Femtoscopic probes of jet-fragmentation mechanisms in INDRA and FAZIA campaigns at GANIL

Q. FABLE

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INDRA-FAZIA collaboration
• **Context and motivations**
  The Equation of State of nuclear matter
  Heavy Ion Collisions at intermediate energies

• **INDRA-VAMOS : HIC peripheral collisions**
  Isospin transport
  Experimental setup
  Observation of isospin transport

• **Nuclear jets fragmentation**
  Ar+Ni INDRA data highlights
  Comparisons with models (BLOB)
  IMF-IMF correlation functions

• **Conclusion and outlooks**
The Equation of State of a nuclear system

- The EOS of a nuclear system is defined by its energy per nucleon: $\mathcal{E}(\rho, T, \delta)$

- The density dependence of the symmetry energy term $\mathcal{E}_{\text{sym}}(\rho, T)$ remains a major issue in modern nuclear physics:
  - describes the energetic cost of converting isospin symmetric matter into neutron matter;
  - constraints well established for $T=0K$ and $\rho=\rho_0$ by fitting with nuclear masses;
  - largely unknown as soon as we move away from normal density.

$\delta = (\rho_n - \rho_p) / \rho$
The Equation of State of a nuclear system

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Density dependance of $\epsilon_{\text{sym}}$

- Taylor expansion:
  $$\epsilon(\rho, \delta) = \epsilon(\rho, \delta=0) + \epsilon_{\text{sym}}(\rho) \cdot \delta^2 + ...$$
- Ex. of parametrization:
  $$\epsilon_{\text{sym}}(\rho) = \frac{C_{\text{kin}}}{2} \left( \frac{\rho}{\rho_0} \right)^{2/3} + \frac{C_{\text{pot}}}{2} \left( \frac{\rho}{\rho_0} \right)^{\gamma}$$

- EOS « stiffness »
- Kinetic term (Fermi gaz)
- Nucleon-nucleon effective interaction term
Density dependance of $\epsilon_{sym}$

- Taylor expansion:
  \[ \delta = (\rho_n - \rho_p) / \rho \]
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- Ex. of parametrization:
  \[ \epsilon_{sym}(\rho) = \frac{C_{kin}}{2} \left( \frac{\rho}{\rho_0} \right)^{2/3} + \frac{C_{pot}}{2} \left( \frac{\rho}{\rho_0} \right)^\gamma \]

  - Kinetic term (Fermi gaz)
  - Nucleon-nucleon effective interaction term

\[ \text{EOS « stiffness »} \]

- $\epsilon_{sym}(\rho)$ largely unknown as soon as we move from $\rho_0$

- Essential information for understanding:
  → Structure of exotic nuclei and neutron skin;
  → Giant Dipole Resonances and Pygmy Dipole Resonances;
  → The dynamic of Heavy Ion Collisions

- ... but also stellar matter:
  → Supernova explosions mechanisms;
  → Cooling and composition of neutron stars.

Context and motivations: $\epsilon_{sym}(\rho, T)$

[2] M. Colonna et al., EPJA50:30
**Heavy Ion Collisions**

- Formation of exotic nuclei over a wide range of n/p asymmetry
- A tool to study transient states of nuclear matter over various $\rho$, $P$, $T$ and $J$
- Relatively high $E^*/A$ can be reached

**Intermediate energies**

- $15 \text{ AMeV} \leq E_{\text{inc}} \leq 100 \text{ AMeV}$
- Dissipative collisions
- Investigation of $\epsilon_{\text{sym}}(\rho)$ in the sub-saturation density regime → Domain expected from model calculations

**Transport models**

- Simulation of the whole dynamic evolution of the colliding system:
  → time evolution of the distributions of the nucleons;
  → consideration of their quantum features.
- Allow to link experimental observables to the density dependance of the symmetry energy
  → requires extensive comparison of a large variety of observables;
  → isospin sensitive quantities: isospin transport, isobaric cluster ratios (t/3He), etc...
  → single particle and multi-particle distributions and correlations.
- Symmetry energy is introduced as:
  → Direct input (Mean-field description)
  → Indirect consequence of specific nucleon-nucleon interaction
Heavy Ion Collisions

