J/Ψ Suppression in Pb–Pb Collisions: A Hint of Quark–Gluon Plasma Production?

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The strong suppression of J/Ψ production recently observed in Pb–Pb collisions can be accounted for by a model which relates the suppression mechanism to the local energy density. In Pb–Pb collisions, the latter reaches values larger than in any other system studied previously.

1. INTRODUCTION

The NA50 collaboration has 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 [2]. Since such models account well for all the published data on J/Ψ production in proton–nucleus and nucleus–nucleus collisions, 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 order to explore this possibility, we adopt a simplified description [4], in which *all the J/Ψ's produced in a region where the energy density exceeds some critical value are suppressed.* As we shall see, this simple picture can account for the data, if one chooses for the critical density a value slightly higher than that achieved in central S–U collisions [5].

2. NUCLEAR ABSORPTION

Hard processes, such as the production of Drell–Yan muon pairs, or that of $c\bar{c}$ pairs, have a cross section proportional to the number of nucleon–nucleon collisions at impact parameter b, i.e. to $T_{AB}(b)\,\mathrm{d}^2b$, where

$$T_{AB}(b) = \int \mathrm{d}^2s\, T_A(\mathbf{s})\, T_B(\mathbf{s}-\mathbf{b}), \tag{1}$$

and

$$T_A(\mathbf{s}) = \int_{-\infty}^{+\infty} \rho_A(\mathbf{s},z)\mathrm{d}z \tag{2}$$

is the density of nucleons in the plane perpendicular to the collision axis. When integrated over impact parameter the cross section of hard processes is therefore proportional to AB.

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By contrast, the J/Ψ production cross section in proton–nucleus or nucleus–nucleus collisions is observed to increase more slowly than AB, an effect commonly referred to as "J/Ψ suppression". The J/Ψ production cross section at impact parameter b can be generally written as follows:

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

The factor $\mathcal{N}(b)$, which is smaller than unity, can be interpreted as the probability that a J/Ψ survives final state interactions.

The contribution of nuclear absorption [6,2] to the survival probability, which we denote by $\mathcal{N}_{abs}$, is approximately given by

$$\mathcal{N}_{abs}(b) \approx \exp\left(-\frac{\sigma_a \bar{n}_{AB}}{2}\right), \tag{4}$$

where σ_a is an absorption cross section, and

$$\bar{n}_{AB}(b) = \frac{1}{T_{AB}(b)} \int \mathrm{d}^2 s\, T_A(\mathbf{s}) T_B(\mathbf{s}-\mathbf{b})\ [T_A(\mathbf{s}) + T_B(\mathbf{s}-\mathbf{b})] \tag{5}$$

is the average density of nucleons, per unit transverse area, as seen by a J/Ψ. According to eq.(4), all dependence of $\mathcal{N}_{abs}(b)$ on the system, and on the impact parameter, is contained in $\bar{n}_{AB}(b)$, or equivalently in the average length traveled by the J/Ψ in the nucleus $\bar{L}_{AB} = \bar{n}_{AB}(b)/2\rho_0$ (ρ_0 is the nuclear density).

This absorption picture explains both the proton–nucleus data and the nucleus–nucleus data up to the S–U system, with a common value of the absorption cross section ($\sigma_a \approx 6.2$ mb [1]). However, the Pb–Pb data exhibit a significant deviation from this common trend. One can measure this deviation by the ratio

$$r_\Psi(b) = \frac{\mathcal{N}(b)}{\mathcal{N}_{abs}(b)}. \tag{6}$$

where $\mathcal{N}(b)$ is the measured value of the survival probability. Assuming that the last bin in transverse energy corresponds to central collisions, i.e. to $b \approx 0$, one extracts from the NA50 data the value $r_\Psi(b=0) \approx 0.50$. Another measure of the "anomaly" of the Pb–Pb data is provided by the ratio of the survival probabilities integrated over the impact parameter:

$$r_\Psi = \frac{\mathcal{N}}{\mathcal{N}_{abs}} \tag{7}$$

where the integrated value $\mathcal{N}$ is related to $\mathcal{N}(b)$ by $\mathcal{N} = (1/AB)\int \mathrm{d}^2 b\, T_{AB}(b)\mathcal{N}(b)$, and similarly for $\mathcal{N}_{abs}$. The value of r_Ψ reported by NA50 is 0.72 ± 0.03.

3. TOTAL SUPPRESSION AT LARGE DENSITY

We shall now show that one can account for the values of these two ratios, r_Ψ defined in eq.(7), and $r_\Psi(b=0)$ defined in eq.(6), by assuming that all the J/Ψ's produced in a region where the energy density exceeds some critical value are destroyed (see also the contribution by D. Kharzeev [7]).

