Experimental observables and transport models: a challenge in HIC from low to high energy regime

Transport models are the main way to extract dynamical information from Heavy Ion Collisions, in particular when looking at the EOS symmetry energy constraints as a function of density.

Main topics

- Observables at low and Fermi Energy regime: some examples and open problems
- Results of the AsyEos@GSI experiment: how these results have contributed to improve the theory for interpretation of data. Open problems and new perspectives
- Particle and IMF correlations: experimental improvements and status of the FARCOS correlator array project.
The nuclear EOS describes the relation among energy, pressure, density, temperature and isospin asymmetry. It is a fundamental ingredient in nuclear physics (exotic nuclei, heavy ion collisions, ...) and astrophysics (neutron stars, supernovae, ...)

Liquid gas coexistence

Nuclear matter phase diagram (schematic)

Heavy ion collisions (HIC): Why and how they provide information on density dependence of Symmetry term of EOS?

With HIC large density variations (density gradients) in nuclear matter can be obtained in a short timescale.

Isospin asymmetry

Relevance of symmetry energy in astrophysical objects

Courtesy S. Gandolfi

\( M_0 \)

Nuclear matter

\( 1 - 2\rho_0 \)
Symmetry energy constrained by ratio or difference of observables \((n/p, \pi^-/\pi^+, \text{etc})\) or \(N/Z\) contents of reaction products.
Symmetry energy at low density: momentum dependence of the nucleonic mean-field potential (an example with MSU data)

More repulsive potential for neutrons


Effective mass splitting not well constrained yet
Symmetry energy at low density: momentum dependence of the nucleonic mean-field potential (an example with MSU data)

Effetive mass splitting not well constrained yet

More repulsive potential for neutrons

SMF model: Impact of mass-splitting on Elliptic Flow Au+Au@400 A.MeV

Effetive mass splitting not well constrained yet

Isospin influence on reaction mechanisms at low energies \((E/A<15\text{ A.MeV})\)

The \(^{78}\text{Kr} + ^{40}\text{Ca}\) and \(^{86}\text{Kr} + ^{48}\text{Ca}\) @10 A.MeV reactions (ISODEC experiment)

Comparison with stochastic transport models (SMF, BLOB, ..) can look at interplay among CN formation, fission, deep-inelastic processes, quasi-fission, etc for systems with different isospin \(\rightarrow\) (exotic beams, Spes - Spiral2 interplay)

<table>
<thead>
<tr>
<th></th>
<th>(\sigma_{ER}) (mb)</th>
<th>(\sigma_{FL}) (mb)</th>
<th>(\sigma_{ER}/\sigma_{FL})</th>
<th>(\sigma_{\text{reac}}) (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{78}\text{Kr} + ^{40}\text{Ca})</td>
<td>455±70</td>
<td>790±120</td>
<td>0.58</td>
<td>2390±250</td>
</tr>
<tr>
<td>(^{86}\text{Kr} + ^{48}\text{Ca})</td>
<td>400±60</td>
<td>560±85</td>
<td>0.71</td>
<td>2520±260</td>
</tr>
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To be submitted to PRC LOI at SPES@LNL \(^{92,94}\text{Kr}\)
1) The “neck” emission where light IMFs (Z≈9) are produced at midrapidity due to the rupture of a piece of nuclear matter a low density (“neck”). This is a FAST process (<100 fm/c)
Properties of dynamically emitted fragments: SMF and Chimera data

- Good reproduction of reactions dynamics
- Asy-stiff (L=75 MeV) better reproduce the N/Z content of IMFs

Open problems

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Open problems:

LQMD calculations for Sn+Ni reaction at 35 A.MeV: More neutron rich particles for a asy-soft case in neck fragmentation dynamics
Zhao-Qing Feng, PRC94,014609 (2016)

Effect of symmetry energy at low density?

Problems of data reproduction by using different models: need different observables at same times both in experiment and theory.

