Anomalous J/ψ suppression and charmonium dissociation cross sections

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We study J/ψ suppression in Pb+Pb collisions at CERN-SPS energies in hadronic matter with energy- and temperature-dependent charmonium dissociation cross sections calculated in the quark-interchange model of Barnes and Swanson. The charmonium dissociation cross sections depend sensitively on energy and increase significantly as temperature increases. We find that the variation of J/ψ survival probability from peripheral to central collisions can be explained as induced by hadronic matter absorption in central collisions.

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I. INTRODUCTION

Following the suggestion of Matsui and Satz [1] to probe quark-gluon plasma (QGP) with heavy quarkonium, the NA50 Collaboration investigated J/ψ suppression in high-energy heavy-ion collisions. Anomalous J/ψ suppression has been observed in Pb+Pb collisions at 158A GeV [2,3]. It is of interest to investigate whether deconfined matter is created in these collisions. Many different mechanisms have been proposed to explain the phenomenon. It has been suggested that the suppression was due to a new phase, the QGP [4], a change of the equation of state due to the QCD phase transition [5], the melting of charmonia in QGP [6], or a percolation deconfinement [7]. It has also been suggested that the anomalous suppression comes from the absorption by various comovers produced in the Pb+Pb collisions [8–14].

In addition to the general suppression over a large region of transverse energy E_T, which is related to the impact parameter b, the data for J/ψ suppression in the large transverse energy region with $E_T>100$ GeV are also of special interest. This region corresponds to the most central Pb+Pb collisions. The possible presence of a rapid drop of the ratio of J/ψ to Drell-Yan production cross sections, $B(J/\psi)\sigma(J/\psi)/\sigma(DY)$, has been interpreted in a comover model as a result of multiplicity fluctuation, subject to a large uncertainty of the measured data [15]. It has also been suggested that large E_T fluctuations lead to increasing probability for deconfinement and therefore possible complete suppresssion of J/ψ [16]. A definitive understanding on the nature of J/ψ suppression in Pb+Pb collisions is still lacking.

The absorption of J/ψ by comovers depends on the J/ψ dissociation cross sections in collision with hadrons. The J/ψ dissociation cross sections in collision with hadrons have been considered previously in several theoretical studies, but the predicted cross sections show great variation at low energies, largely due to different assumptions regarding the dominant scattering mechanism. Kharzeev and Satz and collaborators [17] employed the parton model and perturbative QCD "short-distance" approach of Bhanot and Peskin [18] and found remarkably small low-energy cross sections for collisions of J/ψ with light hadrons. Matinyan and Müller [19], Haglin [20], Lin and Ko [21], Song and Lee [22], and Navarra and collaborators [23] recently reported results for these dissociation cross sections in meson exchange models. These references all use effective meson Lagrangians, but differ in the interaction terms included in the Lagrangian. Results depend on a choice of meson coupling schemes and assumed form factors. Charmonium dissociation by nucleons has also been considered recently using similar effective Lagrangian formulations [24].

We favor the use of the known quark forces to obtain the underlying scattering amplitudes from explicit nonrelativistic quark model wave functions of the initial and final mesons [25,26]. In this approach we first look for the interquark interaction by using the meson spectrum. The wave function and the interaction are then used to evaluate the cross section for the quark-interchange process [25,26]. The calculated cross sections are first compared with experimental data of $I=2$ $\pi\pi$ phase shifts, and excellent agreement between theory and experimental data was obtained [25,26]. Such an approach allows us to calculate all charmonium dissociation cross sections by collisions with hadrons. Martins, Blaschke, and Quack previously reported dissociation cross section calculations using essentially the same approach [27]. Two general characteristics of the cross sections obtained in this approach are: (i) for endothermic reaction, the cross section rises after the hadron energy exceeds some threshold energies and the maximum magnitude of the cross section is in the mb range, (ii) for exothermic reaction, the cross section is infinite at zero kinetic energy and decreases as the energy increases.

The J/ψ dissociation cross section depends on the meson wave functions and the interquark interaction. The latter quantities depend on temperature. By using such a temperature-dependent interquark potential inferred from lattice gauge calculations [28], the temperature dependence of J/ψ dissociation cross sections can be obtained. The new cross sections are now applied to study $B(J/\psi)\sigma(J/\psi)/\sigma(DY)$ versus E_T, to be compared with the CERN-SPS Pb+Pb data of the NA50 Collaboration.

The concept of the temperature dependence of the dissociation process should be clarified as many different processes are involved. There are two types of thermalization [26,29]. First, there is the thermalization of the hadronic matter, in which the J/ψ (or its precursor) resides. It occurs rapidly as it depends on the cross section for the scattering of light hadrons with light hadrons, which is of the order of tens of mb. We expect that the dense hadronic matter is thermalized within a time of the order of 1 fm/c after light hadrons are produced. (In our numerical results below, the thermalization time for the hadronic matter is 1.9 fm/c after the light hadrons are produced.)

The second type of thermalization is the thermalization of the ''charmonium system'' with its surrounding medium. If a quarkonium is placed in a thermalized hadronic medium, there will be nondissociative inelastic reactions between the quarkonium and medium particles which change a charmonium state into another charmonium state: $h+(Q\overline{Q})_{JLS}\leftrightarrow h'+(Q\overline{Q})_{J'L'S'}$. These reactions lead to the thermalization of the charmonium system [26,30]. When the heavy quarkonium system is in thermal equilibrium with the medium, the probabilities for the occurrence of heavy quarkonium states will be distributed according to the Bose-Einstein distribution. The time for the thermalization of such a system depends on the nondissociative inelastic cross sections. As these cross sections are different from the pion-pion scattering cross section, the charmonium system thermalization time is different from the light-hadron matter thermalization time.

The cross sections for nondissociative inelastic reactions between a charmonium and a light hadron and their temperature dependences remain a subject of current research. Previous estimates of $\pi+J/\psi\rightarrow\pi+\psi'$ by Fujii and Kharzeev [31] gave a cross section of the order of 0.01 mb. In the quark-interchange model of Barnes and Swanson [32,33], such a process is forbidden in the first order and takes place only in the second order. The higher order process presumably will lead to a smaller cross section. The nondissociative inelastic cross sections need to be evaluated for the interaction of pions with different charmonia using different models, to provide an estimate of the time for the thermalization of the charmonium system with the hadronic medium. If the nondissociative inelastic charmonium cross sections are of the same order as in $\pi-\pi$ collision, then the charmonium system will be also thermalized and the dissociation of J/ψ should be treated by the method of statistical mechanics. On the other hand, if the nondissociative inelastic cross sections are all of the order of 0.01 mb, as estimated by Fujii and Kharzeev for $\pi+J/\psi\rightarrow\pi+\psi'$, the thermalization time for the charmonium system will be quite long and we will not need to consider a thermalized charmonium system. In the present work, we have not taken the process of dissociation by thermalization into account.

