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PRODUCTION IN HIGH-ENERGY HEAVY-ION COLLISIONS

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Signatures of Absorption Mechanisms for J/ψ and ψ' Production in High-Energy Heavy-Ion Collisions

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J/ψ and ψ' 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 signature of absorption by produced soft particles, as revealed by ψ' production data, consists of a gap and a change of the slope in going from the pA line to the nucleus-nucleus line when we make a semi-log plot of the survival probability as a function of the path length. Using this signature, we find from the J/ψ production data in pA , O-Cu, O-U, and S-U collisions that the degree of J/ψ absorption by produced soft particles is small and cannot account for the J/ψ data in Pb-Pb collisions. 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 local energy density exceeds about 3.4 GeV/fm³. To probe the chemical content of the new phase, we propose to study the abundance of open-charm mesons and charm hyperons which depends sensitively on the quark chemical potential.

1. INTRODUCTION

Following the initial suggestion by Matsui and Satz [1], the NA50 experimental observation [2-4] of a possible discontinuity in the absorption of J/ψ in Pb-Pb collisions has led to a flurry of theoretical activities. While the present author and others presented theoretical findings at the Quark Matter Meeting in 1996 [5-8], other theoretical studies have since been put forth [9-14]. A central question is whether the anomalous suppression in Pb-Pb collisions arises from the occurrence of a new phase of strong J/ψ absorbing matter (possibly a quark-gluon plasma), as suggested in [5-7,9,12], or from the absorption by comovers (produced hadrons), as proposed by [8,10,11].

To shed light on this question, we shall examine the absorption mechanisms both qualitatively and quantitatively and study how different mechanisms can be recognized by their characteristic signatures. From these studies, the deviation of the J/ψ data in Pb-Pb collisions from the results extrapolated from pA , O-Cu, O-U, and S-U collisions suggests that there is a new absorption mechanism which results in the anomalous suppression of J/ψ production in Pb-Pb collisions.

While the debate on the theoretical interpretation of the experimental data continues, it is useful to look for other effects of a quark-gluon plasma so as to provide means for

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its search and identification. We shall examine a possible signature which allows one to study the chemical content of the quark-gluon plasma, if it is ever produced.

2. PRODUCTION AND ABSORPTION of J/ψ AND ψ'

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, those $c\bar{c}$ pairs with large relative energies will separate into $D\bar{D}$ pairs and will not be the subject of our attention. Only those with low invariant masses will have a high probability to evolve into precursors of J/ψ and ψ' . These precursors can be in a color-singlet or color-octet state [15]. With respect to a nucleon, a precursor in a color-octet state has a total cross section of a few tens of millibarns, which is much greater than that in a color-singlet state [16,17]. If the precursor is produced as an incoherent mixture of the two color states, then the survival probability for the precursor will be the sum of two different exponential survival probabilities with two characteristic absorption lengths. In principle, the color-octet production fraction can be inferred from the absorption curve in pA collisions as a function of the atomic number A [18]. However, the sparsity of the data points and the uncertainty of the experimental measurements do not allow a clean separation of the two color fractions. The analysis of experimental data suggests that NA3 [19], NA38 [20], and E772 [21] data are not inconsistent with the theoretical picture [22,23] that color-octet and color-singlet precursors are produced in roughly equal proportions if the produced color-singlet precursors are pointlike and transparent. However, if the color-singlet precursors are not transparent but have a cross section of a few mb, these data do show a definite preference for a larger fraction of color-singlet precursors [18]. In the present work, we shall limit our attention to a single effective color component for our discussions.

A very important property of a precursor is the energy needed to separate it into a $D\bar{D}$ pair. A color-singlet J/ψ particle needs an energy of 640 MeV to break into a $D\bar{D}$ pair, while a $\chi_{1,2}$ needs about 200 MeV, and a ψ' only about 50 MeV. A color-octet precursor will need to emit or absorb a soft gluon in the time scale of nonperturbative QCD to neutralize into a color-singlet state. If it is broken up into a $D\bar{D}$ pair, one of the pair will be in a color-octet state, and the need to emit or absorb a soft gluon remains unchanged. Thus, the average energy required to break a color-octet J/ψ precursor is still about 640 MeV and a color-octet ψ' precursor about 50 MeV, but with a large standard deviation (of about a few hundred MeV), due to the emission or absorption of the soft gluon. For simplicity, we shall group χ particles with the J/ψ because of the large energies required to break them into $D\bar{D}$ pairs.

