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J/ψ SUPPRESSION AS A SIGNAL FOR THE QUARK-GLUON PLASMA

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J/ψ Suppression as a Signal for the Quark-Gluon Plasma

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We review the search for the quark-gluon plasma using the signal of the suppression of J/ψ production in high-energy heavy-ion collisions. Recent anomalous J/ψ suppression in high-energy Pb-Pb collisions observed by the NA50 Collaboration are examined and compared with earlier results from pA and nucleus-nucleus collisions with heavy ions of smaller mass numbers. The anomalous suppression of J/ψ production in Pb-Pb collisions can be explained as due to the occurrence of a new phase of strong J/ψ absorption, which sets in when the number of nucleon-nucleon collisions at a spatial point exceeds about 4 and corresponds to a local energy density of about 3.4 GeV/fm^3.

1. Introduction

The study of high-energy heavy-ion collisions is an emerging area of research (see Ref. [1] for an introduction). One of its objectives is to search for the quark-gluon plasma. What is a quark-gluon plasma? Why do we use high-energy heavy-ion collisions to search for the quark-gluon plasma. Why do we use J/ψ production and suppression as one of the signals for the quark-gluon plasma? What are the latest experimental results of J/ψ production and suppression in high-energy heavy-ion collisions? Why is there recently new excitement concerning the observation of the anomalous suppression of J/ψ production in the collision of Pb on Pb at 158 GeV per nucleon? How do we understand such an anomalous suppression?

We shall discuss the above-mentioned questions in this brief review. We shall then turn to examine a model of J/ψ absorption and the origin of the anomalous suppression in Pb-Pb collisions.

2. The State of Quark-Gluon Plasma

A quark-gluon plasma is a new state of matter in which quarks and gluons are deconfined. This is in distinct contrast to quarks and gluons in hadron matter where the quarks and gluons of a hadron are confined within the hadron which has a radial dimension of about a fermi. Deconfinement does not mean that quarks and gluons can be isolated and individually detected. It only means that quarks and gluons are allowed to move nearly freely to a greater region of space outside the radial domain that is usually associated with a hadron. They are nevertheless still confined within the region of strongly interacting matter. For the quark-gluon plasma which may be produced by high-energy heavy-ion

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collisions, the transverse dimension of the plasma is about the size of the overlapping region of nuclear matter and quarks and gluons can move nearly freely within the distance of a few fermi, typical of the length of the radii of the colliding nuclei.

A quark-gluon plasma is expected to be the state of lowest energy for strongly interacting matter at high temperatures or high baryon densities. Lattice gauge calculations [2–6] show that there is a phase transition between the hadron phase and the quark-gluon plasma phase at a temperature T_c at which the energy density ϵ_c is about $20T_c^4$ [2]. For a pure gauge theory without fermions, the critical temperature was found to be 265^{+10}_{-5} MeV [3]. With quarks, the critical temperature is considerably lower. If one takes 200 MeV to be the order of the critical temperature T_c, the critical energy density ϵ_c of the quark-gluon plasma will be of the order of 4 GeV/fm^3.

In the lattice gauge theory, the gauge field is described in terms of the link variable which is the analogue of the spin variable in ferromagnetism. We can understand qualitatively that the confined state of strongly interacting matter at low temperatures arises from the correlations of the link variables at different spatial locations at short distances, as well as large distances, so as to minimize the total energy, resulting in a linear-confining potential between a quark and an antiquark. At low temperatures, the tendency to maintain the correlations between the link variables at different spatial locations due to the interactions overwhelms the disruptive tendency due to quantum and thermal fluctuations. As the temperature increases, the tendency to disrupt the correlation due to thermal motion overwhelms the tendency to correlate due to the interactions, and quarks and gluons become deconfined.

Theoretical work on matter with a high baryon density has not reached the same degree of sophistication as in the baryon-free case because of the difficulty of treating dynamical fermions [5,6]. One expects qualitatively that as the baryon density increases the density of quarks and antiquarks increases, and the pressure due to degenerate fermions will increase. As the baryon density increases above a critical density, the pressure from the degenerate fermions can overwhelm the bag pressure of confinement, and there can be a phase transition from the state of confined quark matter to a state of deconfined quark-gluon plasma even at zero temperature. The expected phase diagram of strongly interacting matter is shown schematically as in Fig. 1. Searching and mapping out different parts of the phase diagram of Fig. 1 will be one of the main objectives of high-energy heavy-ion physics.

