QGP Physics – From SPS to LHC

9. J/ψ and Quarkonia as probes of deconfinement

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9.1 Quarkonia

- Quarkonia are heavy quark antiquark bound states, i.e. ccbar and bbar
- since masses of charm and beauty quarks are high as compared to QCD scale parameter $\Lambda_{\text{QCD}} \sim 200$ MeV
- non-relativistic Schrödinger equation can be used to find bound states

\[
\left(-\frac{\nabla^2}{2(m_Q/2)} + V(r)\right)\Psi(\vec{r}) = E\Psi(\vec{r})
\]

with quark-quark potential of the form

\[
V(r) = \sigma r - \frac{4}{3} \frac{\alpha_s}{r} + \frac{32\pi\alpha_s}{9} \frac{s_1 \cdot s_2}{m_Q^2} \delta(\vec{r}) + ...
\]

- confinement
- spin-spin int.
- tensor, spin-orbit, higher order rel. corr.
- color Coulomb int.

- with $\sigma \sim 0.9$ GeV/fm, $\alpha_s(m_Q) \sim 0.35$ and 0.20 for $m_c = 1.5$ GeV and $m_b = 4.6$ GeV obtain spectrum of quarkonia
Charmonium and Bottomonium spectra

color singlet states
### Charmonium and Bottomonium spectra

<table>
<thead>
<tr>
<th></th>
<th>$J^P$</th>
<th>$L$</th>
<th>$S$</th>
<th>$M$ (GeV)</th>
<th>$\Gamma_{\text{tot}}$ (MeV)</th>
<th>$B(\gamma \gamma)$</th>
<th>$B(e^+e^-)$, $B(\mu^+\mu^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c(1s)$</td>
<td>$0^-$</td>
<td>0</td>
<td>0</td>
<td>2.98</td>
<td>$\sim 16$</td>
<td>$\sim 0.046%$</td>
<td>$\sim 6%$, $\sim 0.75%$</td>
</tr>
<tr>
<td>$\eta_c(2s)$</td>
<td>$0^-$</td>
<td>0</td>
<td>0</td>
<td>3.65</td>
<td>$&lt; 55$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$J/\psi(1s)$</td>
<td>$1^-$</td>
<td>0</td>
<td>1</td>
<td>3.097</td>
<td>$\sim 0.09$</td>
<td>$B(\gamma J/\psi) \sim 1%$</td>
<td></td>
</tr>
<tr>
<td>$\psi(2s)$</td>
<td>$1^-$</td>
<td>0</td>
<td>1</td>
<td>3.686</td>
<td>$\sim 0.28$</td>
<td>$B(\gamma J/\psi) \sim 32%$</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c0}(1p)$</td>
<td>$0^+$</td>
<td>1</td>
<td>1</td>
<td>3.42</td>
<td>$\sim 11$</td>
<td>$B(\gamma J/\psi) \sim 20%$</td>
<td></td>
</tr>
<tr>
<td>$\chi_{c1}(1p)$</td>
<td>$1^+$</td>
<td>1</td>
<td>1</td>
<td>3.51</td>
<td>$\sim 0.9$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi_{c2}(1p)$</td>
<td>$2^+$</td>
<td>1</td>
<td>1</td>
<td>3.56</td>
<td>$\sim 2.1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Upsilon(1s)$</td>
<td>$1^-$</td>
<td>0</td>
<td>1</td>
<td>9.46</td>
<td>$\sim 53$</td>
<td>$B(\gamma \gamma) \sim 0.43%$, $B(e^+e^-) \sim 1.3%$, $B(\mu^+\mu^-) \sim 1.8%$</td>
<td>$B(e^+e^-) \sim 2.4%$</td>
</tr>
<tr>
<td>$\Upsilon(2s)$</td>
<td>$1^-$</td>
<td>0</td>
<td>1</td>
<td>10.02</td>
<td>$\sim 43$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Upsilon(3s)$</td>
<td>$1^-$</td>
<td>0</td>
<td>1</td>
<td>10.36</td>
<td>$\sim 26$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi_{b0}(1p)$</td>
<td>$0^+$</td>
<td>1</td>
<td>1</td>
<td>9.86</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\chi_{b1}(1p)$</td>
<td>$1^+$</td>
<td>1</td>
<td>1</td>
<td>9.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\chi_{b2}(1p)$</td>
<td>$2^+$</td>
<td>1</td>
<td>1</td>
<td>9.91</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
9.2 Charmonia at finite temperature

Consider $T < m_c$ so QGP of gluons, u,d,s quarks and antiquarks, no thermal heavy quarks
Consider $c\bar{c}$ in environment of gluons and light quarks

$$V(r) \rightarrow V_{eff}(r, T) \text{ and } m_Q \rightarrow m_Q(T)$$

In QGP color singlet and color octet $c\bar{c}$ states can mix by absorption or emission of a soft gluon
Modification of $V_{eff}$

