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χ and J/Ψ suppression in heavy ion collisions and a model for its momentum dependence

F. Karsch [1] and R. Petronzio [2]
[1] CERN, CH-1211 Geneva 23, Switzerland
[2] University of Rome II, Department of Physics, TorVergata, via Orazio Raimondo, I-00173 Rome, Italy

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Abstract. The suppression of J/Ψ resonance production recently observed in heavy ion collisions contains some information also on the suppression of χ states which are known to be the source of a sizeable fraction of the observed J/Ψ. We analyze recent experimental data within a model that assumes quark-gluon plasma formation in a finite volume for a short time. We extract lifetimes for critical isotherms and obtain a value for the ratio of the Debye screening masses for χ and J/Ψ in the plasma consistent with estimates from lattice QCD. We also make some detailed predictions of the Ψ' suppression pattern and speculate about the extrapolation of the present oxygen results to heavier nuclei.

1 Introduction

The recent experimental results on J/Ψ production in heavy ion collisions have shown [1]:

i) a suppression of J/Ψ production with respect to the continuum background correlated with the total transverse energy of the underlying event

ii) a dependence of the effect upon the J/Ψ momentum, in particular a substantial amount of suppression at zero transverse momentum

iii) a disappearance of the Ψ' signal together with the J/Ψ suppression.

These types of effects are expected if a quark-gluon plasma is formed during the hard collision [2]. However, lacking a better analysis of possible nuclear effects, we cannot claim that they represent an unmistakeable signal for plasma creation. In a highly dense nuclear matter the rescattering of resonances may lead to their dissolution and the effect can be larger, the wider the corresponding wave function is.

In a recent letter [3] we have shown that the finite size of the nuclei in a heavy ion experiment will lead to a characteristic momentum dependence of the J/Ψ suppression independent of its underlying mechanism. The resonances can survive when the relative distance of $q\bar{q}$ pairs travelling through the "plasma" is smaller than its normal value in the bound state for which screening effects are important. Analogous effects arise from the finite lifetime of the "hot region" (plasma) [3, 4]. This has been worked out in detail in [4], where a hydrodynamical model has been used to relate the plasma lifetime to its rapid cooling due to longitudinal expansion. Similar ideas have been put forward in [5].

The mechanism which allows the resonances to escape the plasma may serve as well for escaping dense nuclear matter: as long as the pair is very localised, its total colour charge is well screened and its cross-section with nuclear matter lower than normal. The nuclear effects in Drell-Yan production observed so far [6] mainly amount to a broadening of transverse momentum distributions attributed to a rescattering of the initial quarks with the nuclear matter. Of course this could change the continuum contribution under the resonance and simulate a suppression, but we do not see why only the quarks annihilating directly into a photon should undergo a rescattering with the nuclear matter and not also those annihilating into gluons.

In this letter, we will discuss the implications of the observed effects within a model for plasma formation. The model for the momentum dependence of the J/Ψ suppression already proposed contains many parameters which are only approximately known:

i) the dimensions, transverse and longitudinal, of the "hot" disk inside which the plasma has been created

ii) the characteristic formation time and size of a J/Ψ resonance

iii) the plasma lifetime.

Additional model-dependent parameters enter through the modelling of the longitudinal expansion and cooling rate of the plasma [4, 5].

The purpose of this paper is to stress another important feature of J/Ψ production missing in the present approach: the experimental fact that a good fraction of J/Ψ, of the order of 40% [7], are coming from the decays of χ states which are produced in the first place. These states have a different binding radius and are still suppressed by the plasma at a lower critical temperature than the J/Ψ. This is related to the lower critical Debye screening mass needed to inhibit the formation of χ [8] in a plasma. The lifetimes of the corresponding "hot regions" for J/Ψ and χ depend upon these critical temperatures and χ states will therefore feel the plasma effects for a longer time than J/Ψ. In spite of the extra parameters that the χ states add to the model, we will see from the following discussion that a distinction between direct J/Ψ decays and those coming from χ is needed in a quantitative analysis of the experimental data. Moreover, the existence of two different components in the J/Ψ spectrum leads to interesting new threshold effects which may become visible in future experiments with heavier nuclei and/or better statistics for the momentum dependence of the J/Ψ suppression.

