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Production of charmonia by recombination in heavy ion collisions

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Abstract

We study the production of charmonium states in heavy ion collisions by focusing on their production by recombination of charm and anticharm quarks in a quark-gluon plasma. Starting from the discussion on Wigner functions for charmonium states we investigate the dependence of charmonia production on their wave functions. We show that the transverse momentum distribution of charmonium states strongly reflects their wave function distributions in momentum space, providing a plausible explanation for the recent measurement of the nuclear modification factor ratio between the $\psi(2S)$ and J/ψ meson.

Keywords: $\psi(2S)$, recombination, wave function

1. Introduction

The J/ψ meson has been one of important probes in investigating properties of a system of quantum chromodynamic (QCD) matter at extreme conditions since J/ψ suppression was suggested as a useful signature to confirm the production of the quark-gluon plasma (QGP), a system composed of free quarks and gluons [1]. The effects of the QGP formation on the J/ψ suppression is usually measured with a nuclear modification factor R_{AA} of J/ψ, the ratio of the J/ψ yield in heavy ion collisions to that in p+p collisions scaled by the number of binary collisions. From the analysis of J/ψ R_{AA} measured at the Relativistic Heavy Ion Collider (RHIC), it has been shown that the J/ψ production is suppressed significantly; the $R_{AA}^{J/\psi}$ decreases with the increasing centrality [2]. However, though the J/ψ production is still suppressed at higher energies, it has been found that the R_{AA} for J/ψ mesons measured at the Large Hadron Collider (LHC) is independent of the collision centrality at forward rapidity [3, 4].

The less suppression of the J/ψ meson production at LHC energies, or the more production of J/ψ mesons at LHC is considered to be attributable to the J/ψ production from charm quarks by recombination. The enhanced chances for the production of J/ψ mesons by charm quark recombination originated from the larger charm quark densities available LHC leads to larger number of J/ψ meson production at LHC compared to that at RHIC. [5, 6, 7].

Recent measurements of the $\psi(2S)$ R_{AA} relative to the $R_{AA}^{J/\psi}$ at LHC provide chances to study the production of charmonia. The less suppression of the $\psi(2S)$ than in p+p collisions compared to the J/ψ with increasing centralities measured by CMS [8] has not been clearly understood. In this work it is argued that the increasing ratio $R_{AA}^{\psi(2S)}/R_{AA}^{J/\psi}$ at central collisions is due to their production from charm quarks by recombination.

In the recombination picture the formation of hadrons is described by the coalescence of constituent quarks, or the overlap between phase space densities of the constituents and that of the produced hadron, the Wigner distribution functions composed of the hadron wave function. It has been found that the phase space densities of constituent quarks in the QGP at low and intermediate p_T different from that at high p_T is responsible for the quark number scaling of elliptic flows of identified hadrons [9] as well as the enhanced production of baryons at midrapidity [10, 11, 12, 13].

On the other hand, when different hadrons are produced from same constituents, such as the production of

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charmonium states from same charm quark in the QGP by recombination, the phase space density of hadrons, or the hadron Wigner distribution function plays central roles in the formation of hadrons. Thus, charmonia production would be dependent on their Wigner functions, or the formation of charmonium states would be dependent on their wave functions. In this work in order to investigate the dependence of charmonia production on their wave functions, two kinds of Wigner distributions built from both Gaussian and Coulomb wave functions are taken into account, providing a plausible explanation on the enhanced production of the $\psi(2S)$ compared to the J/ψ in heavy ion collisions at LHC energy.

2. Wigner functions for charmonium states

So far mostly Gaussian-type Wigner functions have been used in the studies of hadron production by quark recombination or coalescence since the Wigner function based on harmonic oscillator wave functions is simple and useful; it can reflect the hadron size through the oscillator frequency ω, and also take into account an orbital excitation of the produced hadron using s-, p- [14], and d-wave [15] harmonic oscillator wave functions,

$$W_s(\vec{r},\vec{k}) = 8e^{-\frac{r^2}{\sigma^2}-k^2\sigma^2}$$
$$W_p(\vec{r},\vec{k}) = \left(\frac{16}{3}\frac{r^2}{\sigma^2} - 8 + \frac{16}{3}\sigma^2k^2\right)e^{-\frac{r^2}{\sigma^2}-k^2\sigma^2}$$
$$W_d(\vec{r},\vec{k}) = \frac{8}{15}\Big(4\frac{r^4}{\sigma^4} - 20\frac{r^2}{\sigma^2} + 15 - 20\sigma^2k^2 + 4\sigma^4k^4 + 16r^2k^2 - 8(\vec{r}\cdot\vec{k})^2\Big)e^{-\frac{r^2}{\sigma^2}-k^2\sigma^2}, \quad (1)$$

where $\sigma^2 = 1/(\mu\omega)$ with the reduced mass μ.

