Chiral Symmetry and Heavy-Ion Collisions

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So-called "QCD Phase Diagram"

How much do we really know in theory?
Agenda

- QCD phase diagram is really established?
  - What is robust and what is not?
  - How to draw the phase diagram?

- Lattice does not work at finite $\mu$ . . .
  - What is to be described by the model?
  - QCD critical point
History of the Phase Diagram

The very first "QCD" phase diagram taken from Cabibbo-Parisi (1975).

They say "Quarks are confined in phase I and unconfined in phase II".

Interpretation of the exponentially increasing spectrum by Hagedorn.

Deconfinement Transition
Bielefeld Proceedings in 1980

The very first phase diagram with both the continuous and discontinuous phase transitions taken from Kallen (1980)

First-order by the argument given by Baym based on a color-deconfinement picture.

Deconfinement Transition
Can we exclude this possibility ???

Lee-Wick abnormal matter

Bielefeld Proceedings in 1982

Taken from Baym (1982)
Lattice QCD

Taken from
Kogut, Stone, Wyld, Gibbs, Shigemitsu, Shenker, Sinclair (1983)

\[
\langle \overline{\psi} \psi \rangle \quad \text{Chiral Condensate}
\]

\[
W \sim \exp\left[-\frac{f_q}{T}\right] \quad \text{Polyakov Loop}
\]

Chiral Restoration occurs simultaneously with Deconfinement!
Long Range Plan in 1983

Deconfinement and Chiral Transitions
Why not?

How can we exclude a possibility like...

No, we cannot exclude!

c.f. Poster by McLerran-Pisarski
Low-Energy Chiral Model

No confinement
only chiral dynamics
though looks similar

Chiral Transition

Taken from Hatsuda-Kunihiro (1985)

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Critical End-Point (QCD Critical Point)

First-order Transition but has nothing to do with Baym's argument

Chiral Transition

Taken from Asakawa-Yazaki (1986)

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Theory tells us...

Much about Chiral Phase Transition
- Effective models based on chiral symmetry
- Well-defined order parameter in $m \to 0$ limit

Little about Deconfinement Transition
- Effective models based on center symmetry
- Well-defined order parameter in $1/m \to 0$ limit

The phase structure can be clarified without confinement or deconfinement unless two transitions are distinct.

Confirmed only at $\mu=0$

Lattice QCD simulations cannot draw the phase diagram yet...

→ Talks at Session XI
→ Posters

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Entanglement of Two Dynamics

Ideas
Hatta-Fukushima (2003)

QCD
Gocksch-Ogilvie (1985)
Fukushima (2002)
Strong coupling expansion

Model
Fukushima (2003)
NJL model with the Polyakov loop
(Partial) confinement below $T_c$
Simultaneous transitions

Consistency with Lattice
Named PNJL model

→ Posters on PNJL
by Hansen-Alberico-Costa,
Ghosh-Mukhejee-Mustafa-Ray

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Idea

\[ \langle \text{tr}L \rangle \sim \exp\left[-\frac{f_q}{T}\right] \sim 0 \quad \text{in the confinement phase} \]

Only \( L \cdot L^+ \) and \( L \cdot L \cdot L \) nonvanishing

meson-like \quad baryon-like

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Chiral Condensate

Chiral Condensate

\[ \mu \text{ [MeV]} \]

\[ T \text{ [MeV]} \]

in PNJL
Polyakov Loop

\[ \langle \text{tr} L \rangle \sim \exp \left[- \frac{f_q}{T} \right] \]

Model indication of simultaneous crossover in the whole region
Chiral Susceptibility

→ Talks and Posters on QCD critical point

No evidence of the existence
c.f. Talk by de Forcrand

Chiral Suscept.

\[ \mu [\text{MeV}] \]

\[ T [\text{MeV}] \]

in PNJL
From a different view point
No critical point?

Is it possible for the chiral model studies to lead to NO critical point?

Yes... but the reason is rather technical...

$U_A(1)$ breaking term $\rightarrow$ Flavor Mixing

$\rightarrow$ First-order Transition

could be reduced at high density

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't Hooft interaction dependence

35% reduction of the six-point flavor mixing interaction leads to NO critical point on the QCD phase diagram.
Remarks

- Deconfinement
  - Thermodynamics (Equation of State)
    (QCD critical point is an exception.)
  
- Chiral Restoration
  - Reduction of decay constants
  - Collective excitations (indirect)
    - Mass shift and/or width broadening of mesons
    - Quark spectral functions
  - Fluctuation (only near $T_c$)

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Talk by Nonaka

Not work for the critical point
Poster by Fujii-Tanji
Summary

We should keep in mind that deconfinement and chiral restoration are different phenomena.

It could be still possible to have modification on the (nearly established) QCD phase diagram.

The critical-point search is a big challenge for theory and experiment.