Latest results from INDRA and the new INDRA+FAZIA scientific program at GANIL

Olivier LOPEZ, LPC Caen, France (INDRA-FAZIA)

XXth Colloque GANIL, Amboise
Outlines

Latest results from INDRA

➢ Isospin diffusion vs chemical equilibrium

➢ Transport properties above $E_{\text{Fermi}}$ : $\sigma_{NN}^*$ and $N/Z$ equilibration

➢ Fragment formation dynamics : spinodal instabilities in asymmetric matter

➢ Improving INDRA identification : yes we can...

INDRA+FAZIA experimental program @ GANIL

➢ Thermo. : Phase diagram for asymmetric matter (isospin d.o.f).

➢ EOS : Density dependence of SE (status 2017)

➢ Transport : Isovector properties of $NN$ interaction
Latest results from INDRA
Density Dependence of Symmetry Energy

**Fermi-energy HI collisions**

\[ j_n - j_p \propto E_{\text{sym}}(\rho) \nabla I + I \left( \frac{\partial E_{\text{sym}}}{\partial \rho} \right) \nabla \rho \]

INDRA: measuring both QP and neck isotopic content for Z<4

Isospin transport

Fragment formation

Competing migrations of neutrons & protons between spectators & neck

Symmetry energy density-dependence

n/p symmetry potentials

Fragment/cluster N/Z

Reaction times

Isospin equilibration

Courtesy of J.D. Frankland
SC presentation (2014)

FAZIA@INDRA Scientific Programme

XXth Colloque GANIL, October 15-20, 2017, Amboise, France
Chemical equilibration: Isospin diffusion and migration

$^{124/136}$Xe + $^{112/124}$Sn at 32A MeV: INDRA data

Abundance ratios for small clusters/lcp: $d, t, ^3$He, $\alpha, ^6$He

- Chemical equilibrium for $d, t, ^3$He, $\alpha, ^6$He in central collisions
- but $^3$He ratios are different and never show chem. equilibrium

$^{136}$Xe+$^{112}$Sn $\equiv$ $^{124}$Xe+$^{124}$Sn

R. Bougault et al, arXiv:1703.03694
Transport properties: in-medium $NN$ cross section (I)


Tempered cross section from unitarity limit $\sigma_0$

$$\sigma_{NN}^* = \sigma_0 \tanh(\sigma_{NN}^{\text{free}} / \sigma_0)$$

with: $\sigma_0 = \nu \rho^{-2/3}$ and: $\nu = 0.4 - 0.8$

INDRA meta-analysis for symmetric systems between $30A - 100A$ MeV

\textit{O. Lopez et al., PRC 90, 064602 (2014)}

MSU analysis on asymmetric systems: LMT between $20A - 120A$ MeV

\textit{E. Colin et al., PRC 57, R1032 (1998)}

\[\nu = 0.4 - 0.8\]
In-medium $NN$ cross section (II)


<table>
<thead>
<tr>
<th>observable</th>
<th>reaction system</th>
<th>energies [MeV]</th>
<th>best cross section reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>LMT</td>
<td>$^{40}$Ar + Cu</td>
<td>17–115</td>
<td>Tempered w/ $0.4 \leq \nu \leq 0.6$</td>
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<td>27–115</td>
<td>Tempered w/ $\nu = 0.8$</td>
</tr>
<tr>
<td>$\text{varxz}$</td>
<td>Au + Au</td>
<td>90–1500</td>
<td>Tempered w/ $\nu = 0.8$ or Rostock</td>
</tr>
<tr>
<td>$\text{varxz}$</td>
<td>Ca + Ca</td>
<td>400–1500</td>
<td>Tempered w/ $0.4 \leq \nu \leq 0.8$</td>
</tr>
<tr>
<td>$R_z$</td>
<td>$^{96}$Zr+$^{96}$Ru</td>
<td>400</td>
<td>Tempered w/ $\nu = 0.8$, Rostock, or Fuchs</td>
</tr>
</tbody>
</table>

Recoil velocity ($E,A$)

LMT = $\left\langle \frac{v_{||}}{v_{\text{c.m.}}} \right\rangle$

Rapidity variances ($E,A$)

$\text{varxz} = \frac{\Delta y_x}{\Delta y_z}$

Isospin tracer ($Z,A$)

$R_Z = \frac{2 \times Z - Z_{^{96}\text{Zr}} - Z_{^{96}\text{Ru}}}{Z_{^{96}\text{Zr}} - Z_{^{96}\text{Ru}}}$

INDRA+FAZIA
In-medium $NN$ cross section (II)

Central collisions (high Mult.)

