Condensed matter physics of heavy quarks

a third order phase transition at a finite baryon chemical potential

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Heavy Quarkonia

\[ m_H \gg \Lambda_{QCD}, \alpha_S(m_H) < 1, \quad d \sim (m_H \alpha_S(d))^{-1} \ll \Lambda_{QCD}^{-1} \]

Charm:

\[ m_c \approx 1.3 \text{GeV}, \quad \alpha_S(m_c) \approx 0.3, \quad d \approx 0.5 \text{ fm} \]

The radii of charmonium (J/ψ, ψ′, ...) and bottomonium (ϒ, ϒ′, ...) families provide a unique set of decreasing length scales in QCD.

Due to their small sizes, heavy quarkonia like J/ψ could survive the deconfinement transition.

Good probes of the QGP
Quarkonia in a QGP

1. The potential between the quark and anti-quark in the bound state is weakened by the color screening of the plasma.

   shallower bound state or no bound state at all

2. The bound state can be broken apart by collisions with gluons and quarks in the plasma.

   medium-induced width

A quarkonium will dissociate at a sufficiently high temperature:

dissociation temperature $T_d$
Basic theoretical issues

- **Color screening** in a medium can be characterized by:
  \[ L_S(T): \text{screening length (decreases with } T) \]

- **Dissociation temperature** \( T_d \)
  \[ d \sim L_S(T_d) \quad \text{d: size of a meson} \]

- Ultimately:
  \[ \omega(k) - \frac{i}{2} \Gamma(k) \]

  Important for understanding the strongly coupled QCD QGP
  Needed for interpretation data from heavy ion collisions
Very difficult even in weakly coupled theories.

Lattice:

Screening length: well understood for quarks at rest, not possible for moving quarks

some progress toward:

$$\omega(0) = M(T), \quad \Gamma(0)$$

$$\omega(k), \Gamma(k) \quad \text{not possible} \quad \text{(more interesting question)}$$
Some insights from AdS/CFT
Velocity enhanced screening

HL, Rajagopal, Wiedemann
Peeters, Sonnenschein, Zamaklar, Chernicoff, Garcia, Guijosa;

Color screening in a medium can be characterized by:

\[ L_S(T): \text{screening length (decreases with } T) \]

At finite velocity (\( \mathcal{N}=4 \) SYM at strong coupling)

\[ L_S(v) \approx L_S(0)(1 - v^2)^{1/4} \sim (1 - v^2)^{1/4} \frac{1}{T} \]

\[ T_d(v) \sim (1 - v^2)^{1/4} T_d(0) \]

Important for J/ψ suppression in heavy ion collisions
Testable
Propagation of quarkonia in QGP

Speed limit:

$$\omega = v_C k, \ k \to \infty \quad v_C < 1$$

Mateos, Myers and Thomson

Ejaz, Faulkner, HL, Rajagopal, Wiedemann

As $v > v_C(T)$, quark and anti-quark get completely screened.
Purpose of this talk:

- What AdS/CFT can say about: $\Gamma(k)$ for a strongly coupled QGP.
  
  Worldsheets instantons play an important role

- Phase structure for a strongly coupled SUSY gauge theory with flavor
  
  A third order phase transition driven by instantons
Adding flavors in AdS/CFT

Aharony, Fayyazuddin, Maldacena, Karch, Katz

$\mathcal{N}=4$ SYM theory does not contain dynamical quarks.

Add $N_F$ hypermultiplets in fundamental representation to $\mathcal{N}=4$ SYM $\rightarrow$ $\mathcal{N}=2$ theory with flavors.

On gravity side, this can be achieved by adding $N_F$ D7-branes to the $\text{AdS}_5 \times S^5$ geometry.

Zero temperature

small $T/m_q$
Dictionary

Quarks:

\[ m_q^{(T)}(T) < m_q \]

Mesons: Open strings on D7 branes

Conserved baryon current: U(1) vector field of D7-branes

Baryon chemical potential \[ A_0(\infty) = \mu_q \]
Meson Spectrum

Low lying meson spectrum can be found by solving linearized Laplace equations for small fluctuations on the D7-brane.

One finds a discrete spectrum of mesons:

Bare quark mass: $m_q$ , Meson masses: $M \sim \frac{m_q}{\sqrt{\lambda}}$

$\lambda$: 't Hooft coupling

Very tightly bound: $E_{BE} \approx 2m_q^{(T)}$
Meson “Dissociation”

Babington, Erdmenger, Evans, Guralnik, Kirsch
Mateos, Myers and Thomson, Hoyos, Landsteiner, Montero

Meson dissociation:

\[ T_d \sim M \sim \frac{m_q}{\sqrt{\lambda}} \]

We will focus on:

\[ T < T_d \]

\[ m_q^{(T)} \sim \sqrt{\lambda} \ T \]
Width of mesons?

Gravity approximation:
Mesons are stable for $T < T_d$, no width completely disappear for $T > T_d$

Open strings on D7-brane sees a geometry which is smoothly capped off.

In fact mesons are stable to all orders in perturbative $\alpha'$ expansion.

However, bound states should always have a nonzero width in a finite temperature medium.
Field theory considerations

On the field theory side, meson widths receive contributions from:

- Mesons $\rightarrow$ glue balls, lighter mesons, or other gauge singlets
  
  \((1/N_c\) suppressed, present at zero temperature\)

- Breakup by high energy gluons:

- Breakup by thermal medium quarks

\(O(1)\) in \(N_C\), non-perturbative in \(\alpha'\)
Worldsheet instantons

\[ m_q^{(r)} = \frac{r_m - r_0}{2\pi\alpha'} \]

Worldsheet unit disk
Meson widths (I)

Vertex operator

D7

Horizon

Worldsheet instanton disk

Two-point function in Rindler spacetime

Rindler worldsheet

(analytic continuation)
Meson widths (II)

\[
\Gamma_n^{(\pm1)} = \frac{32\pi^3 \sqrt{\lambda}}{N_c m_q^2} |\psi_n(\theta = 0)|^2 n_\pm
\]

\[
\frac{\Gamma_n(k)}{\Gamma_n(0)} = \frac{|\psi_n(\theta = 0; \vec{k})|^2}{|\psi_n(\theta = 0; \vec{k} = 0)|^2}
\]

\[
\frac{\Gamma(k)}{\Gamma(0)} \sim \frac{T^4 k^2}{M^6}, \quad k \gg \frac{M^3}{T^2}
\]