QCD equation of state at finite densities for nuclear collisions

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with Björn Schenke (BNL) and Chun Shen (Wayne/RBRC)


Quark Matter 2019
6th November 2019, Wuhan, China
Introduction

- Exploration of the QCD phase diagram

Little is known at finite density (sign problem of lattice QCD)
Introduction

- Exploration of the QCD phase diagram

Little is known at finite density (sign problem of lattice QCD)
Exploration of the QCD phase diagram

Little is known at finite density (sign problem of lattice QCD)

Use nuclear collisions to study QCD properties at finite T and $\mu_B$
Introduction

- Modeling nuclear collisions

QCD properties

![Graph showing QCD properties with different values of N.](image)

Experimental data

![Graph showing experimental data with different STAR energies.](image)

- We need a “link” between experimental data of nuclear collisions and QCD properties

Relativistic hydrodynamic model
Better Quantitative Studies

- in relativistic nuclear collisions

Baryon number (B)  
(> 0 in total)  
\[ p \quad +1 \quad n \quad +1 \]

Electric charge (Q)  
(> 0 in total)  
\[ p \quad +1 \quad n \quad 0 \]

Strangeness (S)  
(= 0 in total)  
\[ p \quad 0 \quad n \quad 0 \]

Multiple charges are essential in understanding particle-antiparticle ratios

Dunlop et al., PRC 84 044914

<table>
<thead>
<tr>
<th>hadron</th>
<th>yield</th>
<th>u</th>
<th>d</th>
<th>s</th>
<th>( \bar{u} )</th>
<th>( \bar{d} )</th>
<th>s</th>
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<td>( \pi^+ )</td>
<td>72.9</td>
<td>72.9</td>
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<td>( \pi^0 (*) )</td>
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<tr>
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<tr>
<td>( \bar{K}^0 (*) )</td>
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<td></td>
<td></td>
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<td>46.1</td>
<td></td>
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<td>( n (*) )</td>
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<td>13.4</td>
<td>13.4</td>
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<td>( \bar{\Lambda} )</td>
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<tr>
<td>Sum</td>
<td>305.17</td>
<td>337.33</td>
<td>33</td>
<td>130.07</td>
<td>123.56</td>
<td>28.66</td>
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TABLE I: Left two columns: midrapidity yields of common particles from central Pb+Pb collisions measured by the NA49/SPS Collaboration [26–33] at \( \sqrt{s_{NN}} = 6.41 \) GeV. Starred hadrons are not measured, but estimated from other hadrons.
Overview of hydrodynamic model

- with multiple charges

We construct the QCD equation of state (EOS) at finite densities \((B, Q, S)\)
Equation of state

- Construction

Lattice QCD: Taylor expansion up to the 4\textsuperscript{th} order

\[
\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{C_{l,m,n}^{B,Q,S}}{l!m!n!} \left( \frac{\mu_B}{T} \right)^l \left( \frac{\mu_Q}{T} \right)^m \left( \frac{\mu_S}{T} \right)^n
\]

HotQCD Collaboration, PRD 86, 034509 (2012); PRD 90, 094503 (2014); PRD 92, 074043 (2015); PRD 95, 054504 (2017)
Equation of state

Construction

- Lattice QCD: Taylor expansion up to the 4\textsuperscript{th} order

\[
\frac{P}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{\chi_{l,m,n}^{B,Q,S}}{l!m!n!} \left( \frac{\mu_B}{T} \right)^l \left( \frac{\mu_Q}{T} \right)^m \left( \frac{\mu_S}{T} \right)^n
\]

- Match to hadron resonance gas (HRG) at lower T:
  1. Taylor expansion is not reliable when the fugacity ($\mu/T$) is large
  2. Agreement between lattice QCD and HRG is good in hadronic phase

HotQCD Collaboration, PRD 86, 034509 (2012); PRD 90, 094503 (2014); PRD 92, 074043 (2015); PRD 95, 054504 (2017)

Particle Data Group: PRD 98, 030001 (2018)
Equation of state

Construction

- Match to hadron resonance gas (HRG) at lower T

3. The EOS of hydro model should match the EOS of kinetic theory at freeze-out (otherwise EM/charge conservation is lost)

The Stefan-Boltzmann limits are used as anchors at very high T where lattice QCD data are scarce
Equation of state

- Construction

  - Connect to HRG at low T

    \[
    \frac{P}{T^4} = \frac{1}{2} \left[ 1 - f(T, \mu_J) \right] \frac{P_{\text{had}}(T, \mu_J)}{T^4} + \frac{1}{2} \left[ 1 + f(T, \mu_J) \right] \frac{P_{\text{lat}}(T, \mu_J)}{T^4}
    \]

    \[
    J = \{ B, Q, S \}
    \]

    where \( f(T, \mu_J) = \tanh\left( \frac{(T - T_c(\mu_B))}{\Delta T_c} \right) \)

