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J/ψ AND ψ′ SUPPRESSION IN HIGH-ENERGY HEAVY-ION COLLISIONS

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J/ψ and ψ' Suppression in High-Energy Heavy-Ion Collisions

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The anomalous suppression of J/ψ production in Pb-Pb collisions at 158A GeV observed by the NA50 Collaboration can be explained as due to the occurrence of a new phase of strong J/ψ absorption, which sets in when the local energy density exceeds about 3.4 GeV/fm^3. The peculiar behavior of the ψ'/ψ ratio in p-A and nucleus-nucleus collisions can be understood as due to approximately equal ψ-N and ψ'-N absorption cross sections, but greater absorption cross sections for ψ' than J/ψ with regard to absorption by soft particles and matter in the new phase.

1. INTRODUCTION

The interaction between a c quark and a $\bar{c}$ antiquark is screened in the quark-gluon plasma. The screening length decreases as the temperature increases. Above a critical temperature, the screening length becomes so short that a quasi-bound $c\bar{c}$ system, which evolves otherwise into a J/ψ in free space, cannot form a bound state in the plasma and will be removed from J/ψ production. This led to the suggestion of Matsui and Satz to use the suppression of J/ψ production to probe the presence of the plasma [1] (see e.g. [2] for an introduction). A comparison of the suppression of J/ψ and ψ' has also been suggested to study deconfinement [3]. While the suppression of J/ψ and ψ' has been observed in p-A, O-A, and S-U collisions at 200A GeV [4–7], the phenomenon can be explained by absorption models without assuming the occurrence of the plasma [8–14].

Recent data from NA38 [6,7] and NA50 [15,16] reveal that in Pb-Pb collisions at 158A GeV, J/ψ is anomalously suppressed relative to expectations based on experimental systematics from p-A, O-A, and S-U collisions. The NA38 and NA50 Collaborations also found that ψ'/ψ is nearly independent of the mass number in p-A collisions but depends on mass numbers and centrality in nucleus-nucleus collisions. What are the underlying physical processes which lead to the anomalous J/ψ suppression in Pb-Pb collisions and the peculiar behavior of ψ'/ψ?

2. ABSORPTION OF J/ψ AND ψ' IN NUCLEUS-NUCLEUS COLLISIONS

We envisage that in p-A and A-B (nucleus-nucleus) collisions, the reaction of the parton of a projectile nucleon and the parton of a target nucleon can produce a quasi-bound $c\bar{c}$ system which later evolves into a J/ψ or ψ' in free space. Because J/ψ and ψ' are

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produced predominantly in the central rapidity region, the quasi-bound $c\bar{c}$ system is produced predominantly in the central rapidity region. Soft particles, which exist in the early stage as gluons and later as hadrons, are also produced in nucleon-nucleon collisions, predominantly in the central rapidity region. (Produced hadrons are called comovers in [9].)

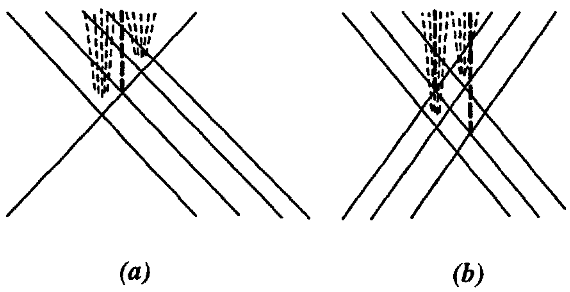

Figure 1. The space-time trajectories in the nucleon-nucleon center-of-mass system for (a) p-A collisions, and (b) nucleus-nucleus collisions. The trajectories of baryons are given as solid lines, the quasi-bound $c\bar{c}$ systems as thick dashed lines, and soft particles as thin dashed lines.

