What have we learnt from quarkonia production in relativistic heavy ion collisions?

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- Introduction
- In-medium properties of quarkonia
- Quarkonia production in HIC
- Nuclear modification factor for charmonia
- Nuclear modification factor for bottomonia
- Comparison of theoretical approaches
- Hot medium effects in p+Pb
- Summary

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**$J/\psi$ suppression by quark-gluon plasma formation**

Matui & Satz, PLB 178, 416 (1986), most cited paper in RHIC (2774 citations in inSpire)

- Correlation of Polyakov loops in lattice gauge theory at finite temperature

  \[
  \Gamma(r, T) \sim \exp \left[ -\frac{r}{\xi(T)} \right]
  \]

- Expect to lead to Debye screening of gluonic interaction

  \[
  V(r, T) \sim - \left( \frac{\alpha_s}{r} \right) \exp \left[ -\frac{r}{r_D(T)} \right]
  \]

- Dissociation of charmonia takes place if $r_D(T)$ or $\xi(T)$ is sufficiently small.

- Melting of charmonia in QGP and thus their suppressed production in HIC.
Free energy $F$ for a pair of $Qar{Q}$ from LQCD [Kacmareck, EJP 61, 811 (2009)]

Two limits of the potential:

$$V(r,T) = F$$

or $V(r,T) = U = F + TS$

Schroedinger equation at finite $T$:

binding energy $\varepsilon(T)$
radius $R(T)$

Dissociation temperature:

$$\varepsilon(T_D) \to 0, \quad R(T_D) \to \infty$$

For $V=U$ (Satz et al.)

<table>
<thead>
<tr>
<th>state</th>
<th>$J/\psi(1S)$</th>
<th>$\chi_c(1P)$</th>
<th>$\psi'(2S)$</th>
<th>$\Upsilon(1S)$</th>
<th>$\chi_b(1P)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\chi_b(2P)$</th>
<th>$\Upsilon(3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_d/T_c$</td>
<td>2.10</td>
<td>1.16</td>
<td>1.12</td>
<td>$&gt; 4.0$</td>
<td>1.76</td>
<td>1.60</td>
<td>1.19</td>
<td>1.17</td>
</tr>
</tbody>
</table>
Charmonium regeneration from QGP

\[
\frac{dN_{J/\psi}}{d\tau} = \lambda_F N_c \rho_c - \lambda_D N_{J/\psi} \rho_g
\]

Thews, Shroedter & Rafelski, PRC 63, 054905 (2001)

Central collisions at RHIC
T_0: Initial temperature
N_{J_1}: Initial J/\psi number

Formation rate: \( \lambda_F = \langle \sigma_{cc\rightarrow J/\psi g} \rangle \)
Destruction rate: \( \lambda_F = \langle \sigma_{J/\psi g\rightarrow cc} \rangle \)

- Charmonia enhancement when initial charm pairs are large.
- Sufficiently large cross section can lead to chemical equilibration and thus the statistical model description of Andronic, Braun-Munzinger and Stachel [NPA 789, 334 (2007)].
- Most J/ψ are survivors from initially produced
- Kink in $R_{AA}$ is due to the onset of initial temperature above the J/ψ dissociation temperature in QGP
- Inclusion of shadowing reduces slightly $R_{AA}$

Song, Han & Ko, PRC 84, 034907 (2011)
Screened Cornell potential for heavy quark and antiquark in QGP

- Screened Cornell potential between charm and anticharm quarks

\[ V(r,T) = \frac{\sigma}{\mu(T)} \left[ 1 - e^{-\mu(T)r} \right] - \frac{\alpha}{r} e^{-\mu(T)r} \]

with string tension \( \sigma = 0.192 \text{ GeV}^2 \) and screening mass

\[ \mu(T) = \sqrt{\frac{N_c}{3} + \frac{N_f}{6} gT} \]

- Its strength is between the internal energy (U) and free energy (F) of heavy quark and antiquark from LQCD; similar to F at \( T_c \) and to U at 4\( T_c \) (\( T_c = 170 \text{ MeV} \)).
QCD sum rule study of J/ψ

\[ \Pi_{\mu\nu}(q) = i \int d^4 x \, e^{i q x} \langle T[\bar{c}(x) \gamma_\mu c(x) \bar{c}(0) \gamma_\nu c(0)] \rangle. \]

- Results favor free energy as the potential between charm and anticharm quarks near \( T_c \).
Thermal properties of charmonia

- Binding energy

\[ \varepsilon_0 = 2m_c + \frac{\sigma}{\mu(T)} - E \]

Charm quark mass \( m_c = 1.32 \text{ GeV} \)

