AN ALTERNATIVE MECHANISM OF J/ψ SUPPRESSION IN HEAVY ION COLLISIONS

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We argue that J/ψ suppression observed recently in high energy oxygen–uranium collisions by the NA38 Collaboration at CERN need not imply that the quark–gluon plasma was produced. A considerable part of the effect may be caused by the disintegration of J/ψ's in collisions with dense hadronic matter (below the phase transition into quark–gluon plasma) produced simultaneously with J/ψ in heavy ion interactions.

In their pioneering paper Matsui and Satz [1] have pointed out that J/ψ suppression in heavy ion collisions could provide a signature of the quark–gluon plasma (QGP) formation. Karsch and Petronzio [2] have studied the dependence of J/ψ suppression on the transverse momentum of J/ψ in a specific model and they have shown that the suppression should decrease with increasing p_T of J/ψ.

The NA38 Collaboration at CERN [3] have recently measured a J/ψ signal (N_ψ) and the dimuon continuum (N_c) in the J/ψ mass region within the pseudorapidity window $2.75<\eta<4.0$ for low and large values of the total neutral transverse energy E_{0T} released within $1.95<\eta<4.15$. They have found that

$$\frac{N_\psi/N_c(E_{0T}>50\ \mathrm{GeV})}{N_\psi/N_c(E_{0T}<28\ \mathrm{GeV})}=0.64\pm0.06\,, \qquad (1)$$

and obtained evidence on the decrease of J/ψ suppression with increasing p_T of the J/ψ. Karsch and Petronzio [4] have presented a qualitative analysis of the NA38 data and have shown that the p_T dependence of J/ψ suppression might be consistent with plasma formation. The longitudinal momentum dependence of J/ψ suppression by the quark–gluon plasma has been studied by Ruuskanen and Satz [5].

At first sight it might seem that the results of the NA38 Collaboration provide evidence for the QGP formation in ^{16}O–U collisions at 200 GeV/nucleon. There are however two items which raise some doubts about this straightforward interpretation.

First, the NA34 and NA35 Collaboration's data [6,7] can be well described as due to incoherent sums of individual nucleon–nucleon collisions [8].

Second, the energy density of the QGP taken as a gas of free quarks and gluons is about 2.5 GeV fm^{-3} at $T_c=200$ MeV. This is about the same as the energy density reached in the NA38 experiment. Consider an NA38 event with $E_{0T}\sim 50$ GeV distributed over two rapidity units. The total transverse energy per one rapidity unit is about 3×25 GeV$=75$ GeV. This is distributed within a volume $\pi R^2 l$, where R is the ^{16}O radius, $R\approx3$ fm, and l is the longitudinal dimension of the volume at the moment when the matter is formed. Taking the standard estimate [9] $l=1$ fm we obtain for the energy density 75 GeV$/\pi R^2 l=2.7$ GeV fm^{-3}, which is only slightly above the energy density of the QGP at $T=T_c$. It seems improbable that the QGP were formed for a time interval long enough to permit the QGP signatures to be seen. Note also that Debye screening responsible for J/ψ suppression should be more efficient at $T\approx1.5\ T_c$ than just at the threshold $T=T_c$.

We believe that in this situation it is useful to have an alternative mechanism for J/ψ suppression in heavy ion collisions with which J/ψ suppression due to QGP could be compared.

The purpose of this note is to discuss the simplest possible alternative: the suppression of J/ψ caused by its disintegration in collisions with hadronic matter that has been formed in the same heavy ion collision, but did not reach the QGP stage.

The energy density of hadronic matter formed in

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central oxygen–uranium collisions in the NA38 experiment is about 2.5 GeV fm^{-3}. In order to be able to estimate the amount of disintegrated J/ψ's, we have to make some assumptions about the composition of this matter and about its interaction with J/ψ's. To keep our model as simple as possible, we shall assume that the hadronic matter is in the form of a pion gas. Taking the average energy of one pion with $y^* \approx 0$ as 0.5 GeV, we obtain for the pion density

$$\rho_\pi \approx 2.5 \text{ GeV fm}^{-3}/0.5 \text{ GeV} = 5 \text{ fm}^{-3} .$$

We realize that such a high density can only be reached at temperatures well above the expected value of T_c. But if we took also other hadron species into consideration, the hadron density of about 5 fm^{-3} would correspond to a reasonable temperature.

