Exploring the QCD Phase Structure with Beam Energy Scan in Heavy-ion Collisions

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Oct. 1st, 2015
Outline

- Introduction
- Experimental Facility
- Selected Experimental Highlights
- Summary
QCD Thermodynamics ($\mu_B=0$)

Chiral susceptibility peaks at $T_c$:

$$\chi_{\psi\bar{\psi}} = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial m^2}$$

Chiral symmetry restoration: temperature: $T_c \sim 154+/-9$ MeV

QCD EoS: Major goals in LQCD since 1980s, Different groups approach similar conclusion.

- Rapid rise of the energy density:
  - Rapid increase in degrees of freedom due to transition from hadrons to quarks and gluons.
- Smooth crossover transition.
QGP and phase diagram studied in high energy collisions of nuclei since 1987 at AGS (5 GeV), 1996 at SPS (17 GeV), since 2000 at RHIC (200 GeV), since 2010 at the LHC at $\sqrt{s_{NN}} = 2.76$ TeV.

Indirect evidences for strongly couple and liquid like QGP formed in high energy nuclear collisions.
It is time to study the QCD Phase Structure!
1. Properties of QGP ?: T dependence, at $\mu_B \sim 0$, of EoS, $\eta/s$, $q^\Delta$, etc.

2. Turning off the QGP signals and/or onset of deconfinement at low energies ?

3. 1st order phase boundary and QCD critical point ?

4. Quarkyonic phase at high baryon density ? Triple point ?
The QCD Phase Diagram

Emergent Properties of QCD!

K. Fukushima & T. Hatsuda

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Xiaofeng Luo - Quark Matter 2015
Experimental Facility for the Beam Energy Scan

**NA61/SPS**  
Started at 2009

**RHIC Beam Energy Scan**

**BES-I (2010-2014) is complete.**

**Collider** \( \sqrt{s_{NN}} = 4-11 \text{ GeV} \)

**Fix target** \( \sqrt{s_{NN}} = 5-17 \text{ GeV} \)

**Collider** \( \sqrt{s_{NN}} = 7.7-200 \text{ GeV} \)

**Fix target** \( \sqrt{s_{NN}} = 2-8 \text{ GeV} \)
Exploring the QCD phase structure by varying the collision energy and/or system size to change temperature and baryon chemical potential.
Chemical Freeze Out

T_{ch} increase with energy and saturate above \sim 10 \text{ GeV} (T_{lim} \sim 160\text{MeV},

depict the phase boundary (\mu_B<300 \text{ MeV})? How about higher baryon density region?)

PBM and Johanna, arXiv: 1101.3167
Chemical Freeze Out: Close to the Transition Lines

- $T_{ch}$ increases with energy and saturates above $\sim 10$ GeV ($T_{lim} \sim 160$ MeV), depicting the phase boundary ($\mu_B < 300$ MeV)? How about higher baryon density region?

PBM and Johanna, arXiv: 1101.3167
Initial Energy Density

Mid-rapidity

$\varepsilon_c \sim 0.34 \pm 0.16$ GeV/fm$^3$

Bjorken Energy Density:

$$\varepsilon_{Bj} = \frac{1}{A_\perp \tau} \frac{dE_T}{dy}$$

Caveat: 1. Boost invariant may not hold at low energy. 2. The critical energy density here is estimated at $\mu_B = 0$, may be different at large $\mu_B (>300$ MeV).

From lattice, critical $\varepsilon_c = 0.34 \pm 0.16$ GeV/fm$^3$: lowest energy 7.7 GeV still likely to be above transition region. A. Bazavov et al. (hotQCD), Phys. Rev. D90 (2014) 094503
Sensitive to quenching and provides possible evidence for where a QGP is formed.

Central data are suppressed for energy above 14.5 GeV. This does not rule out the formation of a QGP at lower energies than 14.5 GeV.

Enhancement: Cronin, Radial Flow etc.
Suppression: Jet Quenching

S. Horvat, Baryon Rich QCD Matter (323)
Require low $\eta/s$ early QGP phase to transfer initial fluctuations to a significant $v_3$.

$v_3$ vanishes for peripheral collisions at lowest RHIC BES energy.

V$_3^2$ Scaled by Energy Density

Minimum are observed for centralities bins in 0-50% collisions for $v_3^2/n_{ch,pp}$.

Softening of EoS?

Estimation for energy density

$n_{ch,PP} = (2/N_{part})dN_{ch}/d\eta$

Liao Song, Tue, 14:40 pm, [258]
Net-proton $v_1$: STAR, PRL 112, 162301 (2014);

- Non-monotonic behavior in net-proton $v_1$ indicate 1st order phase transition?

- Split of net-p and net-K $v_1$ below 14.5 GeV.

D.H. Rischke et al. HIP1, 309(1995)
J. Steinheimer et al., arXiv:1402.7236
P. Konchakovski et al., arXiv:1404.276
Transverse Dynamics in High-Energy Nuclear Collisions

(a) Pions

(b) Kaons

(c) Hadrons

Excitation function of particle \(<m_T>-m_0\) and transverse energy/mul. show a flat pattern above \(~ 8\text{ GeV}\).

Indication of 1\textsuperscript{st} order phase transition?

Fit spectra: \(1/m_T dN/dm_T \sim \exp(-m_T/T)\).

Temperature: \(<m_T>-m_0 \sim T\)

Entropy: \(dN/d\eta \sim \log(\sqrt{s_{NN}})\).