We will discuss in the next section the basic experimental results. In Sect. 3 we discuss relations between the formation of different $c\bar{c}$ resonances and "lifetimes" of certain critical isotherms. Sections 4 and 5 are devoted to an analysis of the parameters entering a discussion of J/Ψ suppression due to plasma formation and we estimate their values with the help of the experimental data. In Sect. 6 we give a detailed comparison of our model with the data and make some concluding remarks about the extension of the present results to larger A.

2 The experimental data

The NA 38 collaboration has studied the ratio of J/Ψ production to continuum as a function of the total transverse energy of a given event. The latter is supposed to be a measure of the initial temperature in the central region. Comparing data in a low E_T bin with those in higher E_T bins one finds an increasing amount of J/Ψ suppression. We concentrate here on the data sets in the transverse energy bins of $E_T < 28$ GeV and of $E_T > 50$ GeV; the first sample will be considered as a reference one, where, by assumption, the new phenomena that we try to explain are absent. The second data set is the highest E_T bin considered by NA 38. The experimental value of the ratio of muon pair production in the J/Ψ mass range over the corresponding continuum contribution – estimated by extrapolating the distribution in the neighbouring bins of the dimuon invariant mass – is different for the two E_T bins: the value in the high E_T bin is about 64% of the one in the low E_T bin. This gives evidence for a suppression mechanism acting on the produced $c\bar{c}$ pair only: any parton's initial state interaction should equally modify the charm and the continuum production and leave, in first approximation, the ratio unaffected.

A more detailed suppression pattern could be obtained from a comparison at different E_T of the analogous ratio as a function of P_T and x_F. This is only partially available at the moment. The NA 38 collaboration has presented the quantity $R(P_T)$ defined as the ratio in the two E_T bins of the ratio of muon pair P_T distributions normalised with respect to the corresponding P_T-integrated continuum contribution [9]. If the ratio of continuum P_T distributions in the two E_T bins does not vary with P_T, as is indeed the case, $R(P_T)$ represents a reasonable measurement of the P_T dependence of a suppression mechanism related to $c\bar{c}$ formation only. In practice, the "absolute" normalisation can be obtained from the one originally used [1] by rescaling the vertical axis by a factor of the order of 0.67 [9]. The data rescaled according to the latter procedure indicate that the suppression is strongest at low P_T and that it vanishes for P_T of the order of 3 GeV. Lacking the corresponding absolute normalisation also for different x_F bins, we have rescaled the data, available in this case with the original arbitrary normalisation only [1], by assuming that also the ratios for distinct x_F bins are equal to 1 at $P_T = 3$ GeV. This has been done on the basis of a straight line fit to the data as given by the NA 38 collaboration:

$$R(P_T) = x(\alpha + \beta P_T) \tag{1}$$

with x chosen such that we obtain $R(3) = 1$. Having fixed the absolute normalization we can determine the suppression at $P_T = 0$. We have calculated the value $R(0)$ by taking the average over the lowest two P_T bins.

$$\begin{aligned} R(0) &= 0.52 \mp 0.07, && \text{all } x_F \\ R(0) &= 0.65 \mp 0.09, && x_F > 0.15 \\ R(0) &= 0.44 \mp 0.11, && x_F < 0.15. \end{aligned} \tag{2}$$

The errors are calculated from the spread of the values in these two bins. They are to be taken as indicative only.

For the purpose of our model calculations we have also parametrized the experimental longitudinal momentum distribution for J/Ψ events which, including the acceptance, is highly peaked around $x_F=0.15$, with the following function:

$$dN/dx_F = 100 x_F/3, \quad 0 < x_F < 0.15$$
$$dN/dx_F = 8 - 20 x_F, \quad 0.15 < x_F < 0.4. \tag{3}$$

Roughly speaking, we can say that about 50% of the $c\bar{c}$ pairs have longitudinal momenta larger than 1.5 GeV in the nucleon-nucleon CM system. This has to be kept in mind when we discuss J/Ψ suppression at $P_T=0$.