For a charmonium placed in a thermal medium, the thermalized hadronic matter alters the interaction between the charm quark and charm antiquark and changes the QCD vacuum surrounding the charmonium. The threshold energy for J/ψ dissociation is shifted and consequently the dissociation cross section changes as a function of the hadronic matter temperature. The dissociation cross section is, however, of the order of a few mb [26]. Thus, in the treatment of the collision of J/ψ with the dense hadronic matter, the cross section is still small enough that we can treat the $\pi-J/\psi$ dissociative collision as a two-body process.

In Sec. II we describe the interquark potential used to obtain meson wave functions. In Sec. III we present the $\pi-J/\psi$ and $\pi-\chi_{cJ}$ dissociation cross sections and show their dependences on temperature. In Sec. IV charmonium suppression in Pb+Pb collisions is examined. Numerical calculations and results are shown and discussed in Sec. V. Conclusions are given in Sec. VI.

II. TEMPERATURE-DEPENDENT POTENTIAL AND WAVE FUNCTIONS

In a medium at high temperatures, the gluon and light quark fields fluctuate and the alignment of the color electric fields due to the QCD interaction is reduced by the thermal motion for a random orientation of the color electric fields. The ''pressure'' from the QCD vacuum to confine the quark and antiquark pair also diminishes with increasing temperature. The interquark potential is thus a sensitive function of temperature, resulting in the vanishing of the string tension at the critical temperature of deconfinement phase transition.

Even at $T=0$, a proper description of the heavy quarkonium state should be based on a screening potential, as the heavy quarkonium becomes a pair of open charm or open bottom mesons when r becomes very large, due to the action of dynamical quark pairs [34]. Recently, the central interquark potential has been obtained from the lattice gauge results of Karsch *et al.* [28] and analyzed by Digal *et al.* [35,36] and by Wong [26]. The temperature-dependent potential for $T<T_c$ can be represented by

$$V_{12}(r,T)=-\frac{4}{3}\frac{\alpha_s e^{-\mu(T)r}}{r}-\frac{b(T)}{\mu(T)}e^{-\mu(T)r}, \tag{1}$$

where α_s is a running coupling constant [25]. The effective string-tension coefficient is

$$b(T)=b_0[1-(T/T_c)^2]\theta(T_c-T), \tag{2}$$

with $b_0=0.35\ \mathrm{GeV}^2$ and the effective screening parameter

$$\mu(T)=\mu_0\theta(T_c-T), \tag{3}$$

where $\mu_0=0.28$ GeV and the step function θ signifies the vanishing of the string tension at the phase transition temperature $T_c=0.175$ GeV.

The charmonium wave functions can be obtained by solving the Schrödinger equation

$$\left(-\nabla\cdot\frac{1}{2\mu_{12}}\nabla+V_{12}(r,T)+\Delta(r,T)\right)\psi_{JLS}(\vec{r},T)=\epsilon(T)\psi_{JLS}(\vec{r},T), \tag{4}$$

where μ_{12} is the reduced mass and the mass difference $\Delta(r,T)$ is

$$\Delta(r,T)=m_1(r,T)+m_2(r,T)-m_1(\infty,T)-m_2(\infty,T). \tag{5}$$

The energy $\epsilon(T)$ is measured relative to two separated mesons $c\bar{q}$ and $q\bar{c}$ at $r\to\infty$ where c and $\bar{c}$ become open charm mesons and $\{m_1(r,T),m_2(r,T)\}=\{M_{c\bar{q}}(T),M_{q\bar{c}}(T)\}$.

The bound-state wave function and energy ϵ have been obtained by diagonalizing the Hamiltonian using a nonorthogonal Gaussian basis with different widths [26]. When the energy ϵ becomes positive, spontaneous dissociation occurs, subject to the selection rules based on the conservation of total angular momentum and parity [26].

III. CHARMONIUM DISSOCIATION CROSS SECTIONS

For meson-meson scatterings $A+B\to C+D$, the differential cross section is given by

$$\frac{d\sigma_{fi}}{dt}=\frac{1}{64\pi s|\vec{p}_A|^2}|\mathcal{M}_{fi}|^2, \tag{6}$$

where t is the momentum transfer squared, s is the center-of-mass (c.m.) energy squared, and $\vec{p}_A$ is the momentum of meson A in the c.m. system. The matrix element $\mathcal{M}_{fi}$ is calculated with the four meson wave functions of A, B, C, and D and the interquark interaction. The latter is the potential in Eq. (1) plus a spin-spin term for quark-quark interaction,

$$V_{\text{spin-spin}}(r)=-\frac{\vec{\lambda}_1}{2}\cdot\frac{\vec{\lambda}_2}{2}\times\frac{8\pi\alpha_s}{3m_1m_2}\vec{s}_1\cdot\vec{s}_2\left(\frac{d^3}{\pi^{3/2}}\right)e^{-d^2r^2}, \tag{7}$$

where $m_1(m_2)$ and $\vec{s}_1(\vec{s}_2)$ are individually the mass and spin of quark 1(2), and d is a spin-spin interaction width including relativistic corrections [26,37]. For quark-antiquark potential, $(\vec{\lambda}_1/2)\cdot(\vec{\lambda}_2/2)$ is replaced by $-(\vec{\lambda}_1/2)\cdot(\vec{\lambda}_2^T/2)$. This potential generates wave functions which are then used to calculate the dissociation cross sections, as discussed in Ref. [26]. The dissociation cross section of J/ψ in collision with π varies as a function of T/T_c and the c.m. kinetic energy $E_{KE}=\sqrt{s}-m_A-m_B$ where m_A and m_B are the masses of the incident mesons. We plot in Fig. 1 the $\pi+J/\psi$ dissociation cross sections. Since about 35% of J/ψ comes from the radiative decay of χ_{cJ}, the dissociation cross sections of χ_{c1} and χ_{c2} in collisions with π are also important. We evaluate these cross sections which are plotted in Fig. 2.