Another paradox connected with high pion density as estimated above is a sizeable overlap of individual pions (the volume occupied by a free pion is about 0.85 fm^3). Hadronic matter in this situation is certainly far away from the ideal pion gas, but could perhaps be approximated as a gas of constituent quarks and antiquarks. Fortunately, the estimates of disintegration rate of J/ψ are more or less independent of whether we look at this matter as a pion gas or a gas of constituent quarks and antiquarks. It follows from the fact that the smaller cross section for J/ψ disintegration in the constituent quark gas (by a factor of 2 if one believes in additive quark model) is compensated by its twofold particle density.

In the next step we have to estimate the probability of J/ψ disintegration caused by collisions with pions. Since nothing is known experimentally about π+J/ψ cross sections we have to be guided by information available on nucleon+J/ψ interactions. From the data on photo- and hadro-production of J/ψ on nuclei [10] it is known that the total nucleon–J/ψ cross section [#1] is 1–3 mb.

The elastic N+J/ψ cross section is negligible, the inelastic one is very small below the threshold for $N+J/\psi \to N+D+\bar{D}$ and raises fast to the quoted value of 1–3 mb above this threshold [11].

For pion+J/ψ interactions we shall assume that the cross section vanishes below the threshold for $\pi+J/\psi \to D+\bar{D}+\pi$ and $\sigma \equiv \sigma(\pi+J/\psi) = 1$ mb or 2 mb above this threshold.

The spatial distribution for the pion gas formed in the central ^{16}O–U collision is taken as

$$\rho(r) = \tfrac{3}{2}\sqrt{1-r^2/R^2}\cdot 150/\pi R^2 l , \qquad (2)$$

where the first factor takes into account that the density of pions is proportional to the number of nucleon–nucleon collisions at a given value of r (the transverse distance in central collision), the number 150 in the numerator is dN_π/dy for an event with E_{0T} of 50 GeV in the NA38 experiment [#2]. Here and in what follows index 1 refers to J/ψ and index 2 to pions. The probability distribution of momenta of pions near $y^* \approx 0$ is taken as

$$P(\boldsymbol{p}_2) = A \exp[-(\boldsymbol{p}_2^2 + m_\pi^2)^{1/2}/T_0] , \qquad (3)$$

where $T_0 = 200$ MeV is a phenomenological parameter, obtained from data on the p_T distribution of pions in pp collisions. The density of pions in space and momentum $\rho(\boldsymbol{p}_2, \boldsymbol{r})$ is simply given by the product $\rho(\boldsymbol{r})P(\boldsymbol{p}_2)$.

Before coming to more detailed calculations we shall perform a simple estimate of the effect expected. Let us consider a J/ψ created with vanishing momentum. the probability for its disintegration by the pion gas is

$$P_{dis} = 1 - \exp(-T) ,$$

$$T \doteq \rho_\pi c \Delta t P(E_2 > E_0) ,$$

where $P(E_2 > P_0)$ is the probability that pion energy E_2 is above the threshold E_0 for the $\pi+J/\psi \to D+\bar{D}+\pi$ reaction with J/ψ at rest. The calculation based on eq. (3) gives $P(E_2 > P_0) = 0.205$. The pion gas is assumed to be present for $\Delta t = R/c = 3$ fm/c. Taking $\sigma = 0.1$ fm^2, $\rho_\pi = 5$ fm^{-3} we obtain $T = 0.31$ and the probability for the J/ψ disintegration becomes $1-\exp(-T) = 0.27$. Higher σ would lead, of course, to even higher suppression. Such a large suppression might seem surprising, since it is

[#1] The photo-production data tend to give lower cross sections, perhaps because the time of the J/ψ formation from c and $\bar{c}$ has not been taken into account. This argument would prefer $\sigma(N+J/\psi) \approx 3$ mb. This value is also acceptable on geometrical grounds; taking the J/ψ radius of 0.3 fm one could expect that J/ψ hadronic cross sections would be about 1/4 of pion–hadron cross sections, what would lead to $\sigma(N+J/\psi) \approx 5$ mb.

[#2] The total (charged plus neutral) energy within two rapidity units is about 150 GeV, what corresponds to 75 GeV per rapidity unit. Taking the transverse energy of a pion of about 0.5 GeV we obtain $dN_\pi/dy \approx 150$.

known that J/ψ absorption in nuclear matter is practically vanishing. The mean free path of J/ψ in nuclear matter is $l=1/\sigma(\mathrm{N}+\mathrm{J}/\psi)\rho_{\mathrm{N}}\approx 1/(0.2\ \mathrm{fm}^2\times 0.15\ \mathrm{fm}^{-3})\approx 30$ fm. But the density of pions that are able to disintegrate J/ψ is roughly 5 $\mathrm{fm}^{-3}\times 0.2=1\ \mathrm{fm}^{-3}$ for J/ψ at rest, what is 7 times larger than the density of nucleons in nuclei.

