J/ψ Suppression in Pb-Pb Collisions: A Hint of Quark-Gluon Plasma Production?

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The NA50 Collaboration has recently observed a strong suppression of J/ψ production in Pb-Pb collisions at 158 GeV/nucleon. We show that this recent observation finds a quantitative explanation in a model which relates the suppression mechanism to the local energy density, whose value is higher in Pb-Pb collisions than in any other system studied previously. The sensitivity of the phenomenon to small changes in the energy density could be suggestive of quark-gluon plasma formation. [S0031-9007(96)00831-9]

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The NA50 Collaboration has recently reported the observation of a strong suppression of J/ψ production in Pb-Pb collisions at 158 GeV per nucleon [1], which is not explained by conventional models of nuclear absorption. Since such models have been found to account reasonably well for all the previous data involving lighter nuclei [2], the immediate implication seems to be that new physics is involved in Pb-Pb collisions, possibly the formation of a quark-gluon plasma [3].

In this Letter, we present an interpretation of the data based on the observation that the *local energy density* is higher in Pb-Pb collisions than in any of the systems studied previously, in particular, the S-U system. In order to explore the possibility that the large suppression which is observed in Pb-Pb collisions could be due to the formation of a quark-gluon plasma, we adopt a simplified description [4] in which one considers that *all the J/ψ's produced in a region where the energy density exceeds some critical value are suppressed*. We emphasize that we do not, and cannot at this stage, make precise statements about detailed microscopic mechanisms (for a recent review, see [5]). Our purpose is only to test the idea that the suppression depends solely on the local energy density, and to see whether consequences of this assumption are supported by the data.

We first review briefly the conventional treatment of nuclear absorption [2,6]. The ratio of the J/ψ production cross section in proton-nucleus collisions (σ_{pA}) to that in proton-proton collisions (σ_{pp}) is given by

$$\mathcal{N}_A = \frac{1}{A}\frac{\sigma_{pA}}{\sigma_{pp}} = \frac{1}{A\sigma_a}\int d^2b\{1 - \exp[-\sigma_a T_A(\mathbf{b})]\}, \tag{1}$$

where $T_A(\mathbf{s}) = \int_{-\infty}^{+\infty}\rho_A(\mathbf{s}, z)dz$ is the nucleon density per unit area in the transverse plane (i.e., the plane transverse to the collision axis), and σ_a is an absorption cross section (although we do not write it explicitly, in our calculations σ_a is multiplied by the correction factor $1 - 1/A$, where A is the mass number of the nucleus [2]). The quantity $\mathcal{N}_A$ may be interpreted as the probability that a produced J/ψ survives nuclear absorption.

In a nucleus-nucleus collision, the survival probability $\mathcal{N}_{AB}$ takes, after integration over the impact parameter, the factorized form $\mathcal{N}_{AB} = \mathcal{N}_A\mathcal{N}_B$. Within the range of A values considered, and for the chosen parametrization of the density, $\ln\mathcal{N}_{AB} \sim A^{1/3} + B^{1/3}$ (see Fig. 1). We use for $\rho(\mathbf{r})$ the expression $\rho_A(\mathbf{r})/\rho_0 = 1/\{1 + \exp[r - R_A/a]\}$ with $R_A = 1.1A^{1/3}$ fm, $a = 0.53$ fm, and ρ_0 is fixed by the normalization $\int\rho_A(\mathbf{r})d^3r = A$ (e.g., in ^{208}Pb, $\rho_0 = 0.17$ fm^{-3}).

As seen in Fig. 1, nuclear absorption explains both the proton-nucleus and nucleus-nucleus data up to the S-U system, with a common value of the absorption cross section (we have adopted the value $\sigma_a \approx 6.2$ mb used by