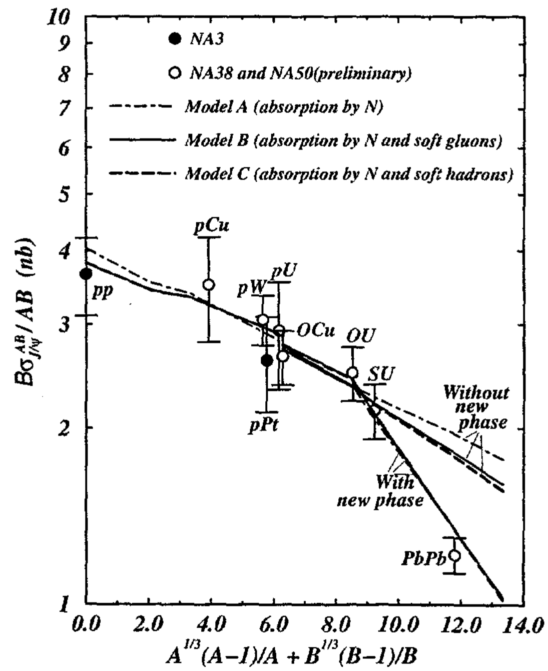

Figure 2. $B\sigma_{J/\psi}^{AB}/AB$ as a function of $A^{1/3}(A-1)/A + B^{1/3}(B-1)/B$.

Upon using the row-on-row picture, the space-time diagram for a typical row in p-A and A-B collisions in the nucleon-nucleon center-of-mass system can be depicted schematically in Fig. 1. The trajectory of a quasi-bound $(c\bar{c})$ system crosses trajectories of baryons, and the ensuing $(c\bar{c})$-N collisions can lead to the breakup of the $(c\bar{c})$ system into $D\bar{D}X$. In p-A and A-B reactions at around 200A GeV, these collisions take place at relatively high energies and constitute the hard component of the J/ψ and ψ' absorption process. For A-B collisions, as illustrated in Fig. 1b, trajectories of produced quasi-bound $(c\bar{c})$ systems cross trajectories of soft particles. Thus, for A-B collisions, there is in addition the soft component of absorption in which the J/ψ and ψ' can be broken up by collision with soft particles produced by other nucleon-nucleon collisions. The soft absorption occurs at low relative energies of about 200 MeV, the temperature of produced particles. Because the energy required to break up the $c\bar{c}$ system is about 640 MeV for J/ψ and is 50 MeV for ψ', one expects that the soft component of absorption is small for J/ψ but large for ψ'.

One can make some general remarks concerning the behavior of the production cross section of J/ψ (or similarly ψ') as a function of mass numbers A and B. A quasi-bound $c\bar{c}$ system produced by the collision of a nucleon in the projectile B and the target A needs to get out of the projectile and target nuclei. The probability of survival of the quasi-bound $c\bar{c}$ system after traveling through an absorbing nuclear medium is an exponential function of its path length. The path length L of the $c\bar{c}$ system averaged over all impact parameters and all production points is approximately proportional to the sum of the two nuclear radii. The cross section from the hard component of absorption is [8]

$$\sigma_{J/\psi}^{AB}|_{\mathbf{hard}}/AB\sigma_{J/\psi}^{NN} = e^{-\rho_0\sigma_{\mathbf{abs}}(\psi N)(L_A+L_B)}, \tag{1}$$

where $\rho_0 = (4\pi r_0^3/3)^{-1}$ is the nuclear matter number density, $r_0(= 1.2 \text{ fm})$ is the radius parameter, and $\sigma_{\mathbf{abs}}(\psi N)$ is the ψ-N absorption cross section. For nuclei with a sharp density distribution, the path length $L = L_A + L_B$ is given by [8] (see e.g. page 370 of [2])

$$L = L_A + L_B = (3r_0/4)\{A^{1/3}(A-1)/A + B^{1/3}(B-1)/B\}. \tag{2}$$

If one plots the logarithm of $\sigma_{J/\psi}^{AB}|_{\mathbf{hard}}/AB$ as a function of $A^{1/3}(A-1)/A+B^{1/3}(B-1)/B$ or L, the result will be a straight line.

