Constraining the nuclear matter equation of state using the elliptic flow of light clusters

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$^1$GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

$^2$SUBATECH, UMR 6457, Ecole des Mines de Nantes - IN2P3/CNRS - Université de Nantes, France

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- Constraining the stiffness of the EOS with the elliptic flow.
- A clusterisation approach…
- Towards the determination of the stiffness of the asymmetry energy.
- Summary and discussion.
Introduction

- The equation of state (EOS) of nuclear matter:
  - of fundamental interest
  - object of intense theoretical efforts since several decades
  - an important ingredient in modeling physical phenomena such as:
    - compact stars [1]
    - core collapse supernovae
  - The calculation of the nuclear EOS, such as very recently attempted in [3], is a very complex task.
  - Nuclear physics based on empirical observations => even the most ‘fundamental’ theory of nuclear forces requires a confrontation with empirical facts.

Introduction

- The equation of state (EOS) of nuclear matter:
  - of fundamental interest
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  - an important ingredient in modeling fascinating astrophysical phenomena such as:
    - compact stars\(^1\)
    - core collapse supernovae\(^2\)

- The calculation of the nuclear EOS from first principles, such as very recently attempted in \(^3\), is a very complex task.

- Nuclear physics based on empirical observations => even the most 'fundamental' theory of nuclear forces requires a confrontation with empirical facts.

- 1st method, from astrophysicists: from 'neutron' star masses and radii. But missing:
  - precise model-independent radii,
  - composition of the matter in the center of the stars.

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Introduction

Alternative method: in earth laboratories, heavy ion collisions over a wide range of incident energies, system sizes and compositions.

- limited to $E_{\text{beam}} < 10 \text{ A.GeV}$ ↔ some kind of a clock is available (sound velocity versus participant-spectator interaction).
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Flows at high density in heavy-ion collisions

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

\( Y = \text{rapidity} \)
\( p_t = \text{transverse momentum} \)
\( \phi_R = \text{reaction plane azimuthal angle} \)

\( V_1 = \text{‘side/directed flow’, } \langle p_x/p_t^2 \rangle \)

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

‘Elliptic flow’: \( \cos(2(\phi-\phi_R)) \) mode, competition between ‘in-plane’ \((V_2>0)\) and ‘out-of-plane’ ejection \((V_2<0)\).
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Constraining the stiffness of the EOS with the elliptic flow.

- **Present work**: improve the situation in the 1 A.GeV regime, from extensive flow data published recently by the FOPI Collaboration (Au+Au @ 0.4-1.5 A.GeV) \[^4\]

- close look at the elliptic flow data with improvements:
  - 1) not only protons: d, t, \(^3\)He \(^4\)He having larger flow signals than single nucleons.
  - 2) not only mid-rapidity data: 80% of the target-projectile rapidity gap.

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Constraining the stiffness of the EOS with the elliptic flow.

Elliptic flow

Au+Au 1.2A GeV 0.25<b0<0.45 protons

Constraining the stiffness of the EOS with the elliptic flow.

Complete shape of $v_2(y_0)$:
- A new observable:
  
  $$v_{2n} = |v_{20}| + |v_{22}|,$$
  
  from fit
  
  $$v_2(y_0) = v_{20} + v_{22} \cdot y_0$$

  $\Rightarrow v_{2n}(E_{\text{beam}})$ varies by a factor
  $\approx 1.6$, $\gg$ measured uncertainty
  ($\approx 1.1$)

  $\Rightarrow$ clearly favors a 'soft' EOS.

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- Phenomenological EOS
  HM and SM include the saturation point at $\rho/\rho_0 = 1$, $E/A = -16$ MeV by construction.
- $\Rightarrow$ fixes the absolute position of the curves:
- the heavy ion data are only sensitive to the shape, i.e. the pressure (derivative).
- $\Rightarrow$ a stiff EOS, characterised by $K_0 = 380$ MeV is not in agreement with the flow data in the incident energy range 0.4 - 1.5 A.GeV.
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Which density has been probed?

Purpose = characterise which 'typical' densities where probed in the FOPI experiments

=> at which time $V_2$ develops, and which conditions influence it the most.