3 Resonance formation and plasma lifetime

We assume that $c\bar{c}$ pairs are produced initially in a disk of about 1 fm height and a transverse radius determined by the size of the projectile ion, i.e. $R_0 = 1.2 A^{1/3}$ fm. Subsequently the $c\bar{c}$ pairs separate until they reach a distance of the order of the size of the resonance they are going to form. This characteristic size is taken to be the radius. The formation time for a specific resonance is then determined from its radius and from the average radial momentum of the $c\bar{c}$ bound state related to the separating velocity. These parameters have been obtained from the solution of the non-relativistic Schrödinger equation for $c\bar{c}$ bound states [8]. In Table 1 we give the mean-square radius, mean-square radial momentum and resulting formation times for the J/Ψ, Ψ' and χ resonances. We also include there the corresponding data for the bottonium system. Compared to J/Ψ and χ states are formed at a rather late stage, may be too late in the evolution of the initial hot fireball to be influenced at all by the presence of the plasma. However, the rather low temperature sufficient to inhibit χ formation [8] may help in this case. The existing Monte Carlo data for the Debye screening length [10], although still rather uncertain, indicate that already at T_c the screening length is small enough to suppress χ formation. If the transition to the plasma phase is first order, these conditions may stay for a relatively long time and make χ suppression the dominant mechanism for J/Ψ suppression. Experimental data seem to require also a direct J/Ψ suppression: at low p_T and low longitudinal momenta they indicate a suppression of the order of 70%, while if direct J/Ψ were unaffected by the plasma one would never expect a value higher than 40%.

Table 1. Mean-square radius (r), mean-square radial momentum (p) and formation time (τ_0) for charmonium and bottonium bound states. The numbers have been obtained from a solution of the non-relativistic Schrödinger equation [8]

Resonance	r [fm]	p [GeV]	τ_0 [fm]
J/Ψ	0.453	0.672	0.89
Ψ'	0.875	0.768	1.50
χ_c	0.696	0.456	2.01
Υ	0.226	1.408	0.76
Υ'	0.509	1.271	1.90
χ_b	0.408	0.744	2.60

The recovery of normal resonance production for resonances with transverse momenta larger than a certain critical value p_c reflects the finite extent of the "hot region" and the finite lifetime of the plasma. The effects of the first have been discussed extensively in [1]: the experimental data suggest that the restoration of normal resonance production sets in rather early, i.e. for $P_T \geqq 3$ GeV, and indicate that the finite lifetime of the plasma plays the dominant role. In this case, the formation times and plasma lifetimes are related as follows. A resonance with a given momentum p forms at a time

$$t = \tau_0 (1 + (p/m)^2)^{1/2} \tag{4}$$

where τ_0 is the formation time in the $c\bar{c}$ rest frame and m the mass of the resonance. The normal resonance production is recovered if at this time the thermal conditions allow for the formation of that particular resonance, i.e. if the temperature is low enough. If we assume that direct J/Ψ as well as χ with momenta larger than a certain critical value p_c, which is in general different for the two resonances, are formed at a time where the conditions for their suppression are no longer satisfied (i.e. the plasma has cooled down below the critical temperature needed for the suppression of the corresponding resonance) we can estimate the "lifetimes" of the critical plasma conditions for J/Ψ and χ from (4).

The existence of two components in the J/Ψ spectrum opens up the possibility of a two-step structure in the suppression pattern where, for instance, first the direct J/Ψ and then also the ones coming from χ will reappear. This is illustrated in Fig. 1 for the idealized case of an infinite, thermalized plasma where the only P_T dependence comes from its cooling. From the two thresholds visible in this figure we can determine the "lifetimes" $t_\Psi (t_\chi)$ of the critical plasma conditions for $J/\Psi(\chi)$ suppression. From the time dependence of the cooling process of the plasma we can extract the ratio of critical temperatures. Assuming a relation between the temperature T of the plasma and the time t of the generic form