In nucleus-nucleus collisions, a produced quasi-bound $c\bar{c}$ system needs to go through the matter of produced soft particles in order to come to the detector. The probability of J/ψ absorption by soft particles is proportional to the density of soft particles which the J/ψ particle encounters. The density of produced soft particles depends on the number of participants [17]. The number of participants in turn is proportional to the longitudinal path length of a produced $(c\bar{c})$ passing through nuclei A and B. Because of such dependence on participant numbers and longitudinal path length, it has been shown by using general arguments given for h-A collisions in [9] and for A-B collisions outlined on pages 376-377 of [2] that the effect of passing through the medium of the soft particles leads to an absorption factor with the exponential index proportional to the path length L,

$$\sigma_{J/\psi}^{AB}|_{\mathbf{soft}}/AB\sigma_{J/\psi}^{NN} = e^{-c'(L_A+L_B)}, \tag{3}$$

where c' is a constant which depends on the length of time of the interaction, the rapidity density of soft particles produced per NN collision, and the absorption cross section for J/ψ-(soft particle) collisions [2]. If one plots the logarithm of $\sigma_{J/\psi}^{AB}|_{\mathbf{soft}}/AB$ as a function of $A^{1/3}(A-1)/A + B^{1/3}(B-1)/B$ or L, there will be another straight line with a different slope. We shall see in the next section and Fig. 2 that results from numerical microscopic calculations for soft particle absorption indeed exhibit such a behavior.

In absorptions where both the hard and soft components are present, $\sigma_{J/\psi}^{AB}/AB\sigma_{J/\psi}^{NN}$ is equal to the product of the absorption factors from the hard and soft components, the righthand sides of Eqs. (1) and (3). The logarithm of $\sigma_{J/\psi}^{AB}/AB$ as a function of $A^{1/3}(A-1)/A + B^{1/3}(B-1)/B$ is again a straight line with a slope which is the sum of the slopes of the two components.

One can deduce from space-time trajectories in Fig. 1 that p-A collisions involve predominantly the hard component while A-B collisions involve both the hard and soft components. One expects to see a change of slopes in going from p-A to A-B collisions. The degree of the change of slopes is an indicator of the importance of the soft component.

Fig. 2 gives experimental $\sigma_{J\psi}^{AB}/AB$ data multiplied by the branching ratio $\mathcal{B}$ for collisions at 200A GeV, with Pb-Pb collisions at 158A GeV rescaled to 200A GeV [15,16]. Consider first experimental data with the exception of the Pb-Pb point. The logarithm of $\mathcal{B}\sigma_{J\psi}^{AB}/AB$ as a function of $A^{1/3}(A-1)/A+B^{1/3}(B-1)/B$ can be described by a single hard component with a straight line. In this case, however, a single straight line passing through p-A, O-A, and S-U data points lies much higher than the Pb-Pb point. We can alternatively describe the data in terms of a hard component plus a small soft component, with a straight line for p-A collisions and another straight line for A-B collisions. In this case, because the slope for A-B collisions in Fig. 2 differs only slightly from that for p-A collisions, the soft component of absorption is small for J/ψ absorption, as explained previously. Within experimental errors, straight lines passing through nucleus-nucleus data of O-Cu, O-U, and S-U lie much higher than the Pb-Pb point. No model with a hard and a soft absorption component can simultaneously describe p-A, O-Cu, O-U, S-U and Pb-Pb data together. A new source of absorption for Pb-Pb collisions is therefore suggested.

