Heavy quark state production and suppression via Xe-Xe collisions at $\sqrt{s_{pp}}=5.44$ TeV

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Abstract

We estimate the differential rapidity cross sections for $J/\Psi$, $\Psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production and $\Psi(2S)$ to $J/\Psi(1S)$, $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression via Xe-Xe collisions at proton-proton energy $\equiv \sqrt{s_{pp}} = 5.44$ TeV. For the $\Psi(2S)$, $\Upsilon(3S)$ states we use the mixed heavy quark hybrid theory, with these states being approximately 50% standard and 50% hybrid charmonium and bottomonium meson states.

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1 Introduction

This new work on Xe-Xe collisions is based on the heavy quark state production formalism in Pb-Pb collisions at $\sqrt{s_{pp}}=p-p$ energy=5.02 TeV[1].

We use the standard model for $J/\Psi$, $\Upsilon(1S)$, and $\Upsilon(2S)$ states and the mixed hybrid theory[2] for $\Psi(2S)$, $\Upsilon(3S)$ states. Here we have also explored $\Psi(2S)$ to $J/\Psi(1S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression scenario as studied in p-Pb 8 TeV collisions[3]. Recently the LHCb collaboration[4] found a suppression of about 40% for $\Upsilon(nS)$ states produced in p-Pb collisions.

In section 2 heavy quark hybrid states and mixed heavy quark hybrid states are reviewed. Both the bottom quark $b$ and the charm quark $c$ are needed, with masses[5] $m_c \simeq 1.27$ GeV and $m_b \simeq 4.18$ GeV. Also the anti-quarks $\bar{c}$ and $\bar{b}$ are needed. As discussed in section 2 the state $J/\Psi(1S)$ is $|c\bar{c}(1S)\rangle$ while state $\Psi(2S)$ is a mixed hybrid $c$ meson. The state $\Upsilon(3S)$ is a mixed mixed hybrid $b$ meson.

In section 3, $\Psi$ and $\Upsilon$ production in Xe-Xe collisions, our new work on heavy quark state production is based on the methods used in heavy quark state production in Cu-Cu and Au-Au collisions at $\sqrt{s_{pp}}=200$ GeV[6] which used the color octet model[7, 8, 9]. Prior to the article[3] $\Psi(2S)$ and $\Upsilon(3S)$ suppression in p-Pb collisions with $E=\sqrt{s_{pp}}=5.02$ TeV was estimated[10] and reviewed[11]. Also, the ALICE collaboration studied $J/\Psi$ production via Xe-Xe collisions at $\sqrt{s_{NN}}=5.44$ TeV[12].

In section 4 $\Psi$ and $\Upsilon$ suppression in Xe-Xe collisions and mixed hybrid theory the suppression, $S_A$, of charmonium or bottomonium states was estimated for Pb-Pb and p-Pb collisions.

In subsection 4.1 $\Psi(2S)$ suppression in Xe-Xe collisions is reviewed.

In subsection 4.2 $\Upsilon(3S)$ suppression in Xe-Xe collisions is estimated to be moderate.
2 Mixed heavy quark hybrid states

The starting point of the method of QCD sum rules is the correlator

$$\Pi^A(x) = \langle |T[J_A(x)J_A(0)]| \rangle,$$

with \( | \) the vacuum state and the current \( J_A(x) \) creates the states with quantum numbers \( A \).

With \( c, \bar{c} \) and \( g \) a charm quark, an anti-charm quark and a gluon, for the charmonium states, \( J_c \) is

$$J_c = f J_{c\bar{c}} + \sqrt{1 - f^2} J_{c\bar{c}g},$$

where \( J_{c\bar{c}} \) creates a normal charmonium state and \( J_{c\bar{c}g} \) creates a hybrid state with an active gluon.

The charm quark \( c \) needed, with mass is \( m_c \approx 1.27 \text{ GeV} \)

Using QCD sum rules it was shown that \( f \approx -\sqrt{2} \) for the \( \Psi(2S) \) and \( \Upsilon(3S) \) heavy quark meson states and \( f \approx 1.0 \) for the other charmonium and bottomonium states.

Therefore,

$$|J/\Psi(1S) > \approx |c\bar{c}(1S) >$$

$$|\Psi(2S) > \approx -\sqrt{2}|c\bar{c}(1S) > + \sqrt{2}|c\bar{c}g(2S) >,$$

with the \( \Psi(2S) \) being a mixed hybrid meson.