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- Terrestrial way to study transient states of nuclear matter over various $\rho$, $P$, $T$ and $J$
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Transport model (ImQMD05)

$^{124}\text{Sn} + ^{124}\text{Sn} @ 50 \text{ AMeV}$

- Peripheral collisions
- Pre-equilibrium emissions
- Mixing
- Fragments formation
- Statistical decays

Zhang et al., PRC 85:024602
Isospin transport: isospin migration

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Isospin migration

- $\rho$ gradient
- Neutron-enrichment of the neck
- Related to $\frac{\partial \epsilon_{\text{sym}}(\rho)}{\partial \rho}$

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Isospin diffusion

- Minimisation of the $N/Z$ concentration gradient
  $\rightarrow$ neutron/proton currents between proj/targ
- Linked to $\epsilon_{\text{sym}}$

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  $\rightarrow$ Domain expected from model predictions

Isospin transport

- Competition between the isospin migration and diffusion
- Transport phenomena directly linked to $\epsilon_{sym}$
- Depends on the time of interaction between projectile and target
  $\rightarrow$ beam energy, impact parameter
- Requires:
  $\rightarrow$ high isotopic resolution
  $\rightarrow$ special attention to evaporation process
  $\rightarrow$ evaluation of the interaction and dissipation time
**INDRA-VAMOS: Setup**

**E503 experiment**

$^{40,48}\text{Ca} + ^{40,48}\text{Ca} @ 35 \text{ AMeV}$

- **VAMOS**
  - Drift chambers
  - Focal plane
  - Ref. traj.
  - CsI(Tl) wall
  - Si-wall (Trigger)
  - Ionization chamber

- **INDRA**
  - Chlo-CsI(Tl)
  - Chlo-Si-CsI(Tl)
  - Beam axis
  - Target

- **Si-wall → Acq. Trigger**
- **Projectile identification (Z,A)**
  - $\theta_{LAB} \approx 2.5^\circ - 6.5^\circ$
  - $\varphi_{LAB} \approx 220^\circ - 320^\circ$
- **12 B$\rho$ settings:**
  - $B\rho_0 \approx 0.661 - 2.220 \text{ T.m}$

- **14 rings (~300 identification modules)**
- **Identification**
  - $\rightarrow (Z,A)$ for Light Charge Particles ($Z \leq 2$)
  - $\rightarrow Z$ up to $Z \sim 25$
- **$\theta_{LAB} \approx 7^\circ - 176^\circ$**
- **Event characterization ($b, E^*$, ...)**
**General properties of the recorded INDRA-VAMOS events**

### General properties

**$^{48}\text{Ca} + ^{48}\text{Ca}$**

![INDRA-VAMOS: General properties diagram](image.png)

#### Dissipative collisions

**3 regions:**
- $\rightarrow$ LCP emissions around $v_{\text{CM}}$
- $\rightarrow$ PLF and TLF from either side of $v_{\text{CM}}$

**PLF (Vamos):**
- $V_z \geq 6 \text{ cm/ns}$
- $\rightarrow V_z \sim v_{\text{proj}}$
- $\rightarrow Z \sim Z_{\text{proj}}$
N-richness of the PLF detected in VAMOS

Evaporative Attractor Line

\[ ^{48}\text{Ca}^{+48}\text{Ca} \rightarrow N/Z=1.4 \]
\[ ^{48}\text{Ca}^{+40}\text{Ca} \]
\[ ^{40}\text{Ca}^{+48}\text{Ca} \rightarrow N/Z=1.2 \]
\[ ^{40}\text{Ca}^{+40}\text{Ca} \rightarrow N/Z=1 \]

INDRA-VAMOS: Isospin diffusion

- ≠ evolution depending on the system:
  1) Projectile
     → number of available neutrons in the entrance channel
  2) Target
     → Isospin diffusion

