Study of deconfined quark matter at zero temperature and high density


IHEP, Protvino, Russia
ITEP, Moscow, Russia
FEFU, Vladivostok, Russia
JINR, Dubna, Russia
University of Stavanger, Norway

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Outline

- Introduction
- Features of QC$_2$D
- Static quark-antiquark potential zero T
- Quarkonia dissociation
- Debye screening
- Conclusions
QCD phase diagram

The Phases of Dense Matter, INT, July 11 - August 12, 2016
No sign problem in QC$_{2D}$

### SU(3) QCD

- Eigenvalues of $\hat{D} : \pm i\lambda$, $\det(\hat{D} + m) = \prod_{\lambda}(\lambda^2 + m^2) > 0$
- But $\det(\hat{D} - \mu \gamma_4 + m)$ is complex

### SU(2) QCD

- $\det[M(\mu_q)] = \det[(\tau_2 C \gamma_5)^{-1} M(\mu_q) (\tau_2 C \gamma_5)] = \det[M(\mu_q^*)]^*$, where $C = \gamma_2 \gamma_4$
- In LQC$_{2D}$ with fundamental quarks $\det[M(\mu_q)]$ is positive definite at real $\mu_q$ [see S. Hands, I. Montvay, S. Morrison, M. Oevers, L. Scorzato, J.-I. Skullerud, EPJ C17, 285 (2000)]

At real $\mu_q$ in QC$_{2D}$

$\det[M(\mu_q)]$ is real, $\det[M^\dagger(\mu_q)M(\mu_q)] > 0$ at $m_q \neq 0$. 
QC$_2$D compared to usual QCD

**Similarities**

- Phase transitions: confinement/deconfinement, chiral symmetry restoration
- Some observables (normalized) are nearly equal in both theories:

  \[ \chi^{1/4}/\sqrt{\sigma} = 0.3928(40) \ (SU(2)), \quad \chi^{1/4}/\sqrt{\sigma} = 0.4001(35) \ (SU(3)) \]

  \[ T_c/\sqrt{\sigma} = 0.7092(36) \ (SU(2)), \quad T_c/\sqrt{\sigma} = 0.6462(30) \ (SU(3)) \]

  **Shear viscosity**:
  \[ \eta/s = 0.134(57) \ (SU(2)) \ [N.Yu. Astrakhantsev et. al., JHEP 1509 (2015) 082] \]
  \[ \eta/s = 0.102(56) \ (SU(3)) \ [H.B. Meyer, PRD 76 (2007) 101701] \]

- Thermodynamical properties (M. Caselle et. al., JHEP 1205 (2012) 135)
The Lagrangian of the QC$_2$D has the symmetry $SU(2N_f)$ instead of $SU_R(N_f) \times SU_L(N_f)$ for $SU(3)$ QCD.

Goldstone bosons ($N_f = 2$): $\pi^+, \pi^-, \pi^0, d, \bar{d}$

Chiral symmetry is restored
thus symmetry breaking pattern is not important

Relevant degrees of freedom are quarks and gluons rather than Goldstone bosons

$N_f = 2$ of rooted staggered quarks

$M_\pi = 740(40)$ MeV, $M_\pi L_s \approx 5$
Tentative phase diagram of QC$\textsubscript{2D}$ at low $T$

Zero temperature profile:

hadronic phase  \arrow{BEC}  \arrow{dense quark matter}  \arrow{BCS}  \arrow{deconfinement}

[For details see JHEP03(2018)161; PRD 94, 114510(2016)]
We observe deconfinement in dense medium
Deconfinement at $\mu_q > 900 – 1100$ MeV

Good fit of $V(r)$ by the Cornell potential at $\mu_q \leq 1100$ MeV
Spatial quark-antiquark potential in dense medium

Different behavior compared to zero $\mu_q$ and finite $T$ case
String tensions

- \( \sigma \) goes to zero around \( \mu_q = 1000\) MeV
- \( \sigma_s \) goes to zero around \( \mu_q = 2000\) MeV
Grand potential of a static quark-antiquark pair

