\( \Psi(2S) \), \( \Upsilon(3S) \) Suppression in p-Pb, Pb-Pb Collisions and Mixed Hybrid Theory

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Abstract We use our mixed hybrid model for the \( \Psi(2S) \) state to estimate \( \Psi(2S) \) to \( J/\Psi(1S) \) suppression in p-Pb collisions, and the \( \Upsilon(3S) \) state to estimate \( \Upsilon(3S) \) to \( \Upsilon(1S) \) suppression in Pb-Pb collisions, and compare to recent experimental measurements.

Keywords p-Pb collisions · Pb-Pb collisions · Mixed heavy quark hybrids · Heavy quark state suppression

1 Introduction

The production of \( \Psi \) and \( \Upsilon \) mesons via \( p - p \) collisions has been of interest for many years as a test of QCD (Quantum Chromodynamics). More than a decade ago it was shown that the relative production of \( \Psi(2S) \) to \( J/\Psi(1S) \) in \( p - \bar{p} \) collisions was not consistent with standard QCD models [1]. Similarly, in experiments on \( \Upsilon(nS) \) production via \( p - p \) collisions it was found [2, 3] that \( \Upsilon(3S) \) to \( \Upsilon(1S) \) production is also not consistent with standard QCD models. In a theoretical study of \( \Psi \) and \( \Upsilon \) production via \( p - p \) or \( p - \bar{p} \) collisions [4] it was shown that the relative probabilities of \( \Psi(2S) \) to \( J/\Psi(1S) \) and \( \Upsilon(3S) \) to \( \Upsilon(1S) \) are consistent with experiment if the \( \Psi(2S) \) and \( \Upsilon(3S) \) are mixed heavy hybrids, discussed below. The fact that \( \Psi(2S) \) is a mixed charmonium hybrid meson and \( \Upsilon(3S) \) is a mixed bottomonium hybrid meson, while \( J/\Psi(1S) \) and \( \Upsilon(1S) \) are standard charmonium and bottomonium mesons is the basis for the present work.

Recent experiments using \( d - Au \) collisions [5, 6] and \( p - Pb \) collisions [7, 8] have shown a strong suppression, \( S_A \), of \( \Psi(2S) \) relative to \( J/\Psi(1S) \). As stated in these articles, this suppression cannot be explained by current theoretical models [9–13]. In an earlier study of \( J/\Psi \) production and absorption [14] two scenarios were used for charmonium
production: 1. charmonium states are produced with the $c\bar{c}$ a color octet $(|c\bar{c}(8)g>)$; and 2. charmonium states are produced as a color singlet $|c\bar{c}>$, which is the standard model.

In the present work on $\Upsilon(2S)$ suppression scenario 1. of Ref [14] is used, as is discussed in Ref [4]. We estimate $S_A$ for both $J/\Psi(1S)$ and $\Upsilon(2S)$ for $p-Pb$ collisions using the mixed heavy hybrid theory, and show that the ratio of $S_A$ for $\Upsilon(2S)$ to $J/\Psi(1S)$ is consistent with experiments. CMS experiments have measured $\Upsilon$ states suppression in Pb-Pb collisions [15, 16], and estimated the yields of $\Upsilon(3S)/\Upsilon(1S)$ relative to those in p-p collisions [16]. We estimate this ratio using our mixed hybrid theory.

Next we briefly discuss the method of QCD Sum Rules, and how this was used to show that the $\Upsilon(2S)$ and $\Upsilon(3S)$ are mixed heavy hybrids, defined in the next section.

2 Mixed Heavy Hybrid States via QCD Sum Rules

The starting point of the method of QCD sum rules [17] for finding the mass of the state referred to as A is the correlator,

$$\Pi^A(x) = \langle J_A(x) J_A(0) \rangle, \quad (1)$$

with $|\rangle$ the vacuum state and the current $J_A(x)$ creating the states with quantum numbers A. The QCD sum rule is obtained by equating a dispersion relation of $\Pi^A$ in momentum space to an operator product expansion of $\Pi^A$ using QCD diagrams with quarks and gluons. After taking a Borel transform [17], $B$, in which the momentum variable is replaced by the Borel mass, $M_B$, the QCD sum rule has the form

