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Heavy quark state production in Pb-Pb collisions at $\sqrt{s_{pp}} = 5.02$ TeV

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ABSTRACT: We estimate differential rapidity cross sections for J/Ψ , $\Psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production via Pb-Pb collisions at proton-proton energy $\equiv \sqrt{s_{pp}} = 5.02$ TeV. For the $\Psi(2S)$ and $\Upsilon(3S)$ states we use the mixed heavy quark hybrid theory and compare the cross section to the standard model. This is an extension of previous work on heavy quark state production via Cu-Cu and Au-Au collisions at $\sqrt{s_{pp}} = 200$ GeV.

KEYWORDS: Heavy Quark Physics, Scattering Amplitudes, Quark-Gluon Plasma

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Contents

1	Introduction	1
2	J/Ψ and $\Upsilon(1S)$ production in Pb-Pb collisions with $\sqrt{s_{pp}} = 5.02$ TeV	2
3	Ratio of $\Psi(2S)$ to J/Ψ cross sections	5
3.1	Ratios for p-p collisions	5
3.2	Ratios for Pb-Pb collisions	5
4	Ratio of $\Upsilon(2S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ cross sections	5
5	Conclusions	6

1 Introduction

In anticipation of measurements of the production of heavy quark states via Pb-Pb collisions with proton-proton energy $\equiv \sqrt{s_{pp}}=5.02$ TeV at the LHC, we estimate the production of J/Ψ , $\Psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ states using the standard model, and $\Psi(2S)$, $\Upsilon(3S)$ states using the mixed hybrid theory. This is an extension of the recent work on heavy quark state production in A-A (Cu-Cu and Au-Au) collisions at $\sqrt{s_{pp}}=200$ GeV [1], based on earlier work on heavy quark state production in p-p collisions [2] which used the color octet model [3–5].

In section 2 we review the production of Ψ and Υ states in Pb-Pb collisions, with small modifications from ref. [1]. In section 3 we discuss the ratio of $\Psi(2S)$ to $J/\Psi(1S)$ production and compare the hybrid vs standard theory to recent experiments with p-p collisions. In section 4 we discuss the ratio of $\Upsilon(3S)$ to $\Upsilon(1S)$, $\Upsilon(2S)$ production and compare the hybrid to the standard theory, also reviewed in ref. [6].

Now we briefly review the mixed hybrid theory for charmonium and bottomonium states. Using the method of QCD sum rules it was shown [7] that the $\Psi(2S)$ and $\Upsilon(3S)$ are approximately 50-50 mixtures of standard quarkonium and hybrid quarkonium states:

$$\begin{aligned}
|\Psi(2s)\rangle &= -0.7|c\bar{c}(2S)\rangle + \sqrt{1-0.5}|c\bar{c}g(2S)\rangle \\
|\Upsilon(3S)\rangle &= -0.7|b\bar{b}(3S)\rangle + \sqrt{1-0.5}|b\bar{b}g(3S)\rangle,
\end{aligned}
\tag{1.1}$$

with a 10% uncertainty in the QCD sum rule estimate of the mixing probability, while the J/Ψ , $\Upsilon(1S)$, $\Upsilon(2S)$ states are essentially standard $q\bar{q}$ states.

2 J/Ψ and $\Upsilon(1S)$ production in Pb-Pb collisions with $\sqrt{s_{pp}} = 5.02$ TeV

The differential rapidity cross section for the production of a heavy quark state Φ with helicity $\lambda = 0$ (for unpolarized collisions [2]) in the color octet model in A-A collisions is given by [1]

$$\frac{d\sigma_{AA \rightarrow \Phi(\lambda=0)}}{dy} = R_{AA}^E N_{\text{bin}}^{AA} \left\langle \frac{d\sigma_{pp \rightarrow \Phi(\lambda=0)}}{dy} \right\rangle, \quad (2.1)$$

where R_{AA}^E is the product of the nuclear modification factor R_{AA} and S_Φ , the dissociation factor after the state Φ is formed [8]. N_{bin}^{AA} is the number of binary collisions in the AA collision, and $\langle \frac{d\sigma_{pp \rightarrow \Phi(\lambda=0)}}{dy} \rangle$ is the differential rapidity cross section for Φ production via nucleon-nucleon collisions in the nuclear medium. Experimental studies show that $R_{AA}^E \simeq 0.5$ both for Cu-Cu [9, 10] and Au-Au [11–13], and we use $R_{AA}^E = 0.5$ for Pb-Pb collisions. The number of binary collisions [14] $N_{\text{bin}}^{PbPb} \simeq 260$ for Pb-Pb. Therefore in Eq. (2.1) $R_{AA}^E N_{\text{bin}}^{AA} \rightarrow R_{\text{PbPb}}^E N_{\text{bin}}^{PbPb} \simeq 130$. The differential rapidity cross section for pp collisions in terms of f_g [2, 15], the gluon distribution function is