- reduced string tension at $T$ approaches $T_c$
- string breaking due to thermal qqbar and gluons leading to D and Dbar
- for $T > T_c$ confining part disappears and short range Coulomb part is Debye screened to give Yukawa type potential

$$V_{eff}(r, T) \rightarrow -\frac{4}{3} \frac{\alpha_s}{r} e^{r/\lambda_D}$$

$$\omega_D = 1/\lambda_D$$

Debye screening mass and length
Debye screening of quarkonia

unlike Coulomb potential, Yukawa potential does not always have bound states

\[ \text{dissociation of quarkonia if } \omega_D \text{ sufficiently large at high } T \]


compare Bohr radius of charmonia \( r_B \) and Debye screening length \( \lambda_D \)

for \( r_B \) smaller than \( \lambda_D \) bound states exist even for \( \sigma = 0 \)
for \( r_B \) larger than \( \lambda_D \) no bound states

equivalently to QED where \( r_B \) (hydrogen) = \( 1/(m_e \alpha) \) we have:

\[ r_B = 3/(2m_Q\alpha_s) \]

and the Debye screening mass:

\[ \omega_D^2 = \frac{4\pi\hbar c}{3}\alpha_s T^2(N_c + \frac{1}{2}N_f) \]

(see textbooks, e.g. Yagi, Hatsuda, Miake, chapter 4, finite temperature field theory)

bound states then disappear for

\[ T \geq 0.15 \times m_Q \sqrt{\alpha_s} \approx 0.16 \text{ GeV for } J/\psi \text{ and } 0.46 \text{ GeV for } \Upsilon \]
Different quarkonia melt at different temperatures

using

\[ V(r, T) = \frac{\sigma}{\omega_D(T)} (1 - \exp(-\omega_D(T)r)) - \frac{\alpha}{r} \exp(-\omega_D(T)r) \]

F. Karsch and H. Satz (Z.Physik C51 (1991) 209) obtain:

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi$</th>
<th>$\psi'$</th>
<th>$\chi_c$</th>
<th>$\Upsilon$</th>
<th>$\Upsilon'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>state</td>
<td>1s</td>
<td>2s</td>
<td>1p</td>
<td>1s</td>
<td>2s</td>
</tr>
<tr>
<td>mass (GeV)</td>
<td>3.1</td>
<td>3.7</td>
<td>3.5</td>
<td>9.4</td>
<td>10.0</td>
</tr>
<tr>
<td>$r$ (fm)</td>
<td>0.45</td>
<td>0.88</td>
<td>0.70</td>
<td>0.23</td>
<td>0.51</td>
</tr>
<tr>
<td>$T_D/T_c$</td>
<td>1.17</td>
<td>1.0</td>
<td>1.0</td>
<td>2.62</td>
<td>1.12</td>
</tr>
<tr>
<td>$\epsilon_D$</td>
<td>1.92</td>
<td>1.12</td>
<td>1.12</td>
<td>43.3</td>
<td>1.65</td>
</tr>
</tbody>
</table>

exact values very model dependent, but basic feature: $J/\psi$, $\psi'$, chic, $\Upsilon$ not bound at or little above $T_c$, $\Upsilon$ survives much longer
Results on Debye screening from lattice QCD

agree qualitatively, quantitatively still a lot of debate, unclear, how to extract effective heavy quark potential
One attempt: correlation of Polyakov lines but there are others
Hadronization of charm quarks

all charm quarks have to appear in charmed hadrons
at hadronization of QGP J/ψ can form again from deconfined quarks
in particular, if number of cc pairs is large (colliders) - $N_{J/\psi} \sim N_{cc}^2$

expect J/psi suppression at low beam energies (SPS, RHIC) and
J/psi enhancement at high energies (LHC)
9.3 Production of charmonia in hadronic collisions

- charm and beauty quarks are produced in early hard scattering processes
- most important Feynman diagram: gluon fusion
- formation of quarkonia requires transition to a color singlet state
- not pure perturbative QCD anymore, some modelling required
- CEM Color Evaporation Model
- CSM Color Singlet Model
- still only moderately successful
relevant time scales

formation of ccbar: in hard initial scattering on time scale \(1/2m_c\)
with \(m_c = 1.3\) GeV \(\rightarrow \) \(\tau_{ccbar} = 0.08\) fm/c

typical hadron formation time: \(\tau_{hadron}\) order 1 fm/c
(Blaizot/Ollitrault 1989  Hufner, Ivanov, Kopeliovich, and Tarasov 2000)
W. Brooks, QM09: description of recent JLAB and HERMES hadron
production data in color dipole model \(\rightarrow\) time scale 5 fm/c

comparable to or longer than QGP formation time: \(\tau_{QGP} \approx 1\) fm/c at SPS,
< 0.5 fm/c at RHIC, \(\approx 0.1\) fm/c at LHC

at LHC even color octet state not formed before QGP
(H.Satz 2006) \(\tau_8 = 1/\sqrt{2m_c\Lambda_{QCD}} \approx 0.25\) fm