E: eigenvalues of Cornell potential

- Dissociation temperature \( T_D \): corresponding to \( \varepsilon_0 = 0 \)

For \( g = 1.87 \), \( T_D \approx 300 \text{ MeV} \) for \( J/\psi \) and \( \sim T_D = 175 \text{ MeV} \) for \( \psi' \) and \( \chi_c \)
Thermal properties of bottomonia

![Graph showing binding energy and radius as a function of temperature

<table>
<thead>
<tr>
<th>State</th>
<th>$\Upsilon(1S)$</th>
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<th>$\Upsilon'(2S)$</th>
<th>$\chi_b'(2P)$</th>
<th>$\Upsilon''(3S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dissociation temp ($T_c$)</td>
<td>4</td>
<td>1.51</td>
<td>1.67</td>
<td>1.09</td>
<td>1.12</td>
</tr>
</tbody>
</table>
Quasiparticle model for QGP


\[
p(T) = \sum_{i=g,q,q} \frac{g_i}{6\pi^2} \int_0^\infty dk f_i(T) \frac{k^4}{E_i} - B(T)
\]

\[
e(T) = \sum_{i=g,q,q} \frac{g_i}{2\pi^2} \int_0^\infty dk k^2 f_i(T) E_i + B(T)
\]

\[
m_g^2 = \left( \frac{N_c}{3} + \frac{N_f}{6} \right) \frac{g^2(T)T^2}{2}
\]

\[
m_q^2 = \frac{g^2(T)T^2}{3}
\]

\[
g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)\ln F^2(T,T_c,\Lambda)}
\]

\[
F(T,T_c,\Lambda) = \frac{18}{18.4e^{-(T/T_c)^2/2} + 1} \frac{T}{T_c} \frac{T_c}{\Lambda}
\]

- Resulting EOS is similar to that from LQCD by the hot QCD collaboration, and the difference is smaller than that between the hot QCD and Wuppertal-Budapest Collaborations
Thermal decay widths of quarkonia

- Dissociation by partons (NLO pQCD)

\[ |M|^2 = \frac{4}{3} g^4 m_c^2 m_{J/\psi} \left| \frac{\partial \psi(p)}{\partial p} \right|^2 \left\{ -\frac{1}{2} + \frac{(k_1^0)^2 + (k_2^0)^2}{2k_1 \cdot k_2} \right\} \]

- Dissociation by hadrons

\[ \sigma(s) = \sum_i \int dx n_i(x,Q^2) \sigma_i(xs,Q^2) \]

- Thermal dissociation width

\[ \Gamma(T) = \sum_i \int \frac{d^3k}{(2\pi)^3} v_{rel}(k) n_i(k,T) \sigma_i^{diss}(k,T) \]
Directly produced J/ψ

- Number of initially produced

\[ N_{J/\psi}^{AA} = \sigma_{J/\psi}^{NN} A^2 T_{AA}(\bar{b}) \]

- \( \sigma_{J/\psi}^{NN} \): J/ψ production cross section in NN collision; ~ 0.774 µb at \( s^{1/2} = 200 \) GeV

- Overlap function

\[ T_{AA}(\bar{b}) = \int d^2 \bar{s} T_A(\bar{s}) T_A(\bar{b} - \bar{s}) \]

- Thickness function

\[ T_A(\bar{s}) = \int_{-\infty}^{\infty} dz \rho_A(\bar{s},z) \]

- Normalized density distribution

\[ \rho(r) = \frac{\rho_0}{1 + e^{(r-r_0)/c}} \]

\( r_0 = 6.38 \text{ fm}, c = 0.535 \text{ fm for Au} \)

- Nuclear absorption

  - Survival probability

\[ S_{\text{nucl}}(\bar{b},\bar{s}) = \frac{1}{T_{AB}(\bar{b})} \int dz dz' \rho_A(\bar{s},z) \rho_B(\bar{b} - \bar{s},z') \times \exp \left\{ - (A - 1) \int_z^\infty dz_A \rho_A(\bar{s},z_A) \sigma_{\text{nuc}} \right\} \times \exp \left\{ - (B - 1) \int_{z'}^\infty dz_B \rho_B(\bar{s},z_B) \sigma_{\text{nuc}} \right\} \]

Song, Park & Lee, PRC 81, 034914 (10)
Regenerated J/ψ

Rate equation for J/ψ production

\[ \frac{dN_i}{d\tau} = -\Gamma_i (N_i - N_i^{eq}), \quad N_i^{eq} = \gamma^2 R n_i^{GC} V \]