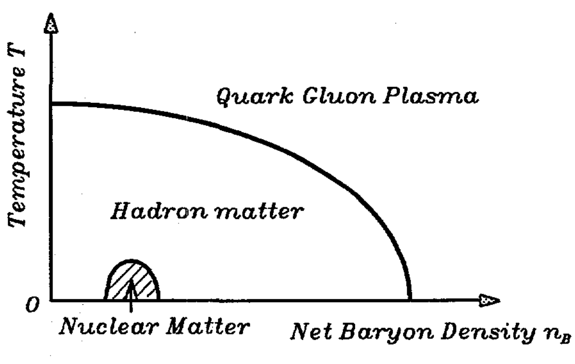

Fig.1. The phase diagram of strongly interacting matter.

3. High-Energy Heavy-Ion Collisions

Why do we use high-energy heavy-ion collisions to search for the quark-gluon plasma. To appreciate this possibility, it is useful to take note of the amount of energy that is involved in these collisions. We can consider the Relativistic Heavy-Ion Collider (RHIC) which is being constructed at Brookhaven National Laboratory and will be operational in 1999. The Collider is designed to accelerate nuclei to an energy of about 100 GeV per nucleon. In the collision of a gold nucleus with another gold nucleus in such a collider, the energy carried by each nucleus is about 100×197 GeV, or 19.7 TeV, and the center-of-mass energy $\sqrt{s}$ is about 2×19.7 TeV, or 39.4 TeV. The magnitude of energy involved in nucleus-nucleus collisions is very large indeed. To attain even greater center-of-mass energies, there will be a program to accelerate heavy ions to a center-of-mass energy of about 3 TeV per nucleon in the Large Hadron Collider (LHC) being planned at CERN. This will lead to a center-of-mass energy of about 1262 TeV for the collision of Pb on Pb [7].

The experimental results in the last two decades indicate that nucleon-nucleon as well as nucleus-nucleus collisions are highly inelastic. Consider first a nucleon-nucleon collision. In such a collision, about half of the longitudinal kinetic energy of the nucleons is lost. The energy lost is deposited in the vicinity of the center-of-mass carried away by the quanta of the fields, which are mostly pions with a small fraction of kaons and baryon pairs. In a nucleus-nucleus collision, many nucleon-nucleon collisions take place and these collisions deposit the energies of the nucleons in the center-of-mass regions. In high-energy collisions, because of Lorentz contraction, all the nucleon-nucleon collisions take place at about the same time in close spatial proximity in the nucleon-nucleon center-of-mass system. As a result, a region of very high energy density, as high as a few GeV per cubic fermi, will be produced. Such an energy density is within the same order as that expected to be the critical energy density leading to the transition from the hadron matter to the quark-gluon plasma. The temperature of the matter in the central region near the center-of-mass is also high. It is therefore reasonable to look for the quark-gluon plasma using high-energy heavy-ion collisions.

4. Signals for the Quark-Gluon Plasma

In a high-energy heavy-ion collision, one starts with a cold nuclear matter in collision. As a result of the collision, a quark-gluon plasma may be formed. The quark-gluon plasma can only be a transient state of matter, as the matter will cool down and will return to the hadron phase at the end. It is during the excursion into the quark-gluon plasma phase that it will leave the signals of the quark-gluon plasma.

There are generally two different methods. The first one is to study the reaction products of the constituents of the quark-gluon plasma. For example, one can use $gq \to \gamma q$, $g\bar{q} \to \gamma\bar{q}$, and $q\bar{q} \to \gamma g$ and look at the momentum distribution of the product gamma particles to infer the momentum distribution of the gluons and quarks in the plasma [8]. One can also use the dilepton spectrum in the reactions of $gq \to l^+l^-q$, $g\bar{q} \to l^+l^-\bar{q}$, and $q\bar{q} \to l^+l^-g$ in order to infer the momentum distributions of the gluons and quarks in the plasma [9].

In the second method, one makes use of the peculiar properties of the plasma to infer the existence of the plasma. One can study the suppression of J/ψ production [10], the enhancement of strangeness production [11], the dependence of the energy density as a function of the temperature [12], or the large effective lifetime of the system [13].

In using any of the above signals to study the quark-gluon plasma, there needs to be a careful subtraction of signals from other sources. Such a subtraction is not without ambiguities and uncertainties. Thus, a clear identification of the quark-gluon plasma will require not just a single piece of data but rather many collaborative pieces of evidence pointing to peculiarities associated with the quark-gluon plasma.

