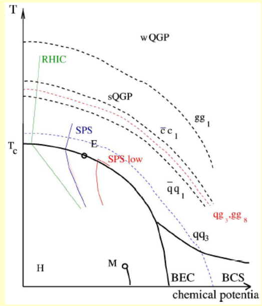
Describing the strongly interacting quark-gluon plasma through the Friedberg-Lee model

Song Shu*

Faculty of Physics and Electronic Technology, Hubei University, China

Motivation

- An important discovery at the BNL Relativistic Heavy Ion Collider (RHIC) in recent years is the strongly interacting quark-gluon plasma (sQGP)
- Shuryak has pointed out there should be lots of bound states especially for light and heavy $q\bar{q}$ bound states at $Tc < T < 4Tc$.
- Recent researches use color Coulomb potential to describe the bound states which lead to sQGP.



Phys. Rev. C **70** 021901

- However, in the present work, to obtain a simple and intuitive picture of sQGP, we will use a simple model to study the possible physical mechanism of the bound state in sQGP and the corresponding phase diagram of deconfinement.

Friedberg-Lee (FL) Model

The Lagrangian of the FL model,

$$\mathcal{L}= \bar{\psi}(i\gamma_\mu\partial^\mu - g\sigma)\psi + \tfrac{1}{2}(\partial_\mu\sigma)(\partial^\mu\sigma) - U(\sigma)$$

where, $U(\sigma) = \frac{1}{2!}a\sigma^2 + \frac{1}{3!}b\sigma^3 + \frac{1}{4!}c\sigma^4 + B.$

ψ represents the quark field, and σ denotes the phenomenological scalar field which is introduced to describe the complicated nonperturbative features of QCD vacuum.

Equations and Thermal Effective Potential

- **The field equations at mean field theory (MFT) approximation:**

$$(i\gamma_\mu\partial^\mu - g\bar{\sigma})\psi = 0$$

$$\partial_\mu\partial^\mu\bar{\sigma} = -\left(\frac{\partial U}{\partial\sigma} + \frac{1}{2}(b + c\bar{\sigma})\langle\sigma'^2\rangle + g\langle\bar{\psi}\psi\rangle\right) \equiv -\frac{\partial V_{eff}}{\partial\bar{\sigma}}$$

- **The thermal excitations and effective potential:**

$$\langle\sigma'^2\rangle = \int\frac{d^3\mathbf{p}}{(2\pi)^3}\frac{1}{E_\sigma}\frac{1}{e^{\beta E_\sigma}-1}, \qquad \langle\bar{\psi}\psi\rangle = -\gamma\int\frac{d^3\mathbf{p}}{(2\pi)^3}\frac{m_q}{E_q}\left(\frac{1}{e^{\beta(E_q-\mu)}+1} + \frac{1}{e^{\beta(E_q+\mu)}+1}\right)$$

$$V_{eff} = U(\bar{\sigma}) + \frac{1}{\beta}\int\frac{d^3\mathbf{p}}{(2\pi)^3}\ln(1-e^{-\beta E_\sigma}) - \frac{\gamma}{\beta}\int\frac{d^3\mathbf{p}}{(2\pi)^3}\left[\ln(1+e^{-\beta(E_q-\mu)}) + \ln(1+e^{-\beta(E_q+\mu)})\right]$$

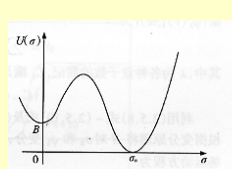
Soliton Solutions and sQGP in Deconfinement

- For the static and spherically symmetric soliton field,

$$\frac{d^2\bar{\sigma}}{dr^2} + \frac{2}{r}\frac{d\bar{\sigma}}{dr} = \frac{\partial V_{eff}}{\partial\bar{\sigma}}$$

- The boundary conditions $\begin{cases} r = 0, & \dfrac{d\bar{\sigma}}{dr} = 0 \\ r = \infty, & \bar{\sigma} = 0 \text{ or } \bar{\sigma} = \sigma_{vac} \end{cases}$

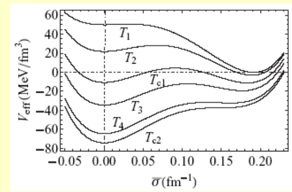
- At different temperatures and chemicals, the soliton equation could be solved under different configurations of V_{eff}
- B is the bag constant which is defined as the energy difference between the two vacuums.
- B is temperature and chemical potential dependent.



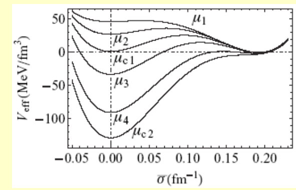
- When B is zero, the deconfinement phase transition occurs.

Numerical Results

- Effective potentials for different temperatures and chemical potentials

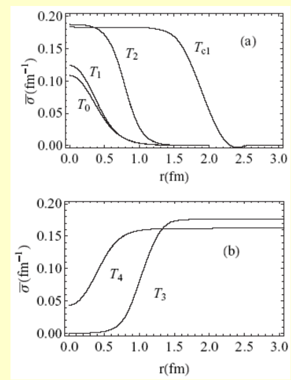


(A) For different temperatures and zero chemical potential.

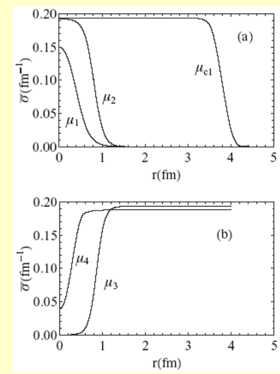


(B) For different chemical potentials and fixed temperature.

- The corresponding soliton solutions



(C) Soliton solutions for different temperatures and zero chemical potential.



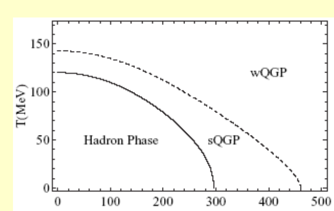
(D) Soliton solutions for different chemical potentials and fixed temperature.

Physical Analysis

- The deconfinement phase transition takes place when the two vacuums degenerate.
- The soliton solutions before deconfinement describe the confinement of hadronic state.
- The soliton solutions after deconfinement describe the bound state of quaks of sQGP.
- The system becomes wQGP when the solitons disappear.

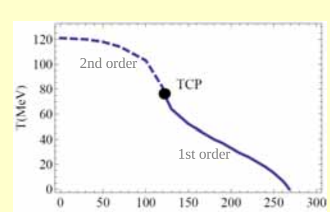
Phase Diagram

- At MFT, the deconfinement phase transition is first order in the whole phase diagram.
- The whole phase diagram has been divided into three phases: the hadronic phase, the sQGP and the wQGP.



Further Discussions

- When nonlinear fluctuations are considered in the FL model, the deconfinement phase transition could possibly be second order.
- In the phase diagram from first order to second order there may exist a tri-critical point (TCP).



*Email: shus@hubu.edu.cn