$$\left\langle \frac{d\sigma_{pp \rightarrow \Phi(\lambda=0)}}{dy} \right\rangle = A_\Phi \frac{1}{x(y)} f_g(\bar{x}(y), 2m) f_g(a/\bar{x}(y), 2m) \frac{dx}{dy}, \quad (2.2)$$

where $a = 4m^2/s$ and $A_\Phi = \frac{5\pi^3\alpha_s^2}{288m^3s} \langle O_8^\Phi(^1S_0) \rangle$ [2] with $m = 1.5$ GeV for charmonium, and 5 GeV for bottomonium. With $\sqrt{s}=5.02$ TeV, $A_\Phi = 1.26 \times 10^{-6}$ nb for $\Phi=J/\Psi$ and 3.4×10^{-8} nb for $\Phi=\Upsilon(1S)$. $a = 3.6 \times 10^{-7}$ for charmonium and 4.0×10^{-6} for bottomonium. See ref. [2] for a detailed discussion of the theoretical basis of Eq. (2.2) for pp collisions in free space, including references to earlier publications that showed that 3P_J contributions are much smaller than the 1S_0 scalar contributions.

The function $\bar{x}$, the effective parton x in a nucleus (A), is given in refs. [16, 17]:

$$\begin{aligned} \bar{x}(y) &= \left(1 + \frac{\xi_g^2 (A^{1/3} - 1)}{Q^2} \right) x(y) \\ x(y) &= 0.5 \left[\frac{m}{\sqrt{s_{pp}}} (\exp y - \exp(-y)) + \sqrt{\left(\frac{m}{\sqrt{s_{pp}}} (\exp y - \exp(-y)) \right)^2 + 4a} \right], \end{aligned} \quad (2.3)$$

with [18] $\xi_g^2 = .12 \text{ GeV}^2$. Therefore for Pb with $A \simeq 208$,

$$\bar{x}(y) = 1.058x(y). \quad (2.4)$$

for $\sqrt{s}=5.02$ TeV, $m/\sqrt{s_{pp}} = 0.0003, 0.001$ for charmonium, bottomonium. The gluon distribution function f_g [2, 15] is

$$f_g(\bar{x}(y), 2m) = 1334.21 - 67056.5\bar{x}(y) + 887962.0(\bar{x}(y))^2. \quad (2.5)$$

With $\Psi(2S), \Upsilon(3S)$ enhanced by $\pi^2/4$ [2] the differential rapidity cross sections are shown in the following figures. The absolute magnitudes are uncertain, and the shapes and relative magnitudes are our main prediction.

Figure 1. $d\sigma/dy$ for $2m=3$ GeV, $\sqrt{s_{pp}}=5.02$ TeV Pb-Pb collisions producing J/Ψ with $\lambda = 0$.

Figure 2. $d\sigma/dy$ for $2m=3$ GeV, $\sqrt{s_{pp}}=5.02$ TeV Pb-Pb collisions producing $\Psi(2S)$, hybrid theory, with $\lambda = 0$. The dashed curve is for the standard $c\bar{c}$ model.

Figure 3. $d\sigma/dy$ for $2m=10$ GeV, $\sqrt{s_{pp}}=5.02$ TeV Pb-Pb collisions producing $\Upsilon(1S)$ with $\lambda = 0$.

Figure 4. $d\sigma/dy$ for $2m=10$ GeV, $\sqrt{s_{pp}}=5.02$ TeV Pb-Pb collisions producing with $\lambda = 0$ $\Upsilon(2S)$ and $\Upsilon(3S)(\text{hybrid})$. For $\Upsilon(3S)$ the dashed curve is for the standard $b\bar{b}$ model.

3 Ratio of $\Psi(2S)$ to J/Ψ cross sections

In this section we discuss the ratios of the charmonium cross sections for p-p and Pb-Pb collisions at the LHC. In order to estimate the $\Psi(2S)$ to J/Ψ ratios in Pb-Pb collisions we make use of recent experimental results on $\Upsilon(mS)$ state production at the LHC.

3.1 Ratios for p-p collisions

In ref. [2] we discussed the $\Upsilon(mS)$ cross section ratios, showing that the error in the ratios is small as it is given by the wave functions for the standard model and the enhancement factor of $(1 \pm .1) \times \pi^2/4$ for the mixed hybrid, as discussed in section 2. Now there are accurate measurements of the $\Psi(2S)$ to J/Ψ ratio for p-p production at RHIC. From the standard (st), hybrid model(hy) one finds for p-p production of $\Psi(2S)$ and J/Ψ

$$\begin{aligned}\sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{\text{st}} &\simeq 0.27 \\ \sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{\text{hy}} &\simeq 0.67 \pm 0.07,\end{aligned}\tag{3.1}$$

while the PHENIX experimental result for the ratio [19] $\simeq 0.59$. Therefore, as in our earlier work the hybrid model is consistent with experiment, while the standard model ratio is too small.