3. PHENOMENOLOGICAL MODELS OF J/ψ SUPPRESSION

We can be more quantitative to study this departure of Pb-Pb data by using the microscopic absorption model of [10]. In this model, each nucleon-nucleon collision is the source of soft particles which can absorb J/ψ particles produced by other nucleon-nucleon collisions. One follows the space-time trajectories of produced $c\bar{c}$ systems, baryons and soft particles. Absorption occurs when trajectories of J/ψ particles cross those of other particles. Using a row-on-row picture in the center-of-mass system and assuming straight-line space-time trajectories, we obtain the differential cross section for J/ψ production in an A-B collision as [10]

$$\frac{d\sigma^{AB}_{J/\psi}(\mathbf{b})}{\sigma^{NN}_{J/\psi}\, d\mathbf{b}} = \int \frac{d\mathbf{b}_A}{\sigma^2_{\mathbf{abs}}(\psi N)} \left\{1 - \left[1 - T_A(\mathbf{b}_A)\sigma_{\mathbf{abs}}(\psi N)\right]^A\right\} \times \left\{1 - \left[1 - T_B(\mathbf{b} - \mathbf{b}_A)\sigma_{\mathbf{abs}}(\psi N)\right]^B\right\} F(\mathbf{b}_A)\,, \tag{4}$$

where $T_A(\mathbf{b_A})$ is the thickness function of nucleus A, and the soft particle absorption factor $F(\mathbf{b_A})$ is

$$F(\mathbf{b}_A) = \sum_{n=1}^{N_<} \frac{a(n)}{N_> N_<} \sum_{j=1}^{n} \exp\{-\theta \sum_{i=1, i\neq j}^{n} (k_{\psi g} t^g_{ij} + k_{\psi h} t^h_{ij})\}\,. \tag{5}$$

$N_>(\mathbf{b}_A)$ and $N_<(\mathbf{b}_A)$ are the greater and the lesser of the (rounded-off) nucleon numbers $AT_A(\mathbf{b}_A)\sigma_{in}$ and $BT_B(\mathbf{b} - \mathbf{b}_A)\sigma_{in}$ in the row at $\mathbf{b}_A$ with an NN inelastic cross section σ_{in}, $a(n) = 2$ for $n = 1, 2, ..., N_< - 1$, and $a(N_<) = N_> - N_< + 1$. The rate constant $k_{\psi m}$ for $m = g, h$ is the product of $\sigma_{\mathbf{abs}}(\psi m)$, the average relative velocity v_m, and the average number density ρ_m per NN collision [10]. The interaction time t^g_{ij} (or t^h_{ij}) is the time for a J/ψ produced in collision j to overlap with the absorbing soft particles in the form of gluons (or hadrons) produced in collision i at the same spatial point. They can be determined from plausible $c\bar{c}$, g, h production time $t_{c\bar{c}}$, t_g, t_h, and the freezeout time t_f [10]. The function θ is zero if $A = 1$ or $B = 1$ and is 1 otherwise.

Because of the uncertainties in the nature of soft particles, we compare experimental data at 200A GeV [15,19,20] with three theoretical models of J/ψ absorption: (A) absorption by baryons only, as in [8]; (B) by baryons and soft gluons, as in [10]; and (C) by baryons and soft hadrons, similar to [9]. We find in Fig. 2 that with the exception of the Pb-Pb data point, the J/ψ production data can be described by these models using the parameters: (Model A) $\sigma_{\mathbf{abs}}(\psi N) = 5.70$ mb, $B\sigma^{NN}_{J/\psi} = 4.04$ nb, and (Model B and C) $\sigma_{\mathbf{abs}}(\psi N) = 4.29$ mb, $B\sigma^{NN}_{J/\psi} = 3.82$ nb. In addition, $k_{\psi g} = 0.150$ c/fm for Model B, and $k_{\psi h} = 0.0774$ c/fm for Model C. Conventional models with hard and soft components reproduce p-A, O-A, and S-U data, but they give results which are much greater than the experimental Pb-Pb data point.