    \( T_c = 0.16 - 0.4 \times (0.139 \mu_B^2 + 0.053 \mu_B^4) \text{(GeV)} \)

    \( \Delta T_c = 0.1 T_c(0) \)

    Crossover-type EOS

    Motivated by chemical freeze-out curve

    J. Cleymans et. al., PRC 73, 034905 (2006)

    The dependences on sub-leading \( \mu \)'s are approximated to be small

  - Effective 6\textsuperscript{th} order susceptibilities are introduced to satisfy thermodynamic conditions:

    \[
    \frac{\partial^2 P}{\partial T^2} = \frac{\partial s}{\partial T} > 0, \quad \frac{\partial^2 P}{\partial \mu_J^2} = \frac{\partial n_J}{\partial \mu_J} > 0
    \]
Strangeness and charge densities

- Strangeness neutrality condition ($n_S = 0$)

  - $\mu_S > 0$ when $\mu_B > 0$

  - $\mu_B > 0$ and $\mu_S = 0$ leads to $n_S \neq 0$

  - $\mu_S > 0$ is needed for $\mu_B > 0$ and $n_S = 0$

  - $s$ quark chemical potential: $\mu_s = \frac{1}{3} \mu_B + \frac{1}{3} \mu_Q - \mu_S = 0$

  - The condition can be modified by initial fluctuations and diffusion

Akihiko Monnai (KEK), Quark Matter 2019, 6th November 2019
Strangeness and charge densities

- Charge-to-baryon ratio \( (n_Q = c \, n_B) \)
  - \( \mu_Q < 0 \) at \( \mu_B > 0 \) for **neutron rich nuclei** \( (Z/A < 1/2) \)

\[
d \text{ quark abundance: } \mu_d = \frac{1}{3} \mu_B - \frac{1}{3} \mu_Q > \mu_u = \frac{1}{3} \mu_B + \frac{2}{3} \mu_Q
\]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>(^1\text{H})</th>
<th>(^2\text{H})</th>
<th>(^3\text{He})</th>
<th>(^{27}\text{Al})</th>
<th>(^{63}\text{Cu})</th>
<th>(^{96}\text{Zr})</th>
<th>(^{96}\text{Ru})</th>
<th>(^{127}\text{Xe})</th>
<th>(^{197}\text{Au})</th>
<th>(^{208}\text{Pb})</th>
<th>(^{238}\text{U})</th>
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<tbody>
<tr>
<td>Z/A</td>
<td>1.000</td>
<td>0.500</td>
<td>0.667</td>
<td>0.481</td>
<td>0.460</td>
<td>0.417</td>
<td>0.458</td>
<td>0.425</td>
<td>0.401</td>
<td>0.394</td>
<td>0.387</td>
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</table>

- proton rich/neutral nuclei  
- relevant for BG analyses of isobars  
- \( c \approx 0.4 \) for Au and Pb nuclei

- We consider 3 cases:  
  - (I) \( \mu_S = \mu_Q = 0 \),  
  - (II) \( n_S = 0, \mu_Q = 0 \) and  
  - (III) \( n_S = 0, \alpha_Q = 0.4n_B \)
Equation of state

- $\mu_S = \mu_Q = 0$ (conventional; denoted as NEOS B)

Thermodynamically consistent smooth EoS is obtained

The strangeness neutrality condition is violated ($n_S < 0$)
Equation of state

- $n_s = 0, \mu_Q = 0$ (strangeness neutral; denoted as NEOS BS)

- A visible modification is observed at larger $\mu_B/T$
- Finite positive $\mu_S$ is seen owing to the neutrality condition
- $\mu_B$ becomes larger at large $T$ for a given $n_B$
Equation of state

- \( n_S = 0, \ n_Q = 0.4n_B \) (realistic in HIC; denoted as NEOS BQS)

- Finite negative \( \mu_Q \) owing to the condition \( n_Q = 0.4n_B \)
- Pressure similar in NEOS BS and BQS because \( \mu_Q = 0 \) implies \( n_Q \sim 0.5n_B \)
µB-µQ-µS space

- Constant pressure plane at fixed T

\( \mu_B^{\text{int}} > \mu_S^{\text{int}} > \mu_Q^{\text{int}} \) in the hadronic phase

Lightest hadrons to carry the charges are ordered in mass as \( m_p > m_K > m_\pi \)