Among the above Wigner functions, $W_s(\vec{r},\vec{k})$ and $W_p(\vec{r},\vec{k})$ can be used to describe the formation of J/ψ and χ_c mesons. In addition, the $2S$ state Wigner function built from $\psi_{10} = \sqrt{2/3}(1/\pi\sigma^2)^{3/4}e^{-r^2/2\sigma^2}(-r^2/\sigma^2 + 3/2)$ can be adopted to explain the production of $\psi(2S)$ mesons in the coalescence model.

$$W_{\psi_{10}}(\vec{r},\vec{k}) = \frac{16}{3}\Big(\frac{r^4}{\sigma^4} - 2\frac{r^2}{\sigma^2} + \frac{3}{2} - 2\sigma^2k^2 + \sigma^4k^4 - 2r^2k^2 + 4(\vec{r}\cdot\vec{k})^2\Big)e^{-\frac{r^2}{\sigma^2}-k^2\sigma^2} \quad (2)$$

ψ_{10} is a wave function with quantum numbers $kl = 01$ in the 3-dimensional harmonic oscillator; $E_n = (n + 3/2)\hbar\omega = (2k + l + 3/2)\hbar\omega$. ψ_{10} is the radially excited state of ψ_{00}, and therefore can play a role of the wave function for the $\psi(2S)$ meson.

Furthermore, Wigner functions built from Coulomb wave functions are considered. The wave function of charmonium states produced by a color Coulomb force between charm and anti-charm quarks can also be described by Coulomb wave functions used to explain the hydrogen atom with an electric field replaced by a chromo-electric field.

The analytic evaluation of Wigner functions based on Coulomb wave functions have been unknown until recently despite their well-known analytic form of Coulomb wave functions. With the help of Feynman parametrization skills in momentum space, the systematic way of generating Wigner functions for all states of hydrogen atom has been presented in 2006 [16].

Here $1S$ and $2S$ Wigner functions constructed from Coulomb wave functions are presented. Under the normalization condition satisfying $\int W_\psi(\vec{r},\vec{k})d^3\vec{r}d^3\vec{k} = (2\pi)^3$, the $1S$ Wigner function is given by [17],

$$W_{\psi_{1S}}(\vec{r},\vec{k}) = \frac{16}{a_0^5}\int_0^1 duu(1-u)e^{-2i(1-2u)\vec{k}\cdot\vec{r}} \times e^{-2rC(u)}\Big(\frac{3}{C(u)^5} + \frac{6}{C(u)^4}r + \frac{4}{C(u)^3}r^2\Big), \quad (3)$$

with $C(u) = (1/a_0^2 + 4u(1-u)k^2)^{1/2}$ from the $1S$ wave function in momentum space $\tilde{\psi}_{1S}(\vec{k}) = 8\sqrt{\pi}a_0^{3/2}/(1 + k^2a_0^2)^2$. Similarly, from the 2S state wave function in momentum space, $\tilde{\psi}_{2S}(\vec{k}) = \sqrt{\pi}(2a_0)^{3/2}(k^2a_0^2 - 1/4)/(k^2a_0^2 + 1/4)^3$ the $2S$ Wigner function is given by, with $D(u) = (1/(2a_0)^2 + 4u(1-u)k^2)^{1/2}$,

$$\begin{aligned}W_{\psi_{2S}}(\vec{r},\vec{k}) = &\frac{1}{32a_0^9}\int_0^1 duu^2(1-u)^2e^{-2i(1-2u)\vec{k}\cdot\vec{r}} \\ &\times\Big(\frac{105}{D(u)^9} + \frac{210}{D(u)^8}r + \frac{180}{D(u)^7}r^2 + \frac{80}{D(u)^6}r^3 \\ &+\frac{16}{D(u)^5}r^4\Big)e^{-2rD(u)} - \frac{1}{4a_0^7}\int_0^1 duu(1-u) \\ &\times e^{-2i(1-2u)\vec{k}\cdot\vec{r}}\Big(\frac{15}{D(u)^7} + \frac{30}{D(u)^6}r + \frac{24}{D(u)^5}r^2 \\ &+\frac{8}{D(u)^4}r^3\Big)e^{-2rD(u)} + \frac{2}{a_0^5}\int_0^1 duu(1-u) \\ &\times e^{-2i(1-2u)\vec{k}\cdot\vec{r}}\Big(\frac{3}{D(u)^5} + \frac{6}{D(u)^4}r + \frac{4}{D(u)^3}r^2\Big) \\ &\times e^{-2rD(u)}. \end{aligned} \quad (4)$$

3. p_T distributions of charmonium states

The transverse momentum spectra of charmonium states, J/ψ, χ_c, and $\psi(2S)$ mesons produced by charm quark recombination are given by [11, 10, 18]

$$\frac{d^2N_\psi}{d^2\vec{p}_T} = \frac{g_\psi}{V}\int d^3\vec{r}d^2\vec{p}_{cT}d^2\vec{p}_{\bar{c}T}W_\psi(\vec{r},\vec{k})$$