MOMENTUM DISTRIBUTION OF J/ψ IN THE PRESENCE OF A QUARK–GLUON PLASMA

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Received 10 April 1987

The presence of a quark–gluon plasma can partly suppress the J/ψ formation leading to a distortion of its normal momentum distributions. We analyse the modifications of the differential cross section $d\sigma/d^3p$ as a function of the fraction of the interaction region occupied by a hot quark–gluon plasma where the J/ψ formation is inhibited.

The idea that hadrons at finite temperature melt into a quark–gluon plasma has received in the last years more and more support from "lattice laboratory experiments", performed inside boxes of a few fermi size. The existence of the transition at a temperature of about a couple of hundred MeV seems established [#1], while the nature of the phase transition is still a matter of debate [1] [#2]. The possibility of providing a standard experimental evidence for the transition relies on heavy ion collisions at high energies where the critical values of matter density and temperature can be reached. A major problem is, however, represented by the identification of the observables which can be used to monitor the occurrence of the transition [3]. An interesting suggestion has been recently made by Matsui and Satz [4]. They argue that J/ψ production is suppressed in a quark–gluon plasma if the temperature is still sufficiently high at the time the J/ψ is formed. The statement relies on the fact that inside the plasma the confining part of the QCD potential does not exist anymore and that the Coulomb part is affected by Debye screening. The standard conditions for binding a $c\bar{c}$ pair into a J/ψ are missing, if the Debye mass (screening length) in the plasma is large (small) enough. The formation of a $c\bar{c}$ bound state being impossible, the $c\bar{c}$ pair will only give rise to charmed particle pairs. In ref. [4] it has been estimated that the screening length ξ in the plasma phase should fullfil the condition

$$\xi < \xi_c = (0.3\text{–}0.5)\ \mathrm{fm} \tag{1}$$

in order to forbid the formation of J/ψ. Monte Carlo simulations seem to indicate that this condition can already be reached for temperatures only little higher than the critical temperature, i.e. $T \geqslant (1.2\text{–}1.5)\ T_c$ [5,6] [#3].

In this letter we want to analyze the dependence of the above mentioned suppression mechanism upon the J/ψ momentum as well as upon the size of the hot plasma region which satisfies eq. (1). We will only discuss the "hard" production mechanism; the so-called "diffractive part" probably escapes in any case the plasma which is typically sitting in the central rapidity region. Our argument goes as follows. The $c\bar{c}$ pair formation is a short distance phenomenon occurring at distances of the order of $1/M$ (approximately equal to 0.05 fm)

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[#1] For a review of Monte Carlo data up to 1985 see ref. [1].
[#2] Recent Monte Carlo calculations indicate the possibility of a first-order chiral transition for QCD with four light flavours.
[#3] Present Monte Carlo calculations try to extract the Debye mass (screening length) from Polyakov loop correlation functions. This procedure does not straigthforwardly give the Debye screening mass of the heavy quark potential [7] and may, indeed, lead to an overestimate of the Debye mass for a given temperature. Thus, in fact, higher temperatures may be necessary to fullfil eq. (1).

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where M is the J/ψ mass [#4]. The quarks are at such a distance when they are created and have to reach the distance of about 0.2 fm which is a typical charmonium radius. Their relative motion is non relativistic, with a momentum of the order of 300 MeV and an energy of the order of their mass of, say, 1.5 GeV. To reach their binding radius, it takes them some time which we denote by τ. In the J/ψ rest frame, we can estimate

$$\tau = E/|\boldsymbol{p}|(0.2\text{–}0.05) \simeq 0.7 \text{ fm} . \tag{2}$$

This is also the time when the system starts to develop its thermal properties [3]. After the time τ, the J/ψ with a given momentum $\boldsymbol{p}$ in the laboratory will have covered a distance $\boldsymbol{r}$ given by

$$\boldsymbol{r} = \tau(\boldsymbol{p}/E)[1 - (|\boldsymbol{p}|/E)^2]^{1/2} = \boldsymbol{p}\tau/M , \tag{3}$$

where p and E refer to the J/ψ. After such a distance the resonance may be out of the plasma region and it can form normally. In order to estimate the influence of a hot plasma we had to make some crude approximations on the plasma region. We distinguish the interaction region, where $c\bar{c}$ pairs are initially formed, from the hot region, where the screening length is too small to allow for the formation of $c\bar{c}$ bound states. This is shown in fig. 1. As interaction region in the center of mass frame of the nucleus–nucleus collision we take a cylinder with the z-axis identified by the incoming nuclei's momentum. The height of the cylinder is assumed to be ~ 1 fm and the radius equal to $A^{1/3}$, A being the atomic number of the (lighter) projectile nucleus. The hot region is defined by a smaller cylinder centered in the interaction region with a radius

$$r_h = hA^{1/3}, \quad 0 < h \leqslant 1 . \tag{4}$$

We will determine a momentum dependent "acceptance function" $R(p_t, p_z)$, which gives the fraction of $c\bar{c}$ pairs created in the interaction region with transverse momentum p_t and longitudinal momentum p_z which converts into J/ψ without being affected by the plasma.