$$T = c\, t^a \tag{5}$$

we find

$$T_{c,\Psi}/T_{c,\chi} = (t_\Psi/t_\chi)^a. \tag{6}$$

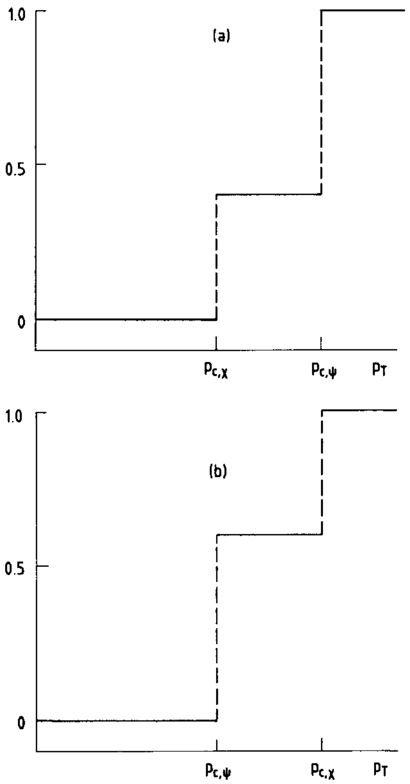

Fig. 1 a, b. Schematic P_T dependence of J/Ψ suppression in an infinite plasma that cools down. **a** shows a situation where one first recovers normal χ production and then production of direct J/Ψ, **b** shows a situation where direct J/Ψ production recovers first

In hydrodynamical models the temperature change in a given volume element of the plasma is related to the change in entropy s. If $s_0(s_1)$ is the entropy at time $t_0(t_1)$ we have the relation $t_1 s_1 = t_0 s_0$. Assuming that the entropy is proportional to T^3 gives $a = -1/3$ for the exponent in (5). In the following we will use this value for a.

Note that in perturbation theory the ratio of critical temperatures, (6), is related to the ratio of critical Debye screening masses which are proportional to T. For n_f light quark flavours one has

$$m_D = (1 + n_f/6)^{1/2} g(T)\, T \tag{7}$$

with $g(T)$ being the temperature-dependent running coupling constant. Non-perturbative lattice calculations also support a linear relation between the Debye mass and the temperature: the ratio of Debye masses gives thus an estimate for the ratio of critical temperatures.

The analysis of the non-relativistic Schrödinger equation [8] gives for the ratio of critical Debye masses

$$m_{D,\Psi}/m_{D,\chi} = 2.0. \tag{8}$$

Presumably this is an upper limit for the ratio of critical temperatures, (6). Monte Carlo data suggest that the Debye mass at the phase transition temperature T_c is already higher than $m_{D,\chi}$ [10]. In this case $m_{D,\chi}$ in (8) should be replaced by the value of m_D at T_c which would lead to a smaller ratio.

An interesting consequence of the above relations between Debye masses and plasma lifetime is the prediction of the critical parameters for Ψ' suppression. We will discuss this in Sect. 6.

4 Plasma lifetimes from experimental data at high P_T

The results for the suppression at $P_T = 0$ in the low x_F bin, (2), indicate that in this case also some of the J/Ψ coming from χ must have disappeared as the suppression is of the order of 60%. As already mentioned, this clearly excludes the possibility that direct J/Ψ are not suppressed. One could still argue that χ are not suppressed at all. However, the absence of a χ suppression leads to additional inconsistencies with the data that we will mention in Sect. 5 and will not be considered further. The suppression of χ formation implies a lifetime of the plasma at the χ screening temperature larger than the formation time for χ resonances, i.e. larger than 2 fm. An upper bound for the plasma lifetimes of both χ and J/Ψ is given by the fact that for J/Ψ with a transverse momentum of the order of 3 GeV no substantial suppression has been observed. The data for the momentum dependence of the suppression still have large errors and do not allow us to identify a two-step suppression pattern as suggested in Fig. 1 for a generic case. For the time being, we thus assume that the critical momenta at which conditions for normal resonance production are recovered are the same for the J/Ψ and χ components:

$$p_{c,\Psi} = p_{c,\chi} = 3\ \text{GeV}. \tag{9}$$

Using (4) we find for the corresponding lifetimes for the critical conditions for J/Ψ and χ suppression,

$$t_\Psi = 1.24\ \text{fm}, \quad t_\chi = 2.65\ \text{fm} \tag{10}$$

respectively. From this we can extract the ratio of critical temperatures. Using $a = -1/3$ for the exponent in the cooling law, (5) we find

$$T_\Psi/T_\chi = 1.3. \tag{11}$$

This value is close to the one obtained from an analysis of Debye screening masses [8, 10].

5 Temperature profile and longitudinal size from experimental data at low P_T

The suppression for small P_T, where the resonance formation time is smaller than the plasma lifetime, depends upon the radial dimensions of the "hot region" with respect to those of the region where the $c\bar{c}$ pairs are created initially and, if the longitudinal momenta are different from zero, upon the longitudinal extension of the plasma. As the $c\bar{c}$ pairs have a maximum longitudinal momentum around 4 GeV they can reach a distance of 1.2 fm (J/Ψ) or 2.3 fm (χ), respectively*. This implies that any longitudinal size larger than 5 fm is equivalent, as far as our effects are concerned, to an infinite extent. This happens if the actual size is of the order of the largest nucleus's diameter and we will assume that this is the case in the rest of our analysis.