As the temperature increases, the temperature-dependent interquark potential becomes weaker. Then the energy for separating c and $\bar{c}$ in the charmonium decreases and the root-mean-square radius of the meson increases. As a consequence, the dissociation cross section for a charmonium in collision with a pion rises with increasing temperatures. For various charmonia, different sizes also lead to different dissociation cross sections. At $T/T_c\approx0.7$, the peak cross section of $\pi+\chi_{c1}$ or $\pi+\chi_{c2}$ is about 2.1 times that at $T=0$. Since the χ_{c2} is less bound compared to χ_{c1}, the dissociation cross section for χ_{c2} is slightly larger. The $\pi+\chi_{c2}$ reaction becomes exothermic at a lower temperature than $\pi+\chi_{c1}$. Comparing Figs. 1 and 2, we find that the peak value of $\pi-J/\psi$ dissociation cross section is larger than the peak values of $\pi-\chi_{c2}$ and $\pi-\chi_{c1}$ dissociation cross sections when T/T_c are larger than 0.65 and 0.55, respectively.

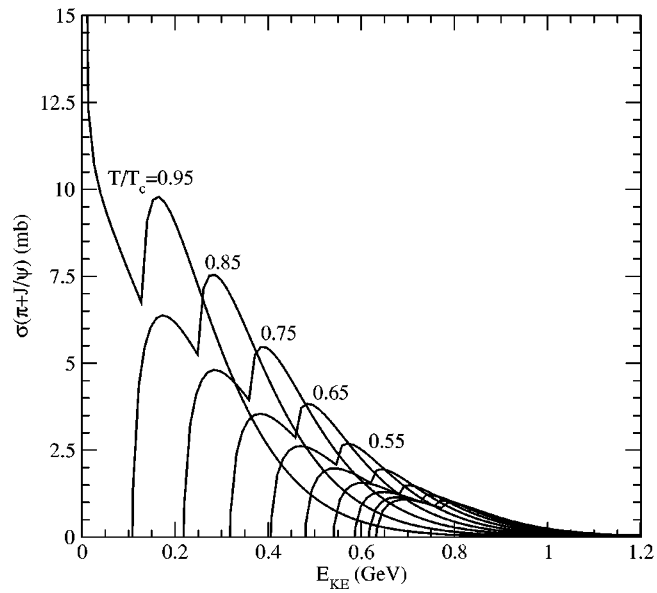

FIG. 1. J/ψ dissociation cross sections for various temperatures as a function of E_{KE}. From left to right are T/T_c $=0.45$, 0.35, 0.25, 0.15, 0.05 for these curves without labels.

IV. CHARMONIUM SUPPRESSION IN Pb+Pb COLLISIONS

Working in the nucleon-nucleon c.m. frame, we assume the following scenarios to investigate J/ψ suppression. In a nucleus-nucleus collision, hadronic matter consisting mainly

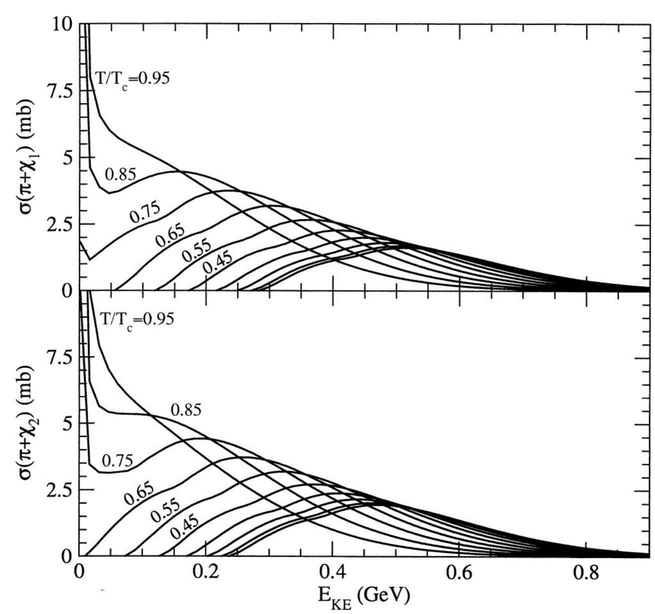

FIG. 2. Upper and lower panels show χ_{c1} and χ_{c2} dissociation cross sections for various temperatures as a function of E_{KE}. From left to right are $T/T_c=0.35$, 0.25, 0.15, 0.05 for these curves without labels.

of pions is produced at $\tau_{\rm form}$ after the collision. The hadronic matter is initially not in thermal equilibrium. It becomes thermalized by elastic scatterings of pions at time $\tau_{\rm therm}$, and the expansion of hadronic matter lowers the temperature and the density until freeze-out at $\tau_{\rm fz}$. On the other hand, $c\bar{c}$ pairs are created by the hard scattering processes between a projectile nucleon and a target nucleon in a very short time. The $c\bar{c}$ pair evolves into a charmonium or its precursor which interacts and becomes dissociated by colliding first with nucleons in the two colliding nuclei and subsequently with the produced hadronic matter. J/ψ will be dissociated by collision with pions during the time from $\tau_{\rm form}$ to $\tau_{\rm fz}$. The differential cross section for J/ψ production with respect to the impact parameter $\vec{b}$ is

$$\frac{d\sigma_{J/\psi}^{AB}(\vec{b})}{d\vec{b}}=\int\frac{d^3p}{E}\left(E\frac{d^3\sigma_{J/\psi}^{NN}}{d^3p}\right)\int\frac{d\vec{b}_A}{\sigma_{NJ/\psi}^2}\{1-[1-T_A(\vec{b}_A)\sigma_{NJ/\psi}]^A\}\{1-[1-T_B(\vec{b}-\vec{b}_A)\sigma_{NJ/\psi}]^B\}\times\exp\left(-\int_{\tau_{\rm form}}^{\tau_{\rm therm}}d\tau v_{\rm rel}\sigma_{\pi J/\psi}n_\pi(b,\tau)\right)\times\exp\left(-\int_{\tau_{\rm therm}}^{\tau_{\rm fz}}d\tau\langle v_{\rm rel}\sigma_{\pi J/\psi}\rangle n_\pi(b,\tau)\right). \quad (8)$$

For the production of Drell-Yan dilepton pairs, the cross section scales with the number of nucleon-nucleon collisions, and we have

$$\frac{d\sigma_{DY}^{AB}(\vec{b})}{d\vec{b}}=\sigma_{DY}^{NN}ABT_{AB}(\vec{b}). \quad (9)$$

The quantities E and $\vec{p}$ are the energy and momentum of J/ψ; $\sigma_{J/\psi}^{NN}$ and σ_{DY}^{NN} are cross sections for J/ψ and Drell-Yan productions in a nucleon-nucleon collision, respectively; $\sigma_{\pi J/\psi}$ is the J/ψ dissociation cross section in collision with π; $\sigma_{NJ/\psi}$ is the J/ψ absorption cross section in collision with nucleons; $\vec{b}_A$ is the nucleon coordinate in the target nucleus A; T_A and T_B are nuclear thickness functions [38]; and $v_{\rm rel}$ is the relative velocity of charmonium and π. The thickness function for the colliding nuclei is

$$T_{AB}(\vec{b})=\int d\vec{b}_A T_A(\vec{b}_A)T_B(\vec{b}-\vec{b}_A). \quad (10)$$

The expression for the differential cross section for χ_{cJ} and ψ' production can be obtained by replacing J/ψ with χ_{cJ} or ψ'.