\( \mu_B^{\text{int}} > \mu_Q^{\text{int}} > \mu_S^{\text{int}} \) in the QGP phase

\( \chi_2^B = 1/3, \chi_2^Q = 2/3, \chi_2^S = 1 \) in the parton gas limit implies \( \mu_B^{\text{int}}/3 \sim 2\mu_Q^{\text{int}}/3 \sim \mu_S^{\text{int}} \)
\( \mu_B - \mu_Q - \mu_S \) space

- Constant pressure plane at fixed \( T \)

\[ \mu_B^{\text{int}} > \mu_S^{\text{int}} > \mu_Q^{\text{int}} \] in the hadronic phase

Lightest hadrons to carry the charges are ordered in mass as \( m_p > m_K > m_\pi \)

\[ \mu_B^{\text{int}} > \mu_Q^{\text{int}} > \mu_S^{\text{int}} \] in the QGP phase

\( \chi_2^B = \frac{1}{3} \), \( \chi_2^Q = \frac{2}{3} \), \( \chi_2^S = 1 \) in the parton gas limit implies \( \mu_B^{\text{int}}/3 \sim 2\mu_Q^{\text{int}}/3 \sim \mu_S^{\text{int}} \)
**μ\(_B\)-μ\(_Q\)-μ\(_S\) space**

- Constant pressure plane at fixed T

\[ P/T^4 = 0.8 \]

\[ (a) \ T = 0.14 \text{ GeV} \]

\[ (b) \ T = 0.2 \text{ GeV} \]

\[ μ^\text{int}_B > μ^\text{int}_S > μ^\text{int}_Q \] in the hadronic phase

Lightest hadrons to carry the charges are ordered in mass as \( m_p > m_K > m_π \)

\[ μ^\text{int}_B > μ^\text{int}_Q > μ^\text{int}_S \] in the QGP phase

\( \chi^B_2 = 1/3 \), \( \chi^Q_2 = 2/3 \), \( \chi^S_2 = 1 \) in the parton gas limit implies \( μ^\text{int}_B /3 \sim 2μ^\text{int}_Q /3 \sim μ^\text{int}_S \)
**μ_B-μ_Q-μ_S space**

- Exploration of the QCD phase diagram

- The BES experiments do not explore the μ_B-T plane, but a slice in the μ_B-μ_Q-μ_S-T hyperplane

- This may well affect the search for the QCD critical point
Hydrodynamic model

- with multiple charges

Initial conditions

Relativistic hydrodynamic model

\[ \partial_\mu T^{\mu\nu} = 0 \]
\[ \partial_\mu N_{B,Q,S}^\mu = 0 \]
\[ \partial_\mu s^\mu \geq 0 \]

Equation of state

\[ P = P(\epsilon, n_B, n_Q, n_S) \]

Transport coefficients

\[ \eta, \zeta, \kappa_B, \kappa_Q, \kappa_S, \ldots \]

Hadronic transport

Information of QCD
Hydrodynamic model

- with multiple charges

- Dynamical Glauber model

- Relativistic hydrodynamic model
  \[ \partial_\mu T^{\mu\nu} = 0 \]
  \[ \partial_\mu N^{\mu}_{B,Q,S} = 0 \]
  \[ \partial_\mu s^{\mu} \geq 0 \]

- Hadronic transport

- Equation of state
  \[ P = P(\epsilon, n_B, n_Q, n_S) \]

- Information of QCD

- Transport coefficients
  \[ \eta, \zeta, \kappa_B, \kappa_Q, \kappa_S, \ldots \]
Hydrodynamic model

- with multiple charges

Dynamical Glauber model → Relativistic hydrodynamic model

\[ \partial_\mu T^{\mu\nu} = 0 \]
\[ \partial_\mu N_{B,Q,S}^\mu = 0 \]
\[ \partial_\mu s^\mu \geq 0 \]

Hadronic transport

Equation of state
\[ P = P(\epsilon, n_B, n_Q, n_S) \]

Information of QCD

Transport coefficients
\[ \eta, \zeta, \kappa_B, \kappa_Q, \kappa_S, \ldots \]
Hydrodynamic model

- with multiple charges

Dynamical Glauber model

Relativistic hydrodynamic model
\[ \partial_\mu T^{\mu\nu} = 0 \]
\[ \partial_\mu N_B^{\mu} = 0 \]
\[ \partial_\mu s^{\mu} \geq 0 \]

UrQMD

Equation of state
\[ P = P(\epsilon, n_B, n_Q, n_S) \]

Transport coefficients
\[ \eta, \zeta, \kappa_B, \kappa_Q, \kappa_S, \ldots \]