5. Suppression of J/ψ Production as a Signal for the Quark-Gluon Plasma

J/ψ is a bound state consisting of a c quark and a $\bar{c}$ quark. In free space, the c and $\bar{c}$ interact through a linear confining potential and a color-Coulomb interaction. In high-energy heavy ion collisions, J/ψ may be produced in one of the many nucleon-nucleon collisions. If a quark-gluon plasma is formed in the meantime and this J/ψ finds itself in the environment of the quark-gluon plasma, then two things will happen. First, the linear confining potential between the charm quark and the charm antiquark will not be present because the temperature of the quark-gluon plasma brings the J/ψ particle to the state of deconfinement. Second, the color-Coulomb interaction between the charm quark and the charm antiquark will be modified because the light quarks, antiquarks, and gluons of the plasma can move around from other locations to screen the charm quark color charge from the charm antiquark. This reduces the color charge seen by the charm quark with respect to the charm antiquark. The color-Coulomb interaction is modified into a color-Yukawa interaction, with the range of the Yukawa depending inversely on the temperature. Such an inverse dependence arises because the greater the temperature , the greater the quark density surrounding the charm quark, and the greater is the degree of screening to diminish the interaction between the charm quark and the charm antiquark.

As the range of the color-Yukawa interaction decreases, the energy levels of the $c\bar{c}$ system rise. In other words, the energy level of the $c\bar{c}$ system rises with temperature. When the temperature rises to a critical temperature, there can be a resonance of c and $\bar{c}$ at $E = 0$ [14]. As the temperature rises even higher, then there will be no bound state between c and $\bar{c}$, and no matter how close the c is brought to $\bar{c}$, the c and $\bar{c}$ will drift apart. When the phase of the quark-gluon plasma has passed, the c and $\bar{c}$ will find themselves so far apart that the formation of a bound state is no longer possible, and the charm quark will pick up a light antiquark, while the charm antiquark will pick up a light quark, to form D and $\bar{D}$ states. They will not be part of the bound state formation process. They are lost from bound state production, and thus in the presence of the quark-gluon plasma, the production of J/ψ is suppressed [10].

6. Advantages and Disadvantages of Using J/ψ Suppression as a Signal for the Quark-Gluon Plasma

One can select the decay product of J/ψ to be dileptons and look for dileptons which carry the signature of J/ψ. As leptons interact only electromagnetically with hadron matter and the interaction is not strong, the leptons are not affected by the final-state interaction due to the presence of the strongly interacting matter. Thus, one advantage of J/ψ as a signal of the quark-gluon plasma is that the detection of J/ψ through dilepton coincidence is less subject to final-state interactions. The dileptons carry information on the system at the moment of their creation. Furthermore, the calibration of the dilepton cross sections can be made reliably by comparing with dilepton production through the Drell-Yan process, which arises from the collision of the quark parton of one nucleon with the antiquark parton from the other nucleon and is quantitatively very well understood.

The disadvantage of J/ψ is that J/ψ is also suppressed by non-quark-gluon plasma sources, and these must be taken into account to get information on the suppression by the quark-gluon plasma. In addition, the production and absorption mechanism for J/ψ with low transverse momenta at a few hundred GeV is not completely understood. Much theoretical and experimental work is needed to construct a picture of J/ψ production and absorption.

7. Experimental J/ψ Suppression Data

Experimental data indeed show that J/ψ production in nucleus-nucleus collisions is suppressed relative to pp collisions. In Figs. $2a$ and $2b$, we plot $\mathcal{B}\sigma(A+B \to J/\psi X)/AB$ and $\mathcal{B}'\sigma(A+B \to \psi' X)/AB$ with $x_F > 0$ as a function of $\eta = A^{1/3}(A-1)/A + B^{1/3}(B-1)/B$, where η is proportional to average path length L through which a produced J/ψ needs to pass in order to come out of the nuclear matter, and $\mathcal{B}$ and $\mathcal{B}'$ are respectively the branching ratio for J/ψ and ψ' to decay into $\mu^+\mu^-$. If there were no absorption, $\mathcal{B}\sigma(A+B \to J/\psi X)/AB$ would be independent of the path length L or the parameter η. However, for pA collisions, the yield of J/ψ per nucleon-nucleon collision depends on the path length in a simple exponential way as shown in Fig. $2a$. We plot the similar yield of ψ' as a function of η in Fig. $2b$.