IQMD transport model\textsuperscript{[5,6]} various phenomenological EOS's:

» 'stiff' = H & HM (+ momentum dependent), $K_0 = 380$ MeV

» 'soft' = S & SM (+momentum dependent), $K_0 = 200$ MeV.

Here: protons in Au+Au at 1.5 A.GeV, $b=3$ fm

full target-projectile overlap

Density

Number of collisions

Mean-field momentum transfer

$\Phi / \langle \Phi \rangle_{\text{c.m.}}$

$\langle \Phi \rangle / \langle \Phi \rangle_{\text{c.m.}}$

$t_{\text{scaled}} = \text{time} / \text{passing time}$

$\Sigma N_{\text{coll}}$

$\langle \Delta p_{\text{f.m.}} \rangle (\text{GeV/c})$

$0.5$ $1$ $1.5$ $2$ $2.5$

$0$ $0.5$ $1$ $1.5$ $2$ $2.5$

$0$ $0.5$ $1$ $1.5$ $2$ $2.5$

$0$ $5$ $10$

$0.05$ $0.1$ $0.15$
Which density has been probed?

- The elliptic flow in his final dependence with rapidity develops fast: during the passing time.

- The elliptic flow in strength and shape is mostly influenced by the force of the mean field.

- The 'typical' density of the 'measured' EOS can be built from the mean value weighted by this force up to the passing time.
Simulations: the scenario

- The density range, relevant to the EOS evidenced by the FOPI Collaboration, spans in the range \( \rho = (1.25 - 2.0) \rho_0 \).
SACA: a clusterisation approach…

2 steps:

1) Pre-select good «candidates» for fragments according to proximity criteria: real space coalescence = Minimum Spanning Tree (MST) procedure.

\[ E = E_{\text{kin}}^1 + E_{\text{kin}}^2 + V^1 + V^2 \]

- Simulated Annealing Procedure: PLB301:328,1993; later called SACA.
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If \( E' < E \) take the new configuration

If \( E' > E \) take the old with a probability depending on \( E' - E \)
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Repeat this procedure very many times…
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1) Pre-select good «candidates» for fragments according to proximity criteria: real space coalescence = Minimum Spanning Tree (MST) procedure.
2) Take randomly 1 nucleon out of one fragment
3) Add it randomly to another fragment

\[ E = E_{1\text{kin}} + E_{2\text{kin}} + V_1 + V_2 \]
\[ E' = E'_{1\text{kin}} + E'_{2\text{kin}} + V'_1 + V'_2 \]

If \( E' < E \) take the new configuration
If \( E' > E \) take the old with a probability depending on \( E' - E \)
Repeat this procedure very many times...
It leads automatically to the most bound configuration.
SACA: a clusterisation approach...

Ingredients of the binding energy of the clusters:

① **Volume** component: mean field (Skyrme, dominant), for NN, NΛ (hypernuclei)

② **Surface effect** correction: Yukawa term.

③ **Asymmetry energy**: $23.3 \text{ MeV}.(\langle \rho_B' \rangle \gamma_{\text{ASY}}^{-1}).(\langle \rho_n' \rangle - \langle \rho_p' \rangle)^2/\langle \rho_B' \rangle$

④ **Extra « structure » energy** $(N,Z,\rho) = B_{\text{MF}}(\rho).(B_{\text{exp}} - B_{\text{BW}})/(B_{\text{BW}} - B_{\text{Coul}} - B_{\text{asy}}))(\rho_0)$

⑤ $^3\text{He}+n$ recombination.

⑥ **Secondary decay**: GEMINI.
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6. **Secondary decay**: GEMINI.

Remarks:

- Advantage of **SACA** : the fragment partitions can reflect the early dynamical conditions (Coulomb, density, flow details, strangeness...). Fragment partitions already determined at the passing time of the colliding system.
- In the framework of QMD, HSD, $\langle \rho_{clusters} \rangle < 0.5$. $\rho_0 \Rightarrow$ isotope yields of **SACA** with $E_{asy}$ probe it at sub-saturation densities.
SACA: a clusterisation approach...

IQMD-SACA central Xe+Sn @ 100 A.MeV
SACA: a clusterisation approach...