- Charm fugacity is determined by

\[ N_{c\bar{c}}^{AA} = \left[ \frac{1}{2} \gamma m_v I_1(\gamma n_0 V) + \gamma^2 n_h \right] V = \sigma_{c\bar{c}}^{NN} A^2 T_{AA}(\vec{b}) \]

- \( \sigma_{c\bar{c}}^{NN} \): charm production cross section in NN collision; \( \sim 119 \mu b \)
at \( s^{1/2} = 200 \text{ GeV} \)

- Charm relaxation factor

\[
R = 1 - \exp \left\{ \int_{\tau_0}^{\tau_{QGP}} d\tau \Gamma_c(T(\tau)) \right\}
\]

\[
\Gamma(T) = \sum_i \int \frac{d^3k}{(2\pi)^3} v_{rel}(k)n_i(k,T) \times \sigma_{i}^{diss}(k,T)(1 - \vec{p} \cdot \vec{p}' / p^2)
\]

as J/ψ is more likely to be formed if charm quarks are in thermal equilibrium

Approximately reproduced by non-equilibrium charm quarks from parton cascade [PRC 85, 954905 (12)]
Nonequilibrium effects can be approximated by the relaxation factor.
Nuclear modification factor for $\Upsilon(1S)$

- Regeneration contribution is negligible
- Primordial excited bottomonia are largely dissociated
- Medium effects on bottomonia reduce $R_{AA}$ of $\Upsilon(1S)$
Bottomonia in anisotropic hydrodynamics

Strickland, PRC 92, 061901 (R) (2015)

- Potential: in-medium Cornell
- Dissociation: LO pQCD
- Dynamics: anisotropic hydro
- Sensitivity to $\eta/s$
**J/ψ production at RHIC by Tsinghua Group**

- Dissociation temperature: $T_d = 1.92 \, T_c$
- Dissociation cross section: vacuum gluo-dissociation
- Dynamics: ideal hydrodynamic

Liu, Qu, Xu & Zhuang, PLB 678, 72 (2009)
T-matrix approach to quarkonia and their production in HIC

Du, He & Rapp, PRC 96, 054901 (2017)

- In-medium binding and dissociation rate using potential from T-matrix fit to lQCD spectral functions.
- Fireball dynamics with lQCD equation of state.
Thermal decay width of $\Upsilon(1S)$ in different models

- Thermal decay width
  - Rapp: quasielastic scattering
  - Zhuang: OPE by Peskin
  - Strickland: LO pQCD
  - Song: NLO pQCD

- Very different thermal decay widths are used in different models
\[ v_2 = \frac{\int d\varphi \cos(2\varphi)(dN/dy d^2p_T)}{\int d\varphi (dN/dy d^2p_T)} \]
\[ = \frac{\int dA_T \cos(2\varphi)I_2(p_T \sinh \rho/T)K_1(m_T \cosh \rho/T)}{\int dA_T I_0(p_T \sinh \rho/T)K_1(m_T \cosh \rho/T)} \]

\[ \rho = \tanh(v_T) = \text{transverse rapidity} \]

Introducing viscous effect at freeze out
\[ T = 125 \text{ MeV} \]
\[ \Delta v = (v_x - v_y) \exp[-Cp_T/n] \]

with \( C = 1.14 \text{ GeV}^{-1} \) and \( n = \text{number of quarks in a hadron} \)

- Initially produced J/\( \psi \) have essentially vanishing \( v_2 \)
- Regenerated J/\( \psi \) have large \( v_2 \)
- Final J/\( \psi \) \( v_2 \) is small as most are initially produced
- Initial fluctuations obtained from AMPT affect $R_{AA}$ of bottomonia in peripheral collisions and at low $p_T$. 
J/ψ production in p+Pb at $\sqrt{s_{NN}} = 5.02$ TeV

- Most central 10% collisions from AMPT

$\frac{dN}{dt} = -\Gamma(N - N^{eq}), \quad N^{eq} = (1 + 1/N_c)\gamma^2 R_n^{GCV}$
Summary

- J/ψ survives up to 1.7 $T_c$ and Y(1S) survives up to 4 $T_c$.

- Most observed J/ψ and Y(1S) are from primordially produced; contribution from regeneration is small at present HIC.

- Various models with different assumptions can describe experimental data.

- Elliptic flow of regenerated J/ψ is large, while that of directly produced ones is essentially zero. Studying $v_2$ of J/ψ is useful for distinguishing the mechanism for J/ψ production in HIC.

- Initial fluctuations affect $R_{AA}$ of bottomonia in peripheral collisions and at low $p_T$.

- Hot medium effects describe better J/ψ data from p+Pb collisions.

- Quarkonia production in HIC is consistent with formation of quark-gluon plasma but has not yet provided information on its properties.