In Coulomb gauge:

\[ \Omega_{\bar{q}q}(r, \mu) / T = -(1/4) \log \left\langle \text{Tr} L(\vec{r}) \text{Tr} L^\dagger(0) \right\rangle + c(\mu) \]

\[ \Omega_1(r, \mu) / T = -(1/2) \log \left\langle \text{Tr} \left[ L(\vec{r}) L^\dagger(0) \right] \right\rangle + c_1(\mu) \]

Color-averaged grand potential may be decomposed into the singlet and triplet components (we study \( N_c = 2 \)):

\[ \exp \left( -\Omega_{\bar{q}q} / T \right) = \frac{1}{4} \exp \left( -\Omega_1 / T \right) + \frac{3}{4} \exp \left( -\Omega_3 / T \right) \]

Renormalization:

\[ \Omega_1(r \to 0) = V^{\text{ren.}}(r \to 0) \]

\[ \Omega_{\bar{q}q}(r \to \infty) = \Omega_1(r \to \infty) \]

Color singlet grand potential

\[ \Omega_1/\sqrt{\sigma} \]

\[ r/a \]

\[ r, \text{ fm} \]

\[ V(\mu = 0.00) \]

\[ \mu = 447 \text{ MeV} \]

\[ \mu = 671 \text{ MeV} \]

\[ \mu = 850 \text{ MeV} \]

\[ \mu = 1119 \text{ MeV} \]

\[ \mu = 1343 \text{ MeV} \]

\[ \mu = 2238 \text{ MeV} \]
Screening radius definition: $V_{\mu=0}(R_{\text{scr.}}) = \Omega_{\bar{q}q}(\infty, \mu)$
\[ \Omega_{\bar{q}q}(\infty, \mu) \text{ in dense medium} \]

Blue circles are obtained from renormalized Polyakov loop:

\[ \Omega_{\bar{q}q}(\infty, \mu) = -2T \log \langle L^R(\mu) \rangle \]
String breaking in dense medium

In QC$_2$D:

Analogous mechanism may be introduced in QCD:
Screening radius and quarkonia dissociation

\[ \sqrt{\langle r^2 \rangle} \] are estimated from NR Schrodinger eq. with Cornell potential

Onset of quarkonia dissociation (?

Blue curve: \( R_{SC} = 1/[A m_D(\mu)] \), where \( m_D^2(\mu) = (4/\pi)\alpha_s(\mu)\mu^2 \)
Debye screening in dense medium

\[ \Omega_1(r, \mu) = \Omega_1(\infty, \mu) - \frac{3}{4} \frac{\alpha_s(\mu)}{r} \exp(-m_D r) \]
Debye mass

\[ m_D(\mu)/\mu \]

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

\[ \mu a \]

\[ 0.20 \ 0.25 \ 0.30 \ 0.35 \ 0.40 \ 0.45 \ 0.50 \]

\[ 1000 \ 1200 \ 1400 \ 1600 \ 1800 \ 2000 \ 2200 \]
In one-loop: \( m_D^2(\mu) = \frac{4}{\pi} \alpha_s(\mu) \mu^2 \)
Conclusions

- We observe deconfinement in dense medium at $\mu_q^{(c)} \approx 1$ GeV for the first time
- Spatial string tension disappears at $\mu_q \geq 2$ GeV
- Onset of quakonia dissociation (?)
- Quark-gluon plasma at large density is probably perturbative
Backup slides
Simulation parameters

- $N_f = 2$ of rooted staggered quarks
- Lattice: $32^4$ ($T = 0$)
- $\beta = 1.8$, $a = 0.044(1) \text{ fm}$ (Sommer parameter), $L_s \approx 1.4 \text{ fm}$
- $ma = 0.0075$, $M_\pi = 740(40) \text{ MeV}$; $M_\pi L_s \approx 5$, $M_\pi / M_\rho \approx 0.55$
- Fixed $\lambda = 0.00075$, $\lambda^2 \ll (ma)^2$
$\alpha_s(\mu)$
String tension with $N_t = 48$

Deconfinement at $\mu_q > 900 - 1100$ MeV

Good fit of $V(r)$ by the Cornell potential at $\mu_q \leq 1100$ MeV
Chiral condensate