Baryonic Effect on $\chi_{cJ}$ Suppression in Au+Au Collisions at RHIC Energies
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Abstract

We predict that initially produced $\chi_{cJ}$ mesons at low transverse momentum in the central rapidity region are almost dissociated by nucleons and antinucleons in hadronic matter produced in central Au+Au collisions at RHIC energies $\sqrt{s_{NN}} = 130$ and 200 GeV. In calculations the nucleon and antinucleon distributions in hadronic matter are results of evolution from their freeze-out distributions which well fit the experimental $p_T$ spectra of proton and antiproton. Any measured $\chi_{cJ}$ mesons at low $p_T$ are generated from deconfined matter and give an explicit proof of regeneration mechanism (recombination mechanism).

Experimental measurements have revealed new phenomena in Au+Au collisions at the Relativistic Heavy Ion Collider (RHIC). Basing with the experimental results, we derive new results in this letter. We predict that $\chi_{cJ}$ mesons at low transverse momentum almost vanish in central Au+Au collisions at RHIC energies $\sqrt{s_{NN}} = 130$ and 200 GeV because of the collisions from nucleons and antinucleons in hadronic matter.

Compared to the widely studied $J/\psi$ physics, $\chi_{cJ}$ physics in nucleus-nucleus collisions is little known even at the CERN-SPS energies. However,
the HERA-B and NA60 collaborations have been measuring the $\chi_{cJ}$ suppression in proton-nucleus collisions [1, 2]. In future the PHENIX collaboration will measure $\chi_{cJ}$ in their upgrade programs [3]. Since copious $\chi_{cJ}$ mesons are expected to be produced by the initial nucleus-nucleus collisions at RHIC energies, and the measured baryon/meson ratios increase with transverse momentum in the central Au+Au collisions [4, 5], it is important to study $\chi_{cJ}$ survival probability in connection with the collisions with nucleons and antinucleons.

At present the transverse mass spectra of light hadrons have been measured [4, 5, 6, 7, 8] and can be accounted for by the hydrodynamic model [9, 10, 11, 12, 13, 14, 15]. Since we attempt to calculate $\chi_{cJ}$ survival probability in connection to the nucleon and antinucleon distributions in hadronic matter, the data measured by PHENIX collaboration are applied to get freeze-out distributions. In Ref. [11], the STAR collaboration data [6] was used, but the hadron spectra were measured at the transverse momentum $p_T < 1 \text{ GeV}/c$ at $\sqrt{s_{NN}} = 130 \text{ GeV}$. Therefore, we have to renew the freeze-out distributions of proton and antiproton obtained in Ref. [11] to fit the PHENIX collaboration data up to $p_T = 4.5 \text{ GeV}/c$ at $\sqrt{s_{NN}} = 130$ and 200 GeV [4, 5].

Assume that the Boltzmann form is satisfied by baryon and antibaryon distributions at a given time $\tau$ in hadronic matter with temperature $T$:

$$f(\lambda, k, T) = g(\tau, \eta, r) e^{-k\cdot u/T}$$

with the degeneracy factor $g = 2$, fugacity $\lambda$, transverse radius $r$, space-time rapidity $\eta$, the four-velocity $u$ of fluid flow and the baryon four-momentum $k$ in the center-of-mass frame of hadronic matter,

$$k = (m_{kT} \cosh y, k_T \cos \varphi, k_T \cos \varphi, m_{kT} \sinh y),$$

where $m_{kT}$, $k_T$ and $y$ are the transverse mass, transverse momentum and rapidity, respectively, and $\varphi$ is the angle between the transverse momentum of hadron and the transverse momentum of $J/\psi$. Derived via the Lorentz transformation, the baryon energy observed in a flow cell is

$$k \cdot u = [m_{kT} \cosh(y - r) - r] k_T \cos(\varphi - \phi)] / \sqrt{1 - v^2}.$$
where $v_r$ is the transverse velocity of flow cell and $\phi$ is the angle between $\vec{v}_r$ and the transverse momentum of $J/\psi$.