$$\frac{1}{\pi} e^{-M_A^2/M_B^2} + B \int_{s_0}^{\infty} \frac{Im[\Pi_A(s)]}{\pi(s-q^2)} ds = B \sum_k c_k^A(q) < 0|O_k|0>, \quad (2)$$

where $M_A$ is the lowest mass of a state with the properties of A and the right-hand side is the Borel transform of the operator product expansion of $\Pi^A$. The operator that produces the mixed charmonium and hybrid charmonium states, with $b$ determined from the Sum Rule, is

$$J_{C-HC} = b J_H + \sqrt{1-b^2} J_{HH}, \quad (3)$$

with $J_H|0> = |c\bar{c}(0)>$, $J_{HH}|0> = [[c\bar{c}(8)g]|0>$, where $|c\bar{c}(0)>$ is a standard Charmonium state, while a hybrid Charmonium state $[[c\bar{c}(8)g]|0>$ has $c\bar{c}(8)$ with color=8 and a gluon with color=8. For the mixed hybrid Charmonium state produced by $J_{C-HC}$ mass $M_A$ of (2) is called $M_{C-HC}$. To find the mass $M_{C-HC}$ one plots the value of $M_{C-HC}^2$ vs $M_B^2$ using (2) with the quantities derived in Ref. [18]. The solution for $M_{C-HC}$ is given by the minimum in the plot. Note that $M_{C-HC} \simeq M_B^2$ for a solution satisfying the method of QCD Sum Rules. This plot is shown in the figure below for (3) $b^2 = 0.5$ (Fig. 1).

![Fig. 1 Mixed Charmonium-hybrid charmonium mass \(\simeq 3.65 \text{ GeV}\)](image)
From this figure one sees that the minimum in $M_{C-HC}^2(M_B^2)$ corresponds to the $\Psi'(2S)$ state, with a mass [19] of 3.686 GeV. Therefore the $\Psi'(2S)$ meson is 50 % normal Charmonium and 50 % hybrid Charmonium, while the $J/\Psi(1S)$ is a normal Charmonium meson. The analysis for Upsilon states was similar, with the $\Upsilon(3S)$ being 50 % normal Bottomonium and 50 % hybrid Bottomonium, while the $\Upsilon(1S)$ and $\Upsilon(2S)$ states are standard Bottomonium mesons. We shall use this to estimate the ratio of suppression of $\Psi(2S)$ to $J/\Psi(1S)$ in p-Pb collisions and $\Upsilon(3S)$ to $\Upsilon(3S)$ in Pb-Pb collisions.

3 Nuclear Modification and Suppression of $\Psi(2S)/J/\Psi(1S)$ in p-Pb Collisions

In this section we derive the relative suppression of $\Psi(2S)$ to $J/\Psi(1S)$ and compare this result to experiment. First the definition of nuclear suppression and experimental data for the relative $\Psi(2S)$ to $J/\Psi(1S)$ suppression is given, and then the theoretical derivation and comparison to experiment is presented.

The mixed Charmonium hybrid theory, with the $\Psi'(2S)$ meson being 50 % normal Charmonium and 50 % hybrid Charmonium is directly used in calculating the relative suppression.

3.1 Experimental $\Psi(2S)$ to $J/\Psi(1S)$ Suppression in p-Pb Collisions

The nuclear modification for $\Phi = J/\Psi(1S)$ or $\Psi(2S)$ produced in A-B collisions is defined as [5, 7]

$$R_\Phi = \frac{dN^{A-B}_{\Phi}/dy}{N_{coll}dN^{pp}_{\Phi}/dy}.$$  \hspace{1cm} (4)

where $dN^{A-B}_{\Phi}/dy$ and $dN^{pp}_{\Phi}/dy$ are the invariant yields of $\Phi$ in A-B and pp collisions. In this work we consider p-Pb collisions ($A=\text{p}, B=\text{Pb}$).