We consider the collision of a projectile nucleus B with a target nucleus A leading to the production of a J/ψ or ψ' precursor, depicted by the big dot at P in Fig. 1. The precursor will collide with two groups of particles at different energies: the projectile and target nucleons and the produced soft particles. The dynamics of precursor-particle collisions is best studied in the nucleon-nucleon center-of-mass frame illustrated in Fig. 1, where γ is the Lorentz contraction factor. In this frame, the nucleons still retain a large fraction of their initial kinetic energies. As J/ψ and ψ' are produced predominantly at central rapidity, the precursors can be envisaged as produced nearly at rest. Collisions between the nucleons and the precursor take place at high energies, much higher than the

separation thresholds of the J/ψ or ψ' precursor, and likely lead to the breakup of the precursor into a $D\bar{D}$ pair. Absorption due to collisions with nucleons can be called the hard component. The precursor survival probability, after colliding with projectile and target nucleons, is $\exp\{-\sigma(J/\psi\text{-}N)\rho L\}$ for J/ψ and is $\exp\{-\sigma(\psi'\text{-}N)\rho L\}$ for ψ' , where L is the sum of the path length L_B in the projectile and L_A in the target nucleus in their respective rest frames, ρ is the nucleon density at rest, and $\sigma(J/\psi\text{-}N)$ and $\sigma(\psi'\text{-}N)$ are respectively the $J/\psi\text{-}N$ and $\psi'\text{-}N$ absorption cross section [24].

From the space-time picture of the collision process, we can infer that the hard absorption component is operative for both pA and (nucleus A)-(nucleus B) collisions. However, in nucleus-nucleus collisions, there is an additional absorption component. There, a J/ψ or ψ' precursor produced at P in Fig. 1 finds itself in the middle of fireballs of soft particles produced by earlier or later nucleon-nucleon collisions centered at the same spatial location (soft particles depicted by the small dots around the point P in Fig. 1). These produced soft particles may exist in the form of virtual gluons in early stages and hadrons at later stages [25]. They will collide with the J/ψ or ψ' precursor and 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 of the fireballs occur at a kinetic energy which is about twice the fireball temperature (of a few hundred MeV). Absorption due to these collisions can be called the soft component of J/ψ and ψ' 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 in which the precursor finds itself. The number of produced soft particles depends on the number of participants [26]. 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. [27]).

From these considerations, we can separate out the two components of absorption by plotting the logarithm of the survival probability as a function of the path length. Following the work of Gerschel and Hüfner[24], the hard component can be separated out by the pA line, and the precursor-nucleon cross section at high energies can be measured by the slopes of the pA lines. In addition, the effect of the soft component can be uncovered by the gap and the change of the slope going from the pA line to the AB lines. The magnitude of the gap and the change of the slope are not independent. A large gap is accompanied by a large slope change. They are related to the magnitude of the (precursor)-(soft particle) cross section at low energies. We expect that because

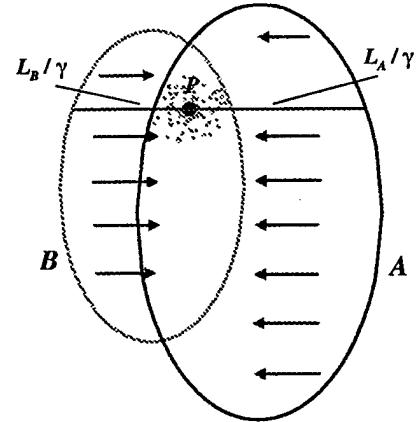


Fig.1. The collision of a projectile nucleus B with a target nucleus A in the nucleon-nucleon center-of-mass system.

the collision energy in the soft absorption component is small compared to the separation threshold of 640 MeV for J/ψ but large compared to the separation threshold of 50 MeV for ψ' , the absorption behavior for J/ψ and ψ' can be quite different for the soft component.