Information of QCD
Hydrodynamic results

- 3+1 D viscous hydro + UrQMD for Pb-Pb 17.3 GeV in SPS

Strange neutrality improves description of strange hadrons
Charge-to-baryon ratio fixing has small effects; π-/π+ ratio (> 1) is improved
Summary and outlook

- The QCD matter at finite density poses us challenges:
  - Interplay of multiple charges (B, Q, S) are important
    - Equation of state is constructed
    - Strangeness neutrality condition leads to finite positive $\mu_S$, realistic charge-to-baryon ratio for Au/Pb to finite negative $\mu_Q$
    - Particle-to-antiparticle ratios are described better in hydro model

- Future prospects:
  - Estimation of baryon, strangeness and charge diffusion including cross-coupling currents
  - $p_T$ spectra, flow harmonics and rapidity distribution
  - Realistic EoS for small systems as well as isobar experiments
Summary and outlook

- Our QCD equation of state model NEOS is publicly available:
  
  https://sites.google.com/view/qcdneos/home

Thank you for listening!

Thank you for listening!
Backup slides
Equation of state

- Where you can probe on the $\mu_B$-T plane

  ▶ $s/n_B$ is constant in a collision when entropy and net baryon number are conserved

    $s/n_B = 420 \quad \sqrt{s_{NN}} = 200$ GeV
    $s/n_B = 144 \quad \sqrt{s_{NN}} = 62.4$ GeV
    $s/n_B = 51 \quad \sqrt{s_{NN}} = 19.6$ GeV
    $s/n_B = 30 \quad \sqrt{s_{NN}} = 14.5$ GeV


  ▶ QGP phase: $s/n_B$ is a straight line because $s \sim T^3$ and $n_B \sim \mu_B T^2$

  Hadronic phase: $s/n_B$ bends to large $\mu_B$ because pions dominate against protons
Hydrodynamic results

- Switching energy density dependence

The preferred switching energy density to UrQMD is $\sim 0.26$ GeV/fm$^3$

Effects of chemical potential becomes larger for lower $e_{SW}$
Stefan-Boltzmann limit

- Parton gas pressure

\[
\frac{P}{T^4} = \frac{8\pi^2}{45} + \frac{7\pi^2}{60} N_f + \frac{1}{2} \sum_{f=u,d,s} \left( \frac{\mu_f}{T} \right)^2 + \frac{1}{4\pi^2} \sum_{f=u,d,s} \left( \frac{\mu_f}{T} \right)^4
\]

where \( \mu_u = \frac{1}{3} \mu_B + \frac{2}{3} \mu_Q \), \( \mu_d = \frac{1}{3} \mu_B - \frac{1}{3} \mu_Q \), \( \mu_s = \frac{1}{3} \mu_B - \frac{1}{3} \mu_Q - \mu_S \)

- The diagonal and off-diagonal susceptibilities are

\[
\chi_2 = \frac{1}{3}, \quad \chi_2^Q = \frac{2}{3}, \quad \chi_2^S = 1, \quad \chi_{1,1}^{B,Q} = 0, \quad \chi_{1,1}^{B,S} = -\frac{1}{3}, \quad \chi_{1,1}^{Q,S} = \frac{1}{3},
\]

\[
\chi_4 = \frac{2}{9\pi^2}, \quad \chi_4^Q = \frac{4}{3\pi^2}, \quad \chi_4^S = \frac{6}{\pi^2}, \quad \chi_{3,1}^{B,S} = -\frac{2}{9\pi^2}, \quad \chi_{2,2}^{B,S} = \frac{2}{3\pi^2}, \quad \chi_{1,3}^{B,S} = -\frac{2}{\pi^2},
\]

\[
\chi_{3,1}^{B,Q} = 0, \quad \chi_{2,2}^{B,Q} = \frac{4}{9\pi^2}, \quad \chi_{1,3}^{B,Q} = \frac{4}{9\pi^2}, \quad \chi_{3,1}^{Q,S} = \frac{2}{9\pi^2}, \quad \chi_{2,2}^{Q,S} = \frac{2}{3\pi^2}, \quad \chi_{1,3}^{Q,S} = \frac{2}{\pi^2},
\]

\[
\chi_{2,1,1}^{B,Q,S} = \frac{2}{9\pi^2}, \quad \chi_{1,2,1}^{B,Q,S} = -\frac{2}{9\pi^2}, \quad \chi_{1,1,2}^{B,Q,S} = -\frac{2}{3\pi^2}
\]
Stefan-Boltzmann limit