4. NEW PHASE OF J/ψ ABSORPTION

The deviation of Pb-Pb data from the conventional theoretical extrapolations of p-A, O-A, and S-U suggests that there is a transition to a new phase of strong absorption, which sets in when the local energy density exceeds a certain threshold. We can extend the absorption model to describe this transition. The energy density at a particular spatial point at a given time is approximately proportional to the number of collisions which has taken place at that point up to that time. We use the row-on-row picture as before, and postulate that soft particles make a transition to a new phase with stronger J/ψ absorption characteristics at a spatial point if there have been N_c or more baryon-baryon collisions at that point. The quantity $k_{\psi g}t_{ij}^{g} + k_{\psi h}t_{ij}^{h}$ in Eq. (5) becomes $k_{\psi g}t_{ij}^{g} + k_{\psi h}t_{ij}^{h} + k_{\psi x}t_{ij}^{x}$, where the new rate constant $k_{\psi x}$ describes the rate of absorption of J/ψ by the produced soft matter in the new phase and t_{ij}^{x} is the time for a J/ψ produced in collision j to overlap with the absorbing soft particles produced in collision i in the form of the new phase, before hadronization takes place. Baryons passing through the spatial region of the new phase may also become deconfined to alter their J/ψ absorption characteristics. Accordingly we also vary the effective absorption cross section, $\sigma_{\mathbf{abs}}^{x}(\psi N)$, for ψ-N interactions in the row in which there is a transition to the new phase, while the absorption cross section $\sigma_{\mathbf{abs}}(\psi N)$ remains unchanged in other rows where there is no transition. As shown in Fig. 2, models with a new phase give good agreement with $\mathcal{B}\sigma_{J/\psi}^{AB}/AB$ data including the Pb-Pb data point, with the parameters $N_c = 4$, $k_{\psi x} = 1$ c/fm, $\sigma_{\mathbf{abs}}^{x}(\psi N) = 14$ mb, $k_{\psi g} = 0.075$ c/fm for Model B, and $k_{h\psi} = 0.039$ c/fm for Model C. The rate constant $k_{\psi x}$ for this new phase is much greater than the corresponding rate constants $k_{\psi g}$ or $k_{\psi h}$, and $\sigma_{\mathbf{abs}}^{x}(\psi N)$ is much greater than $\sigma_{\mathbf{abs}}(\psi N)$.

In Fig. 3 we show theoretical results and experimental data [7,15] for the ratio of $\mathcal{B}\sigma_{J/\psi}^{AB}$ to the Drell-Yan cross section σ_{DY}^{AB} in the interval $2.9 < M_{\mu^+\mu^-} < 4.5$ GeV, as a function of the impact parameter b. Because there is essentially no mass number dependence in σ_{DY}^{AB}/AB [18], the ratio $\mathcal{B}\sigma_{J/\psi}^{AB}/\sigma_{DY}^{AB}$ at a transverse energy is a measure of the production of J/ψ per nucleon-nucleon collision. The average deviation of this ratio from the value of 40-45 for p-p collisions [15] is a measure of the overall absorption as shown in Fig. 2, and the variation of this ratio with the transverse energy reflects the degree of absorption as a function of the impact parameter. Within 5-10%, data for S-U collisions can be described by models either with or without a new phase. For Pb-Pb collisions, theoretical results calculated without the assumption of a transition to a new phase are much greater than the experimental data (Fig. 3b). Good agreement with experiment is obtained when we allow for the possibility of transition to a new phase of J/ψ absorption.

5. SUPPRESSION OF ψ' PRODUCTION

In p-A collisions as depicted schematically in Fig. 1a, a produced quasi-bound $c\bar{c}$ system is absorbed mainly by its collision with baryons in p-A collisions. The collision with baryons takes place at relatively high energies. At these energies, the ψ-N and ψ'-N