Search for the Criticality

- Strongly intensive measure and $p_T$ fluctuations– NA49/NA61.
- Finite Size Scaling analysis for HBT Radii.
- Fluctuations of Conserved Quantities: Net-Q, Net-S, Net-B.
Fluctuations measure from NA49/NA61: 2D Scan

SPS: Scan Nuclear Mass and Collision Energy (2D Scan)

Strongly intensive measure: p+p and Be+Be

\[
\Delta_{\rho,N}^R = \frac{1}{C_\Delta} \left[ \langle P_T \rangle \omega(N) - \langle N \rangle \omega(P_T) \right]
\]

\[
\Sigma_{\rho,N}^P = \frac{1}{C_{\Sigma}} \left[ \langle P_T \rangle \omega(N) + \langle N \rangle \omega(P_T) - 2 \left( \langle N \cdot P_T \rangle - \langle N \rangle \langle P_T \rangle \right) \right]
\]

No clear evidence of CP signal.


Maja Mackowiak-Pawlowska, Mon., 17:00 pm
HBT Radii: Finite Size Scaling

Order Parameter: \( R^2_{\text{out}} - R^2_{\text{side}} \)

Emission duration and compressibility

\[
(R^2_{\text{out}} - R^2_{\text{side}})_{\text{max}} \propto \bar{R}^{\gamma/\nu}
\]

\[
\sqrt{s_{NN}(V)} = \sqrt{s_{NN}(\infty)} - k \times \bar{R}^{-1/(\nu)}
\]

\[
\frac{1}{\bar{R}} = \sqrt{\left(\frac{1}{\sigma^2_x} + \frac{1}{\sigma^2_y}\right)}
\]

\[
\sqrt{s_{CEP}} \sim 47.5 \text{ GeV}
\]

\( \sigma_x \) & \( \sigma_y \) \rightarrow RMS widths of density distribution

Fitted parameters suggest existence of CP at \( \mu_B \sim 95 \text{ MeV}, \ T \sim 165 \text{ MeV} \).

Roy A. Lacey, Mon., 17:20pm

R.Lacey, PRL114, 142301(2015)

Oct. 1st

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PHENIX: Moments of the Net-charge Multiplicity Distribution


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- Smaller error bars are solely due to small acceptance, both (η, φ).

- "No clear evidence for structure attribute to the CP." [Prakhar Garg, Tue., 10:50am.]
Net-Kaon and Net-Charge $\kappa \sigma^2$ are consistent with unity.

More statistics are needed to make a conclusion.

UrQMD (no CP), show no energy dependent.

$$error(\kappa \sigma^2) \propto \frac{1}{\sqrt{N}} \frac{\sigma^2}{\varepsilon^2}$$

$\sigma$: Measured width of distributions.

$\varepsilon$: Efficiency.

In STAR, with the same # of events: error(Net-Q) > error(Net-K) > error (Net-P)
“More is different” – P. W. Anderson

Moments of Net-proton Distribution at STAR

Large acceptance is crucial for fluctuations analysis.

Xiaofeng Luo, CPOD 2014
Energy Dependence of Moments of Net-proton Distributions

Net-proton as proxy for net-baryon.

- Non-monotonic trend is observed for the 0-5% most central Au+Au collisions.

- Separation and flipping for the results of 0-5% and 5-10% centrality are observed at 14.5 and 19.6 GeV. (Oscillation Pattern observed! Very Interesting!)

- UrQMD (no CP) results show suppression at low energies. Consistent with the effects of baryon number conservation.

Jochen Thaeder, Mon, 14:30pm, [153]
Xiaofeng Luo, CPOD2014.
Sign of Kurtosis: Model and Theoretical Calculations

σ model
M.A. Stephanov, PRL107, 052301 (2011).

NJL

VDW

Memory Effects

PQM
Schaefer&Wanger, PRD 85, 034027 (2012)

PQM
V. Skokov, QM2012

MODEL!!!

χ^4/χ^2 \sim 1

CP

NJL

m_2(B)

T(MeV)

\mu_q (MeV)

JW Chen et al., arXiv:1509.04968

Vovchenko et al., arXiv:1506.05763


Oct. 1st

Xiaofeng Luo – Quark Matter 2015
“Oscillation pattern” around baseline for Kurtosis may indicate a signature of critical region.

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<th>$\kappa \sigma^2$</th>
<th>0-5%</th>
<th>5-10%</th>
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<td>14.5 GeV</td>
<td>1+Pos.</td>
<td>1+Neg.</td>
</tr>
<tr>
<td>19.6 GeV</td>
<td>1+Neg.</td>
<td>1+Pos.</td>
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"Oscillation pattern" around baseline for Kurtosis may indicate a signature of critical region.

Propose to scan 16.5 GeV ($\mu_B = 238$ MeV) or even finer step between 14.5 and 19.6 GeV, expect to see bigger dip and no separation for the results of the 0-5% and 5-10%.
STAR Upgrades and BES Phase-II (2019-2020)

- Electron cooling upgrade will provide increased luminosity ~ 3-10 times.
- Inner TPC(iTPC) upgrade : $|\eta| < 1$ to $\eta < 1.5$. Better dE/dx resolution.
- Forward Event Plane Detector (EPD): Centrality and Event Plane Determination. $1.8 < |\eta| < 4.5$

Larger rapidity acceptance crucial for further critical point search with net-protons


Summary

Intriguing structures are observed at low energies.

Dip

Peak

Oscillation

Discovery Potential at High Baryon Density:

First order phase transition and QCD Critical Point etc.

The Race is on.....
Thank you!