Quarkonium Binding and Dissociation in Deconfined Media

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Statistical QCD: ∃ deconfinement transition, QGP

How to probe QGP?

• e-m signals (real or virtual photons)
• quarkonia ($Q\bar{Q}$ pairs)
• jets (fast partons)

Ultimate aim: ab initio calculation of in-medium behaviour of probes
Statistical QCD: ∃ deconfinement transition, QGP

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⇒ spectral analysis of quarkonia in QGP ⇐
Theoretical basis:

- QGP consists of deconfined colour charges, hence there exists colour charge screening for $Q\bar{Q}$ probe.
- Screening radius $r_D(T)$ decreases with temperature $T$.
- When $r_D(T)$ falls below binding radius $r_i$ of $Q\bar{Q}$ state $i$, $Q$ and $\bar{Q}$ cannot bind, quarkonium $i$ cannot exist.
- Quarkonium dissociation points $T_i$, through $r_D(T_i) = r_i$, specify temperature of QGP.
Experimental basis:

- measure quarkonium production in $AA$ collisions as function of collision energy, centrality, $A$
- determine onset of (anomalous) suppression for the different quarkonium states
- correlate experimental onset points to thermodynamic variables (temperature, energy density)
- compare thresholds in survival probabilities $S_i$ of states $i$ to QCD predictions

$\Rightarrow$ direct comparison: experimental results vs. quantitative QCD predictions
In-Medium Behaviour of Quarkonia: Theory

Quarkonia:
heavy quark bound states stable under strong decay

heavy: charm ($m_c \simeq 1.3$ GeV) or beauty ($m_b \simeq 4.7$ GeV)

stable: $M_{c\bar{c}} \leq 2M_D$ and $M_{b\bar{b}} \leq 2M_B$

heavy quarks $\Rightarrow$ quarkonium spectroscopy via
non-relativistic potential theory

Schrödinger equation
\[
\left\{2m_c - \frac{1}{m_c} \nabla^2 + V(r)\right\} \Phi_i(r) = M_i \Phi_i(r)
\]

confining (“Cornell”) potential
\[
V(r) = \sigma r - \frac{\alpha}{r}
\]

string tension $\sigma \simeq 0.2$ GeV$^2$, gauge coupling $\alpha \simeq \pi/12$

$\Rightarrow$ quarkonium masses $M_i$ and radii $r_i$
⇒ good account of quarkonium spectroscopy

<table>
<thead>
<tr>
<th>state</th>
<th>$J/\psi$</th>
<th>$\chi_c$</th>
<th>$\psi'$</th>
<th>$\Upsilon$</th>
<th>$\chi_b$</th>
<th>$\Upsilon'$</th>
<th>$\chi'_b$</th>
<th>$\Upsilon''$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta E$ [GeV]</td>
<td>0.64</td>
<td>0.20</td>
<td>0.05</td>
<td>1.10</td>
<td>0.67</td>
<td>0.54</td>
<td>0.31</td>
<td>0.20</td>
</tr>
<tr>
<td>$\Delta M$ [GeV]</td>
<td>0.02</td>
<td>-0.03</td>
<td>0.03</td>
<td>0.06</td>
<td>-0.06</td>
<td>-0.06</td>
<td>-0.08</td>
<td>-0.07</td>
</tr>
<tr>
<td>radius [fm]</td>
<td>0.25</td>
<td>0.36</td>
<td>0.45</td>
<td>0.14</td>
<td>0.22</td>
<td>0.28</td>
<td>0.34</td>
<td>0.39</td>
</tr>
</tbody>
</table>

NB: error in mass determination $\Delta M$ is less than 1 %

**Ground states:**

**tightly bound** $\Delta E = 2M_{D,B} - M_0 \gg \Lambda_{QCD}$, small $r_0 \ll r_h$

**What happens to binding in QGP?**
Colour screening ⇒ binding becomes weaker and of shorter range

when force range/screening radius become less than binding radius, $Q$ and $\bar{Q}$ cannot “see” each other
⇒ quarkonium dissociates

⇒ quarkonium dissociation points determine temperature, energy density of medium

How to calculate quarkonium dissociation temperatures?

