Lattice QCD study of charmonium dissociation temperatures

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Contents of this talk

Takashi Umeda,
“Constant contribution in meson correlators at finite temperature”
Phys. Rev. D75 094502 (2007) [hep-lat/0701005]

- Introduction
  -- Quark Gluon Plasma & J/\(\psi\) suppression
  -- Thermal J/\(\psi\) on a lattice
- Constant mode in Finite Temp. Field Theory
- Results
- Another approach on this problem
- Summary & future plan
Quark-Gluon Plasma search

- **SPS**: CERN (−2005)  
  Super Proton Synchrotron
- **RHIC**: BNL (2000 − )  
  Relativistic Heavy Ion Collider
- **LHC**: CERN (2009 − )  
  Large Hadron Collider

from the Phenix group web-site
**J/ψ** suppression as a signal of QGP

Confined phase:
- linear raising potential
  → bound state of c - ̄c

De-confined phase:
- Debye screening
  → scattering state of c - ̄c

T.Hashimoto et al.(‘86), Matsui&Satz(‘86)

**Lattice QCD calculations:**
- Spectral function by MEM: T.Umeda et al.(’02), S.Datta et al.(’04), Asakawa&Hatsuda(’04), A.Jakovac et al.(’07), G.Aatz et al.(’06)
- Wave func.: T.Umeda et al.(’00)
- B. C. dep.: H.Iida et al. (’06)

→ all calculations suggest that J/ψ survives till 1.5Tc or higher
Sequential $J/\psi$ suppression scenario

It is important to study dissociation temperatures for not only $J/\psi$ but also $\psi(2S)$, $\chi_c$'s.

<table>
<thead>
<tr>
<th>Particle</th>
<th>$J^{PC}$</th>
<th>Mass (MeV)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$ (1S)</td>
<td>$1^{-+}$</td>
<td>3097</td>
<td>Vector</td>
</tr>
<tr>
<td>$\psi$ (2S)</td>
<td>$1^{-+}$</td>
<td>3686</td>
<td>Vector</td>
</tr>
<tr>
<td>$\chi_c$ (0)</td>
<td>$0^{++}$</td>
<td>3415</td>
<td>Scalar</td>
</tr>
<tr>
<td>$\chi_c$ (1)</td>
<td>$1^{++}$</td>
<td>3511</td>
<td>Axial Vector</td>
</tr>
</tbody>
</table>

PDG('06)
Spectral function on a lattice

\[ C_H(\tau, T) = \sum_{\vec{r}'} \langle J_H(\tau, \vec{r}') J_H^\dagger(\tau, \vec{0}) \rangle \]

Thermal Green func.: \( C_H(\tau, T) \)

\[ C_H(\tau, T) = \int_0^\infty d\omega \ \sigma_H(\omega, T) \frac{\cosh(\omega(\tau - \frac{1}{2T}))}{\sinh(\frac{\omega}{2T})} \]

Spectral func.: \( \sigma_H(\omega, T) \)

brute force \( \chi^2 \) analysis fails (ill-posed problem)

→ Bayesian analysis (Maximal Entropy Method)

Output may be arbitrary when data quality is not sufficient
$\chi_c$ states dissociate just above $T_c$?

$$m_{\text{eff}}(t) = \log \left( \frac{C_H(t, T)}{C_H(t+1, T)} \right)$$

FIG. 19: The scalar spectral function for $\beta = 6.1$ at $T = 1.16T_c$ and at zero temperature reconstructed using $N_{\text{data}} = 12$. At finite temperature two default models $m(\omega) = 0.01$ and $m(\omega) = 0.038\omega^2$ have been used.

A.Jakovac et al. ('07).
(also S. Datta et al. ('04).)
Pentaquark (KN state):
  two pion state:
  $\rightarrow$ Dirichlet b.c.
  
c.f. T.T.Takahashi et al.,

\begin{align*}
\exp(-m_q t) \times \exp(-m_q t) \\
= \exp(-2m_q t) \\
\text{where } m_q \text{ is quark mass} \\
\text{or single quark energy}
\end{align*}

\begin{align*}
\exp(-m_q t) \times \exp(-m_q(L_t-t)) \\
= \exp(-m_q L_t) \\
\text{where } L_t = \text{temporal extent}
\end{align*}

- in imaginary time formalism
  $L_t = 1/\text{Temp.}$
  
gauge field : periodic b.c.
  quark field : anti-periodic b.c.