3. COMPARISON WITH EXPERIMENTAL DATA

We can use the qualitative signatures discussed in the last section to examine the experimental J/ψ and ψ' data in two different ways. We look first at experimental J/ψ and ψ' cross sections for AB collisions when all impact parameters are summed over. If there were no absorption, these cross sections would be proportional to the product AB . The quantities $\mathcal{B}(J/\psi)\sigma(J/\psi)/AB$ and $\mathcal{B}(\psi')\sigma(\psi')/AB$ (where $\mathcal{B}(J/\psi)$ and $\mathcal{B}(\psi')$ are branching constants) give respectively the J/ψ and ψ' survival probabilities, multiplied by constants. In Figs. 1a and 1b, these quantities are presented in a semi-log plot as a function of $\eta = A^{1/3}(A-1)/A + B^{1/3}(B-1)/B$, which is proportional to the path length averaged over all impact parameters [27]. Here, the quantities $A^{1/3}$ and $B^{1/3}$ are proportional to the radii of the two nuclei, and the factors $(A-1)/A$ and $(B-1)/B$ are included to take into account the finiteness of the number of nucleons.

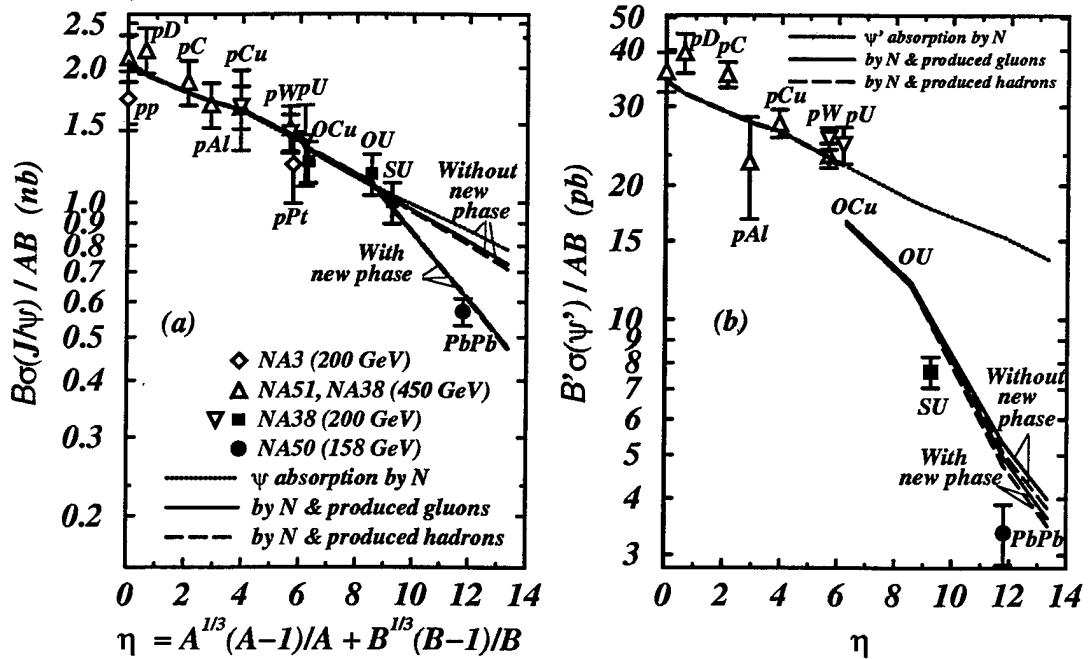


Fig.2. (a) $\mathcal{B}\sigma_{J/\psi}^{AB}/AB$ and (b) $\mathcal{B}'\sigma_{\psi'}^{AB}/AB$ as a function of η . Data are from NA3 [19], NA51 [28], NA38 [20,29,30], and NA50 [2,3].

