The symmetry energy at high density: experimental probes

W. Trautmann
GSI Helmholtzzentrum, Darmstadt, Germany

- The present consensus that a soft EoS including momentum dependent interactions best describes the high-density behavior of symmetric nuclear matter is based on studies of flow and kaon production within the framework of transport theory.

- The elliptic flow in collisions of neutron-rich heavy-ion systems at intermediate energies emerges as an observable sensitive to the strength of the symmetry energy at supra-saturation densities.

EMMI workshop
Dense Baryonic Matter in the Cosmos and the Laboratory

Tübingen, October 11/12, 2012
symmetric matter

1 A GeV Au+Au

pressure contours

density contours

flow data rule out repulsive and super-soft EoS

KAOS data
K$^+$ ratios
Au+Au vs. C+C
normalized to $<A_{\text{part}}>$ ...

... favor soft EoS


Sturm et al., Fuchs et al., PRL 86 (2001)
symmetric matter

FOPI data
1 A GeV Au+Au
deuteron yields and flows
IQMD model calculations favor soft EoS

source: Reisdorf, AsyEos Siracusa (2012)
the symmetry energy

why so uncertain at high density?

related to uncertainty of three-body and tensor forces at high density

Fuchs and Wolter, EPJA 30 (2006)

normal nuclear density
the symmetry energy

Fuchs and Wolter, EPJA 30 (2006)

param. in transport: UrQMD, Q.F. Li et al.

\[
E_{\text{sym}} = E_{\text{sym}}^{\text{pot}} + E_{\text{sym}}^{\text{kin}} = 22\text{MeV} \cdot (p/p_0)^{\gamma} + 12\text{MeV} \cdot (p/p_0)^{2/3}
\]

\[
L = 3p_0 \cdot \frac{dE_{\text{sym}}}{dp} \text{ at } p=p_0
\]

\[\begin{array}{|c|c|}
\hline
\gamma & L \text{ (MeV)} \\
\hline
0.5 & 57 \\
1.0 & 90 \\
1.5 & 123 \\
\hline
\end{array}\]
the symmetry energy

Fuchs and Wolter, EPJA 30 (2006)

param. in transport: MDI, Bao-An Li et al.

force developed by
Das, Das Gupta, Gale, and Bao-An Li,

with explicit momentum dependence in the isovector part
differential flow in heavy-ion collisions minimizes role of isoscalar part of the EoS see Bao-An Li PRL (2000) and subsequent work

differential: neutrons vs. protons $t$ vs. $^3$He, $^7$Li vs $^7$Be, ...

**UrQMD:** significant sensitivity predicted for differential elliptic flow (Qingfeng Li and Paolo Russotto)

**reanalysis of FOPI-LAND data:**

$$\gamma_{\text{pot}} = 0.9 \pm 0.4$$

Trautmann & Wolter, IJMPE 21 (2012) 1230003
results from FOPI/LAND experiment
reanalysis of Au+Au 400 A MeV data

SB: shadow bar for background measurement

acceptance in $p_t$ vs. rapidity

Forward Wall

FOPI Outer Wall

LAND

CHIMERA

four double rings used in ASY-EOS experiment 2011
azimuthal angular distributions relative to the reaction plane for neutrons, background subtracted

near **target rapidity**
mostly directed flow

at **mid-rapidity**
strong squeeze-out

near **projectile rapidity**
mostly directed flow

fitted with:
\[ f(\Delta \phi) = a_0 * (1 + 2v_1 \cos(\Delta \phi) + 2v_2 \cos(2\Delta \phi)) \]
\( \Delta \phi = \phi_{\text{particle}} - \phi_{\text{reaction plane}} \)

and compared to **UrQMD** model predictions

results from FOPI/LAND experiment

\begin{align*}
\gamma &= 1.5 \\
\gamma &= 0.5
\end{align*}

\begin{align*}
\text{neutron/hydrogen} \\
\text{FP1: } \gamma &= 1.01 \pm 0.21 \\
\text{FP2: } \gamma &= 0.98 \pm 0.35
\end{align*}

\begin{align*}
\text{neutron/proton} \\
\text{FP1: } \gamma &= 0.99 \pm 0.28 \\
\text{FP2: } \gamma &= 0.85 \pm 0.47
\end{align*}

 adopted: $\gamma = 0.9 \pm 0.4$
Medium modifications (FU1, ...) and momentum dependence (FP1, ...) of nucleon-nucleon elastic Xsects