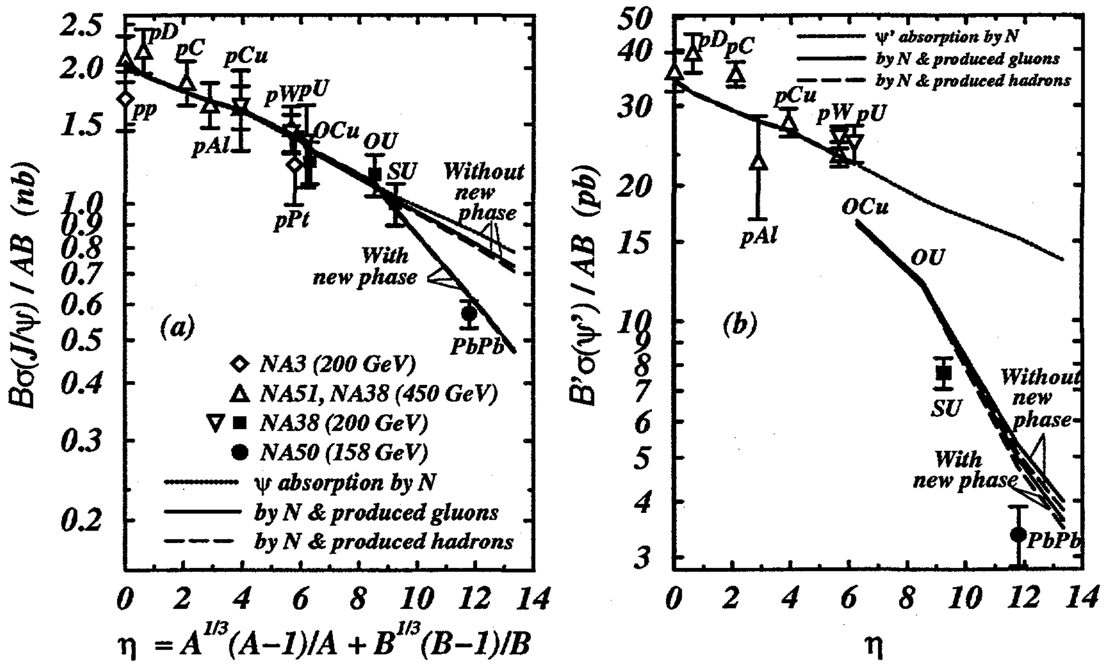

Fig.2. (a) $\mathcal{B}\sigma_{J/\psi}^{AB}/AB$ and (b) $\mathcal{B}'\sigma_{\psi'}^{AB}/AB$ as a function of η. Data are from NA3 [15], NA51 [16], NA38 [17–19], and NA50 [20,21].

As was recognized early by Andersen et al. [22] and by Gershel and Hüfner [23], Fig. $2a$ shows that J/ψ is also suppressed by non-quark-gluon sources, which must be taken into account to get information on the suppression by the quark-gluon plasma.

8. J/ψ Absorption by Collision with Nucleons

In a nucleon-nucleon collision, $c\bar{c}$ pairs are produced by the collision of a parton of one nucleon with a parton of another nucleon. Among the $c\bar{c}$ pairs, only those with low invariant masses will evolve into precursors of J/ψ and ψ'. Because J/ψ are produced predominantly at rapidity zero, the precursor is produced as essentially at rest in the center-of-mass system, and the fate of the precursor can be studied best in the nucleon-nucleon center-of-mass frame. The precursor will encounter projectile and target nucleons at high relative energies. The absorption by collisions with these nucleons constitutes the hard component of absorption which is present in both pA and (nucleus A)-(nucleus B) collisions.

It has been suggested recently that the produced precursor exists as a coherent admixture of color and angular momentum states [24]. The total cross section for this coherent precursor for a collision with a nucleon at high energy can be evaluated by the two-gluon model of the Pomeron [25–27]. The total cross section is approximately the weighted sum of the color-singlet and color-octet total cross sections. As the color-singlet cross section is very small, and the color-octet cross section is very large (of the order of 30 to 60 mb), the absorption cross section depends on the color-octet fraction. The experimental absorption cross section suggests a color-octet fraction of the order of 20%. Different parton combinations will lead to different color admixtures and different absorption cross sections.