In an attempt at a realistic estimate of the experimental J/ψ suppression we have to take into account that about 40% of J/ψ [4,12] are produced via χ decays. The probability for the J/ψ disintegration is then calculated as

$$P_{\mathrm{dis}}=0.6[1-\exp(-T_{\mathrm{J}/\psi})]+0.4[1-\exp(-T_\chi)]\ .$$

The parameter T_χ can be estimated as above with obvious modifications in P and σ. The cross section for $\pi+\chi\to\mathrm{D}+\bar{\mathrm{D}}+\pi$ could be estimated from the calculated radii [4] of χ and J/ψ, $r_{\mathrm{J}/\psi}=0.453$ fm, $r_\chi=0.696$ fm as

$$\sigma(\pi+\chi)=(r_\chi/r_{\mathrm{J}/\psi})^2\sigma(\pi+\mathrm{J}/\psi)\ .$$

The suppression of χ in the pion gas is considerably larger than that of directly produced J/ψ, and it is easy to obtain the total suppression of J/ψ in the vicinity of 0.5, what is the value indicated experimentally, with $\sigma(\pi+\mathrm{J}/\psi)$ of about 1 mb.

We shall now describe the actual calculation in more detail.

The probability $P_{\mathrm{dis}}(\boldsymbol{p}_1,\boldsymbol{r}_1)$ for the disintegration of a J/ψ created with transverse momentum $\boldsymbol{p}_1$ in position $\boldsymbol{r}_1$ is given as

$$P_{\mathrm{dis}}(\boldsymbol{p}_1,\boldsymbol{r}_1)=1-\exp(-T)\ , \tag{4}$$

$$T=\frac{1}{2p_1}\int \mathrm{d}l\int \mathrm{d}^3p_2\,\frac{\rho(\boldsymbol{p}_2,\boldsymbol{r},t)}{E_2}\times\sqrt{(s-s_{\mathrm{a}})(s-s_{\mathrm{b}})}\,\sigma^*(s)\ ,$$

where $s_{\mathrm{a}}=(m_{\mathrm{J}/\psi}+m_\pi)^2$, $s_{\mathrm{b}}=(m_{\mathrm{J}/\psi}-m_\pi)^2$, $\boldsymbol{r}=\boldsymbol{r}_1+\boldsymbol{v}_1t$, $\mathrm{d}l=|\mathrm{d}\boldsymbol{r}|$, and the integral goes over the path travelled by the J/ψ in the pion gas, the factor $[1/(2p_1E_2)]\sqrt{(s-s_{\mathrm{a}})(s-s_{\mathrm{b}})}$ is the flux factor which takes into account noncollinearity of J/ψ and π [13]. The density of pions $\rho(\boldsymbol{p}_2,\boldsymbol{r},t)$ in the coordinate and momentum space is assumed to be factorized as $\rho(\boldsymbol{p}_2,\boldsymbol{r},t)=P(\boldsymbol{p}_2)\rho(\boldsymbol{r})$ with $\rho(\boldsymbol{r})$ and $P(\boldsymbol{p}_2)$ given by eqs. (2) and (3). Finally, $\sigma^*(s)$ is the cross section for the J/ψ disintegration in collinear collisions, nonvanishing only above the threshold for $\mathrm{D}+\bar{\mathrm{D}}+\pi$ formation.

Eq. (4) follows from the standard expression $\mathrm{d}n=\rho_1\rho_2|\boldsymbol{v}_1-\boldsymbol{v}_2|\sigma\mathrm{d}V\,\mathrm{d}t$ for the number of interactions of two crossing beams. In transcribing it to the form of eq. (4), we have used the fact that $E_1E_2|\boldsymbol{v}_1-\boldsymbol{v}_2|\sigma$ is Lorentz invariant and expressed σ for noncollinear collisions in terms of σ^* corresponding to collinear ones [13].