FOPI

IQMD-SACA central Xe+Sn @ 100 A.MeV

Another application of SACA: hypernuclei production

\[ \text{IQMD+SACA} \]
\[ {}^{58}\text{Ni} + {}^{58}\text{Ni} \]
\[ \text{at} \]
\[ 1.91 \text{ AGeV} \]
\[ (b < 6 \text{ fm}) - t_{\text{cluster}} = 20 \text{ fm/c} \]

Soft EOS
with m.d.i.
with Kaon pot.

\[ {}^{4}\text{He} \]
\[ {}^{3}\text{He} \]
\[ {}^{4}\text{H} \]
\[ {}^{6}\text{He} \]
\[ n-\Lambda \]
\[ p-\Lambda \]

\[ {}^{3}\text{H} \]
\[ {}^{4}\text{He} \]
\[ {}^{5}\text{He} \]
\[ {}^{6}\text{He} \]
Towards the determination of the stiffness of the asymmetry energy.

Directed flow

\( \gamma_{\text{asy}} = 1 \)

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Towards the determination of the stiffness of the asymmetry energy.

Directed flow

\[ \gamma_{\text{asy}} = 0.5 \]

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Towards the determination of the stiffness of the asymmetry energy.

Directed flow

\[ \gamma_{\text{asy}} = 1.5 \]

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Towards the determination of the stiffness of the asymmetry energy.

Elliptic flow

\[ \gamma_{asy} = 1 \]
Towards the determination of the stiffness of the asymmetry energy.

Elliptic flow

The differences in $t^3\text{He}$ elliptic flow increases with energy $\gamma_{\text{asy}} = 1$

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Towards the determination of the stiffness of the asymmetry energy.

PRELIMINARY
Towards the determination of the stiffness of the asymmetry energy.

at mid-rapidity

The higher the bombarding energy, the stronger the sensitivity.
Summary and discussion
A single parameter $v_{2n}$, characterising the elliptic flow over a large rapidity interval, for protons and other light isotopes -> clear discrimination for soft EOS.
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- The stiffness of the asymmetry energy can be discriminated by the shape ($v_{2n}$) the elliptic flow over a large range of rapidity (not only mid-rapidity) of $^3\text{He}$ and tritons. -> Preliminary indication of $0.5 \leq \gamma_{\text{asy}} < 1$ by confronting IQMD-SACA to FOPI data.
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See AsyEOS experiment: ongoing analysis, forthcoming talks by P. Russotto and J. Brzychczyk.
Comparison to microscopic calculations

(three representative microscopic calculations compared with our new constraints)

Katayama 2013

--- Au

Dirac-Brueckner-Hatree-Fock (DBHF) calculation\textsuperscript{[10]} using the Bonn A\textsuperscript{[11]} nucleon-nucleon potential

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure.png}
\end{figure}


Comparison to microscopic calculations
(three representative microscopic calculations compared with our new constraints)

![Graph indicating comparison to microscopic calculations](image)

2 symmetric nuclear matter EOS’s from [12]:

1) ‘DBHF’ = meson theoretic potential together with the DBHF method
2) ‘Chiral’ = use of effective field theory (EFT) with density dependent interactions derived from leading order chiral three-nucleon forces.

Comparison to microscopic calculations
(three representative microscopic calculations compared with our new constraints)

Using the chiral approach\cite{13}: 2 rather different EOS’s including or not virtual \(\Delta\) excitations.

- the virtual \(\Delta\)-excitations help locate the EOS at the right horizontal place around \(\rho = 0.16\) fm\(^{-3}\).
- the \(\Delta\) leads to a rather marked stiffening of the EOS (\(K_0 = 304\) MeV)
- because ‘cold’ EOS?
- finite temperature in the reaction \(\Rightarrow\) the \(\Delta\) are real rather than virtual.

The theoretical ‘\(\Delta\) stiffness’ could then be a dispersion effect rapidly changing with temperature.

Beam energy dependence of elliptic flow

- Pressure gradient of compression zone
- Shadowing of spectators
- At low energies
  - Attraction due to mean field of nucleons
- At high energies
  - Lacking shadowing of spectators
Elliptic flow and the nuclear matter EOS

P. Danielewicz et al.
Elliptic flow and the nuclear matter EOS

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