Deuterons

M. Henri (LPC Caen), PHD Thesis

LMT = $\left\langle \frac{v_{\parallel}}{v_{c.m.}} \right\rangle$

\[ \text{var}_{xz} = \frac{\Delta y_x}{\Delta y_z}, \]

\[ R_Z = \frac{2 \times Z - Z_{Zr} - Z_{Ru}}{Z_{Zr} - Z_{Ru}} \]
Spinodal decomposition: isoscalar vs isovector instabilities

Spinodal decomposition and dynamics of fragmentation
High-order correlations in charge: \(^{129}\text{Xe}^{\text{nat}}\text{Sn}\) 32A-50A MeV

- Isospin dependence of the phase diagram?
- Correlations with masses (isoscalar) and isospin (isovector)
Spinodal decomposition: isoscalar vs isovector instabilities

Same analysis done for QF events

$^{124}\text{Xe} + ^{112}\text{Sn} @ 32\text{A}, 45\text{A MeV}$

$^{136}\text{Xe} + ^{124}\text{Sn} @ 32\text{A}, 45\text{A MeV}$

- Equal-sized fragments are **over-produced**
- Statistical confidence is **largely enhanced** (10x statistics) to overcome the $5\sigma$ limit ...

Spinodal instabilities are indeed reduced in neutron-rich matter ...
From Si-CsI raw matrices, get $Z$ (grid) and from CsI light output integration, get $L_{\text{exp}}$

- Start with an initial $A_0$ value (mass tables)
- From the calibrated $\Delta E$ silicon and $A \rightarrow E_{\text{csI},0}$
- From Light-Energy formula*, then estimate $L_0$
- Iterate on $A \rightarrow E_{\text{csI},i} \rightarrow L_i$ until $L_i = L_{\text{exp}}$

**Isotopic identification** $Z<12$
**Isotopic estimation (±3) up to $Z=54$ ...

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* $L(E_0) = a_1 E_0 \left[ 1 - a_2 \frac{AZ^2}{E_0} \ln \left( 1 + \frac{1}{a_2 AZ^2/E_0} \right) + a_2 a_4 \frac{AZ^2}{E_0} \ln \left( \frac{E_0 + a_2 AZ^2}{a_3 A + a_2 AZ^2} \right) \right]$
INDRA + FAZIA
Experimental program at GANIL
Phase diagram of Nuclear Matter

- **Big Bang**

- **Connection to HE Physics : QGP**

- **QGP**
  - 200 AGeV

- **Liquid**

- **Gas**
  - 150 MeV

- **Liquid-Gas coexistence**

- **Spinodal region**

- **1st order PT**

- **Critical points**

- **10-100 AMeV**

- **(outer) Neutron Stars (inner)**

- **Introduction of the Isospin degree of Freedom**

\[ \delta = \frac{(N-Z)}{A} \]

- **Temperature 150 MeV**

- **Density \( \rho/\rho_0 \)**

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Microscopic Description of Nuclei

Self-consistent Mean-Field calculations are probably the only possible framework to understand the structure of medium and heavy nuclei.

\[ E = \langle \psi | H | \psi \rangle \]
\[ H = \langle \phi | H_{\text{eff}} | \phi \rangle \]

\[ H = E[\rho] \]

Direct link to EOS and Symmetry Energy
Symmetry Energy around $\rho_0$

$$E/A (\rho, \delta) = E/A (\rho, 0) + \delta^2 \cdot S(\rho)$$

$$\delta = (\rho_n - \rho_p) / (\rho_n + \rho_p) = (N-Z)/A$$

- Constraints for Astrophysics (NS) and for laboratory experiments
- Needed for transport models and nuclear matter studies (Thermodyn.)
- Link to the $NN$ interaction (isovector) in the nuclear medium ($m_{n,p}^*$)

