\[\Psi(2S)\text{ and } \Upsilon(3S)\text{ Suppression in p-Pb 8 TeV Collisions and Mixed Heavy Quark Hybrid Mesons}\]

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Abstract

This brief report is an extension of a previous publication on \(\Psi(2S)\) to \(J/\Psi(1S)\) suppression in p-Pb collisions at 5.02 TeV to estimate \(\Psi(2S)\) to \(J/\Psi(1S)\) and \(\Upsilon(3S)\) to \(\Upsilon(1S)\) suppression via p-Pb collisions at 8 TeV as proposed by the LHCb.

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1 Introduction

Recently \(\Psi(2S)\) suppression \(S_A = \frac{[\sigma_{\Psi(2S)}/\sigma_{J/\psi}]_{pPb}}{[\sigma_{\Psi(2S)}/\sigma_{J/\psi}]_{pp}}\) in p-Pb collisions at \(E=5.02\) TeV, and \(\Upsilon(3S)\) suppression \(S_A = \frac{[\sigma_{\Upsilon(3S)}/\sigma_{\Upsilon(1S)}]_{PbPb}}{[\sigma_{\Upsilon(3S)}/\sigma_{\Upsilon(1S)}]_{pp}}\) in Pb-Pb collisions, were estimated[1] and compared to experimental[2, 3]. By using the mixed heavy quark hybrid theory[4] it was found that the theoretical estimates agreed with experiments within errors in experiments and theory. This was reviewed[5] before Ref.[1] was published.

Since the article Ref.[1] was published LHCb has recently submitted a document[6] to support the request for p-Pb and Pb-p collisions at 8 TeV to produce \(\Psi\) and \(\Upsilon\) mesons to measure “cold nuclear matter effects”, which we call \(\Psi(2S)/(J/\Psi)\) and \(\Upsilon(3S)/\Upsilon(1S)\) suppression. The objective of the present work is to estimate \(J/\Psi(1S), \Psi(2S), \Upsilon(1S), \) and \(\Upsilon(3S)\) suppression using the mixed heavy quark theory for p-Pb vs p-p collisions in anticipation of the future LHCb experiment[6].

Three decades ago \(J/\Psi\) suppression by the formation of the Quark-Gluon Plasma (QGP) in Relativistic Heavy Ion Collisions (RHIC) was estimated[7]. This is closely related to using the mixed hybrid theory to detect the formation of the QGP via RHIC[8], since gluons in the QGP enhance the production of \(\Psi(2S)\) and \(\Upsilon(3S)\) states due to the active gluon in their hybrid component. This is reviewed in the following section.

In the present work the on \(\Psi(2S), J/\Psi(1S), \Upsilon(1S), \) and \(\Upsilon(3S)\) suppression produced in p-Pb collisions at 8 TeV we employ the theoretical methods of Ref.[1] using scenario 1. of Ref[9], to estimate \(S_A = \frac{[\sigma_{\Psi(2S)/\sigma_{J/\psi}]_{pPb}}{[\sigma_{\Psi(2S)/\sigma_{J/\psi}]_{pp}}}\), \(S_A = \frac{[\sigma_{\Upsilon(3S)/\sigma_{\Upsilon(1S)}]_{PbPb}}{[\sigma_{\Upsilon(3S)/\sigma_{\Upsilon(1S)}]_{pp}}}\), in p-Pb 8 TeV collisions.
2 Theoretical $\Psi(2S)$ to $J/\Psi(1S)$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression in p-Pb collisions and the mixed heavy quark hybrid theory

In this section we start our theoretical estimate of the suppression, $S_A$, of charmonium and bottomonium states by a brief review of the mixed hybrid theory, followed by the theoretical estimate of $S_A$ for $\Psi(2S)$, $J/\Psi(1S)$, $\Upsilon(3S)$, and $\Upsilon(1S)$ in p-Pb collisions.

2.1 Review of Mixed Heavy Hybrid States via QCD Sum Rules

The nature of the $J/\Psi(1S)$, $\Psi(2S)$ as standard, hybrid, or mixed standard-hybrid charmonium states, and $\Upsilon(1S)$, $\Upsilon(3S)$ as standard, hybrid, or mixed standard-hybrid bottomonium states was studied in Ref.[4] making use of QCD Sum Rules[11].