$$R(p_t, p_z) = \frac{\#c\bar{c}\text{ pairs with } p = (p_t, p_z) \text{ outside the hot region at } t = \tau/(1 - p^2/E^2)^{1/2}}{\#c\bar{c}\text{ pairs with } p = (p_t, p_z) \text{ created in the interaction region}} . \tag{5}$$

The calculation we have made is the following: We have generated $c\bar{c}$ pairs in the interaction region at points (x, y, z) according to a probability distribution given by

$$P(z) = 1, \quad P(x, y) = (A^{2/3} - x_t^2)^{1/2}, \quad x_t^2 = x^2 + y^2 . \tag{6}$$

The non-uniform distribution of transverse coordinates accounts for a higher nucleon density in the central

[#4] Indeed for J/ψ with large p_t the quarks are rather produced at a distance $1/(p_t^2 + M^2)^{1/2}$. For the J/ψ this does not change appreciably our considerations.

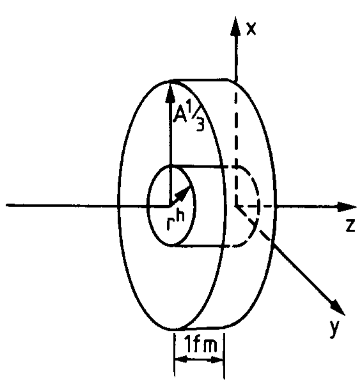

Fig. 1. Interaction region and hot region in the nucleus–nucleus collision.

region resulting from a compression of the spherical nucleus to a Lorentz-contracted disk. Given their momentum $\boldsymbol{p}$ we have calculated according to eq. (3) the position of the resonance at the time when the quark pair is at the binding distance. If this position is inside the hot region we say, following ref. [4], that the J/ψ is not formed, if it is out, we say that its production is not affected by the plasma. This procedure gives an acceptance function which varies between 0 and 1. In figs. 2 and 3 we show the results for $R(p_t, 0)$, i.e. the production of J/ψ with transverse momentum and zero rapidity, for various sizes of the hot region. Fig. 2 shows the results for the oxygen ($A=16$) and fig. 3 those for a heavier nucleus ($A=200$). For low p_t the A dependence is unimportant and the acceptance function is simply related to the distribution of interaction vertices in the hot and interaction region. From eq. (6) one finds

$$R(0,0)=(1-h^2)^{3/2}\,. \tag{7}$$

However, for larger transverse momenta the size of the nucleus becomes relevant. Clearly the suppression of J/ψ production due to a hot plasma is not very efficient for J/ψ with large p_t, as expected. Indeed, we have not taken into account the fact that the time dilatation effect for J/ψ with large p_t will increase the acceptance function for large p_t event more: J/ψ with a p_t of the order of 10 GeV will be formed at a time $t\simeq 3\tau$ (see eq. (5)) in the plasma rest frame. As the plasma cools rapidly and is not expected to last longer than about 2 fm, these high-p_t J/ψ will not be suppressed at all. This is indicated by the shadowed regions in figs. 2 and 3. A more careful study of this effect would require an analysis of the time evolution of the boundary of the hot region which we did not attempt in the present approach.

To achieve a suppression of J/ψ with momenta less than 5 GeV at least 30%, which should be detectable in present experiments with oxygen at the CERN SPS [#5], the radius of the hot region has to be larger than $0.5A^{1/3}$ for $A=16$. This situation improves somewhat in collisions with heavier nuclei as can be seen in fig. 3. The p_z dependence of the function is instead very much the same for different A given that the height of the cylinder is not affected by the nucleus size. Some values for $A=16$ and $p_z\neq 0$ are reported in table 1. In order to get an idea of how this acceptance function may affect real J/ψ distributions we have taken the data on proton–platinum J/ψ production of the experimental collaboration NA3 [9] and rescaled p_t distribution by the rapidity zero acceptance function given in fig. 2. In fig. 4 we report the result: the full line is the orginal distribution and the dashed and dash-dotted ones give distorted distributions for two different sizes of the hot

[#5] For a presentation of first results see ref. [8].

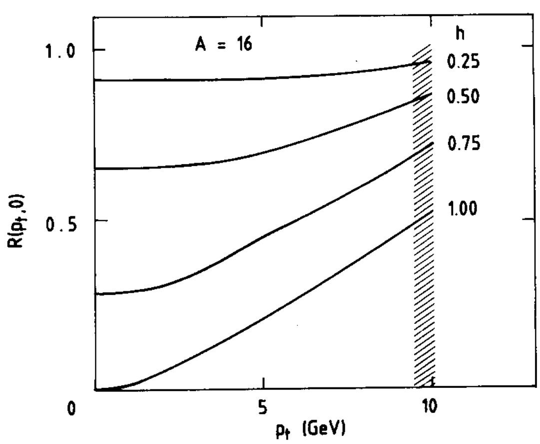

Fig. 2. The acceptance function $R(p_t, 0)$ versus p_t for $A=16$ and various sizes of the hot region, $h=0$, 0.25, 0.5, 0.75 and 1.0.