In a situation where the precursor comes predominantly from a single combination of partons, as in the present case when gg fusion is the dominant process for $c\bar{c}$ quarkonium production at fixed target energies, the precursor state $\Psi_{gg}(L)$ is absorbed in its passage through nuclear matter by a single precursor-nucleon cross section σ_{abs}. The survival probability for the precursor after traveling a path length L in nuclear matter is

$$|\Psi_{gg}(L)> = e^{-\rho\sigma_{abs}L/2}|\Psi_{gg}(L=0)>, \tag{1}$$

with the survival probability $e^{-\rho\sigma_{abs}L}$, where ρ is the number density of nucleons in a nucleus at rest. Because the production of different bound states comes from the projection of the coherent precursor state onto the bound states after the absorption, the production of various $c\bar{c}$ bound states in the nuclear medium are suppressed by the same rate with the same σ_{abs}. Thus, in pA collisions where the precursors are absorbed only by collisions with nucleons, we expect that the survival factors for the production of various $c\bar{c}$ bound states are characterized by approximately the same absorption cross section σ_{abs}.

The approximate equality of the absorption cross sections for J/ψ and ψ' production in pA collisions is indeed observed [18,19,28], as one can see from the approximate equality of the slope of the pA lines for J/ψ and ψ' in Figs. 2a and 2b. This is further collaborated by another piece of data in Figs. 3a and 3b where we plot respectively the ratio $\mathcal{B}(J/\psi)\sigma(J/\psi)/\sigma(\mathrm{Drell-Yan})$ and $\mathcal{B}'(\psi')\sigma(\psi')/\sigma(\mathrm{Drell-Yan})$. Because the Drell-Yan cross section does not suffer much absorption in hadron environments, the ratios of $\mathcal{B}(J/\psi)\sigma(J/\psi)$ and $\mathcal{B}(\psi')\sigma(\psi')$ to the Drell-Yan cross section are proportional to J/ψ and ψ' survival probabilities. These ratios, as a function of the path length L, are presented for J/ψ in Fig. 3a and for ψ' in Fig. 3b. The slopes of the pA lines for J/ψ and ψ' are nearly the same. Therefore for the hard component of the absorption process, the rate of absorption and the associated absorption cross sections by collisions with nucleons at high energies are approximately the same for J/ψ and ψ'.

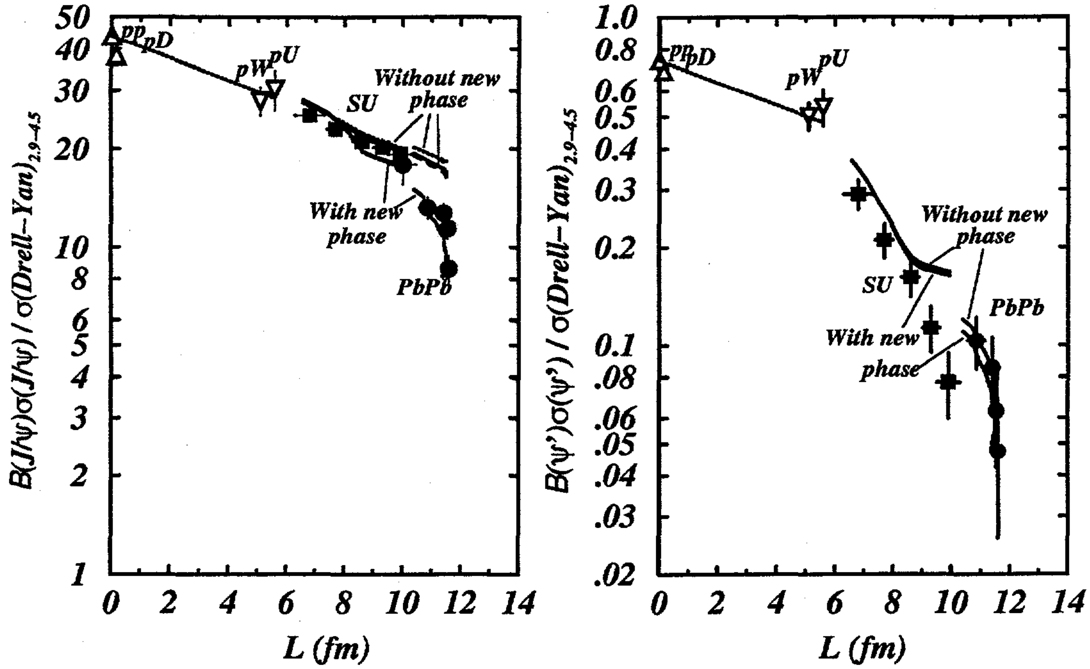

Fig.3. (*a*) $\mathcal{B}\sigma^{AB}_{J/\psi}/AB$ and (*b*) $\mathcal{B}'\sigma^{AB}_{\psi'}/AB$ as a function of the path length L. Data are from NA51 [16], NA38 [17–19], and NA50 [20,21].