If the hadronic matter is in thermal equilibrium, the pion number multiplicities are obtained from the familiar momentum distribution. Before thermalization, the pion number density has to be estimated from experimentally measured multiplicities of charged pions. The total pion number N_π as a function of the impact parameter $\vec{b}$ for Pb+Pb collisions at 158A GeV was measured by the NA49 Collaboration [39]. We assume that the total pion number is conserved in the evolution of hadronic matter. The volume of hadronic matter depends on the impact parameter $\vec{b}$ as well as the proper time τ, which is measured relative to the moment of maximum overlap of the colliding nuclear matter,

$$V(b,\tau)=\left(2\tau+\frac{\sqrt{4R_A^2-b^2}}{\gamma}\right)\times\left\{2(R_A+\tau V_{\rm ex\perp})^2\cos^{-1}\left(\frac{b}{2(R_A+\tau V_{\rm ex\perp})}\right)-b\sqrt{(R_A+\tau V_{\rm ex\perp})^2-\frac{b^2}{4}}\right\}. \quad (11)$$

Here R_A is the lead-nucleus radius, $V_{\rm ex\perp}$ is the transverse velocity for radial flow, and γ is the Lorentz contraction factor, $\gamma=\sqrt{s}/2m_N$, with nucleon mass m_N, and $\sqrt{s}$ is the c.m. energy of a nucleon-nucleon collision. As a result of the above consideration, the pion number density depends on the impact parameter and proper time as

$$n_\pi(b,\tau)=\frac{N_\pi(b)}{V(b,\tau)}. \quad (12)$$

The π-charmonium dissociation cross sections depend on the temperature T and the collision energy. Pions in thermal equilibrium have the momentum distribution $f_\pi(k)\sim 3e^{-E_\pi/T}$ with the pion energy E_π. Integrating the whole pion momentum contribution to $v_{\rm rel}\sigma$ and dividing by the pion number density, we obtain

$$\langle v_{\rm rel}\sigma\rangle=\frac{\int\frac{d^3k}{(2\pi)^3}f_\pi(k)v_{\rm rel}\sigma}{\int\frac{d^3k}{(2\pi)^3}f_\pi(k)}, \quad (13)$$

which depends on p_T and x_F of charmonium and τ.

The differential cross sections with respect to E_T for J/ψ production is given by

$$\frac{d\sigma_{J/\psi}^{AB}}{dE_T}=\int d^2b\frac{d\sigma_{J/\psi}^{AB}}{d\vec{b}}D(b,E_T), \quad (14)$$

and the differential cross section for the Drell-Yan process is

$$\frac{d\sigma_{DY}^{AB}}{dE_T}=\int d^2b\frac{d\sigma_{DY}^{AB}}{d\vec{b}}D(b,E_T), \quad (15)$$

where $D(b,E_T)$ relates b to E_T [40]

$$D(b,E_T)=\frac{1}{\sqrt{2\pi}\sigma(b)}e^{-[E_T-\bar{E}_T(b)]^2/2\sigma^2(b)}, \quad (16)$$

with the average transverse energy

$$\bar{E}_T(b)=\frac{135\ \ {\rm GeV}}{1+\exp[(b-6.7)/3]}, \quad (17)$$

and the variance

$$\sigma(b)=\frac{11\ \text{GeV}}{1+\exp[(b-10)/2]}. \tag{18}$$

V. RESULTS AND DISCUSSIONS

A. Differential cross sections for J/ψ yield in nucleon-nucleon collisions

To generate momentum distribution of J/ψ, we need to parametrize the initially produced J/ψ distributions. The invariant differential cross section for J/ψ production in a nucleon-nucleon collision, $Ed^3\sigma^{NN}_{J/\psi}/d^3p$, is factorized as

$$E\frac{d^3\sigma^{NN}_{J/\psi}}{d^3p}=f(x_F)g(p_T). \tag{19}$$

The parameters of $f(x_F)$ and $g(p_T)$ obtained by fitting experimental data in p-p and p-A collisions have been summarized in Refs. [41,42]. We take the parametrizations

$$g(p_T)\sim\left(1+\frac{p_T^2}{\beta^2}\right)^{-6}, \tag{20}$$

$$f(x_F)\sim\frac{(1-x_1)^a(1-x_2)^a}{x_1+x_2}, \tag{21}$$

where $x_{1,2}=0.5(\sqrt{x_F^2+4M^2_{J/\psi}/s}\pm x_F)$ with the J/ψ mass $M_{J/\psi}$. The quantity β is related to the average transverse momentum $\langle p_T\rangle$ by $\beta=(256/35\pi)\langle p_T\rangle$. The quantity $\beta=2.24\pm0.28$ GeV/c is inferred from $\langle p_T\rangle=0.96\pm0.12$ GeV/c for the J/ψ production in p-Be collisions at $\sqrt{s}=16.8$ GeV [43]. The parameter $a=4.95$ fits the x_F spectra of J/ψ in p-Be collisions at $\sqrt{s}=38.8$, 31.6, and 16.8 GeV [43,44] and p-Li collisions at $\sqrt{s}=23.8$ GeV [45]. The x_F spectrum provides the average value $\langle x_F\rangle=\int_0^{1-\delta}dx_Fx_Ff(x_F)/\int_0^{1-\delta}dx_Ff(x_F)\approx0.16$ with $\delta=M^2_{J/\psi}/s$. The condition $x_{1,2}\leqslant1$ requires $x_F\leqslant1-\delta$. We use the parametrizations of $f(x_F)$ and $g(p_T)$ to generate the x_F and p_T spectra of a charmonium produced in nucleon-nucleon collisions in Pb+Pb collisions at 158 GeV/c per nucleon.

In Eq. (8) we assume J/ψ mesons are produced uniformly in the collision region. The successive collisions of a projectile nucleon in the target nucleus cause the nucleon to lose energy gradually so that J/ψ mesons are not evenly produced in space. Such an effect was discussed in Ref. [46].