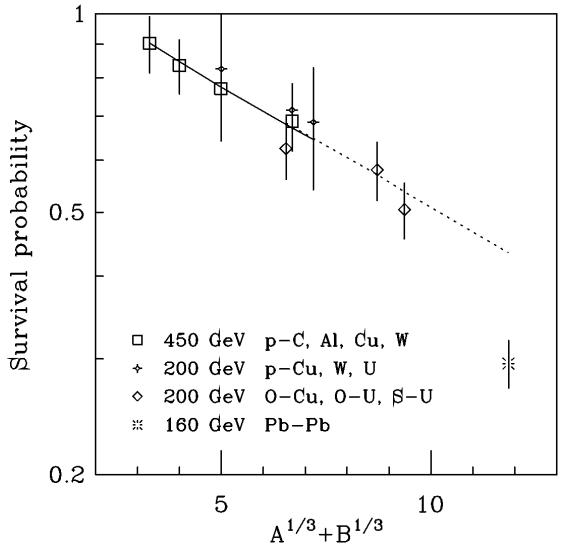

FIG. 1. The J/ψ survival probability after absorption through nuclear matter, as a function of $A^{1/3} + B^{1/3}$, where A and B are the mass numbers of the colliding objects. The full line (dotted line) is the survival probability for the proton-nucleus (nucleus-nucleus) systems, calculated with a cross section $\sigma_a = 6.2$ mb. The data at 450 GeV are obtained from Refs. [1] and [7], those at 200 GeV from Refs. [1] and [8]. In order to obtain the survival probability, each set of data has been rescaled by a constant factor so as to obtain the best fit with the theoretical curve.

the NA50 Collaboration [1]). However, the Pb-Pb system deviates significantly from that common trend. One can measure this deviation by the ratio

$$r_\psi = \frac{\mathcal{N}_{AB}(\text{measured})}{\mathcal{N}_{AB}(\text{estimated})}, \tag{2}$$

where $\mathcal{N}_{AB}$(estimated) is the value of the survival probability to nuclear absorption alone [$\mathcal{N}_{AB}$(estimated) $\approx$ 0.43]. The value of r_ψ, as read from Fig. 1, is 0.68 $\pm$ 0.06. The survival probabilities plotted in Fig. 1 are extracted from absolute cross sections which contain systematic errors of the order of 10% to 20%. These errors have been reported in the figure, although they largely cancel in the relative values of the survival probabilities corresponding to a given set of data. In its analysis, the NA50 Collaboration uses the ratio of the J/ψ production cross section to the Drell-Yan cross section, which reduces most of these systematic errors. It also relies, in extracting nuclear absorption, on the transverse energy dependence of the S-U data, rather than on integrated data alone. It obtains thus, for the ratio r_ψ, the more precise value 0.72 $\pm$ 0.03.

We turn now to the dependence of the effect on the impact parameter of the collision. We write the J/ψ production cross section at impact parameter b as follows:

$$\frac{1}{\sigma_{pp}} \frac{d\sigma_{AB}}{d^2b} = T_{AB}(b)\mathcal{N}(b), \tag{3}$$

where $T_{AB}(b) = \int d^2s\, T_A(\mathbf{s})\, T_B(\mathbf{s} - \mathbf{b})$ is proportional to the probability to produce a $c\bar{c}$ pair, and $\mathcal{N}(b)$ is the survival probability at impact parameter b. The quantity $\mathcal{N}(b)$ is related to $\mathcal{N}_{AB}$ introduced above by $\mathcal{N}_{AB} = (1/AB)\int d^2b\, T_{AB}(b)\mathcal{N}(b)$. If nuclear absorption is the only suppression mechanism,

$$\begin{aligned}\mathcal{N}(b) &= \mathcal{N}_{\text{abs}}(b) \\ &\equiv \frac{1}{T_{AB}(b)} \int d^2s \frac{1}{\sigma_a^2}(1 - e^{-\sigma_a T_A(\mathbf{s})}) \\ &\quad \times (1 - e^{-\sigma_a T_B(\mathbf{s}-\mathbf{b})}).\end{aligned} \tag{4}$$

In analogy with Eq. (2), we define

$$r_\psi(b) = \frac{\mathcal{N}(b)}{\mathcal{N}_{\text{abs}}(b)}. \tag{5}$$

From the NA50 data, assuming that the last bin in transverse energy corresponds to central collisions, i.e., to $b \approx 0$, one extracts the value $r_\psi(b = 0) \approx 0.50$.

We now show that the values of these two ratios, r_ψ defined in Eq. (2) and $r_\psi(0)$ defined in Eq. (5), can be understood quantitatively if one assumes that the suppression mechanism is sensitive only to the local energy density. A central assumption here is that the suppression of the J/ψ takes place at times short compared with the transverse size of the interaction region, i.e., before a substantial transverse expansion of the produced matter has occurred, and before the J/ψ has traveled a long distance in the transverse direction (we consider the production of J/ψ's near central rapidity). We shall therefore ignore both the transverse expansion and the transverse motion of the J/ψ's. Under these conditions, the fate of a J/ψ is determined by the properties of the medium in the region where it is created, and is controlled by the energy density in the transverse plane.