9. Absorption of J/ψ and ψ' Precursors by Produced Soft Particles

An additional absorption component is present in nucleus-nucleus collisions where a J/ψ or ψ' precursor can find itself in the middle of fireballs of soft particles produced by earlier or later nucleon-nucleon collisions centered at the same spatial location. These produced soft particles may exist in the form of virtual gluons in early stages and hadrons at later stages [29]. They will collide with the J/ψ or ψ' precursor to lead to its breakup. The centers of the fireballs of produced soft particles are nearly at rest, and the collisions between the precursor and the soft particles occur at a kinetic energy which is about the fireball temperature (of a few hundred MeV). Absorption of the precursor due to the collisions with soft particles constitutes the soft component of absorption.

The survival probability of J/ψ and ψ' due to the absorption by soft particle collisions is approximately an exponential function whose exponent is proportional to the (precursor)-(soft particle) absorption cross section and the density of soft particles. The number of produced soft particles depends on the number of participants [30]. The number of participants in turn is proportional to the longitudinal path length passing through nuclei A and B. Because of such dependence on participant numbers and the longitudinal path length, the survival probability due to soft particle absorption is approximately $\exp\{-c\sigma(\text{precursor-(soft particle)})L\}$, where c is approximately a constant (see pages 374-377 of Ref. [1]).

How does σ(precursor-(soft particle)) depend on the nature of the produced particles? The collision of the precursor with the soft particle at low energies brings up a different type of interaction between them. Because these collisions take place at low energies, the natural basis states to describe the interaction are the $c\bar{c}$ quarkonium states, and the interaction depends on the separation energy of the bound $c\bar{c}$ quarkonium states. Thus, at such a low energy precursor-(soft particle) collision, one projects out the precursor state into various bound states, and the absorption cross section for each component depends on the separation energy of the bound states. The energy required to break up a $J/\psi, \chi_1, \chi_2$ and ψ' is 640 MeV, 228 MeV, 182 MeV, and 52 MeV respectively. On the other hand, the relative energy between the precursor and soft particles is approximately the temperature of the soft particles, which is about 150 to 200 MeV. Thus, the cross section for the breakup of ψ' is much greater than the cross section for the breakup of J/ψ and χ's. The rate of J/ψ and χ absorption by soft particle collisions is much less than the rate of absorption of J/ψ.

To study the soft component of absorption, one looks for a gap and a change of the slope in going from the pA line to the AB line. From the ψ' data in Fig. 2*b*, one can discern the presence of a gap in going from the pA line to the S-U data point. For the nucleus-nucleus collision data in Fig. 3, one makes use of the information on the transverse energies to select nucleus-nucleus collisions with different impact parameters and different average path lengths L. The ψ' data in Fig. 3*b* show a big gap and a large change of the slope in going from the pA line to the AB line, conforming to the signature of the soft component. Figs. 2*b* and 3*b* indicate that for ψ' production, the absorption due to the soft component is large.

The above analysis of the ψ' data provides us with a clear signature of the soft absorption component. This signature can be used to identify the soft component in other production processes. Upon searching for the signature of the soft absorption component in J/ψ production for pA, O-Cu, O-S, and S-U collisions in Figs. 2*a* and 3*a*, one finds that there is almost no gap and no change of the slope in going from the pA line to the AB line. One concludes that the absorption of J/ψ by soft particles, as revealed by the data of pA, O-Cu, O-U, and S-U, is small.

When one extends one's consideration to Pb-Pb collisions, one finds that the AB line of O-Cu, O-U, and S-U in Figs. 2*a* and 3*a* are much above the Pb-Pb data points. This indicates that the degree of J/ψ absorption by soft particles, as revealed by the data of O-Cu, O-U, and S-U collisions, cannot explain the Pb-Pb data, and a new phase of strong J/ψ absorption in Pb-Pb collisions is suggested [31–33]. Similar conclusions have been reached also by other workers [34,35].