B. J/ψ suppression in hadronic matter

As seen in Eq. (8), the differential cross section explicitly depends on the pion formation time τ_{form}, the pion thermalization time τ_{therm}, and the hadron freeze-out time τ_{fz}. We estimate the formation time τ_{form} to be 1 fm/c from nucleon-nucleon collision data [38]. Then in the most central Pb+Pb collision, $n_\pi(b=0,\tau_{\text{form}})=2.38$ fm^{-3}. We use a freeze-out number density of $n_{\text{fz}}=0.5$ fm^{-3}. The initial temperature of pion matter is close to the QCD phase transition temperature $T_c=0.175$ GeV [28] and is taken as $T_{\text{therm}}=0.16$ GeV.

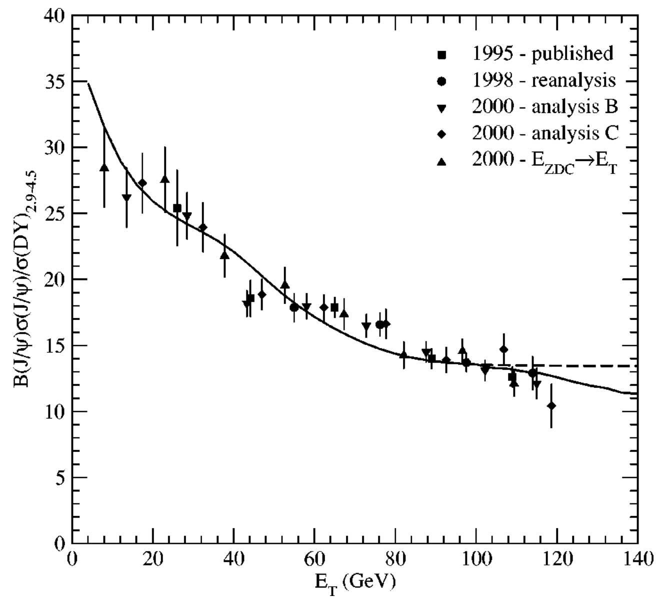

FIG. 3. The experimental data are from Ref. [47]. The solid curve is the theoretical result while $\sigma_{\text{Nabs}}=4.2$ mb. The dashed curve is obtained with no large-E_T fluctuation considered.

In a thermal medium, the charmonium will spontaneously dissociate if the energy ϵ obtained from the Schrödinger equation relative to the mass of two open charm mesons is positive. The energy ϵ varies with temperature. The critical temperature T_d for the spontaneous dissociation (at which ϵ is zero) was determined by Wong [26] to be $T_d/T_c=0.99$, 0.90, and 0.91 for J/ψ, χ_{c1}, and χ_{c2}, respectively. Since $T/T_c\leqslant T_{\text{therm}}/T_c=0.91$ for any centrality, we can neglect the spontaneous dissociation of J/ψ, χ_{c1}, and χ_{c2} in the pion matter.

We assume that all charmonia concerned have the same absorption cross section in collision with nucleons, $\sigma_{NJ/\psi}=\sigma_{N\chi_{c1}}=\sigma_{N\chi_{c2}}=\sigma_{N\psi'}=\sigma_{\text{Nabs}}$. Since these cross sections have not been fixed by p-A reactions, we take a value of 4.2 mb. The remaining adjustable parameter is $\tau_{\text{therm}}(b=0)$ for the most central Pb+Pb collision. The thermalization time has a centrality dependence, $\delta\tau_{\text{therm}}\sim1/[\sigma_{\pi\pi}n_\pi(b,\tau_{\text{form}})]$, where $\sigma_{\pi\pi}$ is the $\pi\pi$ elastic scattering cross section at zero temperature. Since the pion number density is given by Eq. (12), the thermalization time after the formation of hadronic matter can be obtained by

$$\delta\tau_{\text{therm}}(b)=\delta\tau_{\text{therm}}(b=0)\frac{n_\pi(b=0,\tau_{\text{form}})}{n_\pi(b,\tau_{\text{form}})}. \tag{22}$$

The thermalization time measured relative to the moment of maximum overlap of the colliding nuclei is then $\tau_{\text{therm}}(b)=\tau_{\text{form}}+\delta\tau_{\text{therm}}(b)$.

The value of the adjustable parameter $\tau_{\text{therm}}(b=0)$ and the transverse velocity $V_{\text{ex}\perp}$ are obtained by fitting the latest data of $B(J/\psi)\sigma(J/\psi)/\sigma(DY)$ from the NA50 Collaboration [47]. As shown in Fig. 3, the latest data in Ref. [47] are slightly different from the earlier data [2,3] in the peripheral and central collisions. Other quantities such as the pion number density at thermalization n_{therm}, proper time τ_{fz}, and

TABLE I. Values of $\sigma_{\rm Nabs}$, $V_{\rm ex\perp}$, $\tau_{\rm therm}$, $n_{\rm therm}$, $\tau_{\rm fz}$, and $T_{\rm fz}$.

$\sigma_{\rm Nabs}$(mb)	$V_{\rm ex\perp}(c)$	$\tau_{\rm therm}$(fm/c)	$n_{\rm therm}$(fm^{-3})	$\tau_{\rm fz}$(fm/c)	$T_{\rm fz}$(GeV)
4.2	0.75	2.9	0.88	4.44	0.139

temperature $T_{\rm fz}$ at freeze-out are then calculated and also tabulated in Table I for the central collision at $b=0$ fm. The quantity $n_{\rm therm}=n_\pi(b=0,\tau_{\rm therm})$ is calculated with Eq. (12). The freeze-out time $\tau_{\rm fz}$ depends on the centrality. The freeze-out temperature $T_{\rm fz}$, determined in the most central collision, is the same for hadronic matter yielded at any centrality. The temperature between $T_{\rm therm}$ and $T_{\rm fz}$ approximately obey the relation given by Bjorken [48]. In the survival probability of total J/ψ, we include contributions at the level of 58% for direct J/ψ, 20% for χ_{c1}, 14.5% for χ_{c2}, and 7.5% for ψ' [41].