We look next at a different set of data where one uses the information on the transverse energy to select the effective impact parameter. This allows one to study the survival probability as a function of the impact parameter and its associated average path length L . The J/ψ and ψ' production cross section in the absence of absorption is proportional to the Drell-Yan cross section. Because the Drell-Yan cross section does not suffer much absorption in nuclear and 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 good representations of the J/ψ and ψ' survival probabilities, multiplied by constants. These ratios as a function of the path length L are presented for J/ψ in Fig. 2a and for ψ' in Fig. 2b.

In Figs. 1 and 2, we show the pA data as open points, the AB data for O-Cu, O-U and S-U collisions as solid squares, and the Pb-Pb data as solid circles. From the data in Fig. 1, we note that the pA data give approximately straight lines conforming to the signature of the hard absorption component. 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' . It is worth noting that the approximate equality is supported by other experimental data of $\sigma_{\text{tot}}(\psi'-N)/\sigma_{\text{tot}}(\psi-N) \approx 0.75 \pm 0.15$ inferred from the photoproduction of J/ψ and ψ' [31].

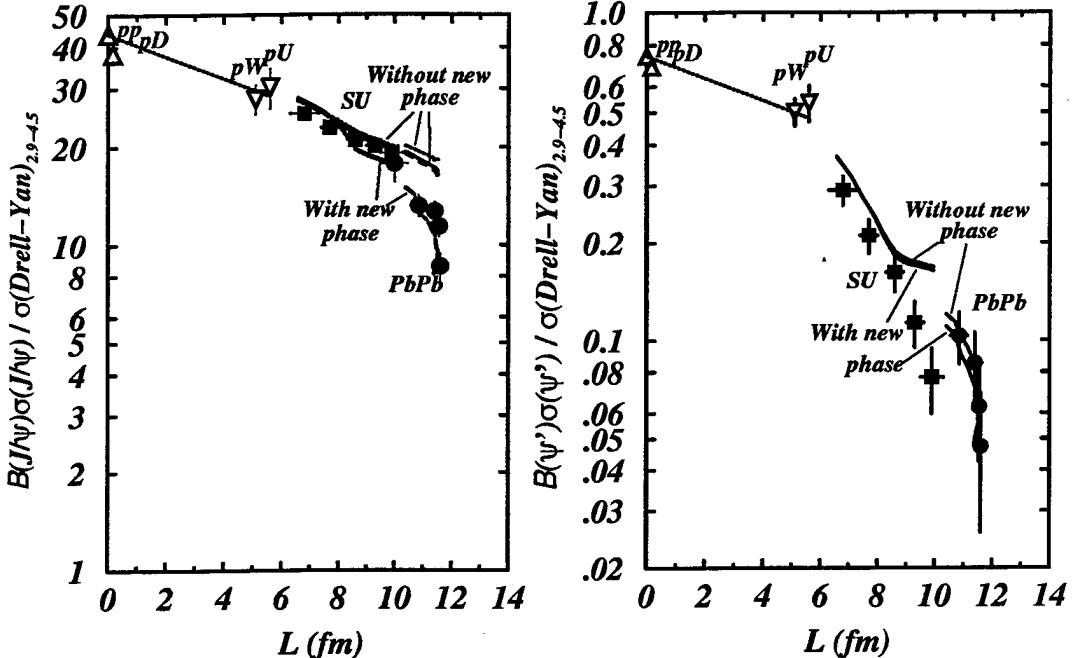


Fig.3. (a) $B\sigma_{J/\psi}^{AB}/AB$ and (b) $B'\sigma_{\psi'}^{AB}/AB$ as a function of the path length L . Data are from NA51 [28], NA38 [20,29,30], and NA50 [2,3].

Theoretically, the approximate equality of $\sigma_{\text{tot}}(\psi'-N) \sim \sigma_{\text{tot}}(\psi-N)$ can be explained by the Glauber picture of hadron-hadron collisions in terms of quark-quark collisions as a generalization of the additive quark model at high energies, for which the absorption cross section for $\psi-N$ collisions and $\psi'-N$ collisions can be shown to be insensitive to the separation between c and \bar{c} [32]. The approximate equality leads immediately to the experimental observation of the independence of ψ'/ψ with mass numbers in p -A collisions [29,30]. Other, different theoretical models interpret the approximate equality as arising from the same separation between the color-octet $(c\bar{c})_8$ and a gluon in the hybrid $(c\bar{c})_8-g$ for J/ψ and ψ' production [33], or a coherent J/ψ - ψ' admixture [34,17]. 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.