The Lorentz-invariant spectra at the freeze-out time $\tau_{fh}$ in the central rapidity region is obtained from the Cooper-Frye formula [16]:

$$
\frac{d^2N(\tau_{fh})}{k_Tdk_Tdy} = \frac{g\tau_{fh}}{(2\pi)^2} \int_0^{R(\tau_{fh})} dr \int_{\eta_{min}}^{\eta_{max}} d\eta \int_0^{2\pi} d\phi r \lambda_{fh} m_{kT} \cosh(-\eta) \exp\{-[m_{kT} \cosh(-\eta) - v_r k_T \cos \phi]/T_{fh}\sqrt{1 - v_r^2}\},
$$

(4)

where hadronic matter freezes out with the transverse radius $R(\tau_{fh})$ and the space-time rapidity spans from $\eta_{min} = -5.5$ to $\eta_{max} = 5.5$.

We get two sets of fugacities and transverse velocities. The first set is

$$
\lambda_{fh} \propto \begin{cases} 
1, & r < a \\
e^{-(r-a)^2}, & r \geq a 
\end{cases}
$$

$v_r = r/14.8$

(5)

which shows a linear dependence of transverse velocity on $r$ and the second set is

$$
\lambda_{fh} \propto \begin{cases} 
1, & r < b\pi \\
e^{-(r/b-\pi)}, & r \geq b\pi 
\end{cases}
$$

$v_r = \tanh(r/11.6)$.

(6)

which exhibits a hyperbolic dependence of transverse velocity on $r$. In each set the fugacities of proton and antiproton have the same form but a constant normalized to the experimental data.

The parameters $a$ and $b$ are determined in the fit of our theoretical $p_T$ spectra at midrapidity to the experimental data for the central Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV [4] and 200 GeV [5]. Results are listed in Table 1 along with the proper time $\tau_f$ at which the parton plasma hadronizes and $\tau_{fh}$ at which hadronic matter freezes out with the temperature $T_{fh} = 0.13$ GeV.

| $\sqrt{s_{NN}}$(GeV) | a   | b   | $\tau_f$(fm/c) | $\tau_{fh}$ (fm/c) | $R(\tau_{fh})$(fm) |
|----------------------|------|------|----------------|-------------------|-------------------|
| 130                  | 9    | 2    | 4              | 9.6              | 12.2              |
| 200                  | 10   | 2.3  | 4.3            | 10.3             | 12.6              |

Table 1: Parameters for the central Au+Au collisions

Here the values of the hadronization time $\tau_f$ are on the scale of 4 fm/c given in Ref. [17] and the freeze-out times are similar to that provided in Ref. [18]. The two transverse velocities are independent of $\sqrt{s_{NN}}$. The transverse momentum spectra obtained from Eq. (4) are compared to the experimental...
With either of the two sets of the fugacities and the transverse velocities at freeze-out, we can obtain \( v_r(\tau, r) \) at any position and any time prior to freeze-out by the hydrodynamic equation regarding the energy-momentum tensor and \( \lambda(\tau, r) \) by the number conservation followed by the evolution equation [19]:

\[
\partial_t \lambda + v_r \partial_r \lambda + \frac{\lambda}{\gamma T^3} \partial_t (\gamma T^3) + \frac{\lambda v_r}{\gamma T^3} \partial_r (\gamma T^3) + \lambda \partial_r v_r + \lambda \left( \frac{v_r}{r} + \frac{1}{t} \right) = 0
\]  

(7)

where \( \gamma = \frac{1}{\sqrt{1 - v_r^2}} \). The evolution equation is numerically solved until the temperature of hadronic matter very close to the phase transition point of lattice gauge results \( T_c = 0.175 \) GeV [20].