collision time: \(t_{coll} = 2R/\gamma_{cm}\) at RHIC 0.1 fm/c at LHC < 5 \(10^{-3}\) fm/c
ccbar pairs are formed at collision time scale \( t_{\text{coll}} = \tau_{\text{ccbar}} \)

collision time scale comparable to plasma formation time scale and hadron formation time scale at FAIR and SPS \( t_{\text{coll}} = \tau_{\text{ccbar}} \approx \tau_{\text{QGP}} \approx \tau_{\text{hadron}} \)

but at RHIC and much more pronounced at LHC there is the following hierarchy: \( t_{\text{coll}} = \tau_{\text{ccbar}} \ll \tau_{\text{QGP}} \ll \tau_{\text{hadron}} \)

expect that cold nuclear matter absorption effects decrease from SPS to RHIC and are totally irrelevant at LHC
Production of charm and beauty

J/Ψ is only a small fraction of order of 1% of these 6% detected via l⁺l⁻ decay

<table>
<thead>
<tr>
<th>N(qq) per central AA (b=0)</th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>charm</td>
<td>0.2</td>
<td>10</td>
<td>130</td>
</tr>
<tr>
<td>bottom</td>
<td>---</td>
<td>0.05</td>
<td>5</td>
</tr>
</tbody>
</table>
### 9.4 Measurement of quarkonia

\[
\begin{align*}
\text{BR}(J/\psi \to \text{hadrons}) & \approx 0.88 \\
\text{BR}(J/\psi \to e^+e^-) & \approx 0.06 \\
\text{BR}(J/\psi \to \mu^+\mu^-) & \approx 0.06 \\
\text{BR}(\psi' \to \text{hadrons}) & \approx 0.98 \\
\text{of these BR}(\psi' \to J/\psi) & \approx 0.60 \\
\text{BR}(\psi' \to \mu^+\mu^-) & \approx 0.008 \\
\end{align*}
\]

\(J/\Psi, \Psi'\) and \(\Upsilon\) via e+e- or \(\mu+\mu-\)

\(\chi_c\) very difficult, usually done via

\(\chi_c \to J/\psi + \gamma\)

of measured \(J/\Psi\) typically

\(\approx 60\%\) directly produced

\(\approx 10\%\) from \(\psi' \to J/\psi\)

\(\approx 30\%\) from \(\chi_c \to J/\psi\)
In pA collisions at moderate energies (200-450 GeV) universal picture: prehadronic state absorbed in nuclear matter

\[ \sigma(J/\psi) \propto \exp(-\rho \sigma_{\text{abs}} L) \]

with \( \rho = 0.17/\text{fm}^3 \)

and \( \sigma_{\text{abs}} = (4.1 \pm 0.4) \text{ mb} \)

light nuclear collisions follow the same picture

\[ \frac{3}{4}(J=1) / (J=0) \]

\[ \frac{3}{4} \alpha \beta \sigma \left( L \right) \]

\[ \frac{1}{4} (4:1) \sigma_0 (4:4) \]
J/Ψ production in PbPb collisions at SPS energy

normalization to Drell-Yan process

In central PbPb collisions about 40% less J/Ψ than expected from pA systematics

Normal J/Ψ suppression on nuclear matter

Anomalous J/Ψ suppression due to QGP?
SPS data consistent with suppression at critical density

Dissolution in QGP at critical density $n_c$ (red dashes) and in addition with energy density fluctuations (solid)

J/Ψ production in AuAu collisions at RHIC

at mid-rapidity suppression at RHIC very similar to SPS
suppression at forward/backward rapidity stronger!

but prediction:

at hadronization of QGP
J/Ψ can form again
from deconfined quarks,
in particular if number of
ccbar pairs is large

\[ N_{J/Ψ} \propto N_{cc}^2 \]
comparison of statistical model predictions to RHIC data: centrality dependence and rapidity distribution


pp open charm cross section FONLL Cacciari et al., PRL 95 (2005) 122001 \[ \sigma_{cc} = 256^{+400}_{-146} \ \mu b \]

good agreement, no free parameters

but need for good open charm measurement obvious (this is a lesson for LHC as well!)
energy dependence of quarkonium production in statistical hadronization model

A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel  

note: stat. model does not make any prediction about ccbar production cross section, this is input; depending on ccbar cross section in nuclear collisions at LHC there can be J/psi enhancement
First data from PbPb collisions at the LHC

Contribution from B feed-down small:
~ 10% from p-p measurement
(LHCb, arXiv:1103.0423)

J/ψ RAA in central collisions is larger at LHC in 2.5<y<4 than at RHIC in 1.2<|y|<2.2
And shadowing at LHC estimated to be large
Conclusion: the $R_{AA}$ for J/ψ is large!
statistical hadronization of charmonia at LHC?

this looks compatible! but is very preliminary
no measured ccbar cross section in PbPb at this energy yet

way out: scale data with calculated shadowing
compare to ccbar cross section from pQCD

A. Andronic et al, QM2011
First information on Upsilon states for PbPb at LHC

Consistent with expectation that more loosely bound 2S and 3S states are more strongly suppressed