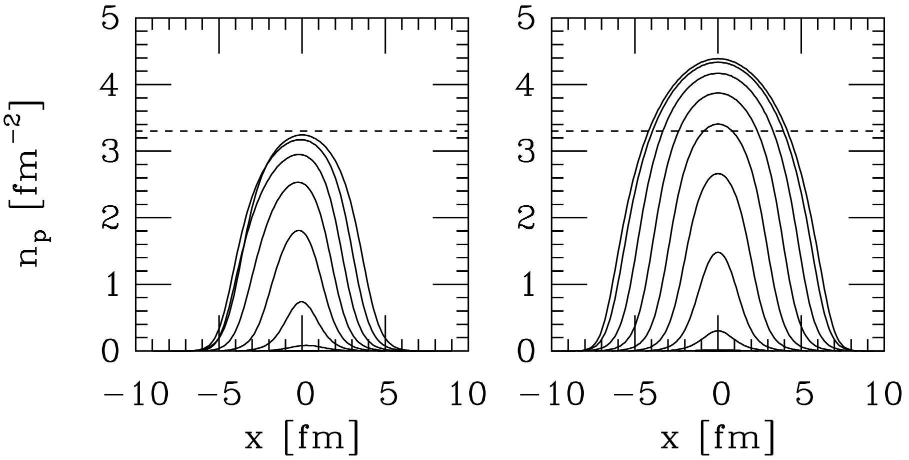

Figure 1. The density of participants $n_p(s)$, for s along the direction of the impact parameter, for various values of the impact parameter: $b = 0, 2, 4 \cdots$ fm. The origin is at a distance $b/(1 + R_B/R_A)$ from the center of nucleus A. Left: S–U collision; right: Pb–Pb collision. The horizontal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

To estimate this density, we assume that it is proportional to the density of participant nucleons per unit transverse area. 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 [8]. The density of participants per unit transverse area is given by

$$n_p(\mathbf{s}, b) = T_A(\mathbf{s}) \left[1 - \exp\left(-\sigma_N T_B(\mathbf{s} - \mathbf{b})\right)\right] + T_B(\mathbf{s} - \mathbf{b}) \left[1 - \exp\left(-\sigma_N T_A(\mathbf{s})\right)\right], \quad (8)$$

where $\sigma_N \approx 32$ mb is the nucleon–nucleon inelastic cross section. A plot of n_p is shown in Fig.1 for the two systems S–U and Pb–Pb. One sees that up to impact parameters of about 8 fm, there are regions in the Pb–Pb system where this density exceeds that in central S–U collisions (this should be contrasted with the average energy density $(1/R^2)\mathrm{d}E_T/\mathrm{d}y$ which is approximately the same in the two systems). The maximum density achieved in Pb–Pb is about 35% larger than in S–U.

Given the fact that no suppression is needed in S–U collisions other than nuclear absorption, the critical density n_c has to be bigger than the highest value attained in S–U collisions, i.e. 3.3 fm^{-2}. Choosing this particular value for n_c yields the maximum suppression. We obtain thus $r_\Psi = 0.66$, to be compared with the value $r_\Psi = 0.72$ obtained by NA50. Furthermore, for central collisions, we find $r_\Psi(b = 0) = 0.44$, to be compared with the value $r_\Psi(b = 0) \approx 0.50$ of NA50. Thus the two main observations of NA50 can be accounted for quantitatively by this simple picture. The fact that one gets slightly more absorption than observed can be easily remedied by raising the value of the critical density. On the other hand, we note that an absorption stronger than that predicted by the present model would have been difficult to explain.

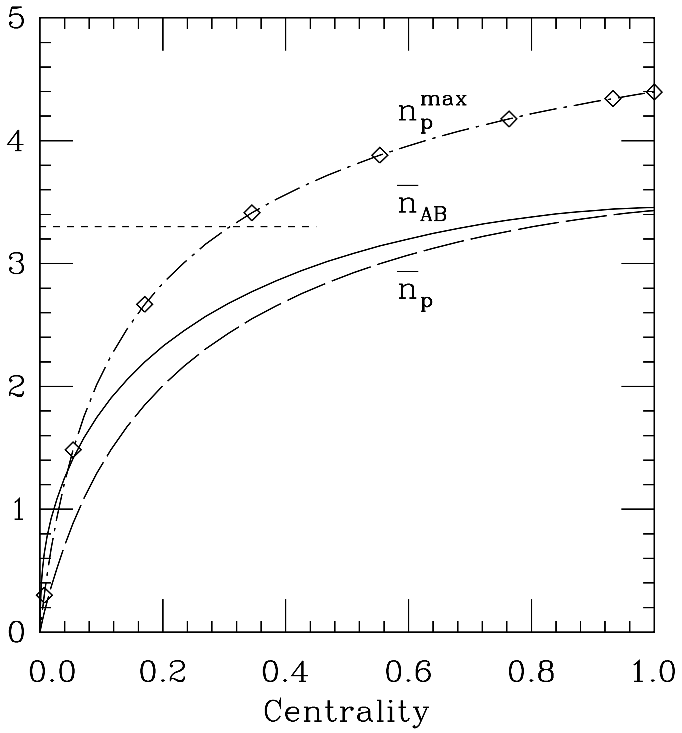

Figure 2. Average densities in fm^{-2} of nucleons ($\bar{n}_{AB}$) and participants ($\bar{n}_p$) as a function of centrality for a Pb–Pb collision. Also shown is n_p^{max}, the maximum value of n_p. The diamonds indicate the values of the impact parameter b. From right to left: $b = 0, 2, \cdots, 16$ fm.