- in confined phase: $m_q$ is infinite
  $\rightarrow$ the effect appears
  \text{only in deconfined phase}
$\chi_c$ states dissociate just above $T_c$?

$$m_{\text{eff}}(t) = \log\left( \frac{C_H(t, T)}{C_H(t + 1, T)} \right)$$

FIG. 19: The scalar spectral function for $\beta = 6.1$ at $T = 1.16T_c$ and at zero temperature reconstructed using $N_{\text{data}} = 12$. At finite temperature two default models $m(\omega) = 0.01$ and $m(\omega) = 0.038\omega^2$ have been used.

A. Jakovac et al. ('07).
(also S. Datta et al. ('04.).)
Midpoint subtraction analysis

Midpoint subtracted correlators

$$C_{\text{H}}^{\text{sub}}(t,T) = C_{\text{H}}(t,T) - C_{\text{H}}(N_t/2,T)$$

→ cut off only constant mode

The drastic change of P-wave states is due to the const. contribution.

Small changes in SPFs (except for constant mode effects) for not only J/psi but also $\chi_c$’s

Previous MEM analysis for $\chi_c$ states may be misleading
$\chi_c$ states may survive up to 1.4$T_c$ (?)
Another approach to study charmonium at $T>0$

In a finite volume,
discrete spectra does not always indicate bound states!

In order to study a few lowest states,
the variational analysis is one of the most reliable approaches!

$N \times N$ correlation matrix: $C(t)$

\[ C(t) \psi = \lambda(t, t_0) C(t_0) \psi \quad \lambda_i(t, t_0) = e^{-F_i(t-t_0)} \]
How to identify the states

We know three ways to identify the state in a finite volume:

1. **Volume dependence**
   - $E$: energy
   - $V$: volume
   - $\Phi(r)$: wave function
   - $r$: c - $\bar{c}$ distance

2. **Wave function**

3. **Boundary Condition (B.C.) dep.**

H.Iida et al. (’06), N.Ishii et al. (’05)
Results of wave functions at $T>0$

Temp. dependence of “Wave function” (Bethe-Salpeter amplitude)

$$BS(\vec{r}, t) = \sum_{\vec{x}} \langle \bar{q}(\vec{x} + \vec{r}, t) \Gamma q(\vec{x}, t) \bar{q}(\vec{0}, 0) \Gamma q(\vec{0}, 0) \rangle$$
$$\Phi(|\vec{r}|, t) = BS(\vec{r}, t) / BS(\vec{0}, t)$$

**Lattice setup**
- Quenched approximation (no dynamical quark effect)
- Anisotropic lattices
  - Lattice spacing: $a_s = 0.0970(5)$ fm
  - Anisotropy: $a_s/a_t = 4$
- Variational analysis with $6 \times 6$ correlation matrix
- $T = 0.9T_c - 2.3T_c$ ($N_t = 32 - 16$), $V = 16^3, 20^3, 32^3$
Charmonium wave functions at $T=2.3T_c$

- Wave functions are constructed by the variational analysis.
- Clear signals of bound states even at $T=2.3T_c$ ($!$)
- Large volume is necessary for P-wave states.

$\rightarrow$ H. Ohno et al. 24aZC AM10:30
Summary and future plan

- There is the constant mode in charmonium correlators above $T_c$
- The drastic change in $\chi_c$ states is due to the constant mode

- Another approach to study charmonium at $T>0$
  with no Bayesian analysis
- No evidence for unbound charm quarks up to $T = 2.3 T_c$

The result may affect the scenario of $J/\psi$ suppression.

Future plan
- Discussion on the experimental results of $J/\psi$ suppression
- Full QCD calculations (Nf=2+1 Wilson is now in progress)
the drastic change in P-wave states disappears in $m_{\text{eff}}^{\text{sub}}(t)$

→ the change is due to the constant mode
Midpoint subtraction analysis

- extended op. enhances overlap with const. mode
- small constant effect is visible in V channel
- no large change above $T_c$ in $m_{eff}^{\text{sub}}(t)$