Baryonic Matter and Beyond

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Summary

Baryonic Matter
- Deconfinement at high $T$
- Nuclear matter
- Deconfinement at high $\mu$

... and Beyond — Speculative Scenarios
- Critical point and/or modulation
- Strangeness
- Diquark mixture
- Chiral ("whatever you like") effect
Summary and Conclusion

Baryonic Matter

- Deconfinement at high $T$  What we believe we know
- Nuclear matter  What we are supposed to know
- Deconfinement at high $\mu$  What we don’t know

... and Beyond — Speculative Scenarios

- Critical point and/or modulation  Chiral symmetry
- Strangeness  Baryon density and deconfinement
- Diquark mixture  Exotic components
- Chiral (“whatever you like”) effect  Topological vacua

Is “quarkyonic matter” real?
Baryonic Matter
Deconfinement at high $T$

Where would you find deconfinement?

Borsanyi et al. (mod.)
Deconfinement at high $T$

\[ \mathcal{O}(N_c^2) \]

\[ \mathcal{O}(1) \]

More color $\rightarrow$ More pressure

$O(1)$

$O(N_c^2)$

Color freed here

$\varepsilon(T)$

$p(T)$

$p(T)/T^4$

$\varepsilon(T)/T^4$

$N_t=6$

$N_t=8$

$N_t=10$

Borsanyi et al. (mod.)

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Deconfinement at high $T$

Challenged by:

Hadron Resonance Gas (HRG)

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Thermal Model Fit

Lattice meets phenomenology

Andronic, Becattini, Cleymans, Redlich, Stachel, Braun-Munzinger, etc...

Bazavov et al.

$T, \mu :$ fixed by the fit

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Deconfinement at high $T$

More hadrons \(\rightarrow\) More pressure

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Deconfinement at high $T$

No interaction $\rightarrow$ No saturation

(Large-$N_c$ QCD : Non-interacting mesons)
Deconfinement at high $T$

Elementary d.o.f. through interaction
Deconfinement at high $T$

Interaction $\rightarrow$ Saturation $\rightarrow$ Deconfinement

$\varepsilon(T) \sim N_t = 6$

$\varepsilon(T) \sim N_t = 8$

$\varepsilon(T) \sim N_t = 10$

$\rho(T)/T^4$
Deconfinement at high $T$

Interaction~QGP

s(trongly-coupled) QGP

$\varepsilon(T) / T^4$

$\rho(T) / T^4$

$N_t = 6$

$N_t = 8$

$N_t = 10$

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Deconfinement at high $T$

Interaction~QGP

semi-QGP (Polyakov LP)

Now ready to go to finite density!
Nuclear matter (symmetric)

Self-bound Fermi System

First-order Liquid-Gas

Critical point (Phase diagram)
Nuclear matter (symmetric)

FIG. 1: Curve of constant baryon number density

FIG. 2: Number density of baryons as a function of the化学冻结相变温度

FIG. 3: Chiral order parameter as a function of the temperature

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Nuclear matter (symmetric)

"Good" theory

Florchinger-Wetterich

Extrapolation

"Good" theory
Nuclear matter (symmetric)

"Good" theory

Interpolation

Extrapolation

"Good" theory
In-medium chiral condensate

“Reliably” calculable with $\chi$PhT

Weise et al. (modified)
**STAR Beam-Energy-Scan**

\[
N = N_p - N_{\bar{p}}
\]

Skellam

Poisson

Poisson

\[\text{Skewness } \tanh(\mu/T)\]

\[\text{Kurtosis } 1\]

Extra(inter)polation from nuclear matter?

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STAR

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STAR Beam-Energy-Scan

Quasi-particle + Interaction (mean-field)

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STAR Beam-Energy-Scan

A crazy idea?

KF-Sasaki

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A crazy idea?  
Maybe, but not more crazy than …  
More calc with $\chi$PhT needed
Where would you find quarks?

\[ \mathcal{O}(1) \xrightarrow{\text{(Interacting)}} \mathcal{O}(N_c) \]

Baryonic matter

\[ N_c \Lambda_{QCD}^4 \]

Quark matter
Deconfinement at high $\mu$

Where would you find quarks?