From central to peripheral collisions, pion number density decreases and thermalization time increases according to Eq. (22). At $b=8.9$ fm the pion number density at $\tau_{\rm therm}$ is equal to the freeze-out number density and no thermalization is attained. For $b>8.9$ fm, the zero-temperature charmonium dissociation cross sections are relevant for J/ψ suppression. Since the peak dissociation cross sections for J/ψ, χ_{c1}, and χ_{c2} in collision with π at $T=0$ are about 1.1, 1.6, and 1.9 mb, respectively, the suppression of J/ψ due to the collision with π is very small. Therefore the absorption by $N-J/\psi$ collisions completely dominates J/ψ suppression at $b>8.9$ fm. For $b<8.9$ fm, thermalized hadronic matter sets in with $T_{\rm therm}=0.16$ GeV and freezes out at $T_{\rm fz}=0.139$ GeV. The dissociation cross section jumps from 1.1 mb (1.6 mb, 1.9 mb) at $T=0$ to 6.5 mb (4.1 mb, 4.8 mb) at $T_{\rm fz}=0.139$ GeV and even higher at $T_{\rm therm}=0.16$ GeV for J/ψ (χ_{c1}, χ_{c2}). But this sudden rise does not induce a sudden fall of $B(J/\psi)\sigma(J/\psi)/\sigma(DY)$ at $E_T\approx 40$ GeV since the time in which J/ψ interacts with pion matter in thermal equilibrium increases gradually as the impact parameter decreases from $b=8.9$ fm to zero. In these calculations, the suppression of ψ' has been taken into account (see the following paragraph), as ψ' comprises about 7.5% of the unsuppressed J/ψ yield.

To study ψ' suppression, we note from Ref. [26] that the spontaneous dissociation of ψ' begins with $T_d/T_c=0.50$. The pion matter freezes out at $T_{\rm fz}/T_c\approx 0.79$ for any centrality. Thus ψ' spontaneous dissociation takes place throughout the pion matter. For a full description of the ψ' spontaneous dissociation, a suitable treatment will be needed in future work. The effect of ψ' dissociation, alternatively, can be accounted for by an approximate effective treatment where we assume a constant ψ' dissociation cross section independent of energy, $\sigma_{\pi\psi'}=12$ mb. As shown in Fig. 4, the experimental data for $B(\psi')\sigma(\psi')/\sigma(DY)$ reported in Ref. [49] and exhibited in Ref. [42] can be represented by such a $\pi-\psi'$ cross section of 12 mb. We shall include this constant ψ' dissociation cross section in our analysis of the ψ' absorption in our model. It can be considered as an effective representation of the experimental data to include the effect of ψ' suppression.

In addition to the spontaneous dissociation, J/ψ suppression may receive contributions from the thermalization of charmonium in hadronic matter. The thermalization process leads to a thermal distribution of charmonium, and the states above the dissociate threshold can dissociate spontaneously [26,30]. The thermalization of charmonia depends on the dynamic processes such as scatterings of lower charmonium states in collision with pions leading to higher charmonium states. The work of Fujii and Kharzeev [31] gave the cross sections for $\pi+J/\psi\to\pi+\psi'$ less than 0.01 mb in the region of interest. We assume implicit generalization of this cross section to other pion-charmonium scatterings. Then the thermalization time of charmonia is very long and the charmonia cannot be in thermal equilibrium before pionic matter freezes out. Therefore the dissociation by thermalization for J/ψ, χ_{c1}, and χ_{c2} have not been included. If we calculate cross sections for processes such as $\pi+J/\psi\to\pi+\chi_{cJ}$ in the quark-interchange mechanism, we need to interchange the quarks twice and the quark-interchange processes are of higher order. The calculations for these cross sections are complicated and are left for a future work.

To illustrate the role of charmonium dissociations in collisions with pions in hadronic matter, we set $\sigma_{\rm Nabs}=0$ and calculate $B(J/\psi)\sigma(J/\psi)/\sigma(DY)$ with different assumptions on the $\pi-(c\bar{c})_{JLS}$ cross sections for the dissociation of the charmonium $(c\bar{c})_{JLS}$. In Fig. 5 we show the results with $\pi-(c\bar{c})_{JLS}$ dissociation cross sections as given by: (i) $\sigma[\pi-(c\bar{c})_{JLS}]$ for $T=0$ [25] (dashed curve); (ii) $\sigma[\pi-(c\bar{c})_{JLS}]=1$ mb (dot-dashed curve); (iii) $\sigma[\pi-(c\bar{c})_{JLS}]$

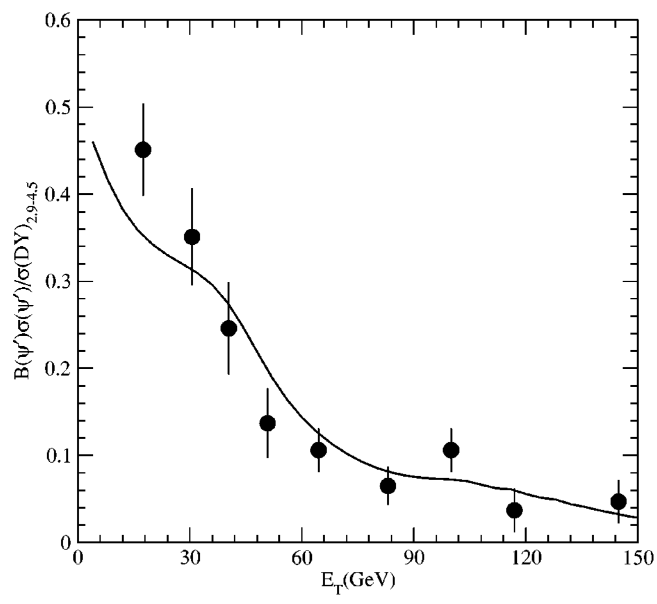

FIG. 4. Solid curve obtained with $\sigma_{\rm Nabs}=4.2$ mb is compared with the 1996 data of $\sigma(\psi')/\sigma(DY)$ ratio.

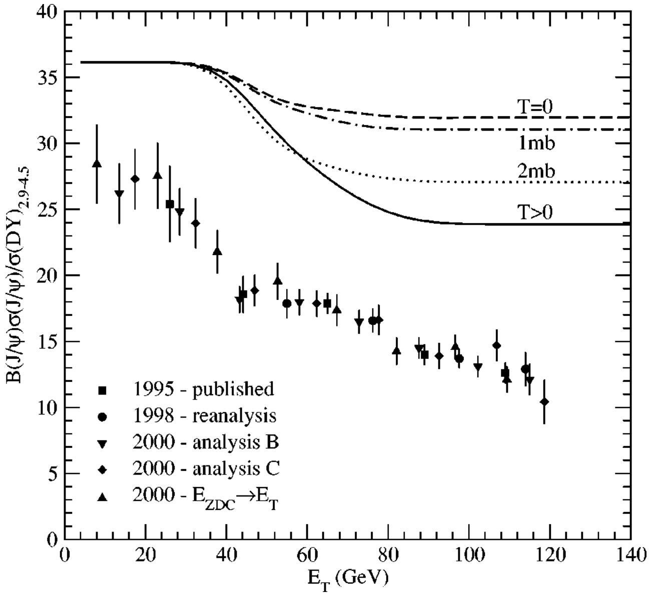

FIG. 5. The same experimental data as Fig. 3. All curves have $\sigma_{\mathrm{Nabs}}=0$ mb. The solid, dashed, dotted, and dot-dashed curves are obtained by using the cross sections at $T>0$ and $T=0$, the two constant cross sections $\sigma_{\pi J/\psi}=\sigma_{\pi\chi_{cJ}}=\sigma_{\pi\psi'}=2$ and 1 mb, respectively.