- Initial N-Z not reached
  → Statistical decay
INDRA-VAMOS: Isospin migration

For a given range of $Z_V$:

- \[ \left( \frac{\langle N \rangle}{\langle Z \rangle} \right)_{CP} = \sum_{Nevts} \sum_{\nu} \frac{N_{\nu}}{\sum_{Nevts} \sum_{\nu} Z_{\nu}} \]
- \( \nu = 2, 3 \) H, \( 3, 4, 6 \) He, \( 6, 7, 8, 9 \) Li, \( 7, 9, 10 \) Be
- Neutron-enrichment if \( \left( \frac{\langle N \rangle}{\langle Z \rangle} \right)_{CP} > 1 \)

Neck of nuclear matter at mid-rapidity

Isospin migration

- \( \rho \) gradient
- Mid-rapidity n-enrichment
- Linked to \( \frac{\partial \epsilon_{sym}(\rho)}{\partial \rho} \)
Isotopic ratios

For a given range of $Z_V$ :

- $\frac{\langle N \rangle}{\langle Z \rangle}_{CP} = \sum_{N_{\text{evts}}} \sum_{\nu} \frac{N_{\nu}}{\sum_{N_{\text{evts}}} \sum_{\nu} Z_{\nu}}$
- $\nu = ^2,^3\text{He}, ^3,^4,^6\text{He}, ^6,^7,^8,^9\text{Li}, ^7,^9,^{10}\text{Be}$
- Neutron-enrichment if $\frac{\langle N \rangle}{\langle Z \rangle}_{CP} > 1$

In the case of symmetric systems :

- $\rightarrow$ mid-rapidity neutron-enrichment
- $\rightarrow$ direct experimental measure of the isospin migration
**Head-on collisions**

- When the impact parameter decreases and the beam energy increases, the fragmentation may become more complicated than the former case...

- Illustration from $^{36}\text{Ar}+^{58}\text{Ni}$ central collisions @ 32, 40, 52, 63, 74, 84 and 95 AMeV

- Observed topology different from multifragmentation and vaporisation:
  - Break-up asymmetry in forward vs backward CM
  - Granular projectile fragmentation topology
Comparisons with BLOB simulations

Jet fragmentation in BLOB

• Boltzmann-Langevin One-Body:
  → Stochastic transport theory (3D)
  → Mean-field description
  → n-n collisions
  → Langevin-type fluctuations

• Symmetric ($^{36}$Ar+$^{36}$Ar or $^{58}$Ni+$^{58}$Ni):
  → significant radial expansion
  → signature of multifragmentation and vaporization mechanisms

$^{36}$Ar+$^{36}$Ar and $^{58}$Ni+$^{58}$Ni @ 74 AMeV with BLOB
(b varying uniformly from 0 to 1 fm)

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- $^{36}$Ar+$^{58}$Ni:
  - Columnar jet formation in the forward sector relative to the biggest fragment
  - Since early time this jet experiences a density drop along longitudinal axis

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  → a collisionless approach leads to a neck-like pattern instead

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→ Projectile region = prediction intense volume-like fast break-up;
→ Target region = long time-scale surface-like emissions (evaporative).

Femtoscopy and correlation functions

- **Femtoscopy**:
  - Term used for estimating distances, lifetimes and densities on the femtosopic scale.

- **IMF-IMF (Z>2) correlation functions**:
  - Interferometry studies;
  - Allows to probe space-time properties of the collision products;
  - The shape of the correlation function is strongly affected by fragment emission time at small relative velocities (Coulomb anti-correlation).

\[ 1 + R(V_{\text{red}}) = C \cdot \frac{\sum Y_{\text{coinc}}(p_1, p_2)}{\sum Y_{\text{unco}}(p_1, p_2)} \]

Two-IMF coincident yield

\[ V_{\text{red}} = \frac{V_{\text{rel}}}{\sqrt{Z_1 + Z_2}} \]

Approximation of the yields of two uncorrelated IMF (event mixing)