The relative suppression of $\Psi(2S)$ to $J/\Psi(1S)$ is defined as

$$R_{\Psi(2S)-J/\Psi(1S)} = \frac{R_{\Psi(2S)}}{R_{J/\Psi(1S)}}.$$  \hspace{1cm} (5)

The experimental results for rapidity $0 \leq y \leq 3$, as shown in the figure below is

$$R_{\Psi(2S)-J/\Psi(1S)}|_{exp} \simeq 0.65 \pm 0.1.$$  \hspace{1cm} (6)

As stated in Refs. [5–8], the observed suppression of $\Psi(2S)$ compared to $J/\Psi(1S)$ cannot be explained in standard charmonium models. As stated by J. Matthew Durham [6], “the difference in suppression is too strong to be explained by breakup effects in the nucleus...these observations raise interesting questions about the mechanism of $\Psi(2S)$ suppression when it is produced in a nuclear target.”

Recently there was an attempt to explain the $\Psi(2S)$ versus $J/\Psi(1S)$ suppression using a comover interaction approach [20]. In the present work we show that the mixed hybrid theory for the $\Psi(2S)$ state, which has been successful in predicting ratios of $\Psi(2S)$ to $J/\Psi(1S)$ production cross sections in p-p [4] and A-A [21] collisions, can explain the mystery of the $\Psi(2S)$ versus $J/\Psi(1S)$ suppression.

The experimental results for p-Pb (ALICE) and d-AU (PHENIX) collisions are shown in Fig. 2, with $\sqrt{s_{NN}} = E_{NN} = \text{nucleon-nucleon center of mass energy.}$
Fig. 2 The relative suppression of $\Psi(2S)$ to $J/\Psi(1S)$ for $E_{NN} = 5.02$ TeV p-Pb (ALICE) with rapidity $\simeq -4$ and 3; and $E_{NN} = 200$ GeV d-Au (PHENIX) with rapidity $\geq 0$

3.2 Theoretical $\Psi(2S)$ to $J/\Psi(1S)$ Suppression in p-Pb Collisions

The suppression, $S_A$, of charmonium states is given by the interaction with nucleons as it traverses the nucleus. For a standard charmonium meson state $|c\bar{c}\rangle$ or hybrid meson state $|c\bar{c}g\rangle$, with the $c\bar{c}$ having octet color, the equation for suppression is given by [22]

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

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.

The cross section for standard charmonium $c\bar{c}$ meson via strong QCD interactions with nucleons is given by [22]

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

where the strong coupling constant $\alpha_s \simeq 0.118$ [19], and the charmonium meson radius $r_{c\bar{c}} \simeq h/(2Mc)$, with $M_c$ the charm quark mass. Using $2M_c \simeq M_{J/\Psi} \simeq 3$ GeV,

$$r_{c\bar{c}} \simeq h/(3 \text{ GeV } c) \simeq 6 \times 10^{-17} \text{ m} = 0.06 \text{ fm}$$

From (8), (9)

$$\sigma_{c\bar{c}N} \simeq 3.2 \times 10^{-3} \text{ fm}^2 = 3.2 \times 10^{-2} \text{ mb}.$$  

Taking $L \simeq 8$–10 fm and $n_o = .017$ fm$^{-3}$, from (10),

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

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

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 [22] as $\sigma_{c\bar{c}gN} \simeq 6$–7 mb. In the present work we use

$$\sigma_{c\bar{c}gN} \simeq 6.5 \text{ mb}.$$  

(12)
From this, using $L \simeq 8\text{–}10\ \text{fm}$ and $n_o = 0.17\ \text{fm}^{-3}$, from (7) we obtain

$$n_o \sigma_{c\bar{c}N}L \simeq 0.88 \text{ to } 1.1 \quad S_A^{c\bar{c}g} \simeq 0.4 \text{ to } 0.33. \quad (13)$$

Using our mixed hybrid model, with 50% $|c\bar{c}>$ and 50% $|c\bar{g}>$, from (4), (11), (19), we find

$$R_{\Psi(2S)−J/\Psi(1S)}|_{\text{theory}} \simeq \frac{1+0.4 \text{ to } 0.33}{2} = 0.7 \text{ to } 0.66. \quad (14)$$

Comparing (14) to (6), one finds that the mixed hybrid theory for the state $\Psi(2S)$ solves the mystery of the large suppression of $\Psi(2S)$ vs $J/\Psi(1S)$ in p-Pb collisions, and therefore in other A-B collisions.