$=2$ mb (dotted curve); (iv) $\sigma[\pi-(c\bar{c})_{JLS}]$ of Figs. 1 and 2 for $T>0$ (solid curve). The flat curve below $E_T=28$ GeV comes mainly from the collisions at $b>8.9$ fm where no thermalization is attained. This flatness arises as the π-charmonium dissociation cross section is small and the pion number density is not high at $b>8.9$ fm. Indeed, the dashed curve gives a small J/ψ suppression if only the π-charmonium dissociation cross sections at $T=0$ are used. Even the J/ψ suppression obtained by using 1 mb cross section is larger than that for the cross sections at $T=0$. It is obvious that the suppression obtained from the cross sections at higher temperatures is greater than that from using a 2-mb cross section. This is related to the larger charmonium dissociation cross sections at higher temperatures as shown below.

The cross sections in Figs. 1 and 2 depend on the temperature and $\pi-(c\bar{c})_{JLS}$ relative momenta. What are the average cross sections? Figure 6 exhibits cross sections averaged over the pion and $(c\bar{c})_{JLS}$ momenta in the collision at $b=0$ fm, which is defined as

$$\langle\sigma\rangle=\int\frac{d^3p}{E}\left(E\frac{d^3\sigma^{NN}_{J/\psi}}{d^3p}\right)\frac{d^3k}{(2\pi)^3}\times f_\pi(k)\sigma/\left[\int\frac{d^3p}{E}\left(E\frac{d^3\sigma^{NN}_{J/\psi}}{d^3p}\right)\int\frac{d^3k}{(2\pi)^3}f_\pi(k)\right]. \tag{23}$$

The average cross sections $\langle\sigma_{\pi J/\psi}\rangle$, $\langle\sigma_{\pi\chi_{c1}}\rangle$, and $\langle\sigma_{\pi\chi_{c2}}\rangle$ decrease with time. At the thermalization time, they are 3.47, 2.74, and 2.95 mb, respectively. At 2.9 fm$<\tau$ <4.25 fm,$\langle\sigma_{\pi J/\psi}\rangle$ is larger than $\langle\sigma_{\pi\chi_{c1}}\rangle$. At 2.9 fm$<\tau$ <3.4 fm,$\langle\sigma_{\pi J/\psi}\rangle$ even surpasses $\langle\sigma_{\pi\chi_{c2}}\rangle$. These are not surprising since the peak value of J/ψ dissociation cross section exceeds that of $\chi_{c1}(\chi_{c2})$for $T/T_c>0.55(0.65)$ and the temperature of hadronic matter before freeze-out is $T/T_c\geqslant0.79$.

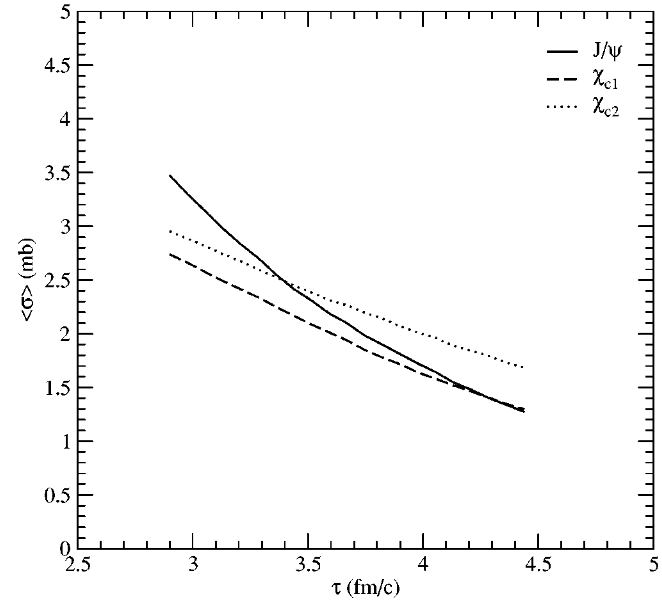

FIG. 6. The solid, dashed, and dotted curves are $\langle\sigma_{\pi J/\psi}\rangle$, $\langle\sigma_{\pi\chi_{c1}}\rangle$, and $\langle\sigma_{\pi\chi_{c2}}\rangle$, respectively.

We further calculate the quantity

$$\overline{v_{\mathrm{rel}}\sigma}=\int_{\tau_{\mathrm{therm}}}^{\tau_{\mathrm{fz}}}d\tau\langle v_{\mathrm{rel}}\sigma\rangle/(\tau_{\mathrm{fz}}-\tau_{\mathrm{therm}}). \tag{24}$$

The p_T and x_F dependences of $\overline{v_{\mathrm{rel}}\sigma}$ are shown in Figs. 7 and

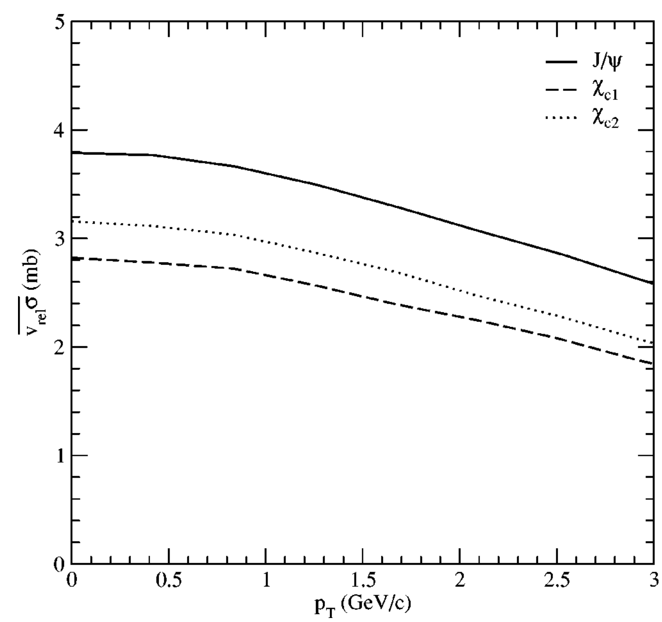

FIG. 7. The solid, dashed, and dotted curves are $\overline{v_{\mathrm{rel}}\sigma_{\pi J/\psi}}$, $\overline{v_{\mathrm{rel}}\sigma_{\pi\chi_{c1}}}$, and $\overline{v_{\mathrm{rel}}\sigma_{\pi\chi_{c2}}}$ at $x_F=0$, respectively.