• Model heavy quark potential $V(r, T)$, solve Schrödinger equation:

  Karsch et al. 1988
  Digal et al. 2001

  $T_{J/\psi} \gtrsim T_c$, $T_\chi$ & $T_{\psi'} \lesssim T_c$
• Determine heavy quark potential $V(r, T)$ in finite $T$ lattice QCD, solve Schrödinger equation

<table>
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<tr>
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<th>$\chi_c(1P)$</th>
<th>$\psi'(2S)$</th>
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<tbody>
<tr>
<td>$T_d/T_c$</td>
<td>2.10</td>
<td>1.16</td>
<td>1.12</td>
</tr>
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</table>

Shuryak & Zahed 2004  
Wong 2004, 2005  
Alberico et al. 2005  
Digal et al. 2005  
Mocsy & Petreczky 2005, 2006

• Calculate quarkonium spectrum in finite $T$ lattice QCD

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<tr>
<td>$T_d/T_c$</td>
<td>$\geq 2.0$</td>
<td>$&lt; 1.1$</td>
<td>?</td>
</tr>
</tbody>
</table>

charmonia quenched:  
Umeda et al. 2001  
Asakawa & Hatsuda 2004  
Datta et al. 2004  
Iida et al. 2005

charmonia unquenched:  
Morrin et al. 2005  
bottomonia quenched  
Datta et al. 2005  
Velytsky et al. 2006

$T_\Upsilon \gtrsim 2 \ T_c$, $T_{\chi_b} \lesssim 1.15 \ T_c$ [?]
$\Rightarrow J/\psi, \ Upsilon$ survive up to $T \geq 2 \ T_c \Rightarrow \epsilon_{J/\psi} \geq 25 \ \text{GeV/fm}^3$

$\Rightarrow \chi_c$ and $\psi'$ melt near $T_c \Rightarrow \epsilon_{\psi',\chi} \simeq 0.5 - 2 \ \text{GeV/fm}^3$

Caveat: survival, but with what modifications?
- radii, binding, widths, continuum as $f(T)$?

compare lattice & potential studies: Mocsy & Petreczky 2006
- for which temperatures, for which variables do potential models provide a good approximation to reality?
- modify screened binding to include $\Gamma(T)$, decreasing continuum threshold?

What were the new theory inputs for increased $T_{\text{diss}}(J/\psi)$?

- colour singlet free energy in lattice QCD
- free $\rightarrow$ internal energy in potential models
- direct finite $T$ lattice calculations for quarkonia
In-Medium Behaviour of Quarkonia: Phenomenology

$J/\psi$ production in $AA$ collisions:

- observed modifications due to
  - cold nuclear matter of target and projectile
  - secondary medium produced in collision

- observed $J/\psi$ production contains
  - directly produced $1S$ states
  - decay products from $\chi_c(1P)$ and $\psi'(2S)$ production
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Operational solution:

- identify effects due to cold nuclear matter by
  - $pA$ or $dA$ studies
  - Glauber analysis in terms of $\sigma^{i}_{\text{abs}}$ for $i=J/\psi$, $\chi_c$, $\psi'$
    includes initial & final state effects: shadowing, parton energy loss, pre-resonance/resonance absorption – different dependence on $A$, centrality?
• for AA collisions, use $\sigma_{abs}^i$ and Glauber analysis to
  – obtain prediction for normal $J/\psi$ suppression
  – identify anomalous $J/\psi$ suppression
  – parametrize through survival probability

$$S_i = \frac{(dN_i/dy)_{\text{exp}}}{(dN_i/dy)_{\text{Glauber}}} \quad \text{for quarkonium state } i$$

• assume $J/\psi$ origin in $pA$ and $AA$ same as in $pp$:
  – 60 % direct $1S$, 30 % decay of $1P$, 10 % decay of $2S$
  – NB: could this be checked experimentally?

If $AA$ collisions produce a fully equilibrated QGP:

$$\Rightarrow \text{sequential suppression of } J/\psi, \Upsilon \Leftarrow$$

$$\Rightarrow \text{thresholds predicted by statistical QCD} \Leftarrow$$
Sequential $J/\psi$ suppression:

Karsch & HS 1991
Gupta & HS 1992
Digal et al. 2001
Karsch, Kharzeev & HS 2005

If $J/\psi(1S)$ survives up to $2T_c \sim \epsilon \geq 25 \text{ GeV/fm}^3$:

- all anomalous suppression observed at SPS and RHIC due to dissociation of excited states $\chi_c$ and $\psi'$
- onset of anomalous suppression at $\epsilon(T_c) \simeq 1 \text{ GeV/fm}^3$
- $J/\psi$ survival probability for central $Au - Au$ collisions at RHIC same as for central $Pb - Pb$ collisions at SPS
Cross-check: $J/\psi$ transverse momentum behaviour