In a "static" model of the plasma, the radius of the hot region, i.e. the critical isotherm, is kept constant in time. Taking into account the finite lifetime of the plasma we may write

$$r(t) = h\,\Theta(t_f - t) \qquad 0 \leqq h \leqq R_0 \tag{12a}$$

for the radial extent of the plasma. Of course a realistic description of the plasma expansion has to deal with a time-dependent radial extent of the plasma. We will do so following the general ideas proposed in [4]. The transverse extent of the plasma region which leads to a suppression of a certain resonance is then described by a time-dependent radius $r(t)$ of the form [4]

$$r(t) = R_0(1 - (t/t_f)^b)^{1/2} \tag{12b}$$

with b being an additional free parameter and t_f denoting the plasma lifetimes given in (10). The parameter b characterizes the initial state of the plasma [4]. We may think of it as giving the initial distribution of $c\bar{c}$ pairs. For two equal nuclei Lorentz contracted to thin discs, that perform a central collision, the natural choice would be $b=4$, while for a small nucleus hitting a large nucleus with a nearly constant density distribution we would have $b=2$ [3] for a central collision. The latter scenario is more suitable for present heavy ion experiments where a small oxygen nucleus hits a heavy uranium nucleus. However, as also non-central collisions contribute, the effective density distribution in the uranium nucleus is also varying and we may use b as a free parameter**.

In our model the amount of suppression at $P_T=0$ is controlled by the parameter b. In this case the $c\bar{c}$ pairs propagate parallel to the collision axis and cannot escape from the plasma in the transverse direction. Only the transverse size of the plasma with respect to the radius of the nucleus matters. In order to get a strong suppression at $P_T=0$, $r(t)$ has to be close to R_0 at the time of resonance formation. The value of b can be determined for instance from the measured suppression at $P_T=0$ in the integrated x_F bin. The suppression factors in the different x_F bins will then come as a prediction. In Fig. 2 we give the suppression at $P_T=0$ as a function of the free parameter b, using the distribution function, (3), for the longitudinal momenta. In order to achieve a suppression of about 55% as suggested by the experimental data we need $b \simeq 3.3$. For values b between 2 and 4, which are suggested by our geometrical considerations, the suppression varies between 35% and 60%. Remember that we have assumed an infinite extent of the plasma in the longitudinal direction: a finite extent would reduce the suppression further, but this could be compensated for by a different choice of b.

* A momentum of 4 GeV corresponds to $x_F=0.4$ if one uses the value of the total energy of the nucleon-nucleon centre-of-mass frame of about 20 GeV

** We assume here that the initial distribution of $c\bar{c}$ pairs reflects the initial density (temperature) distribution. Thus we take for both distributions the same radial dependence, (12b), characterized by a single free parameter b. In [4] two independent parameters have been introduced

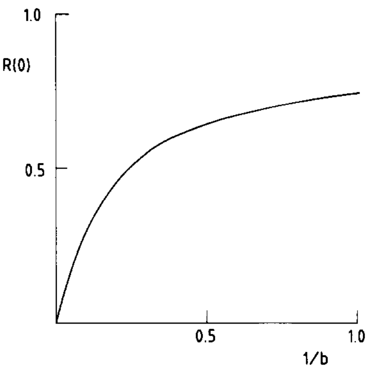

Fig. 2. J/Ψ suppression at $P_T=0$ versus 1/b

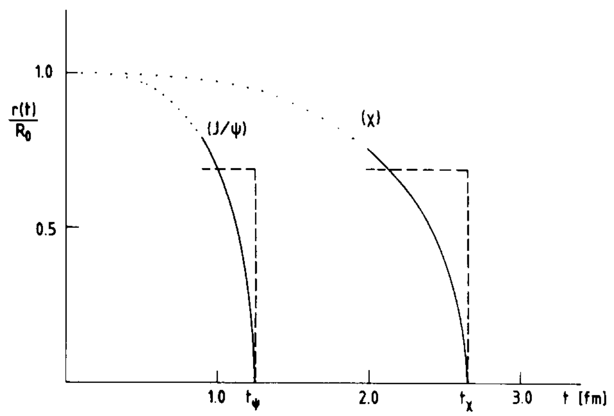

Fig. 3. Time dependence of critical isotherms for direct J/Ψ suppression and χ suppression. The dotted part of the curves indicates the time interval during which no resonances form. Also shown are the time-independent isotherms needed in a static model to obtain the same amount of suppression at $P_T=0$