10. Microscopic Absorption Model of J/ψ and ψ' Absorption

We can be more quantitative to study this departure of Pb-Pb data by using the microscopic absorption model of [31–33]. In this model, each nucleon-nucleon collision is a possible source of J/ψ and ψ' precursors. It is also the source of a fireball of soft particles which can absorb J/ψ and ψ' precursors produced by other nucleon-nucleon collisions. One follows the space-time trajectories of precursors, baryons, and the centers of the fireballs of soft particles. Absorption occurs when the space-time trajectories of the precursors 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 AB collision as [31]

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

where $T_A(\mathbf{b_A})$ is the thickness function of nucleus A, and $F(\mathbf{b}_A,\mathbf{b})$ is the survival probability due to soft particle collisions. To calculate $F(\mathbf{b}_A,\mathbf{b})$, we sample the target transverse coordinate $\mathbf{b}_A$ for a fixed impact parameter $\mathbf{b}$ in a row with the nucleon-nucleon inelastic cross section σ_{in}^{NN}. In this row, $BT_B(\mathbf{b}-\mathbf{b}_A)\sigma_{in}$ projectile nucleons will collide with $AT_A(\mathbf{b}_A)\sigma_{in}$ target nucleons. We construct the space-time trajectories of these nucleons to locate the position of their nucleon-nucleon collisions. These collisions are the sources of J/ψ and ψ' precursors and the origins of the fireballs of produced particles. For each precursor source from the collision j and each absorbing fireball from the collision i at the same spatial location, we determine the time when the precursor source coexists with the absorbers as virtual gluons t^g_{ij} or as produced hadrons t^h_{ij}. The survival probability due to this combination of precursor source and absorber is then $\exp\{-k_{\psi g}t^g_{ij}-k_{\psi h}t^h_{ij}\}$, where the rate constant $k_{\psi m}$ for $m=g,h$ is the product of $\sigma_{\rm abs}(J/\psi\text{-}m)$, the average relative velocity v_m, and the average number density ρ_m per NN collision. When we include all possible precursor sources and absorbers, $F(\mathbf{b}_A,\mathbf{b})$ becomes

$$F(\mathbf{b}_A,\mathbf{b})=\sum_{n=1}^{N_<}\frac{a(n)}{N_>N_<}\sum_{j=1}^{n}\exp\{-\theta\sum_{i=1,i\neq j}^{n}(k_{\psi g}t^g_{ij}+k_{\psi h}t^h_{ij})\}, \qquad (3)$$

where $N_>(\mathbf{b}_A)$ 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 $BT_B(\mathbf{b}-\mathbf{b}_A)\sigma_{in}$, $a(n)=2$ for $n=1,2,...,N_<-1$, and $a(N_<)=N_>-N_<+1$. The function θ is zero if $A=1$ or $B=1$ and is 1 otherwise. The survival probability F 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 [31]. The cross section for ψ' production can be obtained from the above equations by changing J/ψ into ψ'.

We use this microscopic absorption model to study the experimental data [31–33]. Consider first the J/ψ data in pA, O-Cu, O-U, and S-U collisions. If one assumes that there is no soft particle absorption, the results with the least χ^2 are obtained with $\sigma_{\rm abs}(J/\psi\text{-}N)=6.94$ mb, shown as dotted curves in Figs. 2*a* and 3*b*. If one assumes additional absorption by soft particles in the form of produced gluons or produced hadrons, one obtains fits shown respectively as the solid and dashed curves marked by "without new phase" in Figs. 2*a* and 3*a*. The results indicate that the soft component of J/ψ absorption, as revealed by O-Cu, O-U, and S-U collisions, is small, and the extrapolated results from any one of these three descriptions are much greater than the Pb-Pb data points. The Pb-Pb data cannot be explained by the absorption due to collisions with nucleons and soft particles.

We next examine the ψ' data in Figs. 2*b* and 3*b*. The theoretical results with no soft particle absorption are given by the dotted curves, which fit the pA data, but are much too large for the S-U data. Theoretical results calculated with $\sigma(\psi'\text{-}N)=6.36$ mb with additional absorption by produced gluons or produced hadrons are shown respectively as the solid and dashed curves marked by "without new phase" in Figs. 2*a* and 3*a*. These theoretical results indicate that soft particle absorption leads to a gap and a change of the slope when one goes from the pA line to the AB line. A large soft component is needed to explain the ψ' data in S-U collisions. The flattening of the theoretical ratio of $B(\psi')\sigma(\psi')/\sigma(\text{Drell}-\text{Yan})$ as a function of L for S-U collisions in Fig. 3*b* arises because the distribution of soft particle densities in the central region of ψ' production is insensitive to the impact parameter for small impact parameters when the masses of the two colliding nuclei are very different.