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. 1b, one can discern the presence of a gap in going from the pA line to the S-U data point. The ψ' data in Fig. 2b 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. 1b and 2b 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 data for pA , O-Cu, O-S, and S-U collisions in Figs. 1a and 2a, 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.

The difference in the behavior of the J/ψ precursor and ψ' precursor with regard to absorption by soft particles can be easily understood as due to their difference in the threshold energies mentioned above. The average relative kinetic energies between the soft particles and the precursor are much below the J/ψ threshold but much above the ψ' threshold, and thus the rate of absorption of J/ψ by soft particle collisions is small compared with the rate of absorption of ψ' by soft particle collisions.

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. 1a and 2a 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.

4. 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 [32]. 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 [32]

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

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, $B T_B(\mathbf{b} - \mathbf{b}_A) \sigma_{in}$ projectile nucleons will collide with $A T_A(\mathbf{b}_A) \sigma_{in}$ 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_{ij}^g or as produced hadrons t_{ij}^h . The survival probability due to this combination of precursor source and absorber is then $\exp\{-k_{\psi g}t_{ij}^g - k_{\psi h}t_{ij}^h\}$, where the rate constant $k_{\psi m}$ for $m = g, h$ is the product of $\sigma_{\text{abs}}(J/\psi-m)$, 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

$$F(\mathbf{b}_A, \mathbf{b}) = \sum_{n=1}^{N_<} \frac{a(n)}{N_> N_<} \sum_{j=1}^n \exp\left\{-\theta \sum_{i=1, i \neq j}^n (k_{\psi g} t_{ij}^g + k_{\psi h} t_{ij}^h)\right\}, \quad (2)$$

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 $n = 1, 2, \dots, N_<-1$, 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 [32]. 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 (see also [5,9]). 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 $\sigma_{\text{abs}}(J/\psi-N) = 6.94$ mb, shown as dotted curves in Fig. 1a and 2b. If one assumes nucleons and virtual gluons as absorbers, the least χ^2 fits shown as the solid curves marked by “without new phase” in Figs. 1a and 2a are obtained with $\sigma_{\text{abs}}(J/\psi-N) = 6.36$ mb and $k_{\psi g} = 0.049$ c/fm (which corresponds to a J/ψ -gluon cross section of about 0.3 mb). Alternatively, if one assumes nucleons and produced hadrons as absorbers, the least χ^2 fits shown as the dashed curve marked by “without new phase” are obtained with $\sigma_{\text{abs}}(J/\psi-N) = 6.36$ mb and $k_{\psi g} = 0.096$ c/fm (which corresponds to a J/ψ -hadron cross section of about 0.68 mb). The results in Figs. 1a and 2a 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. 1b and 2b. 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 $\sigma(\psi'-N) = 6.36$ mb, and $k_{\psi g} = 3$ c/fm (which corresponds to a ψ' -gluon cross section of about 20 mb for virtual gluon as absorbers) are shown as the solid curve marked by “without new phase” in Fig. 1b and as the upper solid curves in Fig. 2b. Theoretical results calculated with $\sigma(\psi'-N) = 6.36$ mb, and $k_{\psi h} = 3$ c/fm (which corresponds to a ψ' -hadron cross section of about 20 mb for produced hadrons as absorbers) are shown as the dashed curve marked by “without new phase” in Fig. 1b and coincide with the upper solid curves in Fig. 2b. These theoretical results show 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. 2b 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. Nuclear deformation may play a role in leading to a greater density of soft particles for collisions with the largest transverse energies and may lead to the discrepancy of the theoretical results with experimental data for those S-U collisions with the largest transverse energies (or the largest apparent path lengths in Fig. 2b). The comparison of S-Pb and S-U collisions will shed light on the deformation effect.

