch)
  - CAMAC standard for amplifiers, pulsers (8 ch)
  - commercial CAEN 64 channels HV boards
- Versatile Trigger, allowing different configurations and coupling with other detectors

# Question : symmetry term of the EOS $\varepsilon_{sym}(\rho)$

$$\varepsilon(\rho, I) = \varepsilon(\rho, I=0) \; + \varepsilon_{sym}(\rho) \times I^2$$

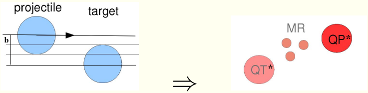
$$\varepsilon = \frac{E}{A} \qquad I = \frac{\rho_n - \rho_p}{\rho} = \frac{N-Z}{A}$$



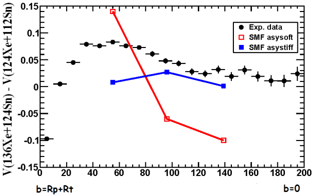

## Element of answer :

data favour “asystiff” $\varepsilon_{sym}(\rho)$

## Method : isospin transport




Study QP from semi-peripheral collisions, at E/A = 32 MeV.
$^{136}$Xe+$^{112}$Sn and $^{124}$Xe+$^{124}$Sn




G. Ademard *et al.* EPJ A 50 (2014)

# Question : Origin of multifragmentation

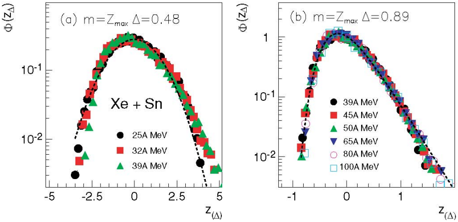
**Phase transition ? fragment formation ?**

**Method : Scaling law of $Z_{max}$ fluctuations**

$\langle m\rangle^{\Delta} P[m] = \Phi\left(\frac{m-\langle m\rangle}{\langle m\rangle^{\Delta}}\right)$

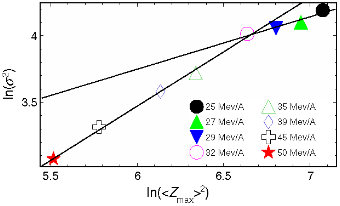
$(1/2 \leq \Delta \leq 1)$ $\sigma^2 \sim \langle m\rangle^{2\Delta}$

Central collisions




J. D. Frankland *et al.* PRC 71 (2005)

Change of $\Delta$ with $E^*$ $(T)$ :
ordered phase $\rightarrow$ disordered phase




D. Gruyer *et al.* PRL 110 (2013)

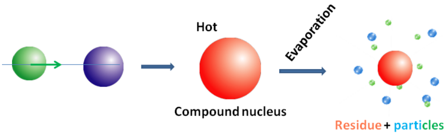
$m \equiv Z_{max} \Rightarrow$ Multifragmentation is an aggregation phenomenon

**Element of answer :**

possible origin of multifragmentation : density fluctuations in spinodal region

# Compound Nucleus evaporation

## N/Z dependence ?




**Detect and measure A, Z, $\vec{v}$ :**

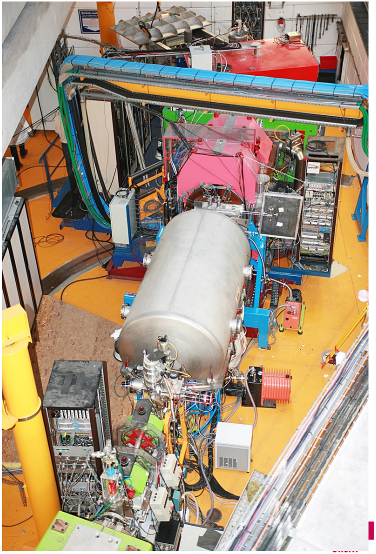
Residue in spectrometer VAMOS (0-8°)

All particles in INDRA (7-176°)

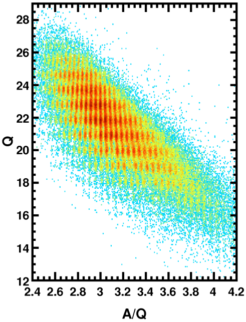
**Study :**

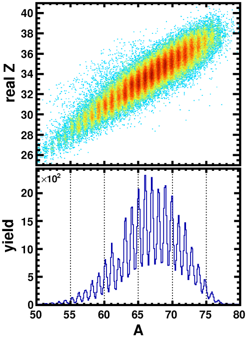
$^{34,36,40}Ar + ^{58,60,64}Ni \rightarrow ^{92,94,96,100,104}Pd$

$E/A_{Ar} \sim 13$ MeV $\quad E^*/A_{Pd} = 2.9$ MeV



# Example of (preliminary) data

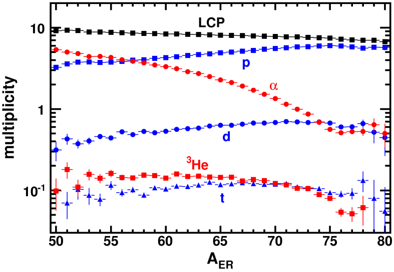


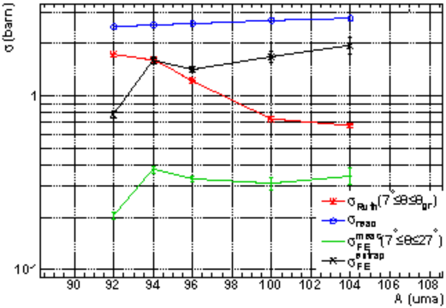

G. Ademard *et al.* Proceedings IWM-EC2014

$^{36}Ar + ^{58}Ni \rightarrow \, ^{94}Pd$

$B\rho = 0.638$ T.m - $\theta_{VAMOS} = 0°$



# Question : Dependence on N/Z




ER measured in INDRA ($\theta_{ER} \geq 7°$) : $\sigma_{ER}$ decreases close to proton drip-line. To be confirmed with VAMOS data($0 \leq \theta_{ER} \leq 12°$).

P. Marini *et al.* EPJ Web Conf. 2 (2010)

**Which process replaces fusion-evaporation for $^{92}$Pd ?**

Part of the PhD work of Tomasz Twarog

# Perspectives

Go on with studies of isospin effects on nuclear dynamics and thermodynamics :

- Couple INDRA and FAZIA demonstrator → improve mass identification and granularity
- Need exotic beams, particularly neutron-rich ions in the Fermi energy domain

# Gumbel distribution

Statistical distribution of the maximum extreme value of a random variable

$$f(x) = \frac{1}{b}\ exp\left[-\frac{x-a}{b} - exp\left(-\frac{x-a}{b}\right)\right]$$

# Phase diagram