To estimate this density, we assume that it is proportional to the density of participants. This assumption is motivated by the fact that, in nucleus-nucleus collisions, the multiplicity and the transverse energy grow approximately linearly with the number of participants [9]. The participants are the nucleons which collide at least once during the collision of nucleus A on nucleus B at impact parameter $\mathbf{b}$. They have a density per unit transverse area given by

$$\begin{aligned}n_p(\mathbf{s},\mathbf{b}) &= T_A(\mathbf{s})\{1 - \exp[-\sigma_N T_B(\mathbf{s} - \mathbf{b})]\} \\ &\quad + T_B(\mathbf{s} - \mathbf{b})\{1 - \exp[1 - \sigma_N T_A(\mathbf{s})]\},\end{aligned} \tag{6}$$

where $\sigma_N \approx 32$ mb is the nucleon-nucleon inelastic cross section. The total number of participants at impact parameter b is $N_p(b) = \int d^2s\, n_p(\mathbf{s},\mathbf{b})$.

A plot of n_p for the two systems S-U and Pb-Pb is given in Fig. 2. One sees that, up to impact parameters of about 8 fm, there are regions in the Pb-Pb system where the density exceeds that in central S-U collisions. The transverse energy dE_T/dy achieved in central collisions is roughly proportional to $N_p(0)$. From this, one deduces that the average energy density produced in central collisions, proportional to $N_p(0)/R^2$, is approximately the same in the S-U and Pb-Pb systems. However, the maximum density achieved in Pb-Pb is about 35% larger than in S-U. One may get an estimate of the maximum value of n_p by using sharp sphere densities. One then gets $n_p^{\max}(b) = 2\rho_0\sqrt{(R_A + R_B)^2 - b^2}$, which, for central collisions, is proportional to $A^{1/3} + B^{1/3}$. Note that the J/ψ production, being proportional to $T_A\, T_B$, occurs dominantly in the regions of largest density.

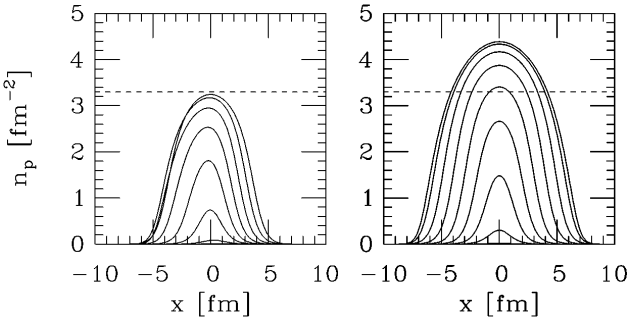

FIG. 2. The density of participants $n_p(s)$, for s along the direction of the impact parameter, for various values of the impact parameter: $b = 0, 2, 4, \ldots$ fm. The origin is at a distance $b/(1 + R_B/R_A)$ from the center of nucleus A. Left, S-U collision; right, Pb-Pb collision. The horizontal dashed line corresponds to the largest density achieved in the S-U system, $n_p = 3.3$ fm^{-2}.

Following [4], we now model the effect of quark-gluon plasma formation by assuming that the J/ψ produced at point $\mathbf{s}$ is completely destroyed whenever the density at that point exceeds a critical value. That is, we calculate

$$\mathcal{N}(b) = \frac{1}{T_{AB}(b)} \int d^2s \frac{1}{\sigma_a^2}(1 - e^{-\sigma_a T_A(\mathbf{s})}) \times (1 - e^{-\sigma_a T_B(\mathbf{s}-\mathbf{b})})\theta(n_c - n_p(s)). \quad (7)$$

A plot of $\mathcal{N}(b)$ as a function of centrality, defined as $N_p(b)/N_p(b=0)$, is shown in Fig. 3 for various values of the critical density n_c. Given the fact that no suppression is observed in S-U collisions other than nuclear absorption, the critical density has to be bigger than the highest value attained in S-U collisions, i.e., 3.3 fm^{-2} (see Fig. 2). Choosing this particular value for n_c, one obtains $\mathcal{N}_{AB} = 0.28$. Therefore, $r_\psi = 0.28/0.43 = 0.66$, to be compared with the value $r_\psi = 0.72$ obtained by NA50. Furthermore, for central collisions, we find $r_\psi(0) = 0.17/0.39 = 0.44$, to be compared with the value $r_\psi(0) \approx 0.50$ of NA50. Thus the two main observations of NA50 can be accounted for quantitatively by this simple picture.