G. Verde, EPJA 30 (2006)

\[ ^{36}\text{Ar}^{58}\text{Ni} \text{ @ 40 AMeV with INDRA} \]

Backward (slow)

Forward (fast)

\[ ^{36}\text{Ar}^{58}\text{Ni, E/A=40 MeV, } b_{\text{red}} < 0.3 \]

\[ \uparrow \text{ All} \]

\[ \uparrow v_{\parallel} > v_{\text{cm}} \]

\[ \uparrow v_{\parallel} < v_{\text{cm}} \]
Conclusion

- INDRA-VAMOS experiment allowed to probe the isospin transport phenomena, predicted by transport models, with $^{40,48}$Ca+$^{40,48}$Ca peripheral collisions
  → experimental evidence of isospin diffusion and migration;
  → due to the use of VAMOS and the trigger conditions, complementary results can be accessed with INDRA-FAZIA.

- For more central collisions:
  → $^{36}$Ar+$^{58}$Ni asymmetric collisions measured with INDRA show a particular topology that has not been explicitly addressed so far;
  → BLOB dynamical simulations evidenced the appearance of nuclear jets formation in the forward direction;
  → These collimated streams of clusters are expected to be at low-density;
  → Interplay of surface and volume instabilities.

- These predictions point to new detection systems measuring on a event-by-event basis:
  → isotopic identification;
  → angular correlations;
  → cluster coincidences.
Outlooks: Extension to INDRA-FAZIA campaigns

- Isospin transport:
  → INDRA-VAMOS drawbacks (normalization, trigger condition)
  → Effect of beam energy (density)?
  → Impact parameter estimation?
  → Complementary results with INDRA-FAZIA (see Caterina Ciampi talk)

- Correlation function:
  → Improved angular resolution with FAZIA;
  → Fix and establish procedures for the study of correlation functions (event mixing, effect of global observables and conservation laws) using existing INDRA data;
  → Extension to INDRA-FAZIA

- Extensive comparisons with different models to link the observations to transport properties:
  → BLOB
  → QMD
  → AMD (see Catalin Frosin talk) ...
Back-up slides: imbalanced ratios

\[ R^x_{\nu_i} = \frac{2(x^M - x^{eq})}{(x^H - x^L)} \]

\[ x^{eq} = \frac{x^H + x^L}{2} \]

where:
- \( x = \) observable sensitive to isospin transport
- \( x = +/- 1 \rightarrow \) no diffusion
- \( x = 0 \rightarrow \) diffusion with complete equilibrium
Jet fragmentation in BLOB

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- Symmetric ($^{36}$Ar+$^{36}$Ar or $^{58}$Ni+$^{58}$Ni):
  - Significant radial expansion
  - Signature of multifragmentation and vaporization mechanisms

- $^{36}$Ar+$^{58}$Ni:
  - Jet formation of fast-streaming low-density matter
  - This density drop also triggers isospin effects

$^{36}$Ar+$^{58}$Ni @ 40 AMeV with BLOB

Taylor-Young development around $\delta=0$:

$$
\epsilon(\rho, \delta) = \epsilon(\rho, \delta=0) + \epsilon_{sym}(\rho) \cdot \delta^2 + \ldots
$$

$$
\epsilon_{sym} = \frac{1}{2} \left. \frac{\partial^2 \epsilon(\rho, \delta)}{\partial^2 \delta} \right|_{\delta=0}
$$

Example of parametrization:

$$
\epsilon_{sym}(\rho) = \frac{C_{kin}}{2} \left( \frac{\rho}{\rho_0} \right)^{2/3} + \frac{C_{pot}}{2} \left( \frac{\rho}{\rho_0} \right)^\gamma
$$

Fermi gas

N-N interaction

Example: Second-order limited development around $\rho_0$:

$$
\epsilon_{sym}(\rho) = S_0 + \frac{L}{3} \left( \frac{\rho - \rho_0}{\rho_0} \right) + \frac{K_{sym}}{18} \left( \frac{\rho - \rho_0}{\rho_0} \right)^2 + \mathcal{O} \left\{ \left( \frac{\rho - \rho_0}{\rho_0} \right) \right\}^3
$$