$\mathcal{O}(1) \rightarrow \mathcal{O}(N_c)$

(Interacting) Baryonic matter

$N_c \Lambda_{QCD}^4$

Quarkyonic matter

Quark matter

McLerran, Pisarski
Hidaka, Kojo

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Deconfinement at high $T$

Quarkyonic ~ a counterpart of sQGP
Deconfinement at high $\mu$

Coulomb phase / Confining phase $\sim$ Higgs phase

Decofinement

Hadron

CSC

$pQCD$ at high $\mu$ $\rightarrow$ Color Super Conductivity

Fermi surface + Attractive interaction

$pQCD$ without CSC $\rightarrow$ IR catastrophe

Non-perturbative for magnetic gluons

CSC parametrically enhanced

Son

cf. Kurkela-Romatschke-Vuorinen ($\mu_q > 1$ GeV)
Deconfinement at high $\mu$

U(1)$_A$ Broken

\begin{align*}
\sigma &\geq \Delta \neq 0 \\
\Delta &\geq \sigma \neq 0
\end{align*}

induced by $\Delta^2 \sigma$

quark-hadron continuity

We can never see color

Superfluid Nuclear Matter (pairing interaction)

CFL (all gluon screened)

2SC $\sim$ pure YM (confining gluon)

Schafer-Wilczek / Berges et al.
Hatsuda et al.

Rischke-Son-Stephanov

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Deconfinement at high $\mu$

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CSC  Quarkyonic

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... and Beyond
— Speculative Scenarios —
Critical point and/or modulation

Critical enhancement
- Fluctuation measurement (of conserved quantities)

First-order transition
- Mixed state ~ Inhomogeneity  (no practical difference)
- Density bubbles — fluctuations and harmonics
- Caloric flattening, Fisher/Δ scalings
  (interacting nucleons ~ non-interacting fragments)

Chiral symmetry restoration
- In-medium hadron properties (V-A mixing / sum rules)
- Physics of not gluons but quarks — topological effect
and hadron gas such as the HRG model gas, leading to uncorrelated observables that have an identical interpretation in the free parameters, when the sDoF are described by a gas of uncorrelated hadrons irrespective of their masses. The two additional when the sDoF are non-interacting massless quarks, these observables will generically attain di
erence of continuum extrapolated results will not alter the physical picture presented in this paper.

The shaded region indicates the chiral crossover temperature $T_c = 154(9) \text{ MeV}$ [13]. The LQCD results for the values of $\chi^B_2, \chi^B_4$ are obtained for two different partial pressures of all baryons, for instance in a medium where the sDoF are correlated gas of strange as well as non-strange baryons. The LQCD results presented here are not obtained for the very mild lattice spacing dependence of our results though the LQCD results presented here are not obtained for the values of $\chi^B_2, \chi^B_4$.

The values of $\chi^B_2, \chi^B_4$ correspond to temporal extents $a = 6$ and $8$ lattices are shown by the open and filled symbols. Further details of the relations schemes for (2 + 1) flavor QCD. The up and down quark-like quasi-particles.
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Strangeness: Measure of Baryon Density

- Baryon density
  - More $\Lambda$ ($s$)
  - Canceled by anti-$s$
  - Strangeness $\mu_s$

Fig. 3. Energy dependence of hadron yields relative to pions. The points are experimental data from various experiments. Lines are results of the Statistical Model calculations. The figure is taken from [20,22]).

With the parametrizations of $T$ and $\mu_B$ from Fig. 1 one can compute the energy dependence of the production yields of various hadrons relative to pions, shown in Fig. 3. Important for our purposes is the observation that there are peaks in the abundances of strange to non-strange particles at center of mass energies near 10 GeV. In particular, the $K^+/\pi^+$ and $\Xi^-/\pi^-$ ratios exhibit rather pronounced maxima there. We further note that in the region near 10 GeV, there is also a minimum in the chemical freeze-out volume obtained from the Statistical Model fit to particle yields [18], as well as in the volume 4.

We will discuss the relationship between the above Statistical Model descriptions of the transition to both the Quark-Gluon Plasma and Quarkyonic Matter, the triple point where three phases of matter coexist, and the underlying contribution to the spectrum of strange particles below, and argue that generic features of these curves may be explained in this context.