4. COMOVERS

The J/Ψ can also be destroyed by scattering on particles produced during the collision, usually referred as comovers. At short times, the density of comovers is proportional to the density of participants n_p and decreases with time like $1/t$ as a result of the longitudinal expansion. The fraction of J/Ψ's surviving at time t is approximately given by a formula analogous to eq.(4) [9,4]:

$$\mathcal{N}_c(b) \approx \exp\left(-\sigma_c \bar{n}_p \log(t/t_0)\right). \tag{9}$$

In this equation, σ_c is an effective cross section and $\bar{n}_p(b)$ is the average density of participants seen by the J/Ψ. $\bar{n}_p(b)$ is obtained by replacing $T_A(\mathbf{s}) + T_B(\mathbf{s}-\mathbf{b})$ with $n_p(\mathbf{s}, b)$ in eq.(5). The logarithmic factor accounts for the longitudinal dilution, and t_0 is some initial time.

The variation of J/Ψ suppression with nuclear size and impact parameter, as given by eq.(9), is governed by the average density of participants $\bar{n}_p$, in the same way as nuclear absorption is governed by the average density of nucleons $\bar{n}_{AB}$ (see eq.(4)). As can be seen in Fig. 2, $\bar{n}_p(b)$ and $\bar{n}_{AB}(b)$ are not too different, and exhibit similar behaviours as a function of the centrality of the collision (we define the centrality as the ratio $N_p(b)/N_p(b=0)$, where $N_p(b)$ is the total number of participants at impact parameter b: $N_p(b) =$

$\int d^2s\, n_p(\mathbf{s},\mathbf{b})$). This means that the absorption by nucleons, or that by comovers at short times, vary essentially in the same way, so that one mechanism may easily hide the other.

However, unlike nuclear absorption which only takes place at short times, comover absorption continues until the system becomes too dilute. The total suppression by comovers can be written in the form

$$\mathcal{N}_c(b) \approx \exp\left(-\sigma_c \bar{n}_p \log(t_f/t_0)\right), \tag{10}$$

where t_f is an effective freeze out time, of the order of the transverse size of the interaction region. The logarithmic term makes the absorption by comovers more strongly dependent on the projectile size and impact parameter than nuclear absorption. Note, however, that there is a large arbitrariness in the choice of t_0, and that the dependence of t_f on impact parameter is not accurately determined.

Eq.(10) indicates the qualitative behaviour one can expect from comover calculations. Since the logarithmic term does not vary in proton–nucleus systems, comover absorption and nuclear absorption are indistinguishable in these systems. One could then play with the logarithmic term to reproduce both p–A data and Pb–Pb data, but at the expense of getting too much absorption in the S–U system (since the latter is well accounted for by nuclear absorption alone). Of course, this is just the general trend: how well one can account for the data in this way needs to be determined by careful calculations [10].

5. FLUCTUATIONS IN CENTRAL COLLISIONS

The transverse energy E_T of an event is not exactly a function of the impact parameter, because of statistical (approximately gaussian) fluctuations, of the order of 10–20% from event to event. Nuclear absorption depends only on the impact parameter and is therefore insensitive to the fluctuations in E_T : as a result, it saturates for very central collisions, as is seen for example in S–U collisions. However, the other sources of J/Ψ suppression (comovers or quark–gluon plasma) are sensitive to the fluctuations in E_T, since a higher E_T means a higher density of produced particles.

One can estimate simply the corresponding variation of $r_\Psi(0)$ by assuming that the density of produced particles is proportional to the transverse energy. In the case of comovers, r_Ψ decreases exponentially as $r_\Psi = \exp(-kE_T)$, with k constant. Then a fluctuation δE_T produces a variation δr_Ψ with

$$\frac{\delta r_\Psi}{r_\Psi(0)} = \log(r_\Psi(0))\frac{\delta E_T}{E_T} \tag{11}$$

In the case of a quark–gluon plasma formed above a threshold density n_c, one may get a simple estimate by considering sharp sphere nuclear densities, and neglecting nuclear absorption. One finds $r_\Psi(0) = (n_c/n_p^{\max})^4$ for $n_p^{\max} > n_c$. Taking again the density of particles to be proportional to E_T, this gives $r_\Psi(0) \propto E_T^{-4}$. One then obtains instead of eq.(11):

$$\frac{\delta r_\Psi}{r_\Psi(0)} = -4\frac{\delta E_T}{E_T} \tag{12}$$

Thus, the variation δr_Ψ given by eq.(12) is much stronger than with comovers, eq.(11). This could be used to disentangle the various suppression mechanisms.

6. CONCLUSIONS

In summary, we have shown that the new data on J/Ψ production in Pb–Pb collisions can be understood quantitatively in a scenario in which what suppresses the J/Ψ depends only on the local energy density. It is clearly too early to draw definite conclusions from this observation. But the present data certainly provide a strong motivation to carefully reexamine the various theoretical aspects of J/Ψ production in nuclear collisions.

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