4 Nuclear Modification and Suppression of $\Upsilon(3S)/\Upsilon(1S)$ in Pb-Pb Collisions

This section is similar to the previous one, with the main difference being that we use the experimental results of Ref [16] for the ratios of the standard $\Upsilon(3S)$ to $\Upsilon(1S)$ rather than the theoretical estimate for $\Psi(2S)$ to $\Psi(1S)$ used in the previous section.

4.1 Experimental $\Upsilon(3S)$ to $\Upsilon(1S)$ Suppression in Pb-Pb Collisions

As stated in Ref [16], although the ratios of observed yields of $[\Upsilon(2S)/\Upsilon(1S)]_{pp}$, $[\Upsilon(2S)/\Upsilon(1S)]_{PbPb}$, $[\Upsilon(3S)/\Upsilon(1S)]_{pp}$, and $[\Upsilon(3S)/\Upsilon(1S)]_{PbPb}$ must be corrected for difference in acceptance and efficiency of the $\Upsilon(2S)$ and $\Upsilon(3S)$ states to the $\Upsilon(1S)$ state, by taking ratio of ratios these corrections are not needed.

The results for the ratio of ratios needed for the present work is

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} = 0.06 \pm 0.06(\text{stat}) \pm 0.06(\text{syst}); \quad (15)$$

We also use the result from Ref [16] for the $\Upsilon(2S)$:

$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07(\text{stat}) \pm 0.02(\text{syst}); \quad (16)$$

Since the $\Upsilon(2S)$ state in the theory of Ref [18], upon which the present work is based, is a standard $b\bar{b}$ state, we shall use this modified by the relative bottomium to charmonium nucleation time [22] to estimate the suppression ratio for the standard component of the $\Upsilon(3S)$ state in the next subsection.

4.2 Theoretical $\Upsilon(3S)$ to $\Upsilon(1S)$ Suppression in Pb-Pb Collisions

In deriving $S_A^{c\bar{c}}$, the suppression for a standard model $c\bar{c}$ state we used (8) to obtain the cross section for standard charmonium-nucleon cross section. Since the $\Upsilon(2S)$ is a standard $b\bar{b}$ state, we can get a more accurate result for standard bottomium supression Pb-Pb to pp for
the $b\bar{b}$ component of the $\Upsilon(3S)$ from (16) modified by the relative neutralization time \cite{22} of $b\bar{b}$ vs $c\bar{c} = \sqrt{M_c/M_b} \simeq 0.55$

\[ S_A^{b\bar{b}} = \frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}}|_{sm} \simeq 0.11. \] (17)

For the cross section for hybrid bottomonium $b\bar{b}g$ meson via strong QCD interactions with nucleons \cite{22} $\sigma_{b\bar{b}gN} = \sigma_{c\bar{c}gN}(M_c/M_b)^2 \simeq 0.09\sigma_{c\bar{c}gN}$, therefore from (12)

\[ \sigma_{b\bar{b}gN} \simeq 0.59 \text{ mb}. \] (18)

Using $L \simeq 15$ fm for Pb-Pb collisions and $n_o = .017$ fm$^{-3}$, from (7) we obtain

\[ n_0\sigma_{b\bar{b}gN} L \simeq 0.15 \]

\[ S_A^{c\bar{c}g} \simeq 0.017. \] (19)

From (17), (19) one obtains

\[ R_{\Upsilon(3S) - \Upsilon(1S)}|_{\text{theory}} \simeq \frac{.11 + .017}{2} \]

\[ \simeq 0.06, \] (20)

in agreement with the experimental ratio shown in (15), within experimental and theoretical errors.

5 Conclusions

Using our mixed hybrid theory for the $\Psi(2S)$ and $\Upsilon(3S)$ states we have found approximate agreement with experiment for the $\Psi(2S)$ to $\Psi(1S)$ cross section ratio for p-Pb vs p-p collisions, and the $\Upsilon(3S)$ to $\Upsilon(1S)$ cross section ratio for Pb-Pb vs p-p collisions.

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