Need coherent results by different models

Some experimental signatures:
Clear distinction of dynamical (DE) and statistical emission (SE)
Production of DE light IMFs at low densities $\rho \approx 1/3 \rho_0$
N/Z enrichment for dynamical emitted fragments
Link between IMFs emission time-scale, isotopic composition and phase-space alignments
Enhanced IMF production for neutron rich systems
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Effect of early cluster productions: influence on dynamics

Reduced isospin migration and diffusion through the neck.
Less sensitivity to EOS parametrization


Open problems:

At which density does cluster formation appear? (see L. Qin et al. ....)

Inclusion of cluster formation as “ingredient” in transport models (AMD [Ono] has cluster production)

Realistic production of light fragments in the models
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Yield of clusters vs. density

\[ K_c = \frac{\rho(A,Z)}{\rho_p^2 \rho_n^2} \]
Isospin dependence on projectile break-up

Main experimental signature:
Probability of dynamical emission enhanced for neutron rich system

Open problems:
Calculations need to follow the full range of times scale involved and the whole IMF mass spectrum

HIGH DENSITIES: COLLECTIVE FLOWS

\[ \frac{dN}{d(\phi - \phi_R)}(y, p_t) = \frac{N_0}{2\pi} \left( 1 + 2 \sum_{n \geq 1} v_n \cos n(\phi - \phi_R) \right) \]

**Transverse flow**

\[ V_1(y, p_t) = \left\langle \frac{p_x}{p_t} \right\rangle \]

**Elliptic flow**

\[ V_2(y, p_t) = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle \]

**Elliptic flow**: competition between in plane ($V_2 > 0$) and out-of-plane ejection ($V_2 < 0$)

**Transverse flow**: it provides information on the azimuthal anisotropy in the reaction plane
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Elliptic flow from FOPI /LAND experiment \(\text{Au+Au 400 A.MeV}\)

UrQMD model: \(\text{Au+Au @ 400 AMeV}\)

5.5\(<b<7.5 \text{ fm}\)


UrQMD vs. Tubingen QMD: searching for model invariance

UrQMD:
- momentum dep. of isoscalar field
- momentum dep. of NNECS
- momentum independent power-law parameterization of the symmetry energy

\[ \gamma = 0.9 \pm 0.4 \]
\[ L = 83 \pm 26 \]

Y. Leifels et al., PRL 71, 963 (1993)
P. Russotto et al., PLB 697 (2011)

Tübingen-QMD:
- density dep. of NNECS
- asymmetry dep. of NNECS
- soft vs. hard EoS
- width of wave packets
- momentum dependent (Gogny inspired) parameterization of the symmetry energy

\[ x = -1.0 \pm 1.0 \]
\[ L = 122 \pm 57 \]

M.D. Cozma et al., PLB 700, 139 (2011); PRC 88 044912 (2013)
Flow ratios of neutrons/Charged particles in comparison with UrQMD predictions

$\gamma = 0.75 \pm 0.1$

$b < 7.5 \text{ fm}$

HIC: (mainly Sn+Sn . . . )

M.B. Tsang et al., PRC 86, 015803 (2012)

Neutron skin thickness, binding energies, . . . :


FOPI DATA : P.Russotto et al., Phys. Lett. B 697 (2011) : $\gamma = 0.9 \pm 0.4$ ; $L=83\pm26$

ASYEOS DATA (with final corrections):

$\gamma = 0.72 \pm 0.19$ ; $L=72\pm13$
OUTLOOK: UrQMD prediction for some interesting beams (and $\delta^2$)

- $^{197}$Au+$^{197}$Au @ 400, 600, 800, 1000, 1500 AMeV (0.039+0.039)
- $^{132}$Sn+$^{124}$Sn @ 400, 600, 800 AMeV (0.059+0.037)
- $^{106}$Sn+$^{112}$Sn @ 400, 600, 800 AMeV (0.003+0.011)
NeuLAND @ FAIR/GSI

- TDR finalized in Oct 2011 and submitted
- total volume 2.5x2.5x3 m³
- each bar readout by two PMT
- 3000 modules (plastic scintillator bars) 250x5x5 cm³
- 30 double planes with 100 bars each, bars in neighboring planes mutually perpendicular
- σₜ ≤ 150 ps and σₓ,y,z ≤ 1.5 cm
- one-neutron efficiency ~95% for energies 200-1000 MeV
- multi-neutron detection capability
Open problems ... or opportunities?