Up to now the distribution functions of protons and antiprotons have been obtained. Then we start studying the interactions of \( \chi_{cJ} \) with nucleons and antinucleons in hadronic matter. The thermal average of the product of the dissociation cross section \( \sigma \) and the relative velocity \( v_{rel} \) of baryon and \( \chi_{cJ} \) is

\[
\langle \sigma(s)v_{rel} \rangle = \frac{1}{n(\tau)} \int \frac{d^3k}{(2\pi)^3} \sigma(s)v_{rel}f(\lambda,k,T)
\]

(8)

where \( n(\tau) \) is the baryon number density

\[
n(\tau) = \int \frac{d^3k}{(2\pi)^3} f(\lambda,k,T)
\]

(9)

The baryon-\( \chi_{cJ} \) dissociation cross section which depends on the center-of-mass energy of baryon and \( \chi_{cJ} \) is taken from Ref. [21].

We consider that a \( \chi_{cJ} \) with transverse momentum \( P_T \) at midrapidity is produced at the position \( r' \) while the two colliding gold nuclei completely overlap. The initial \( \chi_{cJ} \) production is assumed to be proportional to the number of binary nucleon-nucleon interactions \( N_A(r') = A^2(1 - r'^2/R_A^2)/2\pi R_A^2 \).

Integrating \( \vec{r}' \), we obtain the survival probability of initially produced \( \chi_{cJ} \) in hadronic matter:

\[
S(P_T) = \frac{\int d^2r'(R_A^2 - r'^2) \exp \left[ - \int_{\tau_{min}}^{\tau_{max}} d\tau n(\tau) \langle \sigma(s)v_{rel} \rangle \right]}{\int d^2r'(R_A^2 - r'^2)}
\]

(10)

where \( \tau_{min} \) is the smaller one of the freeze-out time and \( \tau_{max} \) the maximum time of stay of \( \chi_{cJ} \) in hadronic matter, \( \tau_{min} = \min(\tau_{th}, \tau_{max}) \). The time \( \tau_{max} \) depends on the \( \chi_{cJ} \) velocity and the flow velocity of lateral face of hadronic matter \( v_{sf} \) by

\[
M_T P_T (1 - \frac{r}{R_A M_T v_{sf}})
\]
\[
-\sqrt{R_A^2 + v_{st}^2 r'^2 \frac{M_T^2}{P_T^2} - 2R_A v_{st} r' \cos \varphi' \frac{M_T}{P_T} - r'^2 \sin^2 \varphi'}
\]  

(11)

where \( M_T \) is the \( \chi_{cJ} \) transverse mass, \( R_A \) is the radius of gold nucleus and \( \varphi' \) is the angle between the position vector \( \vec{r}' \) and \( \vec{P}_T \). We count time from the moment when the two colliding nuclei completely overlap.

Since the neutron and antineutron yields have not been measured, we assume that neutron and antineutron have the same distribution functions as proton and antiproton, respectively. The \( \chi_{cJ} \) dissociation cross section in collision with an antiproton, a neutron or an antineutron is identical to the cross section with a proton. The survival probability as a function of \( P_T \) at midrapidity is calculated and plotted in Fig. 3 where the left and right panels show results of using the freeze-out fugacities and transverse velocities in Eqs. (5) and (6), respectively.

The survival probability reflects the extent to which a \( \chi_{cJ} \) meson survives after the collisions with nucleons and antinucleons in hadronic matter. In either of the two panels, the dashed curve for the central Au+Au collision at \( \sqrt{s_{NN}} = 200 \) GeV is close to the solid curve at \( \sqrt{s_{NN}} = 130 \) GeV, but slightly lower because the nucleons and antinucleons are denser in the higher-energy Au+Au collision. A larger transverse momentum corresponds to a larger center-of-mass energy of \( \chi_{cJ} \) and nucleon (antinucleon), which leads to a smaller \( \chi_{cJ} \) dissociation cross section \([21]\). At large \( P_T \), more \( \chi_{cJ} \) can escape quickly from hadronic matter. The two factors make the survival probability increasing rapidly when the transverse momentum of \( \chi_{cJ} \) is larger than 6 GeV/c. At low \( P_T \), the \( \chi_{cJ} \) velocity doesn’t exceed the flow velocity of lateral face of hadronic matter, \( v_{st} = 0.6c \). Hence \( \chi_{cJ} \) stays inside hadronic matter until freeze-out. The survival probability at low \( P_T \) approaches zero as shown by Fig. 3. and \( \chi_{cJ} \) mesons are almost suppressed by the nucleons and antinucleons alone. This result is meaningful to the coming RHIC experiments as explained below.