Within the present model, the value $r_\psi = 0.66$ is to be looked at as the lowest possible value since we have considered the most extreme scenario: total suppression above n_c and lowest possible value of n_c. The fact that the resulting r_ψ is only slightly smaller than the experimental one puts very severe constraints on the suppression mechanism. It seems, for instance, difficult to arrive at a value of r_ψ as small as 0.72 by a mechanism which would set in gradually beyond S-U, and/or suppress only a fraction of the ψ's, as in a scenario advocating the suppression of resonances decaying into J/ψ, such as χ, for example. In order to attain the value $r_\psi \approx 0.7$, *all* resonances have to be suppressed above n_c.

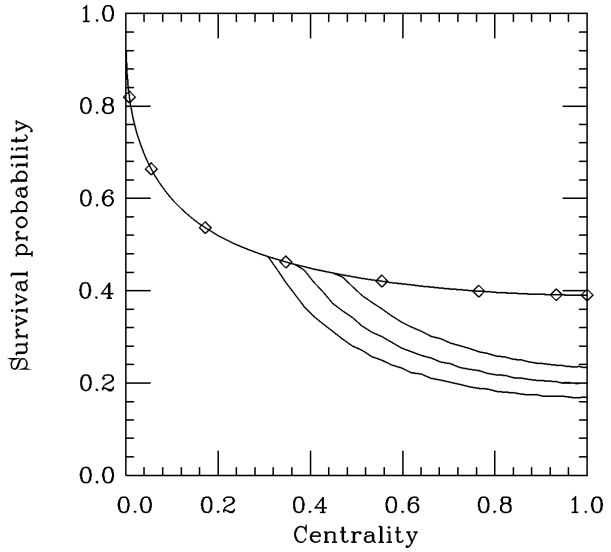

FIG. 3. The survival probability of a J/ψ in Pb-Pb collisions after absorption in nuclear matter and dissolution in a quark-gluon plasma [Eq. (7)]. For values $n_c > 4.4$ fm^{-2}, there is no suppression beyond nuclear absorption. The three curves showing an effect of the quark-gluon plasma correspond to $n_c = 3.7$, 3.5, and 3.3, respectively. The corresponding values of the ratio r_ψ [Eq. (2)] are, respectively, 0.82, 0.74, and 0.66. The diamonds indicate the value of the impact parameter, $b = 0, 2, \ldots, 14$ fm.

Since the suppression mechanism is very sensitive to the local energy density, the obtained value of r_ψ will also be sensitive to a number of factors. For example, it is sensitive to the parametrization of the nuclear density. Thus, by taking another common parametrization ($R_A = 1.19A^{1/3} - 1.61A^{-1/3}$, $a = 0.54$ fm) which makes the S nucleus smaller, we get $r_\psi = 0.72$ instead of 0.66. The deformation of the uranium nucleus could also slightly alter the value of r_ψ. We should also mention that, in comparing the two systems S-U and Pb-Pb, we have neglected the variation of the colliding energy, from 200 to 160 GeV. Such an energy shift results in a slight decrease of the multiplicity density (in p-p collisions, this can be estimated from [10] to be about 4%). On the other hand, the energy density is likely to increase with the number of participants faster than linearly, as was assumed in our calculation. These effects should be taken into account in a more complete calculation. It should also be stressed that none of the results on which we rely are totally model independent, since the ratios r_ψ are obtained after extraction of nuclear absorption.

It would obviously be desirable to get confirmations of the present scenario from independent observables. In particular, it is worth recalling that the existence of a threshold effect is not a clear-cut theoretical prediction [11]. It is therefore crucial to confirm experimentally such an effect and to determine the corresponding density; this could be achieved by exploring collisions with smaller targets. There are also several effects which could be looked for in the Pb-Pb data, and which, if observed, would give confidence in the overall picture. These include the effect of fluctuations at large transverse energy, and the expected saturation with centrality of the ratio $r_{\psi'}/r_\psi$ and of the average transverse momentum squared of the J/ψ's. We now discuss these three points.