Qingfeng Li et al., PRC 83 (2011)
new: result obtained with Tübingen QMD*)

M.D. Cozma, PLB 700, 139 (2011); arXiv:1102.2728

difference of neutron and proton squeeze-outs
Au + Au @ 400 A MeV

- with FOPI filter
- bands show uncertainty due to isoscalar field “soft to hard”

conclusion in paper:
super-soft not compatible with FOPI-LAND data

tested in UrQMD:
momentum dep. of isoscalar field
momentum dep. of NNECS

tested in T-QMD:
density dep. of NNECS
asymmetry dep. of NNECS
soft vs. hard EoS
width of wave packets

HIC scenario:
fast neutron emission (mean field effect), transformation of neutron into proton in inelastic channels, and NN>NA threshold effects (no-chemical equilibrium)

isotopic particle (double) ratios

**K⁺/K⁰ ratio**

- **FOPI data**
- **K⁺/K⁰ ratio**

**π⁻/π⁺ ratio**

- **Reisdorf et al., NPA 781 (2007)**
- **π⁻/π⁺ ratio**

HIC scenario: Data Vs Models

- **0.4A GeV**
- **Au+Au**

---

Ferini et al. (RMF) stiffer for ratio up
Xiao et al. (IBUU) softer “
Feng & Jin (ImIQMD) stiffer “

consequence: extremely stiff (soft) solutions
inconsistent results from pion ratios

analysis of $\pi^-/\pi^+$ ratios in Au+Au at 400 A MeV
FOPI data, Reisdorf et al., NPA (2007)

$\pi$ ratios + IBUU04:
$\times=1$ super soft
Xiao et al., PRL 102 (2009)

$\pi$ ratios + ImIQMD:
SLy6 with $\gamma=2$ very stiff
Feng and Jin, PLB 683 (2010)
analysis of $\pi^-/\pi^+$ ratios in Au+Au

Zhigang Xiao et al.
PRL 102, 062502 (2009)
FOPI data of Reisdorf et al.

central Au+Au

normalized $\pi$ multiplicity
outlook

- $L \approx 60$ MeV ($\gamma \approx 0.6$) from nuclear structure and reactions probing densities of $\approx 2/3 \rho_0$; **big expectations** on PREXII

- increasingly more precise data from neutron-star observations, typically $L \approx 40$ MeV

- high-densities probed in reactions at SIS energies; analysis of **ASY-EOS** experiment in progress!

- kaon and pion ratios interesting probes but results presently inconclusive: **new activity** at RIKEN (Samurai) and MSU; analysis of HADES kaon data for Ar+KCl and Au+Au

- remarkable progress in theory (3N force in ChEFT)
SAMURAI dipole magnet at RIKEN

Superconducting Analyzer for Multi-particle from Radio Isotope Beam with 7Tm of bending power

TPC project for SAMURAI Tsang, Isobe, McIntosh, Murakami et al.
Experiment S394, CHIMERA-Kraków-LAND-μBall-Zagreb-Daresbury-Liverpool et al., May 2011
µ-ball, CHIMERA, ALADIN ToF wall for impact parameter orientation and modulus

AsyEos experiment S394 in May 2011

studied reactions:

\[ {^{197}}\text{Au} + {^{197}}\text{Au} @ 400 \text{ A MeV} \]
\[ {^{96}}\text{Ru} + {^{96}}\text{Ru} @ 400 \text{ A MeV} \]
\[ {^{96}}\text{Zr} + {^{96}}\text{Zr} @ 400 \text{ A MeV} \]
The Asy-Eos Collaboration

Co-Speakers: R.C. Lemmon¹ and P. Russotto²

Collaboration

\[ L = 3\rho_0 \cdot \partial E_{\text{sym}} / \partial \rho \]

- **IAS** isobaric analog states
- **HIC** heavy-ion collisions
- **PDR** pygmy dipole resonance

- IAS: Danielewicz/Lee 2008
- HIC: Isospin diffusion, n/p ratios
- PDR: Tsang et al., 2009

\[ S_0 = E_{\text{sym}}(\rho_0) \]

- From elliptic n/p flow

From M.B. Tsang et al., PRL 102, 122701 (2009)

Vertical lines: analyses with ImQMD (Zhang et al.) and IBUU04 (Li and Chen)