Density dependence for SE

$$S(\rho) = S_k (\rho/\rho_0)^{2/3} + S_i (\rho/\rho_0)^\gamma$$

$$L(\rho) = 3\rho \frac{\partial S(\rho)}{\partial \rho}$$

$$K_{sym}(\rho) = 9\rho^2 \frac{\partial^2 S(\rho)}{\partial \rho^2}$$
Symmetry Energy around $\rho_0$ (II)

Latest evaluation for $E_{\text{sym}}(\rho_0)$ and slope $L(\rho_0)$

B.A. Li and X. Han, Phys. Lett. B727 (2013) 276

Today (2017):

$E_{\text{sym}}(\rho_0) = 31.9 \pm 2.5 \text{ MeV} \quad \rightarrow 8\%$ uncertainty

$L(\rho_0) = 55.3 \pm 28.1 \text{ MeV} \quad \rightarrow 51\%$ uncertainty

$K_{\text{sym}}(\rho_0)$ not constrained at all
Tensor effects: SRC in ground state nuclei

- due to the tensor component
- mainly $p-n$ SRC (> 90%)
- SRC are enhanced in $N=Z$ nuclei
Short-Range Correlations in nuclei

- SRC is the result of the tensor part of the \(NN\) interaction

- Nucleon momentum distribution at high \(p\) present a tail \(\alpha 1/p^4\)

- Mainly proton distribution are affected by this effect, 20 times more than neutrons

- 20 \% of protons in nuclei experience SRC

- Modify the uncorrelated Fermi gas picture, in terms of Fermi energy for protons/neutrons

- Change the sharing between kinetic and potential parts of the symmetry energy

Uncorrelated (no SRC)

\[
E_{\text{sym}}^{\text{kin}} \approx 12 \left(\frac{\rho}{\rho_0}\right)^{2/3} \\
E_{\text{sym}}^{\text{pot}} \approx 20 \left(\frac{\rho}{\rho_0}\right)\gamma \quad \text{with} \quad \gamma = 0.6-1
\]

\[
E_{\text{sym}}(\rho_0) \approx 32 \text{ MeV} \\
L_{\text{sym}}(\rho_0) \approx 50 - 70 \text{ MeV}
\]

Correlated (SRC)

\[
E_{\text{sym}}^{\text{kin}} \approx -5 \left(\frac{\rho}{\rho_0}\right)^{2/3} \\
E_{\text{sym}}^{\text{pot}} \approx 37 \left(\frac{\rho}{\rho_0}\right)\gamma \quad \text{with} \quad \gamma = 0.35-0.6
\]

\[
E_{\text{sym}}(\rho_0) \approx 32 \text{ MeV} \\
L_{\text{sym}}(\rho_0) \approx 30 - 55 \text{ MeV}
\]

O. Hen et al., PRC 91, 025803 (2015)
Density Dependence of Symmetry Energy: neck + QP

Fermi-energy HI collisions

\[ j_n - j_p \propto E_{\text{sym}}(\rho) \nabla I + I \left( \frac{\partial E_{\text{sym}}}{\partial \rho} \right) \nabla \rho \]

INDRA+FAZIA: measuring both QP and neck isotopic content

Isospin transport
Fragment formation

Competing migrations of neutrons & protons between spectators & neck

Symmetry energy density-dependence
n/p symmetry potentials

Fragment/cluster N/Z
Reaction times
Isospin equilibration

Courtesy of J.D. Frankland
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Density Dependence of Symmetry Energy: neck

SMF simulations $^{58/68}\text{Ni}+^{58/68}\text{Ni}$ 15A, 40A MeV
P. Napolitani et al., PRC 81, 044619 (2010)

Ternary events for $^{68}\text{Ni}+^{68}\text{Ni}$ at 40A MeV
1 QT + 1 neck IMF + 1QP
0.45 < $b_{\text{red}}$ < 0.75

FAZIA data could be sensitive to $E_{\text{sym}}$ stiffness ...