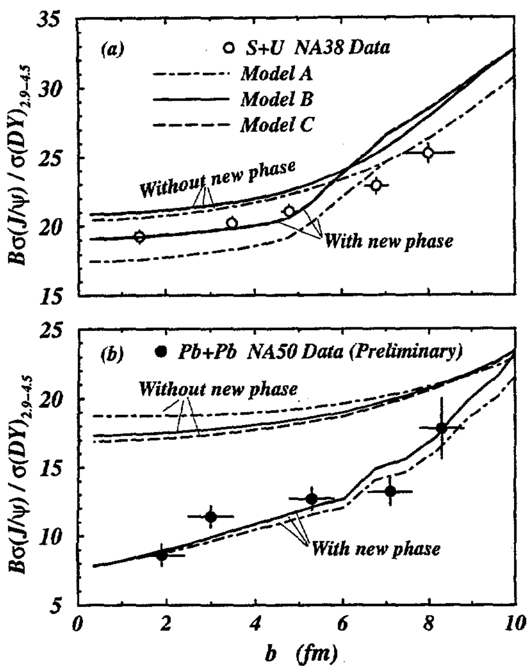

Figure 3. The ratio $\mathcal{B}\sigma^{AB}_{J/\psi}/\sigma(DY)_{2.9-4.5}$ as a function of the impact parameter b for (a) S-U collisions, and (b) Pb-Pb collisions.

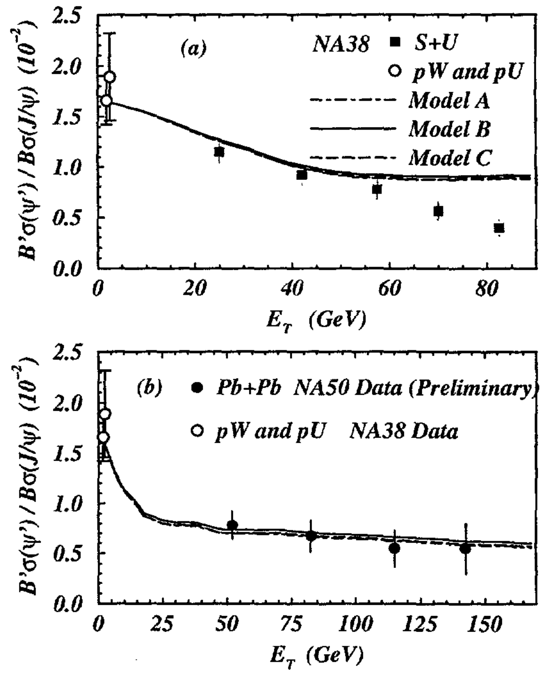

Figure 4. $\mathcal{B}'\sigma(\psi')/\mathcal{B}\sigma(\psi)$ as a function of the transverse energy E_T (a) for S-U collisions and (b) for Pb-Pb collisions.

absorption cross sections are approximately equal. The approximate equality is supported by experimental data of $\sigma_{\text{tot}}(\psi'\text{-}N)/\sigma_{\text{tot}}(\psi\text{-}N) \approx 0.75 \pm 0.15$ from photoproduction of J/ψ and ψ' [21]. Theoretically, the approximate equality can be explained by the Glauber picture of hadron-hadron collisions in terms of quark-quark collisions, for which the absorption cross section for ψ-N collisions and ψ'-N collisions can be shown to be insensitive to the separation between c and $\bar{c}$ [10]. The approximate equality of ψ-N and ψ'-N absorption cross sections leads immediately to the experimental observation of the independence of ψ'/ψ with mass numbers in p-A collisions [10]. Many other different theoretical models have also been put forth [10–14]. As hadron-hadron cross sections involve nonperturbative aspects of QCD dynamics, much more work remains to be done to clarify the origin of this approximate equality.

J/ψ and ψ' are further absorbed by soft particles in A-B collisions. The energy threshold for J/ψ absorption is 640 MeV, and is 50 MeV for ψ'. The relative energy between the $(c\bar{c})$ system and the soft particle is about 200 MeV. Therefore, ψ' is much more readily absorbed by soft particles than J/ψ. Hence, the ratio ψ'/ψ depends on mass numbers and centrality in nucleus-nucleus collisions.