5. 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. (2) 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. 1a and 2a, model results assuming a new phase give good agreement with $B\sigma_{J/\psi}^{AB}/AB$ 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. 1b and the lower solid curves in Fig. 2b. 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, is approximately

$$\epsilon_c = N_c \frac{dn}{dy} \frac{m_t}{\sigma_{in} d/\gamma} \quad (3)$$

where $dn/dy \sim 1.9$ [35] is the particle multiplicity 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 $\gamma = \sqrt{s}/2m_{\text{nucleon}} = 9.2$ is the Lorentz contraction factor. For $N_c = 4$ we find $\epsilon_c \sim 3.4$ GeV/fm³, which is close to the quark-gluon plasma energy density, $\epsilon_c \sim 4.2$ GeV/fm³, calculated from the lattice gauge theory result of $\epsilon_c/T_c^4 \sim 20$ [36] 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.

6. OTHER SIGNATURES OF THE QUARK-GLUON PLASMA

The above analysis shows that some domains of matter produced in Pb-Pb collisions may be in a new phase of strong J/ψ absorption. Whether this new absorbing matter is the quark-gluon plasma will require collaborative evidence. If the quark-gluon plasma can suppress J/ψ production, it will also have other detectable consequences. In particular, it will affect the abundance of the u , d , and s quarks and antiquarks which may lead to a definite pattern of the abundance of the D mesons and charm hyperons. The abundance of open-charm mesons and charm hyperons may be used to probe and identify the chemical content of the quark-gluon plasma.

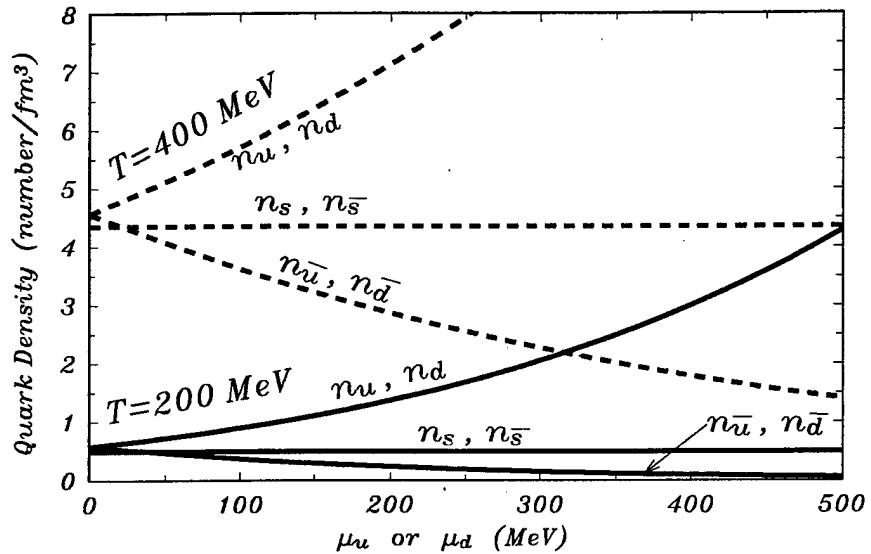


Fig.4. Densities of various types of quarks and antiquarks as a function of the up and down quark chemical potential.

To illustrate the salient features of the physics, we can consider a free quark gas with three flavors at thermal and chemical equilibrium. The quark and antiquark densities

as a function of the chemical potential of u and d quarks are given in Fig. 4 (from Fig. 18.2 of Ref. [27]). For a quark-gluon plasma with no net baryon content, as would be expected in the “transparent region” in very energetic heavy-ion collisions when the baryons are not stopped but proceed forward after collision, the densities of all quark species are approximately equal. On the other hand, for a quark-gluon plasma with a large net baryon content, such as would be expected in the “stopping region” of high-energy heavy-ion collisions, the densities of u and d quarks are much greater than the densities of s and \bar{s} quarks, which are in turn greater than the densities of \bar{u} and \bar{d} quarks.