The suppression of χ is calculated also by eq. (4) with trivial modifications. In calculations we have to take into account also the formation times [#3] of J/ψ and χ [2,4]. In pp and A+B collisions the $\mathrm{c\bar{c}}$ system is formed in a very short time of about $\hbar/2m_{\mathrm{c}}$ with c and $\bar{\mathrm{c}}$ being close nearby. Only after a proper time $\tau_{\mathrm{J}/\psi}=0.89$ fm/c and $\tau_\chi=2.01$ fm/c J/ψ and χ are formed as bound states of c and $\bar{\mathrm{c}}$ [2,4]. For J/ψ and χ moving with velocity v this formation time is correspondingly Lorentz dilated. The J/ψ and χ interact with pions only after being formed so that for $t<\tau(1-v_1^2)^{-1/2}$ disintegration is prohibited.

The pion gas is assumed to be formed in time $t_1=1$ fm/c after the collision. then it expands and its density gradually decreases. In simplified calculations performed here we have taken $\rho(\boldsymbol{p}_2,\boldsymbol{r},t)$ as nonvanishing and time independent for $t_1=1\ \mathrm{fm}/c<t<t_2$ and vanishing for $t>t_2$ with t_2 between 2.5 and 3 fm/c. This simplification does not change the qualitative features of the results.

In calculating the probability of the disintegration of the J/ψ created with the transverse momentum p_{T} and CMS [#4] $y_1^*=0$ we proceed as follows. The $\mathrm{c\bar{c}}$ pair is created in a point r_0 with the probability density proportional to the number of nucleon–nucleon collisions in a central ^{16}O–Pb interaction. The probability density is proportional to $\sqrt{1-r_0^2/R^2}$. The J/ψ is fully formed after $\tau_{\mathrm{J}/\psi}/\sqrt{1-v_1^2/c^2}$. After that time it starts interacting with the pion gas formed at $t_1=1$ fm/c. the interaction stops either when pion gas disappears at t_2 or when the J/ψ leaves the cylinder with $R=3$ fm. The probability of J/ψ disintegration is then calculated by eq. (4) and the result is averaged over

[#3] Note that when discussing π+J/ψ collisions, the formation time should include also the time required for "dressing up" the $\mathrm{c\bar{c}}$ system by wee partons. We shall not consider this complication here and accept formation times as given in refs. [2,4].

[#4] Nucleon–nucleon CMS is meant.

the points $\mathbf{r}_0$ in which a $c\bar{c}$ pair is created and over the directions in which it moves.

The suppression of χ is calculated in the same way and both results are then weighted by 60% for J/ψ and 40% for χ.

In fig. 1 we plot the p_T dependence of J/ψ and χ suppression separately. Note that the amount of surviving J/ψ's decreases up to about 3 GeV/c. This is due to the increasing probability that $E_{CMS}(\pi+J/\psi)$ is above the $D+\bar{D}+\pi$ threshold. For J/ψ this effect is up to 3 GeV/c stronger than the increasing probability to escape from the region occupied by dense pion gas. For χ with its larger formation time and different threshold the latter effect dominates and the χ suppression decreases with p_T monotonically. In fig. 2 we compare the "experimental" (60% J/ψ and 40% χ) J/ψ suppression with the data. The comparison should serve only for illustrative purposes, because of numerous reasons: (i) our calculations are performed for $x_F=0$, whereas the data are integrated over x_F, (ii) we make no attempts at fits, since there are many parameters with uncertain values, like $\sigma(\pi+J/\psi)$, $\sigma(\pi+\chi)$, formation times, etc., (iii) we have not taken into account the expansion of the pion gas, except for possible changes in the parameter t_2, (iv) if J/ψ and χ are suppressed by the pion gas at

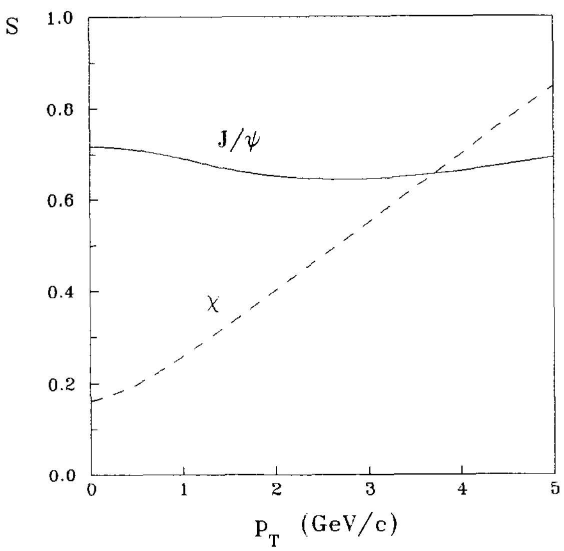

Fig. 1. P_T-dependence of directly produced J/ψ and χ suppression. $\sigma(\pi+J/\psi)=1$ mb, $\sigma(\pi+\chi)=2.36$ mb, $t_2=4$ fm.