The operator that produces the mixed charmonium and hybrid charmonium states, with $f$ determined from the Sum Rule, is

$$J_{C-HC} = fJ_H + \sqrt{1-f^2}J_{HH},$$

(1)

with $J_H|0>= |c\bar{c}(0)>$, $J_{HH}|0>= |c\bar{c}(8)(0)>$, where $|c\bar{c}(0)>$ is a standard Charmonium state, while a hybrid Charmonium state $|c\bar{c}(8)(0)>$ has $c\bar{c}(8)$ with color=8 and a gluon with color=8. In Ref.[4] it was found that for $J/\Psi(1S)$ $f^2 \simeq 1.0$ while for $\Psi(2S)$ $f^2 \simeq 0.5$. Thus

$$|J/\Psi> \simeq |c\bar{c}(0)(1S)>$$

$$|\Psi(2S)> \simeq 0.7071|c\bar{c}(0)(2S)> + 0.7071|c\bar{c}(8)(0)(2S)>,$$

(2)

therefore the $\Psi(2S)$ meson is 50% normal charmonium and 50% hybrid charmonium, while the $J/\Psi$ is a normal charmonium meson.

Using a similar QCD Sum Rule calculation for bottomonium states[4] it was found that the $\Upsilon(1S)$ is a standard bottomonium meson, while the $\Upsilon(3S)$ is 50% normal and 50% hybrid bottomonium meson:

$$|\Upsilon(1S)> \simeq |b\bar{b}(0)(1S)>$$

$$|\Upsilon(3S)> \simeq 0.7071|b\bar{b}(0)(3S)> + 0.7071|b\bar{b}(8)(0)(3S)>.$$  

(3)

We shall use this to estimate the ratios of suppression of $\Psi(2S)$ to $J/\Psi$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ is in p-Pb collisions.

2.2 Theoretical $\Psi(2S)$ to $J/\Psi(1S)$ suppression in p-Pb collisions

The suppression, $S_A$, of a charmonium state is given by the interaction with nucleons as it traverses the nucleus. In this subsection we give a brief review of $S_A$ for standard and hybrid charmonium mesons derived in Ref.[1].

$$S_A = e^{-n_0\sigma_{NN} L},$$

(4)
where $\Phi$ is a $c\bar{c}$ or $c\bar{c}g$ meson, $L$ is the length of the path of $\Phi$ in nuclear matter $\simeq 8$ to $10$ fm for p-Pb collisions, with nuclear matter density $n_o = .017 fm^{-3}$, and $\sigma_{\Phi,N}$ is the cross section for $\Phi$- nucleon collisions.

From Refs.[10] the cross section for standard charmonium $c\bar{c}$ meson via strong QCD interactions with nucleons is given by

$$\sigma_{c\bar{c}N} = 2.4\alpha_s \pi r_{c\bar{c}}^2,$$

(5)

where $\alpha_s \simeq 0.118$, and the charmonium meson radius $r_{c\bar{c}} \simeq \hbar/(2M_c c)$, with $M_c$ the charm quark mass. Using $2M_c \simeq M_{J/\Psi} \simeq 3$ GeV, $4r_{c\bar{c}} \simeq 6 \times 10^{-17} m = 0.06 fm$. Therefore, $\sigma_{c\bar{c}N} \simeq 3.2 \times 10^{-3} fm^2 = 3.2 \times 10^{-2}$ mb.

Taking $L \simeq 8-10$ fm and $n_o = .017 fm^{-3}$

$$n_o \sigma_{c\bar{c}N} L \simeq 0.0022$$

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

(6)

On the other hand, the cross section for hybrid charmonium $c\bar{c}g$ meson via strong QCD interactions with nucleons has been estimated in Ref[10] as $\sigma_{c\bar{c}gN} \simeq 6$-7 mb. In the present work we use

$$\sigma_{c\bar{c}gN} \simeq 6.5 mb ,$$

(7)

with the result

$$n_o \sigma_{c\bar{c}gN} L \simeq 0.88 \text{ to } 1.1$$

$$S_{c\bar{c}g}^c \simeq 0.4 \text{ to } 0.33 .$$

(8)