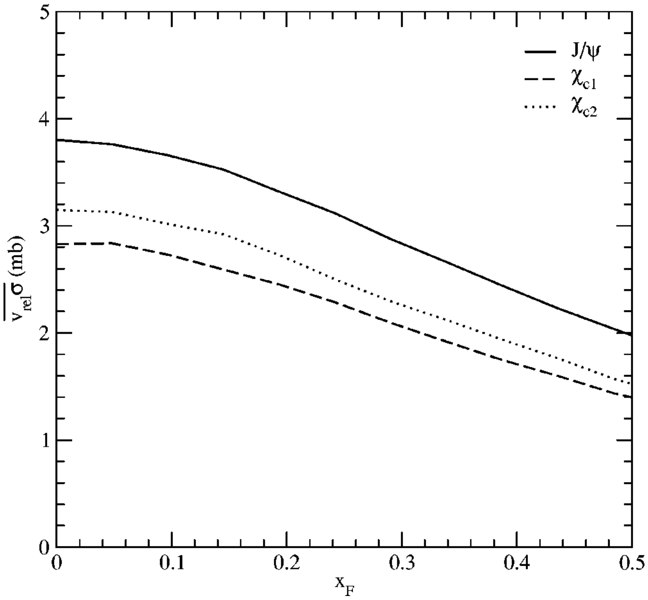

FIG. 8. The same as Fig. 7 except for x_F dependence at $p_T = 0$.

8. These results indicate that the average absorption effects due to J/ψ, χ_{c1}, and χ_{c2} are not significantly different. The above discussion will be useful to understand data from the NA60 Collaboration [50] where the χ_{cJ} suppressions will be stressed.

C. J/ψ suppression at large E_T

In addition to the general suppression over a broad region of transverse energy E_T, the data for J/ψ suppression in the large transverse energy region with $E_T > 100$ GeV are also of special interest. For $E_T > 100$ GeV, we consider the effects arising from the large E_T fluctuation. Since $D(b,E_T)$ has not been constrained to give E_T by the average

$$\langle \overline{E_T} \rangle = \frac{\int d^2b \overline{E}_T(b) D(b,E_T)}{\int d^2b D(b,E_T)}, \tag{25}$$

the measured E_T is larger than $\langle \overline{E_T} \rangle$ for $E_T > 100$ GeV, i.e., the so-called large-E_T fluctuation happens [15,16]. In our calculations, the fluctuation increases not only the pion number density by the replacement $n_\pi(b,\tau) \rightarrow n_\pi(b,\tau) E_T / \langle \overline{E_T} \rangle$ but also the lifetime of pion matter by $V[b,\tau_{\rm fz}(b)] = V[b,\tau_{\rm therm}(b)] n_\pi[b,\tau_{\rm therm}(b)]/n_{\rm fz}$. The two changes lead to the solid curve in Fig. 3 decreasing continually beyond $E_T = 100$ GeV.

The large E_T fluctuation does not increase the initial temperature since we do not consider here the QCD phase transition to a QGP. The spontaneous dissociations of J/ψ, χ_{c1}, and χ_{c2} can still be neglected. The factor $E_T / \langle \overline{E_T} \rangle$ shows the fluctuation increases smoothly from $E_T = 100$ GeV. Therefore we see that the solid curve does not drop rapidly in the large-E_T region and does not pass the rightest experimental point within the error bar. This behavior is similar to the theoretical J/ψ suppression obtained by Capella *et al.* [15]. If experimental data at $E_T > 120$ GeV can be provided with good statistics by additional NA60 measurements [50], then we need compare our result to the experimental data in this region to see the possibility of additional suppression due to the QGP.

VI. CONCLUSIONS

We have studied π-charmonium dissociation cross sections and the J/ψ suppression in Pb+Pb collisions at the CERN-SPS. We use dissociation cross sections calculated in the Barnes-Swanson quark-interchange model [32,33] with the potential obtained from the lattice gauge results. Making reasonable assumptions about the absorption scenario, we find that the J/ψ production cross section calculated with these dissociation cross sections can describe the general features of the anomalous J/ψ suppression data. An important element of the agreement arises from the increase of the dissociation cross sections as the temperature increases. For the large E_T region at $E_T > 100$ GeV, the anomalous additional suppression can be explained by the fluctuation of E_T or multiplicity.

The π-charmonium dissociation cross sections depend on the temperature and the kinetic energy, but the averages $\overline{v_{\rm rel}\sigma}$ in hadronic matter for $\pi + J/\psi$, $\pi + \chi_{c1}$, and $\pi + \chi_{c2}$ dissociation cross sections are nearly the same. Thus the dissociations of direct J/ψ, χ_{c1}, and χ_{c2} give nearly the same contributions to the suppression of the measured J/ψ.

We have chosen the constant absorption cross sections of charmonia on nucleons. However, the absorption cross sections are expected to depend on the c.m. energy of charmonium and nucleon. Determining the nucleon absorption cross sections is an important task. It will be of interest to evaluate the $N - J/\psi$ dissociation cross sections in the Barnes-Swanson quark-interchange model [32,33].

The temperature effects on the quark-quark potential and charmonium wave functions have been considered in our evaluation of the dissociation cross sections. Following the earlier results of the spectral analysis of Hatsuda using the $O(4)$ linear σ model [51], we assume that the pion wave function in the finite-temperature hadronic matter to be approximately unaffected by temperature. We note, however, from recent lattice results using the maximum entropy method [52,53] that the light-quark pseudoscalar and vector spectral functions change significantly with temperature. On the other hand, the heavy-quark vector spectral functions are only moderately affected by temperature [52]. It should be pointed out, however, that these spectral functions have been obtained in the quenched approximation. The effects of virtual production of dynamical fermion pairs on the interaction between the heavy quark and antiquark are not included. The stability of the heavy quarkonium state is affected by the presence of dynamical fermions. There remains therefore uncertainties in these latest lattice results. It will be of great interest to see how the dissociation of charmonium may be modified when the properties of the interacting pion and heavy quarkonium are obtained including the effects of dynamical light quark pairs.

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