3.2 Ratios for Pb-Pb collisions

The recent CMS/LHC result comparing Pb-Pb to p-p Upsilon production [22] found

$$\left[\frac{\Upsilon(2S) + \Upsilon(3S)}{\Upsilon(1S)} \right]_{\text{Pb-Pb}} / \left[\frac{\Upsilon(2S) + \Upsilon(3S)}{\Upsilon(1S)} \right]_{p-p} \simeq 0.31^{+.19}_{-.15} \pm .013(\text{syst}),\tag{3.2}$$

while in our previous work on $p-p$ collisions we found the ratio $\sigma(\Upsilon(3S))/\sigma(\Upsilon(1S))|_{p-p}$ of the standard $|b\bar{b}\rangle$ model was $4/\pi^2 \simeq 0.4$ of the hybrid model. This suggests a suppression factor for $\sigma(b\bar{b}(3S))/\sigma(b\bar{b}(1S))$, or $\sigma(c\bar{c}(2S))/\sigma(c\bar{c}(1S))$ of $0.31/.4$ as these components travel through the QGP; or an additional factor of 0.78 for $\Psi(2S)$ to J/Ψ production for $A-A$ vs $p-p$ collisions. Therefore from Eq. (3.1) one obtains our estimate using our mixed hybrid theory for this ratio

$$\sigma(\Psi(2S))/\sigma(J/\Psi(1S))|_{\text{Pb-Pb collisions}} \simeq 0.52 \pm 0.05\tag{3.3}$$

4 Ratio of $\Upsilon(2S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ cross sections

In our previous work [2] we estimated the ratios of $\Upsilon(2S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ cross sections in comparison with an experiment published in 1991 [20]. Our result for p-p collisions, with uncertainty due to separating $\Upsilon(2S)$ from $\Upsilon(3S)$, was

$$\Upsilon(3S)/\Upsilon(1S)|_{p-p} \simeq 0.14 - 0.22,\tag{4.1}$$

for our mixed hybrid theory, while the standard model would give $\frac{\Upsilon(3S)}{\Upsilon(1S)} \simeq 0.06$. A recent CMS result [21], with a correction factor for acceptance and efficiency of the $\Upsilon(3S)$ to the $\Upsilon(1S)$ state, which was estimated to be approximately 0.29 [22], was found to be [1]

$$\Upsilon(3S)/\Upsilon(1S)|_{p-p} \simeq 0.12,\tag{4.2}$$

with the mixed hybrid theory in agreement within errors, while the standard model differs by a factor of two.

The new CMS experiment's main objective [21] is to test for Υ suppression in PbPb collisions. A recent (unpublished) CMS (preliminary) estimate of Υ ratios is [23]

$$\begin{aligned}\frac{[\Upsilon(2S)/\Upsilon(1S)]_{\text{PbPb}}}{[\Upsilon(2S)/\Upsilon(1S)]_{pp}} &\simeq 0.2 \text{ to } 0.4 \\ \frac{[\Upsilon(3S)/\Upsilon(1S)]_{\text{PbPb}}}{[\Upsilon(3S)/\Upsilon(1S)]_{pp}} &\simeq 0.0 \text{ to } 0.26.\end{aligned}\tag{4.3}$$

The studies of Pb-Pb collisions for bottomonium states, which cannot be carried out at RHIC but are an important part of LHC programs, will be carried out in our future research.

5 Conclusions

We have studied the differential rapidity cross sections for J/Ψ , $\Psi(2S)$ and $\Upsilon(nS)$ ($n = 1, 2, 3$) production via Pb-Pb collisions at the LHC ($\sqrt{s_{pp}}=5.02$ TeV) using R_{AA}^E , the product of the nuclear modification factor R_{AA} and the dissociation factor S_Φ , N_{bin}^{AA} the binary collision number, and the gluon distribution functions from previous publications. This should give some guidance for future LHC experiments, although at the present time the $\Upsilon(nS)$ states cannot be resolved.

The ratio of the production of $\sigma(\Psi(2S))$, which in our mixed hybrid theory is 50% $c\bar{c}(2S)$ and 50% $c\bar{c}g(2S)$ with a 10% uncertainty, to $J/\Psi(1S)$, which is the standard $c\bar{c}(1S)$, will be an important test of the production of the quark-gluon plasma. Using the hybrid model and suppression factors from previous theoretical estimates and experiments on $\Upsilon(mS)$ state production at the LHC, we estimate that the ratio of $\Psi(2S)$ to $J/\Psi(1S)$ production at the LHC via Pb-Pb collisions will be about 0.52 ± 0.05 .

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