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Density Dependence of Symmetry Energy : QP

- **Isoscaling**: observed scaling law of fragment \((N,Z)\) production for two reactions involving different isotopes (ex. \(^{40/48}_{20/28}\)Ca, \(^{124/136}_{52/54}\)Xe)
- **Isoscaling**: can be related to the symmetry energy
- **Relationship**: different parametrizations from macro/microscopic approaches

**3D Lattice-Gas Model**: the isotopic distribution of the largest cluster in each event is more sensitive to the symmetry energy of the fragmenting system as compared to previous studies using mostly Light or Intermediate Mass Fragments \((Z=1-8)\)

**Example**: \(^{40,48}_{40}Ca + ^{40}_{40}Ca @ 35A - 50A\) MeV

- Measure the **isoscaling law** of the largest fragments for selected impact parameters
- Measure the density of the fragmenting system through fragment-fragment correlations
- Extract the **density dependence** of the symmetry energy as presented here

Symmetry Energy for $\rho << \rho_0$

Described by a weakly-interacting quantum gas of nuclear species in thermal and chemical equilibrium

The neutrino-sphere, where the last scattering of neutrinos occurs during the collapse of the supernovae core, is a warm low-density neutron-rich matter. The energetics of these low density neutron-rich matter is determined by the symmetry free energy far from saturation which is poorly known.

Vaporization events of $^{40,48}$Ca-like projectiles with FAZIA
- Evolution of the cluster mixing among nucleon-gas
- Including isotopes heavier than helium
- In-medium properties of clusters
- Exploring densities, temperatures and N/Z on the path from multifragmentation to vaporization

To be done with FAZIA

Example: $^{58,64}$Ni + $^{58,64}$Ni 50A -90A MeV

Unique set of experimental data to constrain theoretical descriptions. Dedicated calculations will be done with the recently proposed extended NSE model, which is optimized to study equilibrium properties of subsaturation exotic matter to constrain the symmetry free energy far from saturation ($\rho << \rho_0$)
Shear viscosity and transport quantities: perfect fluid limit

The shear viscosity $\eta$ measures the amount of dissipation in a fluid; in Kinetic Theory, it is related to the rate of momentum transport by quasi-particles in the medium.

Classically, it is defined in terms of the friction force per unit area $S$ created by a shear flow characterized by a transverse flow gradient $\nabla v_z$: $F/S = \eta \nabla v_z$

In Kinetic Theory, we have: $\eta = 1/3 \rho \langle v \rangle \lambda_{NN}^*$

Superfluidity when $\eta/s \ll 1$

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$P$ (Pa)</th>
<th>$T$ (K)</th>
<th>$\eta$ (Pa s)</th>
<th>$\eta/n$ ($\hbar$)</th>
<th>$\eta/s$ ($\hbar/k_B$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>$0.1 \times 10^6$</td>
<td>370</td>
<td>$2.9 \times 10^{-4}$</td>
<td>85</td>
<td>8.2</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$0.1 \times 10^6$</td>
<td>2.0</td>
<td>$1.2 \times 10^{-6}$</td>
<td>0.5</td>
<td>1.9</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>$22.6 \times 10^6$</td>
<td>650</td>
<td>$6.0 \times 10^{-5}$</td>
<td>32</td>
<td>2.0</td>
</tr>
<tr>
<td>$^4$He</td>
<td>$0.22 \times 10^6$</td>
<td>5.1</td>
<td>$1.7 \times 10^{-6}$</td>
<td>1.7</td>
<td>0.7</td>
</tr>
<tr>
<td>$^6$Li ($\alpha = \infty$)</td>
<td>$12 \times 10^{-9}$</td>
<td>$23 \times 10^{-6}$</td>
<td>$\leq 1.7 \times 10^{-15}$</td>
<td>$\leq 1$</td>
<td>$\leq 0.5$</td>
</tr>
<tr>
<td>QGP</td>
<td>$88 \times 10^{33}$</td>
<td>$2 \times 10^{12}$</td>
<td>$\leq 5 \times 10^{11}$</td>
<td>$\leq 0.4$</td>
<td></td>
</tr>
</tbody>
</table>

"Nearly perfect fluidity: from cold atomic gases to hot quark gluon plasmas"

$\eta/s$ is limited at low values (most perfect fluid) by the quantum universal ratio limit $\eta/s = 1/4\pi$

What is the viscosity of the nuclear matter in the Fermi energy domain? Can it be used to probe the LG phase transition?
Shear viscosity in nuclear matter: how far from the perfect fluid?