Consider now the production of $c\bar{c}$ pairs in nucleon-nucleon collisions when there is the occurrence of the quark-gluon plasma. We focus our attention to those $c\bar{c}$ pairs which will not form bound $c\bar{c}$ states, either because of their large initial relative kinetic energies or eventual breakup by interaction with other particles. These c and \bar{c} particles will coalesce with light quarks and antiquarks to hadronize when the temperature drops below the transition temperature. The abundance of the different types of D and \bar{D} mesons will depend on the densities of the different kinds of quarks present in the quark-gluon plasma.

A \bar{c} can coalesce with u , d , and s to form $\bar{D}^0(\bar{c}u)$, $D^-(\bar{c}d)$, and $D_s^-(\bar{c}s)$ respectively, while a c can coalesce with \bar{s} , \bar{u} , and \bar{d} to form $D_s^+(c\bar{s})$, $D^+(c\bar{d})$, and $D^0(c\bar{u})$ respectively. Thus, if the chemical potential is zero, the abundances of the six D mesons will be approximately equal:

$$\bar{D}^0(\bar{c}u) \sim D^-(\bar{c}d) \sim D_s^-(\bar{c}s) \sim D_s^+(c\bar{s}) \sim D^+(c\bar{d}) \sim D^0(c\bar{u}). \quad (4)$$

On the other hand, for a quark-gluon plasma with a large net baryon content having $\mu_u \sim \mu_d$, the quark densities are related by $n_u \sim n_d \gg n_s$ and

$$\bar{D}^0(\bar{c}u) \sim D^-(\bar{c}d) \gg D_s^-(\bar{c}s). \quad (5)$$

For this case, we have similarly $n_s = n_{\bar{s}} \gg n_{\bar{d}} \sim n_{\bar{u}}$ and

$$D_s^-(\bar{c}s), D_s^+(c\bar{s}) \gg D^+(c\bar{d}) \sim D^0(c\bar{u}). \quad (6)$$

As a concrete example, we can study the case of $\mu_u = \mu_d = 400$ MeV at $T = 200$ MeV for which the u and d quark densities are about 6 times that of the s and \bar{s} quarks, which are in turn approximately 6 times the densities of \bar{u} and \bar{d} antiquarks. In that case, Eqs. (5) and (6) give

$$\bar{D}^0(\bar{c}u) : D^-(\bar{c}d) : D_s^-(\bar{c}s) \approx 6 : 6 : 1, \quad (7)$$

$$\text{and } D_s^-(\bar{c}s) : D_s^+(c\bar{s}) : D^+(c\bar{d}) : D^0(c\bar{u}) \approx 6 : 6 : 1 : 1. \quad (8)$$

For a chemical potential as large as $\mu_u = \mu_d = 400$ MeV, it is more likely to find two quarks of u and d type than a \bar{u} , \bar{d} or an \bar{s} antiquark. It will be more likely for the c quark to combine with u and d quarks to form charm hyperons $\Lambda_c^+(udc)$, $\Sigma_c^{++}(uuc)$, $\Sigma_c^+(udc)$, and $\Sigma_c^0(ddc)$ than forming an open charm meson. The production of these charm hyperons with c quarks will be enhanced.

It is expected that while the primary abundance will be related to the chemical potential of the quark-gluon plasma, the final abundance of the D mesons will be subject to small modifications by final-state interactions. In particular, reactions such as $D^\pm + K^\pm \rightarrow D_s^\pm + \pi^\pm$ are exothermic and take place without additional energy. They will shift the abundances of D^\pm and D_s^\pm and need to be taken into account. It will be both an experimental and theoretical challenge to use the abundance of the D mesons and charm hyperons to probe the chemical content of the quark-gluon plasma.

7. CONCLUSIONS 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. These mechanisms need to be well understood if one wants to extract information on J/ψ and ψ' absorption by the presence of the quark-gluon plasma. 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 is 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 further collaborative experimental evidence. One can use the abundance of D-mesons and charm hyperons to probe the chemical content of the new absorbing phase, so as to infer the chemical state of the system. 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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