It is known that experimentalists measure prompt \( J/\psi \) production which includes the direct \( J/\psi \) production, the radiative feeddown from \( \chi_{cJ} \) and the decay of \( \psi' \). The contribution to the prompt \( J/\psi \) production from \( \chi_{cJ} \) occupies about 30\% \([22]\). On the other hand, the measurements of the PHENIX
suppressed pion production in the central Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV \cite{4,5}. Therefore, the result of the very strong suppression of initial $\chi_{cJ}$ will affect the prompt $J/\psi$ production.

The nucleus-nucleus collisions at RHIC and LHC energies have been divided into four stages: initial parton-parton scatterings, prethermal parton matter, thermalized parton plasma and hadronic matter \cite{23}. Study of Ref. \cite{18} suggested that the prompt $\chi_{cJ}$ production around $P_T = 3$ GeV at midrapidity may be enhanced by the yield of color singlet and color octet $c\bar{c}$ pairs from the partonic system in the prethermal and thermal stages. If the yield can compete with the amount of $\chi_{cJ}$ dissociated, the survival probability of $\chi_{cJ}$ cannot be zero at low $P_T$. An observation offering finite survival probability would hint the existence of deconfined matter in Au+Au collisions at RHIC energies. In the first measurement of $J/\psi$ production in Au+Au collisions a good analysis on the central collision \cite{24} was not conducted. But we can speculate two cases for the central collision: A sudden drop of data in the central collision would reflect a strong suppression of $J/\psi$, $\chi_{cJ}$ and $\psi'$; A flat or even rising transition of data from collisions at midcentrality to the central collision would indicate a large amount of prompt $J/\psi$ yielded from the deconfined matter. Therefore, any experimental result in future will give a feedback to examine our prediction of the very strong suppression of initial $\chi_{cJ}$ in the central collision.

Recent lattice gauge results give a critical temperature of 0.151 GeV \cite{25}. If this value is used, the lifetime of hadronic matter gets shorter but any initially produced $\chi_{cJ}$ at low $p_T$ are also almost dissociated since gluons, quarks and antiquarks in quark-gluon plasma can break $\chi_{cJ}$. Therefore, any measured $\chi_{cJ}$ mesons at low $p_T$ at midrapidity offer a proof of regeneration mechanism (recombination mechanism) \cite{26}.

In summary, we have calculated survival probability of initially produced $\chi_{cJ}$ at midrapidity with the nucleon and antinucleon distributions in the central Au+Au collisions at $\sqrt{s_{NN}} = 130$ and 200 GeV. The survival probability is only related to the collisions of $\chi_{cJ}$ and nucleons and antinucleons. The prominent result is that the survival probability at low $P_T$ is almost zero, which significantly affect the $J/\psi$ suppression at low $P_T$, but any measured $\chi_{cJ}$ at low $P_T$ must come from deconfined matter and obviously exhibits...
regeneration mechanism (recombination mechanism).

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Figure 1: Proton and antiproton invariant yields in the central rapidity region with $\lambda_{th}$ and $v_r$ in Eqs. (5) (solid) and (6) (dashed) at $\sqrt{s_{NN}} = 130$ GeV.

Figure 2: Proton and antiproton invariant yields scaled by $N_{\text{coll}}$, which is the average number of binary nucleon-nucleon collisions, in the central rapidity region with $\lambda_{th}$ and $v_r$ in Eqs. (5) (solid) and (6) (dashed) at $\sqrt{s_{NN}} = 200$ GeV.
Figure 3: Survival probability of $\chi_{cJ}$ in collisions with nucleons and antinucleons in hadronic matter. Solid curves: $\sqrt{s_{NN}} = 130$ GeV; Dashed curves: $\sqrt{s_{NN}} = 200$ GeV. Left panel: Eqs. (5); Right panel: Eqs. (6).