- $L$ = 3$\rho_0$ $\left. \frac{\partial \epsilon_{sym}(\rho)}{\partial \rho} \right|_{\rho=\rho_0}$
  
  "Slope" parameter

- $K_{sym}$ = 9$\rho_0^2$ $\left. \frac{\partial^2 \epsilon_{sym}(\rho)}{\partial^2 \rho} \right|_{\rho=\rho_0}$

  "Incompressibility" parameter
Particle ID

VAMOS

- ΔE-E → Z-identification:

- A-identification:

INDRA

- ΔE-E → Z-identification:

- Pulse-shape (slow/fast) CsI(Tl):

$\Delta E$-channel Vs $E_{CsI}$

$Z=20$

$\Delta E$-channel Vs $A/Q$
Particle ID

- **VAMOS**
  - ΔE-E → Z-identification:
  - Pulse-shape (slow/fast) CsI(Tl):
    - CsI(Tl) fast

- **INDRA**
  - ΔE-E → Z-identification:
  - Charge state Q ID:
    - Q=18+
    - Q=13+

Charge state Q ID

- E CsI (channel)
- Chamber à ionisation Si ~540 μm
- DC 1, DC 2
- Plan focal
- Reconstruction au plan focal
- Reconstruction au point cible
- A/Q
- θ LAB
- φ LAB
- B
- ρ B
- φ

Identification

- Z=20
- ΔE Si (channel)
- E CsI (channel)
- θ F
- φ F
- X, Y, 1, 2, 3, 4
- Q=18+
- Q=13+

Back-up slides: Particle ID with VAMOS
INDRA-VAMOS coupling: setup

E503 experiment

\[ ^{40,48}\text{Ca} + ^{40,48}\text{Ca} @ 35 \text{ AMeV} \]

[1] S. Pullanhiotan et al., NIM A 593
[3] M. Rejmund et al., NIM A 646

\[ B \rho = \frac{\gamma m v}{Q} \]
E503 experiment

$^{40,48}\text{Ca} + ^{40,48}\text{Ca} @ 35 \text{ AMeV}$

« Software spectrometer » : trajectory reconstruction from focal plane to the target point using simulations

[1] S. Pullanhiotan et al., NIM A 593
[3] M. Rejmund et al., NIM A 646

Detection chamber

Focal plane

Drift Chamber 1

Drift Chamber 2

Ionization Chamber

(18)Si-wall
(80)CsI-Wall

Reference trajectory ($B\rho=B\rho_0$)
Backup slides: Particle identification

Particle ID with VAMOS

Drift Chambers

- DC$_1$
- DC$_2$

Ionisation Chamber

- $\Delta E$
- $E_{\text{ToF (stop)}}$
- $E_{\text{res}}$

- Si: $\sim 540\mu m$
- CsI(Tl): $\sim 1\text{cm}$

Focal Plan

1. Reconstruction at focal plan
2. Reconstruction at target point

- Drift chambers
- Simulations (ZGOUBI)

Identification

- $A_E = \frac{E_{TOT}}{m_0(y-1)}$
- $A = \frac{B\rho}{3.107\beta}$

ToF: start = HF signal HF (cyclotron)
stop = Si signal
How to normalize the events?

- Beam intensity corrections → $I_{beam}$
- Dead Time corrections → $DT$
- Magnetic rigidity overlaps → $\delta$
- VAMOS acceptance corrections:
  $$\epsilon_{geo}(\delta, \theta_{LAB}) = \frac{\Delta^2\Omega(\delta, \theta_{LAB})}{4\pi}$$
  - efficacité géométrique
  - angle solide effectif
  - $\delta = B\rho / B\rho_0$
  - Simulation of more than $10^6$ trajectoires with Zgoubi to estimate $\epsilon_{geo}(\delta, \theta_{LAB})$

A weight $W(I_{beam}, DT, \delta, \theta_{LAB})$ is applied event-by-event.