Sensitivity of observables to density. TuQMD calculations

Possibility to look simultaneously to flow data and pions data in future experiments: SπRIT TPC, new AsyEos@R3B projects?

New perspectives and advances with PIONS ratios

Short range correlations may influence results


B. Lynch, AsyEos 2015

M.B. Tsang et al., arXiv 1612.06561

Gao-Chan Yong, Phys. Rev. C 93, 044610 (2016)
F. Zhang, Gao-Chan Yong, EPJA 52, 350 (2016)

Possibility to look simultaneously to flow data and pions data in future experiments: SπRIT TPC, new AsyEos@R3B projects?
### Experimental PERSPECTIVES in CHIMERA group: The FARCOS project

<table>
<thead>
<tr>
<th>Year</th>
<th>Tel.</th>
<th>Operation</th>
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<tbody>
<tr>
<td>2015</td>
<td>6</td>
<td>test acq. GET for FARCOS construction of 2 telescopes purchase of final GET electronics</td>
</tr>
<tr>
<td>2016</td>
<td>10</td>
<td>test dual gain module test GET electronic +DAQ Study of alignment system</td>
</tr>
<tr>
<td>2017</td>
<td>14(10)</td>
<td>test newasic pre-amplifiers final design modular support implementationasicpre-amplifier new DAQ VME+ GET running First experiments with new Chimera+Farcos front-end</td>
</tr>
<tr>
<td>2018</td>
<td>18(?)</td>
<td>Construction of new telescopes</td>
</tr>
<tr>
<td>2019</td>
<td>20+2</td>
<td>20 telescopes ready</td>
</tr>
</tbody>
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Final cost prediction: $\approx 1 \text{ M\€}$
High energy and angular resolution ($\Delta \theta < 1^\circ$)
Low thresholds (<1 MeV/A):
Pulse-shape on first Si layer for low energy experiments
High counting rate (1KHz)
Large Dynamic range (20MeV to 2GeV)
Flexibility, Modularity, Trasportability
Easy coupling to $4\pi$ detectors or spectrometers
Integrated Electronics (GET)
Dynamical processes in projectile break-up and IMFs at 20 A.MeV studied with the CHIMERA and FARCOS devices.

CHIFAR: CHImera-FARcos

(Approved LNS-PAC proposal)

Spokes: E.V. Pagano, E.d.F., P. Russotto

Dynamical processes in projectile break-up and Intermediate Mass Fragments production at 20 A.MeV beam incident energy studied with the CHIMERA and FARCOS devices.

CHIMERA + 8 FARCOS telescopes

$^{124}$Xe, $^{124}$Sn + $^{64}$Ni, $^{64}$Zn

$^{112}$Sn + $^{58}$Ni @ 20 A.MeV

IMF-IMF correlations function

See E.V. Pagano talk
Transport models are a fundamental tool to learn about the behaviour of the nuclear effective interaction and EOS and at the same time reactions dynamics that can be compared with experimental results. More work on code consistency needed yet. Results (not a review) at low and intermediate energies have been shown.

The AsyEos (S394) experiment results that have given a stringent constraint for the symmetry energy at supra-saturation density, contributing also to improve the understanding of models by careful comparison of data with transport codes.

New experiments like SπIRIT TCP or NeuLand@R3B at GSI or should improve accuracy in observable measurements, giving new results for flows and particles ratios (like p, n, light clusters, π−, π+, Kaons, etc) possibly looking simultaneously at different observables by using stable and radioactive beams.