Similarly, it was shown with \( b \) and \( \bar{b} \) a bottom and anti-bottom quark, with mass \( m_b \approx 4.18 \text{ GeV} \), that

$$|\Upsilon(3S) > \approx -\sqrt{2}|b\bar{b}(3S) > + \sqrt{2}|b\bar{b}g(3S) >,$$

After a larger production of \( \Psi(2S) \) states via high energy collisions than standard model predictions, and the anomalous production of sigmas in the decay of \( \Upsilon(3S) \) to \( \Upsilon(1S) \) was found, the solution of these anomalies was found in the mixed hybrid theory. The \( \Psi(2S) \) state was found to be

$$|\Psi(2S) > = \alpha |c\bar{c}(2S) > + \sqrt{1 - \alpha^2} |c\bar{c}g(2S) >,$$

where \( c \) is a charm quark, and the \( \Upsilon(3S) \) state was found to have the form

$$|\Upsilon(3S) > = \alpha |b\bar{b}(3S) > + \sqrt{1 - \alpha^2} |b\bar{b}g(3S) >,$$

where \( b \) is a bottom quark and \( \alpha = -0.7 \pm 0.1 \), as in Ref.\[13\].

That is, these states have approximately a 50% probability of being a standard quark-antiquark, \( |q\bar{q} > \), meson, and a 50% probability of a hybrid, with the \( |q\bar{q}g > \) a color octet and an active gluon, which we use for both the production and suppression of heavy quark states via Xe-Xe collisions.

It is important to use the mixed hybrid theory as the \( \Psi(2S), \Upsilon(3S) \) cross sections are enhanced by a factor of \( \pi^2/4 \).

This is in the following section on \( \Psi \) and \( \Upsilon \) production in Xe-Xe collisions.
3 Ψ and Υ production in Xe-Xe collisions with $\sqrt{s_{pp}} = 5.44$ TeV

The differential rapidity cross section for the production of a heavy quark state Φ with helicity $\lambda = 0$ (for unpolarized collisions[16]) in the color octet model in Xe-Xe collisions is given by[3]

$$\frac{d\sigma_{AA\rightarrow \Phi(\lambda=0)}}{dy} = R_{AA}^{E} N_{AA}^{NN} < \frac{d\sigma_{pp\rightarrow \Phi(\lambda=0)}}{dy} >,$$

(7)

where $R_{AA}^{E}$ is the product of the nuclear modification factor $R_{AA}$ and $S_{\Phi}$, the dissociation factor after the state Φ is formed (see FIG. 3 in Ref[17]). $R_{AA}$ is defined in Ref[18] as

$$R_{AA}(p) = \frac{d^{2}N_{AA}^{\text{bin}}/dpd\eta}{T_{AA}d^{2}\sigma_{NN}/dpd\eta},$$

(8)

where $N_{AA}^{\text{bin}}$ is the number of binary collisions in the AA collision, $\eta$ is the pseudo-rapidity[19], $T_{AA} = N_{AA}^{\text{bin}}/\sigma_{NN}$, where $\sigma_{NN}$ is the cross section for N-N collisions and $< \frac{d\sigma_{pp\rightarrow \Phi(\lambda=0)}}{dy} >$ is the differential rapidity cross section for Φ production via nucleon-nucleon collisions in the nuclear medium. For Xe-Xe collisions we use $R_{XeXe}^{E} = 0.5$ as $R_{AA}^{E} \approx 0.5$ both for Cu-Cu[17, 20] and Au-Au[21, 22, 23] and $R_{PbPb}^{E} = 0.5$ was used in Ref[1]. $N_{XeXe}^{\text{bin}}$ is the number of binary collisions in Xe-Xe collisions, and $< \frac{d\sigma_{pp\rightarrow \Phi(\lambda=0)}}{dy} >$ is the differential rapidity cross section for Φ production via nucleon-nucleon collisions in the nuclear medium. The number of binary collisions for Pb-Pb from Ref[24] used in Ref[1] was $N_{bin}^{PbPb} \approx 260$.

The cross sections at $\sqrt{s_{pp}} \approx 5.0$ TeV[25] $\sigma(b) \approx 7.66, 3.34, 5.61$ for PbPb, CuCu, XeXe. Using $N_{bin}^{PbPb} = 260$, for Cu-Cu collisions $N_{bin}^{CuCu} \approx 51.5[6, 24]$. From $N_{bin}^{PbPb} = 260$ and the Xe-Xe, Pb-Pb cross sections we estimate $N_{bin}^{XeXe} \approx 216$. Therefore in Eq(6) $R_{XeXe}^{E} N_{XeXe}^{\text{bin}} \rightarrow R_{XeXe}^{E} N_{XeXe}^{\text{bin}} \approx 108$.