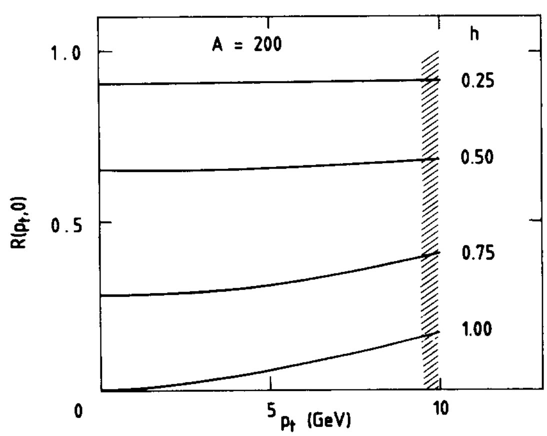

Fig. 3. Same as fig. 2 but for $A=200$.

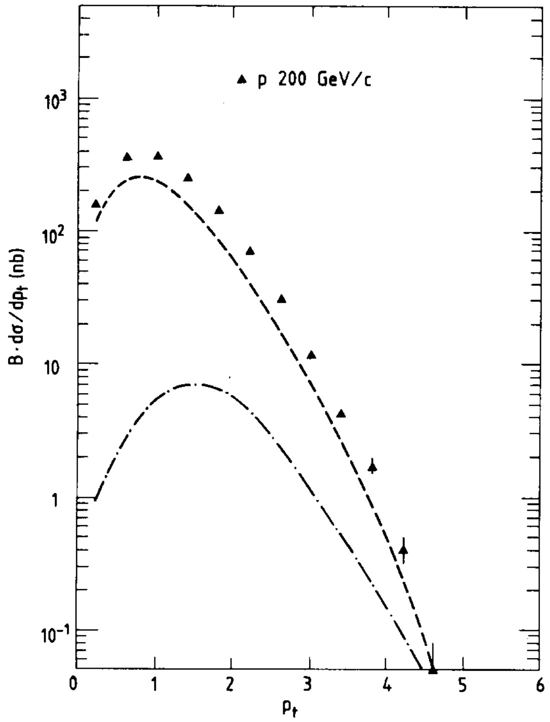

Fig. 4. Distortion of the J/ψ distribution in the presence of a quark–gluon plasma. The triangles show the original data of ref. [9] for the p_t distribution integrated over x_F in proton–platinum collisions at 200 GeV times the branching ratio B into a muon pair. The dashed (dash-dotted) curves indicate the shape of the distribution in the presence of a plasma, if the radius of the hot region is assumed to be $0.5A^{1/3}$ ($1.0A^{1/3}$). We have used the acceptance function for $x_F = 0$, since the p_t distribution does not vary much with x_F [9].

region. The distortion of the spectrum that we find depends in the details upon the explicit form used for the plasma, but the general features of the acceptance function are rather stable. The fact that the J/ψ does not completely disappear but is produced with a modified distribution leaves open the possibility of triggering on

Table 1
$R(p_t, p_z)$ for $A = 16$ and $h = 1.0$.

p_t	p_z						
	0.0	0.5	1.0	1.5	2.0	2.5	3.0
0.0	0.000	0.115	0.234	0.341	0.448	0.568	0.684
0.5	0.005	0.120	0.238	0.345	0.451	0.570	0.686
1.0	0.018	0.130	0.246	0.353	0.458	0.576	0.689
1.5	0.035	0.145	0.258	0.364	0.465	0.583	0.694
2.0	0.052	0.164	0.274	0.377	0.478	0.591	0.700
2.5	0.073	0.180	0.291	0.392	0.491	0.600	0.708
3.0	0.098	0.201	0.308	0.406	0.504	0.610	0.716
3.5	0.121	0.223	0.327	0.422	0.516	0.619	0.723
4.0	0.149	0.246	0.347	0.439	0.531	0.631	0.732
4.5	0.178	0.272	0.366	0.458	0.549	0.645	0.742
5.0	0.206	0.295	0.391	0.479	0.563	0.658	0.751
5.5	0.239	0.321	0.414	0.497	0.578	0.669	0.760
6.0	0.264	0.351	0.438	0.516	0.597	0.685	0.769
6.5	0.298	0.376	0.456	0.538	0.613	0.696	0.779
7.0	0.329	0.408	0.486	0.557	0.634	0.713	0.789

its signal, into muon pairs for example, which should still stem out from the very abundant background of hadrons produced in heavy ions collisions.

We thank M. Gyulassy and H. Satz for stimulating discussions.

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