- initial state parton scattering causes $p_T$ broadening of charmonia; random walk in $pA$ collisions →

$$\langle p_T^2 \rangle_{pA} = \langle p_T^2 \rangle_{pp} + N_c^A \delta_0$$

$N_c^A$ number of collisions before parton fusion to $c\bar{c}$ (Glauber, include $\sigma_{abs}$)

$\delta_0$ kick per collision, determined in $pA$

- in $AA$ collisions, initial state parton scatterings in target & projectile; random walk →

$$\langle p_T^2 \rangle_{AA} = \langle p_T^2 \rangle_{pp} + N_c^{AA} \delta_0$$
$N_{c}^{AA}$ total number of collisions in target and projectile before $c\bar{c}$ fusion (again Glauber, include $\sigma_{abs}$)

- If observed $J/\psi$ in central AA collisions undisturbed $J/\psi(1S)$, centrality dependence of $p_T$ broadening fully predicted by initial state parton scattering

Karsch, Kharzeev, HS 2005
Borges, Lourenço, Thews, HS - in progress

Expected Behaviour for SPS and RHIC Experiments:
Conclude: Present results are compatible with equilibrium QGP formation

NB: this is NEW and largely due to the following TH & EX changes

- finite $T$ lattice QCD suggests (caveat: width) direct $J/\psi$ suppression at energy densities beyond RHIC range; previous TH onset values much lower

- SPS $In - In$ data suggest onset of anomalous suppression at $\epsilon \simeq 1 \text{ GeV/fm}^3$; previous EX onset values much higher, $2 - 2.5 \text{ GeV/fm}^3$

- within statistics, no further drop of survival rate below 50 - 60 %; second drop in SPS $Pb - Pb$ no longer claimed
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But: $\exists$ alternative account of results?

Crucial aspect of QGP $J/\psi$ suppression:

dissociated charmonia never “recreated” in hadronizing QGP, since thermal $c/\bar{c}$ abundance negligible

non-thermal $c/\bar{c}$ production?
thermal charm production:

\[
\frac{c\bar{c}}{q\bar{q}} \simeq \exp\left\{-\frac{m_c}{T_c}\right\} \simeq 6 \times 10^{-4}
\]

with \( m_c = 1.3 \text{ GeV} \), \( T_c = 0.175 \text{ GeV} \)

initial charm production is hard process \( \sim N_{\text{coll}} \)

\( u, d, s \) production \( \sim N_{\text{part}} \)

in \( AA \) collisions \( (A = 200) \)

initial exceeds thermal rate

what happens to excess in evolution?
Regeneration Scenario

Basic Input:  
Braun-Munzinger & Stachel 2001; Thews et al. 2001;  
Grandchamps and Rapp 2002

- increased collision energy $\rightarrow$ increased initial charm content in produced system
- assume the charm excess survives the subsequent evolution (chemical non-equilibrium)
- $c$ or $\bar{c}$ from a given nucleon-nucleon collision can at hadronization bind with charm constituents from different collisions (“off-diagonal” pairs)
  $\exists$ new exogamous charmonium production mechanism;  
  $c$ and $\bar{c}$ in such charmonia have different parents, in contrast to endogamous production in $pp$

High energy $\Rightarrow$ enhanced $J/\psi$ production in $AA \rightarrow pp$
When does this set in?

Present work assumes

- direct $J/\psi$ production strongly suppressed for $\epsilon \geq 3$ GeV/fm$^3$ (in contrast to lattice results)
- statistical combination of all $c\bar{c}$ (with or without wave function correction)
- at RHIC energy, new exogamous $J/\psi$ just compensate drop of direct endogamous rate; at LHC, off-diagonal production $\rightarrow J/\psi$ enhancement

How to distinguish between
- sequential suppression in equilibrium QGP and
- $J/\psi$ regeneration by charm increase?
• overall $J/\psi$ survival: suppression vs. enhancement at high energy densities

• $p_T$ behaviour:
  initial state parton scattering vs. final state charm production

Karsch, Kharzeev & HS 2005
Mangano & Thews 2005

• in general, regeneration $\rightarrow$ quarkonium momentum distributions $\sim$ convolution of open charm momenta

Mangano & Thews 2005
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• for a QGP with surviving charm excess, off-diagonal quarkonium formation by statistical combination may destroy this connection
$\varepsilon$ [GeV/fm$^3$]

- **Pb−Pb $S(J/\psi)$**
- **In−In $S(J/\psi)$**
- **Pb−Pb $0.4 S(\psi') + 0.6$**