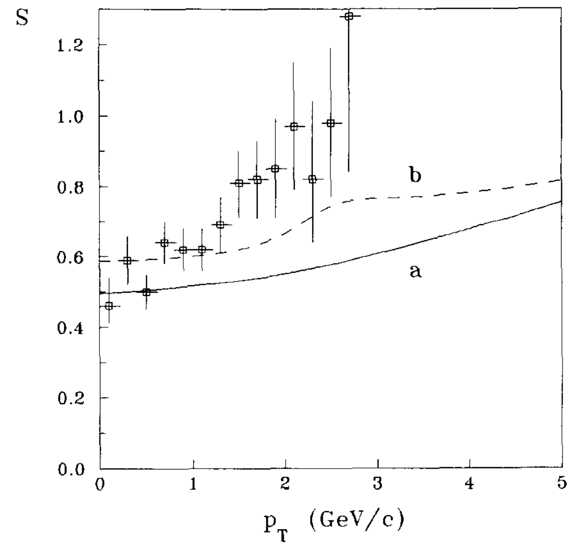

Fig. 2. The calculated ("experimental") J/ψ suppression (calculated as 60% J/ψ and 40% χ) compared with the data: (a) $\sigma(\pi+J/\psi)=1$ mb, $\sigma(\pi+\chi)=2.36$ mb, $t_2=4$ fm/c; (b) $\sigma(\pi+J/\psi)=2$ mb, $\sigma(\pi+\chi)=4.72$ mb, $t_2=2.5$ fm/c.

$E_{0T}>50$ GeV we should expect some, although smaller suppression of J/ψ and χ also at total transverse energy E_{0T} below 25 GeV. The data are in fact ratios of these suppressions at $E_{0T}>50$ GeV and $E_{0T}<25$ GeV, (v) we have taken the hadronic matter formed in the collision as consisting only of pions, what is also unrealistic and other hadrons should be included, (vi) we have neglected the J/ψ and χ suppression due to nucleons originally present in colliding nuclei.

Note that our results in fig. 2 have systematically smaller slope than calculations by Karsch and Petronzio [4] based on their model of the behaviour of QGP and smaller than indicated by the data [3]. Still, we believe that our oversimplified model gives indications that a considerable part of the experimentally observed J/ψ suppression might be caused by the J/ψ and χ disintegrations by collisions with hadrons in a dense hadronic matter produced in O+U collisions.

To conclude: J/ψ suppression is not a specific feature of the quark–gluon plasma, J/ψ is suppressed also in collisions with the dense hadronic matter formed in heavy ion collisions [#5]. The amount of J/ψ suppression by this hadronic matter is of the same order of magnitude as the data obtained by the NA38 collaboration. Stronger statements can hardly be made since the J/ψ suppression by hadronic matter depends on poorly known parameters like the disintegration cross section of pion$+J/\psi$ and pion $+\chi$ collisions, formation time of J/ψ and χ and formation time of hadronic matter.

It is most desirable to have simple qualitative criteria permitting to distinguish the J/ψ suppression by dense hadronic matter and by the presence of the quark–gluon plasma. Some of the possibilities are:

(i) looking for threshold effects in E_{0T} – in more peripheral collisions with lower E_{0T} QGP formation is expected, the suppression caused by the QGP should vanish below some value of E_{0T}, whereas the suppression by collisions with hadronic matter is present and in principle calculable;

(ii) looking for thresholds in nucleon numbers of interacting nuclei (for smaller nuclei no QGP formation is expected).

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Note added. Just before submitting the amended version for publication we have received a preprint [14] where the J/ψ suppression by disintegration in dense hadronic matter is also studied. The results are in qualitative agreement with ours. We are indebted to the authors of ref. [14] for sending us their preprint.

[#5] In fact, both mechanisms may be rather similar – in the QGP J/ψ is suppressed by Debye screening, in a collision of J/ψ with a constituent quark (within a pion) the gluons exchanged between c and $\bar{c}$ are terminated on the constituent quark and the binding of c and $\bar{c}$ gets weaker what might lead to disintegration of J/ψ.

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