2 Quarkyonic Matter and the QCD Phase Diagram

In the following we show that by considering Quarkyonic Matter, which was recently proposed [32–36], the two regimes observed in the phase diagram and described above can be understood as arising from a triple point where Hadronic Matter, the Quark-Gluon Plasma, and Quarkyonic Matter all coexist. This triple point is located where the temperature is reaching its limiting value and, hence, is naturally also situated in the vicinity of the peaks in the observed hadron production ratios. A sketch of a possible phase diagram for QCD is shown in Fig. 5.
Non-trivial trivial

Largest baryon density
Largest strangeness

Free Nucleon Density [fm^{-3}]

Temperature [MeV]

Baryon Chemical Potential [MeV]
Deconfinement at high $\mu$

Higher Density

$\rightarrow$ More Strangenesseness

$\rightarrow$ Smoother Deconfinement

(cf. center symmetry)

Quarkyonic (counterpart of sQGP) widened
Diquark mixture
Diquark mixture

Nuclear matter = Quark + Diquark matter

A model easily built
... but ...
Difficult to avoid diquark cond.

Bentz, Ishii, Yazaki
Baym, Kojo, Pawlowski
etc...

Who is in trouble if CSC lives close to NM?
**Diquark mixture**

Nuclear matter = Quark + Diquark matter

A model easily built … but …
Difficult to avoid diquark cond.

Who is in trouble if CSC lives close to NM?

Diquarks strike back?

Bentz, Ishii, Yazaki
Baym, Kojo, Pawlowski
etc…
Diquark mixture

Nuclear matter = Quark + Diquark matter

A model easily built
... but ...
Difficult to avoid diquark cond.

Who is in trouble if CSC lives close to NM?

Diquarks strike back?

💕 CSC    💞 Quarkyonic 💞
cf. Diquark search at J-PARC

Spectroscopy of $Q$-($qq$) system ($\sim \Lambda c$)

3-body geometry probed with $Q$

Hosaka et al.
Chiral XXX Effects

\[ \theta \quad E \cdot B \]

Magnetolectric Effect

\[ E \Rightarrow B \]
\[ B \Rightarrow E \]

Topological Insulator \[ \theta = \pi \quad (\text{Cr}_2\text{O}_3) \]
Chiral XXX Effects

\[ \theta \ E \cdot \ B \]

Magnetoelectric Effect

In-medium \( \theta \), why not in HIC?

Topological Insulator \( \theta = \pi \) (Cr\(_2\)O\(_3\))
Chiral XXX Effects

Temperature is a geometrical effect

Density is a gauge effect \( \sim A_0 \)

\[
\begin{align*}
\dot{j} & \propto \mu_5 B \\
\dot{j}_5 & \propto \mu B 
\end{align*}
\]

Local Parity Violation — zero net effect

Chiral Imbalance — finite net effect
Chiral XXX Effects

Zero-density

\[ \langle j \rangle = 0 \]

\[ \langle j^2 \rangle \neq 0 \]

Finite-density

\[ \langle j_5 \rangle \neq 0 \]

\[ \langle j_5^2 \rangle \neq 0 \]

Parity / Charge-parity even quantity
Chiral XXX Effects

Zero-density

\[ \langle j \rangle = 0 \]

\[ \langle j^2 \rangle \neq 0 \]

Finite-density

\[ \langle j_5 \rangle \neq 0 \]

\[ \langle j_5^2 \rangle \neq 0 \]

Chiral Magnetic Wave

Finite density ~ More protons ~ Charge imbalance

Difficult to subtract the background effects

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Chiral XXX Effects

Zero-density
\[ \langle j \rangle = 0 \]
\[ \langle j^2 \rangle \neq 0 \]

Finite-density
\[ \langle j_5 \rangle \neq 0 \]
\[ \langle j_5^2 \rangle \neq 0 \]

Axial-vector condensation (polarization)
Helicity transmutation (chiral symmetry)

Observable? Ohnishi-Yamamoto
Chiral XXX Effects

Chiral (solitonic) Spiral

v.s. \( j_5 \neq 0 \)

Buballa, Carignano, Nakano, Tatsumi, etc etc…
Yamamoto (Lattice-QCD)
Chiral XXX Effects

Chiral (solitonic) Spiral

\[ j_5 \neq 0 \]

affects the spiral

KF-Morales

Buballa, Carignano, Nakano, Tatsumi, etc etc…
Yamamoto (Lattice-QCD)
Summary
Phase diagram of “concepts”

- Gluesonic matter
- Maximum baryons strangeness
- Quarkyonic matter
- Topological chiral media
- Proto NS simulator
- Nuclear matter with CSC

\[ T \]

\[ \mu \]
Phase diagram of “concepts”

Gluesonic matter

Maximum baryons strangeness

Quarkyonic matter

Topological chiral media

Proto NS simulator

Nuclear matter with CSC

Place where QCD and Nuclear Physics meet