11. New Phase of J/ψ Absorption

The deviation of the J/ψ data in Pb-Pb collisions from the conventional theoretical extrapolations in p-A, O-A, and S-U collisions 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 nucleon-nucleon collisions which has taken place at that spatial 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 spatial point. The quantity $k_{\psi g}t_{ij}^g + k_{\psi h}t_{ij}^h$ in Eq. (3) becomes $k_{\psi g}t_{ij}^g + k_{\psi h}t_{ij}^h + k_{\psi x}t_{ij}^x$. Here, the new rate constant $k_{\psi x}$ describes the rate of absorption of J/ψ by the produced soft matter absorber in the new phase. Also, the quantity t_{ij}^x is the time for a J/ψ produced in collision j to coexist at the same spatial location 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, $\sigma_{\text{abs}}^x(\psi N)$, for ψ-N interactions in the row in which there is a transition to the new phase, while the absorption cross section $\sigma_{\text{abs}}(\psi N)$ remains unchanged in other rows where there is no transition. As shown on the curves marked by "with new phase" in Figs. 2*a* and 3*a*, model results assuming 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. The rate constant $k_{\psi x}$ for this new phase is much greater than the corresponding rate constants $k_{\psi g}$ or $k_{\psi h}$.

We can study the ψ' data to see how the presence of the new phase will affect ψ' production. Theoretical results obtained by assuming the new phase are shown as the curves marked by "with new phase" in Fig. 2*b* and the lower solid curves in Fig. 3*b*. They indicate that as far as ψ' suppression is concerned, the ψ' particles are so strongly absorbed by collisions with soft particles that the presence of an additional source of absorption leads only to a very small additional absorption. Seen in this light, J/ψ is a better probe for a new phase of absorption than ψ' because of its large threshold value which does not allow it to be destroyed in great proportion by soft particles.

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 about 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 can be estimated by knowing the average number of produced particles per nucleon-nucleon collision, the average energy carried by each particle, and the spatial separation between adjacent collisions. 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 $\epsilon_c/T_c^4 \sim 20$ [2] 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.

12. Conclusion and Discussions

J/ψ and ψ' precursors produced in high-energy heavy-ion collisions are absorbed by their collisions with nucleons and produced soft particles, leading to two distinct absorption mechanisms. The absorption by nucleons occurs at high kinetic energies between the precursor and the nucleon and constitutes the hard component of absorption. It is operative in pA and AB collisions. The absorption by soft particles occurs at low relative energies, and constitutes the soft component of absorption. It occurs mainly in AB collisions.

The signature for the hard component is an approximately straight line in the semi-log plot of the survival probability for pA collisions as a function of the path length or $\eta = A^{1/3}(A-1)/A + B^{1/3}(B-1)/B$. The slope of the line gives the precursor-nucleon absorption cross section.

The signature for the soft component consists of a gap and a change of the slope from the pA line to the AB line in the semi-log plot of the survival probability as a function of the path length or η. The greater the gap, the greater the change of the slope, and vice versa. Application of these signatures to examine the J/ψ and ψ' data indicates that the degree of absorption by soft particles on J/ψ production, as revealed by the O-Cu, O-U, and S-U data, is small. The absorption by soft particles on ψ' production is, however, quite large.

A microscopic absorption model which takes care of all precursor sources and absorbers is used to examine these two mechanisms. The microscopic model results support the above qualitative descriptions.

When one extends one's consideration to Pb-Pb collisions, one finds that the degree of J/ψ absorption by soft particles as constrained by the data of O-Cu, O-U, and S-U collisions cannot explain the Pb-Pb data, and a new phase of strong J/ψ absorption in Pb-Pb collisions is suggested. The anomalous suppression of J/ψ production in Pb-Pb collisions can be explained as due to the occurrence of a new phase of strong J/ψ absorption, which sets in when the number of nucleon-nucleon collisions at a spatial point exceeds about 4 and corresponds to a local energy density of about 3.4 GeV/fm^3.

In order to demonstrate that the anomalous suppression in Pb-Pb collisions arises from the occurrence of the quark-gluon plasma, it is necessary to obtain additional pieces of collaborative experimental evidence. Much future work remains to be done to identify the quark-gluon plasma if it is ever produced in high-energy Pb-Pb collisions.

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