We can study ψ' absorption by changing J/ψ into ψ' in Eqs. (4) and (5). To describe ψ-N, ψ'-gluon, and ψ'-hadron absorption, we use $\sigma_{\text{abs}}(\psi' N) = \sigma_{\text{abs}}(\psi N)$, $k_{\psi' g} = 3$ c/fm in Models A and B, and $k_{\psi' h} = 3$ c/fm in Model C [10]. For the interaction of ψ' with soft matter in the new phase, we take $k_{\psi' x} = 3$ c/fm, which is substantially greater than $k_{\psi x} = 1$ c/fm for ψ. Under the assumption of transition to the new phase for $N_c = 4$, the results for ψ'/ψ are given in Fig. 4. There is a good agreement with the Pb-Pb data (Fig. 4b). This indicates that at low relative energies the rate constants and the corresponding absorption cross sections are larger for ψ' than for J/ψ, with regard to absorption by soft particles and matter in the new phase. For S-U collisions, although theoretical results for small and moderate values of E_T agree with experimental data, theoretical ratios deviate from experimental data for large E_T. We note that the greater the longitudinal length of the nucleus, the greater the number of soft particles produced, and the greater will be the suppression of ψ' relative to ψ. As data points with large transverse energies involve greater weights for the major axis of the U nucleus to lie along the beam direction, the deviation of ψ'/ψ in S-U collisions at high E_T may be a deformation effect which can be tested experimentally by studying S-Pb collisions. The deformation effect can be utilized to study matter under transition to the new phase by focusing on high E_T events in U-U collisions. Future experiments involving S-U and U-U collisions will be of great interest.

6. CONCLUSIONS AND DISCUSSIONS

We have seen that the anomalous suppression of J/ψ in Pb-Pb collisions can be explained by models in which a new phase of strong absorption sets in when the number of baryon-baryon collisions at a local point exceeds or is equal to N_c =4. We can inquire what is the approximate threshold energy density ϵ_c which corresponds to the onset of the new phase. Evaluated in the nucleon-nucleon center-of-mass system, the energy density at the spatial point which has had N_c prior nucleon-nucleon collisions is approximately

$$\epsilon_c = N_c \frac{dn}{dy} \frac{m_t}{\sigma_{in} d/\gamma} \tag{6}$$

where $dn/dy \sim 1.9$ [22] is the particle mutiplicity per unit of rapidity at $y_{CM} = 0$ for an NN fixed-target collision at 158A GeV, $m_t \sim 0.35$ GeV is the transverse mass of a produced pion, $d \sim 2.46$ fm is the internucleon spacing, and $\gamma = \sqrt{s}/2m_{\mathbf{nucleon}} = 9.2$ is the Lorentz contraction factor. For $N_c = 4$ we find $\epsilon_c \sim 3.4$ GeV/fm^3, which is close to the quark-gluon plasma energy density, $\epsilon_c \sim 4.2$ GeV/fm^3, calculated from the lattice gauge theory result of $\epsilon_c/T_c^4 \sim 20$ [23] with $T_c \sim 0.2$ GeV. Therefore, it is interesting to speculate whether the new phase of strong absorption may be the quark-gluon plasma. In an equilibrated or non-equilibrated quark-gluon plasma, the screening of the c and $\bar{c}$ quarks by deconfined quarks and deconfined gluons will weaken the interaction between c and $\bar{c}$ and will enhance the breakup probability of a quasi-bound $(c\bar{c})$ system. Furthermore, one envisages the quark-gluon plasma to be accompanied by the deconfinement of the baryon matter of the colliding nuclei when the baryons pass through the region of the new phase. One can show by using the two-gluon model of Pomeron exchange [24,13] that the total cross section between a $c\bar{c}$ system and a baryon system is substantially enhanced when the quarks in the baryon are deconfined [25], because the cancellation between the amplitudes involving the exchange of two gluons to the same quark and to different quarks in a colorless baryon is now absent. However, much work remains to be done to confirm whether indeed the anomalous suppression comes from the occurrence of the quark-gluon plasma.

After this work was completed and the main results reported at the Quark Matter '96 Conference in Heidelberg, May 1996, theoretical analyses of J/ψ suppression in Pb-Pb collisions were also reported by Blaizot *et al.* [26], Gavin *et al* [27], Capella *et al.* [28], and Armesto *et al.* [29].

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