**IQMD** calc. for $^{129}$Xe+$^{119}$Sn central collisions: Entropy density with momentum-dependent Skyrme interaction ($K=220$ MeV)

Boltzmann-Uehling-Uhlenbeck simulations
RHIC energies: Glauber MC model


$\eta$ is constrained by INDRA data from stopping

Universal lower limit $1/4\pi$

Critical Temperature $\sim 170$ MeV

H. L. Liu, Y. G. Ma, A. Bonasera, X. G. Deng, O. Lopez, and M. Veselsky,
To be published in PRC
Shear viscosity and phase transition


- Degenerate Fermi fluid at low $T$: due to Pauli exclusion principle
  Lack of collisions $\Rightarrow$ High viscosity, $\eta$ goes as $1/T$

- Classical (nucleon) gas at high $T$: $\eta$ goes as $\sqrt{T}$

Phase transition...
Coupling FAZIA demonstrator with INDRA

**FAZIA** demonstrator (est. 2016), 12 blocks:
- 192 20x20mm² high-quality Si-Si-CsI telescopes from 2 to 14 deg.
- + customized full digital electronics

**Between 2-14 deg.**
- FAZIA geom. acceptance 82% (90%)
- Granularity x2 as compared to **INDRA**

**INDRA** (rings 1,2/3,4/5 removed)

FAZIA at 80cm from target

Beam

Ring 6/7 (INDRA)

Distance FAZIA-target 80 cm
Beam aperture 2 deg.

Transverse plane
Indra + Faizia scientific program at GANIL

Isovector dependence of the nuclear interaction and EOS

- **In-medium properties of clusters**: clustering @ low density (i.e. \( \alpha \)-Hoyle states), cluster emission in n-rich/poor systems

- **Study of EOS at low density**: vaporization and cluster mixing with nucleon gas

- **Density dependence of Symmetry Energy**: isospin diffusion in DIC, isoscaling using the largest fragment, neutron enrichment in the neck (migration/diffusion)

- **Transport properties @ Fermi energy**: \( NN \) collisions in the isovector sector, isospin tracer, short-range correlations in nuclei, effective masses, and also: radial flow, viscosity ...
The End?
The Beginning !
Stopping power in central HIC

42 (quasi)-symmetric systems, Only protons for $<R_E>$...

$$R_E(\alpha) = \frac{1}{1 + 5(\alpha P_{rel}/P_{Fermi})^2}$$

**Nuclear Stopping**

- **Fermi Spheres Calculation**
  - $\alpha=1$ : Entr. Channel
  - $\alpha=0$ : Full Stopping

**INDRA data for High $M_{\text{LCP}}$ gate, Z=1 (total)**
- □ Gd/U+U, $A_{\text{tot}}=404-476$
- ○ Ta/Au+Au, $A_{\text{tot}}=378-394$
- ● Xe+Sn, $A_{\text{tot}}=248$
- ■ Ni+Ni, $A_{\text{tot}}=116$
- △ Ar+Ni, $A_{\text{tot}}=94$
- ▲ Ar+KCl, $A_{\text{tot}}=72$

**Graph:**
- Adiabatic Full stopping
- Sudden approx. Full transparency

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Nucleon mean free path in nuclear medium

Assuming: $<\lambda_{NN}^* > = L/d$

$\Rightarrow \lambda_{NN}^* = 4 - 11 \text{ fm}$

$\lambda_{NN}^* = 4 - 5 \text{ fm}$

- $\lambda_{NN} \geq R$: complete stopping and thermalization not achieved...
  - J. Su and F.S. Zhang, PRC 87, 017602 (2013) [AMD]