It can be seen in Fig. 3 that r_ψ is very sensitive to the value of the critical density. One can get a simple estimate by considering sharp sphere nuclear densities, and by neglecting nuclear absorption. Then $r_\psi(0) = (n_c/n_p^{\max})^4$ for $n_p^{\max} > n_c$, in rough agreement with the results displayed in Fig. 3. We can write this same ratio in terms of energy densities: $r_\psi(0) = (\epsilon_c/\epsilon_{\max})^4$. Thus, ϵ_c being fixed, a 10% increase in $\epsilon_{\max}$ due to fluctuations, leads to a decrease of about 30% in $r_\psi(0)$. One could therefore observe a further noticeable decrease of r_ψ in collisions involving the largest transverse energies.

It has been observed in the S-U system that the ratio $r_{\psi'}/r_\psi$ decreases with increasing centrality. Because there are evidences that the J/ψ and the ψ' suffer the same nuclear absorption [12], it is natural to attribute the extra suppression to collisions with comovers (it is

plausible that the loosely bound ψ' is more easily destroyed in hadronic collisions than the J/ψ). However, in the present scenario, both the J/ψ and the ψ' are destroyed before the comovers have a chance to do anything. As a result, the ratio $r_{\psi'}/r_\psi$ remains approximately constant as a function of centrality, as soon as the critical density is reached, i.e., for $b < b_c$. This is easily deduced from Eq. (7): When $b \leq b_c$, $r_{\psi'}(b)/r_\psi(b) \approx \mathcal{N}_{\rm com}(b_c)\mathcal{N}_{\psi'}(b_c)/\mathcal{N}_\psi(b_c)$, and is approximately independent of b, while it should decrease if no plasma is produced. We have made a crude estimate, using the model discussed in [4] of the quantity $\mathcal{N}_{\rm com}$, which is the survival probability of the J/ψ after its interactions with comovers. The values that we obtain depend somewhat on parameters. However, the saturation of the ratio $r_{\psi'}(b)/r_\psi(b)$ with increasing centrality is a fairly robust consequence of the model.

A natural explanation for the variations of the J/ψ p_T distributions observed in nuclear collisions has been given in terms of initial state scatterings [13]. In this picture, the increase of $\langle p_T^2 \rangle$ at impact parameter b is given by $\langle p_T^2 \rangle = \langle p_T^2 \rangle_0 + C\,\bar{n}_{AB}(b)$, where C is a constant whose value can be determined from proton-nucleus data and

$$\bar{n}_{AB}(b) = \frac{1}{T_{AB}(b)} \int d^2s\, T_A(\mathbf{s}) T_B(\mathbf{s} - \mathbf{b}) \times [T_A(\mathbf{s}) + T_B(\mathbf{s} - \mathbf{b})]\, \mathcal{N}(b) \qquad (8)$$

is the average density of nucleons seen by a J/ψ. The factor $\mathcal{N}(b)$ has been left out in previous analysis. However, it is important whenever the suppression is large. In particular, it is responsible here for the fact that $\bar{n}_{AB}(b)$ remains roughly constant when $b < b_c$, while, in the absence of a plasma, $\bar{n}_{AB}(b)$ would continue to increase by some 25%. This result, at variance with early expectations that a quark gluon plasma would strongly affect the J/ψ momentum distribution [14], comes from the fact that in the present scenario *all* the J/ψ's need to be suppressed, irrespective of their transverse momentum, when $b < b_c$.

In conclusion, we have explored a scenario in which J/ψ production is totally suppressed in regions where the energy density exceeds some critical value. Quantitative agreement with the present NA50 data is obtained by choosing the critical density slightly greater than the density attained in central S-U collisions. The fact that the maximum densities reached in the Pb-Pb and S-U systems may differ by no more than 35% suggests a strong sensitivity of the suppression mechanism to small changes in the energy density. It makes it difficult to interpret the present Pb-Pb data in terms of collisions with comovers (such an interpretation is also made difficult by the theoretical arguments developed in [15]). It is therefore tempting to speculate that the large increase in the suppression is due to a dramatic change in the properties of the produced matter, pointing to the possible production of the quark-gluon plasma. We wish to stress, however, that the picture presented in this letter is very crude, and although it appears to account for the bulk features of the present data, many refinements need to be worked out, and detailed confrontations with more data need to be made, before unambiguous conclusions can be drawn.

We wish to thank the members of the NA50 Collaboration for discussions concerning their data.

Note added.—After this work was completed, we learned from D. Kharzeev that he and H. Satz have done similar estimates.

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