The chemical potential ratio

\[
\begin{pmatrix}
  n_B \\
  n_Q \\
  n_S
\end{pmatrix} = T^2 \begin{pmatrix}
  \chi_2^B \\
  \chi_2^{B,Q} \\
  \chi_2^{B,S}
\end{pmatrix} \begin{pmatrix}
  \chi_1^B \\
  \chi_1^{B,Q} \\
  \chi_1^{B,S}
\end{pmatrix} \begin{pmatrix}
  \mu_B \\
  \mu_Q \\
  \mu_S
\end{pmatrix} + O(\mu^3)
\]

\[
n_J = \left. \frac{\partial P}{\partial \mu_J} \right|_{T,\mu_K}
\]

NEOS B (\(\mu_S = 0\) and \(\mu_Q = 0\))

\[
\mu_B \simeq 3n_B / T^2, \quad \mu_S = 0, \quad \mu_Q = 0
\]

NEOS BS (\(n_S = 0\) and \(\mu_Q = 0\))

\[
\mu_B \simeq 4.5n_B / T^2, \quad \mu_S \simeq 1.5n_B / T^2, \quad \mu_Q = 0
\]

NEOS BQS (\(n_S = 0\) and \(n_Q = 0.4n_B\))

\[
\mu_B \simeq 4.6n_B / T^2, \quad \mu_S \simeq 1.6n_B / T^2, \quad \mu_Q \simeq -0.2n_B / T^2
\]


Sound velocity $c_s$

- $s/n_B$ dependence

$$c_s^2 = \left. \frac{\partial P}{\partial e} \right|_{n_K} + \sum_J \frac{n_J}{e + P} \left. \frac{\partial P}{\partial n_J} \right|_{e, n_K} \quad J \neq K$$

- In dense systems, $c_s$ is suppressed at lower $T$

- The effect of strangeness neutrality becomes more apparent

- Finite $n_s$ is relevant to $c_s^2$ in NEOS B

$$\left. \frac{\partial P}{\partial e} \right|_{n_B} + \frac{n_B}{e + P} \left. \frac{\partial P}{\partial n_B} \right|_e \neq c_s^2$$

The “conventional definition” w/o Q and S leads to underestimation
μ_B-μ_Q-μ_S space

- Constant pressure plane at fixed T

μ_B^{int} > μ_S^{int} > μ_Q^{int} in the hadronic phase

Lightest hadrons to carry the charges are ordered in mass as \( m_p > m_K > m_\pi \)
\( \mu_B - \mu_Q - \mu_S \) space

- Constant pressure plane at fixed \( T \)

\[ \mu_B^{\text{int}} > \mu_Q^{\text{int}} > \mu_S^{\text{int}} \] in the QGP phase

\[ \chi_2^B = 1/3, \ \chi_2^Q = 2/3, \ \chi_2^S = 1 \] in the parton gas limit implies \( \mu_B^{\text{int}}/3 \sim 2\mu_Q^{\text{int}}/3 \sim \mu_S^{\text{int}} \)
Susceptibilities

- Lattice QCD vs. Hadron resonance gas: 2nd order

![Graph showing susceptibilities vs. temperature (MeV)](image-url)
Susceptibilities

- Lattice QCD vs. Hadron resonance gas: 4\textsuperscript{th} order

![Graph showing susceptibilities vs. temperature for different models: QGP param, HRG, and HotQCD for various susceptibilities such as $\chi_{S4}$, $\chi_{BS13}$, $\chi_{BS22}$, and $\chi_{BS31}$.](image)
Susceptibilities

- Lattice QCD vs. Hadron resonance gas
Is hydro good at BES energies?

- A historical point of view

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<td>$\sqrt{s_{NN}}$</td>
<td>1</td>
<td>10</td>
<td>100</td>
<td>1000</td>
<td>1</td>
</tr>
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- Discovery of a nearly-perfect fluid
- Not hydro
- Hydro
- Bevalac
- AGS
- SPS
- RHIC
- RHIC-BES
- LHC

Akihiko Monnai (KEK), Quark Matter 2019, 6th November 2019
Is hydro good at BES energies?

- A historical point of view (around 2000)

![Graph showing the evolution of hydrodynamics at BES energies from 1980 to 2020, with different energy levels and facility names like Bevalac, AGS, SPS, and RHIC.]
Is hydro good at BES energies?

- A historical point of view (around 2019)

![Graph showing hydrodynamic behavior at different energies over time.](image)

- Bevalac
- AGS
- SPS
- RHIC
- RHIC-BES
- LHC

Shear viscosity: Csernai, Kapusta & McLerran, PRL 97, 152303 (2006)