- Contradictory findings with SMF by E. Bonnet, et al., PRC 89, 034608 (2014)
FAZIA COR status for Identification

G. Verde (IPNO/LNS Catania)
D. Gruyer (LPC Caen)
Online results are promising: in-medium clustering for light nuclei, here $^{20}\text{Ne}$ and $^{32}\text{S}$ with 3-α correlation ($^{12}\text{C}^*$).
Radial Flow systematics

➢ Linear behavior as a function of $E_{cm}$: at $E_{cm}/A=10$ MeV, we get: $\varepsilon_{rad} = 1.5-2$ AMeV
but some discrepancies appear ...

➢ Radial flow is obtained from multifragmentation models (SMM-like): freeze-out volume

→ model-independent estimation for radial flow is needed...

Radial flow: toward an experimental determination

From central collisions at same $E^*$ or $T$:

- Same fragmentation pattern: Partitions and multiplicities are similar
- Differences for the Kinetics:
  - Radial flow $\varepsilon_{rad}$
  - Experimental determination of $\varepsilon_{rad}$ for $Z>4$ with isotopic resolution (A)


Proposed experiment

- Cover the Fermi energy domain
- Benefit from the maximal $N/Z$ with stable beams at $E_{fermi}$
- Also study the isospin diffusion/migration in dissipative collisions

$^{124,129,136}$Xe @ 30, 39, 50 AMeV on $^{40,48}$Ca and $^{nat}$Sn targets
Radial flow: toward an experimental determination

3 components for $E_k$: $<E_k> = <E_{coul}(Z)> + <T> + <E_{rad}(A)>$

- Coulomb: $<E_{coul}(Z)> \propto Z (Z_s - Z_0) (\rho/\rho_0)^{1/3}$
- Thermal: $<T>$: thermal component, no dep.
- Radial: $<E_{rad}(A)> = <\varepsilon_o> \cdot A$ where $<\varepsilon_o>$ is the average radial flow component

Freeze-out volume $V = (\rho_0/\rho) r_0^3 A_s$
Radial flow: toward an experimental determination

SMM Calculations

$Z=90, \ E^*/A=7.5 \ MeV$

$\rho = \rho_0 / 3$

Carbon isotopes

Even better for higher species?...

Courtesy of R. Bougault

Olivier LOPEZ (lopezo@in2p3.fr)
FAZIASym: Isospin diffusion for $^{48}\text{Ca}$ QP

$^{48}\text{Ca} + ^{40}\text{Ca} @ 35\text{A MeV}$

B0Q3T3, Si-Si
$\theta = 2.7\text{deg.}$

Only inclusive events ... preliminary!

Entries 425555
Angular range:
\[ \theta = 2 - 8^\circ \text{ (polar)} \]

\[ ^{40}\text{Ca} + ^{40,48}\text{Ca} \text{ (+ C layer)} \]
\[ ^{48}\text{Ca} + ^{40,48}\text{Ca} \text{ (+ C layer)} \]
@ 35A MeV

\[ \theta_{\text{grazing}} (^{40}\text{Ca}) = 1.93^\circ \]
\[ \theta_{\text{grazing}} (^{48}\text{Ca}) = 1.85^\circ \]

1 Block = 16 telescopes Si-Si-CsI
- Si(NTD) : 300 µm thick.
- Si(NTD) : 500 mm thick.
- CsI(Tl) : 10 cm thick.

\( Q,I \) readout from PACI
In-vacuum Front-End Electronics
Sampling at 250 MHz, 14 bits
Isotopic Identification is OK up to Z=20, even for $^{48}\text{Ca}$ combining $PSA + E - \Delta E$
Short Range Correlations

Features of SRC:

- Nucleons can stay at closer distance (<1 fm)
- Strong attraction and repulsion
- Nucleons can carry much higher momenta
  Exceed the limit of IPSM – \( k > k_F \)
- Zero total momentum:
  A real ground state, not an excited state.
- Break-up these correlated nucleons:
  Detect a nucleon with much higher momentum;

**Momentum distribution**: All possible momentum values that nucleons carry inside the nucleus.