The differential rapidity cross section for pp collisions in terms of $f_{g}[16]$, the gluon distribution function is

$$< \frac{d\sigma_{pp\rightarrow \Phi(\lambda=0)}}{dy} > = A_{\Phi} \frac{1}{x(y)} f_{g}(\bar{x}(y), 2m) f_{g}(a/\bar{x}(y), 2m) \frac{dx}{dy},$$

(9)

where from Ref[16] $A_{\Phi} = 1.26 \times 10^{-6}$ nb for $\Phi = J/\Psi$ and $3.4 \times 10^{-8}$ nb for $\Phi = \Upsilon(1S)$; and $a = 4m^{2}/s = 3.6 \times 10^{-7}$ for charmonium and $4.0 \times 10^{-6}$ for bottomonium.

The function $\bar{x}$, the effective parton $x$ in a nucleus (A), is given in Refs[24, 27]:

$$\bar{x}(y) = (1 + \frac{\xi_{g}^{2}(A^{1/3} - 1)}{Q^{2}}) x(y)$$

$$x(y) = 0.5 \left[ \frac{m}{\sqrt{s_{pp}}} (\exp y - \exp (-y)) + \sqrt{\frac{m}{\sqrt{s_{pp}}} (\exp y - \exp (-y))^{2} + 4a} \right],$$

(10)

with[28] $\xi_{g}^{2} = .12 GeV^{2}$ and $Q^{2}$ defined in Ref[26].

Therefore for Xe with $A \simeq 132, Q^{2} \simeq 10.18 GeV^{2}$

$$\bar{x}(y) = 1.048 x(x).$$

(11)

For $\sqrt{s_{pp}} = 5.44$ TeV the gluon distribution function $f_{g}[29][16]$ is

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

(12)

With $\Psi(2S), \Upsilon(3S)$ enhanced by $\pi^{2}/4[16]$ 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 predictions. In Eq(10) $m = m_{c} = 1.5$ GeV for charmonium and $m = m_{b} = 5$ GeV for bottomonium quarks.
Figure 1: $d\sigma/dy$ for $2m_c=3$ GeV, $\sqrt{s_{pp}}=5.44$ TeV Xe-Xe collisions producing $J/\Psi$ with $\lambda = 0$.

Figure 2: $d\sigma/dy$ for $2m_c=3$ GeV, $\sqrt{s_{pp}}=5.44$ TeV Xe-Xe 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 $2m_b=10$ GeV, $\sqrt{s_{pp}}=5.44$ TeV Xe-Xe collisions producing $\Upsilon(1S)$, $\lambda = 0$

Figure 4: $d\sigma/dy$ for $2m_b=10$ GeV, $\sqrt{s_{pp}}=5.44$ TeV Xe-Xe collisions producing with $\lambda = 0$ $\Upsilon(2S)$ and $\Upsilon(3S)$(hybrid). For $\Upsilon(3S)$ the dashed curve is for the standard $b\bar{b}$ model.
4 Ψ and Υ suppression in Xe-Xe collisions and mixed hybrid theory

The suppression, $S_A$, of charmonium or bottomonium states is given by the interaction of the meson with nucleons as it traverses the nucleus. From Ref[30]

$$S_A = e^{-n_o \sigma_{\Phi N} L},$$

(13)

where $\Phi$ is a standard $c\bar{c}$, hybrid $c\bar{c}g$ charmonium meson, or a standard $b\bar{b}$, $b\bar{b}g$ bottomonium meson. $L$ is the length the path of $\Phi$ in nuclear matter, $n_o = 0.17 \text{ fm}^{-3}$ is the nuclear matter density, and $\sigma_{\Phi N}$ is the $\Phi - N$ cross section. For Xe-Xe collisions $L \simeq 12 \text{ fm}$.

$S_A$ was estimated for Pb-Pb collisions[1] and p-Pb collisions[10]. From Ref[10] $\sigma_{\Phi N}$ for $\Phi = c\bar{c}, c\bar{c}g, b\bar{b}, b\bar{b}g$ were estimated to be (with a mb $\rightarrow$ fm$^2$ correction)

$$\sigma_{c\bar{c}N} \simeq 3.2 \times 10^{-2} \text{ fm}^2$$

$$\sigma_{c\bar{c}gN} \simeq 6.5^2 \text{ fm}^2$$

$$\sigma_{b\bar{b}N} \simeq 2.9 \times 10^{-3} \text{ fm}^2$$

$$\sigma_{b\bar{b}gN} \simeq 0.59 \text{ fm}^2.$$  

(14)

Note that the present results for $n_o \sigma_{\Phi N} L$ differ from those in Ref[10] for Pb-Pb suppression by a factor of about 1.25 as $L \simeq 15 \text{ fm}$ for Pb and 12 fm for Xe.