Using the mixed hybrid model one finds for the ratio of $\Psi(2S)$ to $J/\Psi(1S)$ suppression in p-Pb collisions

$$R^{\Psi(2S)/(J/\Psi)|_{theory}} \simeq \frac{1 + 0.4 \text{ to } 0.33}{2}$$

$$\simeq 0.66 \text{ to } 0.7 .$$

(9)

As pointed out in Ref.[12], the Color Glass Condensate model[13] overestimates the suppression, while other theoretical models successfully estimate $J/\Psi$ suppression, but do not treat the $\Psi(2S)$ suppression. Since they would use a standard $c\bar{c}$ rather than the mixed hybrid theory with a $c\bar{c}g$ component as in the present work, they would probably underestimate the $\Psi(2S)$ suppression.

### 2.3 Theoretical $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression in p-Pb collisions

For a standard bottomonium meson state or a hybrid bottomonium state the equation for suppression is given by Eq(4) where $\Phi$ is a $b\bar{b}$ or $b\bar{b}q$ meson. As for charmonium $L$ is the length of $\simeq 8$ to $10$ fm for p-Pb collisions, with nuclear matter density $n_o = .017 fm^{-3}$. 


From Eq(5) the cross section for standard bottomonium $b \bar{b}$ meson via strong QCD interactions with nucleons, $\sigma_{b\bar{b}N} = 2.4\alpha_s\pi r_{b\bar{b}}^2$ differs from $\sigma_{c\bar{c}N}$ by a factor of $M_c^2/M_b^2 \approx 0.09$. Therefore, $\sigma_{b\bar{b}N} \approx 0.09 \times 3.2 \times 10^{-2} mb \approx 3 \times 10^{-3} mb$

$$
\begin{align*}
S_A^{\bar{c}} &= e^{-n_0 \sigma_{c\bar{c}N} L} \approx 1.0 .
\end{align*}
$$

Similarly, the cross section for hybrid bottomonium $b\bar{b}g$ meson via strong QCD interactions with nucleons $\sigma_{b\bar{b}gN} = \sigma_{c\bar{c}gN} (M_c/M_b)^2 \approx 0.09 \sigma_{c\bar{c}gN} \approx 0.59 mb$. Therefore,

$$
\begin{align*}
n_0 \sigma_{b\bar{b}gN} L &\approx 0.08 \text{ to } 0.1 \\
S_A^{b\bar{b}g} &\approx 0.92 \text{ to } 0.90 .
\end{align*}
$$

Using the mixed hybrid model one finds for the ratio of $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression in p-Pb collisions

$$
\begin{align*}
R^{\Upsilon(3S)/\Upsilon(1S)}_{\text{theory}} &\approx \frac{1 + 0.90 \text{ to } 0.92}{2} \\
&\approx 0.95 \text{ to } 0.96 .
\end{align*}
$$

3 Conclusions

Using the mixed heavy quark hybrid theory for $\Psi(2S)$ and $\Upsilon(3S)$ states we have estimated $\Psi(2S)$ to $J/\Psi$ and $\Upsilon(3S)$ to $\Upsilon(1S)$ suppression ratios, $R^{\Psi(2S)/(J/\Psi)}_{\text{theory}}$ and $R^{\Upsilon(3S)/\Upsilon(1S)}_{\text{theory}}$, for p-Pb vs p-p collisions at 8 TeV in anticipation of future LHCb experiments[6]. Note that previous experiments[2] measuring $R^{\Psi(2S)/(J/\Psi)}$ used p-Pb collisions at 5.02 TeV.

If future experiments measure the $R^{\Psi(2S)/(J/\Psi)}$ and $R^{\Upsilon(3S)/\Upsilon(1S)}$ ratios for p-Pb vs p-p collisions, with the $\Psi(2S)$ meson predicted to be 50% normal charmonium and 50% hybrid charmonium and the $\Upsilon(3S)$ meson predicted to be 50% normal bottomonium and 50% hybrid bottomonium[4], one would have another test of the mixed heavy quark hybrid theory.

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