4.1 Ψ(2S) suppression in Xe-Xe collisions

From Eq(14) for $J/\Psi = \Psi(1S) = |c\bar{c}; 1S>$

$$n_o \sigma_{c\bar{c}N} L \simeq 0.065$$

$$S_A^{c\bar{c}} = e^{-n_o \sigma_{c\bar{c}N} L} \simeq 1.0,$$

(15)

so the $J/\Psi = \Psi(1S)$ meson is not suppressed in Xe-Xe collisions. For a charmonium hybrid meson $c\bar{c}g$ with $L=12 \text{ fm}$

$$n_o \sigma_{c\bar{c}gN} L \simeq 13.3$$

$$S_A^{c\bar{c}g} \simeq e^{-13.3} \simeq 0.0.$$  

(16)

Since from Eq(5) the $\Psi(2S)$ is 50% standard and 50% hybrid

$$S_A^{\Psi(2S)} \simeq (1 + 0.0)/2 \simeq 0.5.$$  

(17)

With the definition of $R^{\Psi(2S) - J/\Psi(1S)}$ the ratio of the suppression of the $\Psi(2S)$ to the $\Psi(1S)$ states, from Eqs(15,16)

$$R^{\Psi(2S) - J/\Psi(1S)}|_{Xe-Xe-theory} \simeq 0.5,$$

(18)

The experimental result[31] for d-Au collisions and[32] for p-Pb collisions is

$$R^{\Psi(2S) - J/\Psi(1S)}|_{exp} \simeq 0.65 \pm 0.1$$

(19)

which is somewhat larger than $R^{\Psi(2S) - J/\Psi(1S)}|_{Xe-Xe-theory}$. 

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4.2 Υ(3S) suppression in Xe-Xe collisions

From Eq[14] for Υ(1s) = |bb; 1S >

\[ n_0\sigma_{bbN}L \simeq 0.0 \]
\[ S_{bb}^{A} \simeq 1.0. \]  

(20)

so the Υ(1S) and Υ(2S) are not suppressed.

For a hybrid bottomonium meson \( b\bar{b}g \) from Eq(14)

\[ n_0\sigma_{b\bar{b}gNL} \simeq 1.2 \]
\[ S_{b\bar{b}g}^{A} \simeq 0.3. \]  

(21)

For the mixed hybrid Υ(3S)

\[ S_{A}^{\Upsilon(3S)} \simeq (1 + .3)/2 \simeq 0.65. \]  

(22)

Therefore for Xe-Xe collisions the Υ(3S) suppression is moderate and could be measured in future CERN LHC Xe-Xe collision experiments.

5 Conclusions

In section 2 mixed heavy quark hybrid states are reviewed.

In section 3 we have extended and reviewed our work on heavy quark state production in Pb-Pb collisions[1] we have studied the differential rapidity cross sections for \( J/\Psi, \Psi(2S) \) and \( \Upsilon(nS)(n = 1, 2, 3) \) production via Xe-Xe collisions with \( \sqrt{s_{pp}} = 5.44 TeV \) using \( R_{XeXe}XeXe/N_{binXeXe} \simeq 108. \) This will give guidance for future CERN LHC experiments[25].

In section 4 an extension of estimates of suppression for Pb-Pb collisions[10] and p-Pb collisions[3] was reviewed.

In subsection 4.1 we have estimated the suppression of \( \Psi(2S) \) compared to \( J/\Psi(1S) \) via Xe-Xe collisions. In subsection 4.2 we have estimated the suppression of \( \Upsilon(nS)(n = 1, 2, 3) \) for Xe-Xe collisions. We used \( L=12 \text{ fm} \) rather than \( 15 \text{ fm} \) for Pb-Pb collisions for \( n_0\sigma_{\Phi N}L \) to estimate suppression \( S_{A} = e^{-n_0\sigma_{\Phi N}L} \), with \( \Phi = \Psi(1, 2) \) and \( \Upsilon(1, 2, 3) \). Since \( \Psi(2S) \) and \( \Upsilon(3S) \) are mixed hybrid mesons, \( S_{A}^{\Psi(2S)} \simeq (S_{A}^{bb} + S_{A}^{b\bar{b}g})/2 \) and \( S_{A}^{\Upsilon(3S)} \simeq (S_{A}^{bb} + S_{A}^{b\bar{b}g})/2. \) Our results are that the \( J/\Psi, \Upsilon(1S) \) and \( \Upsilon(2S) \) are not suppressed in Xe-Xe collisions and \( S_{A}^{\Psi(2S)} \simeq 0.5, S_{A}^{\Upsilon(3S)} \simeq 0.65 \) for Xe-Xe collisions.

The experimental results[31] for d-Au collisions and[32] for p-Pb collisions for the ratio of \( \Psi(2S) \) to \( J/\Psi(1S) \) are almost consistent with our present results for Xe-Xe collisions. From our results \( \Psi(2S) \) and \( \Upsilon(3S) \) suppression could be measured in future CERN LHC Xe-Xe collision experiments[25].

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