For $b=3$ we show in Fig. 3 the time evolution of the critical isotherms for J/Ψ and χ suppression, respectively. The dotted parts of the curves indicate the time intervals which have no dynamical significance as no J/Ψ (χ) states from for $t<\tau_{0,\Psi}$ ($\tau_{0,\chi}$). For comparison, the dashed Θ-functions on the same figure represent the approximation of the "static" plasma, (12a), which gets smoothed by dynamical effects. From this figure, we find that at the time where the first resonances form, the plasma covers about 55% of the transverse volume of an oxygen ion, i.e. the transverse radius is about $0.75\,R_0$.

6 Comparison with full experimental data and extrapolation to larger A

We have shown how we can use the experimental data at high P_T and at $P_T=0$ to fix the parameter of the model which can now be used to predict the distributions for the entire P_T range and for different x_F bins. At present the determination of p_c as well as the absolute scale of the suppression ratios in the low and high x_F bins involves large uncertainties. We thus did not attempt a systematic fit of the data. We rather compare the data with the model predictions for the specific choice $p_c=3$ GeV and $b=3$. As can be seen in Fig. 4 the agreement is reasonable. In fact for the x_F integrated data sample we get a χ^2 of 0.56. In Fig. 5 we present our model predictions for two different x_F bins and compare with the x_F integrated result. This shows that we expect stronger suppression rates in lower x_F bins. The analysis of the experimental data in different x_F bins is presently not fully completed. A detailed anaylsis would be interesting as our result differs from model calculations that assume a boost-invariant plasma expansion [4, 5]. In that case no x_F dependence of the suppression pattern would be expected.

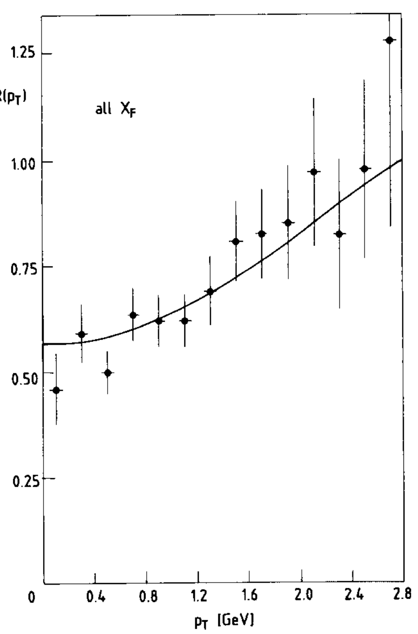

Fig. 4. J/Ψ suppression as a function of P_T. Shown is a comparison of our model prediction with the data of NA 38 [1]. The vertical scale has been rescaled as described in Sect. 2 with $x=0.67$

For the above set of parameters we get for the ratios at $P_T=0$ in the different x_F bins:

$$\begin{aligned} &R(0)=0.57, \quad \text{all } x_F \\ &R(0)=0.69, \quad x_F>0.15 \\ &R(0)=0.37, \quad x_F<0.15 \end{aligned} \tag{12}$$

to be compared with the experimental results given in (2). The spread in these values is somewhat larger than suggested by the experimental data. In the present analysis we tried to introduce a minimal set of parameters in the model. Some of the approximations may turn out to be too crude (same critical momenta for J/Ψ and χ suppression, same profile function for $c\bar{c}$ and temperature distributions) and could be used to adjust the spread at $P_T=0$. A more subtle way to reduce the spread of $R(0)$ for different x_F bins would be to consider the possibility of a residual plasma component in the low E_T bin, which is excluded in the present analysis.

The pattern of Ψ' suppression, unfortunately beyond the precision of present data, can also be predicted. The only unknown parameter is the corresponding plasma lifetime. However, the analysis of the $c\bar{c}$ bound state problem [8] has shown that Ψ' and χ bound states disappear at essentially the same critical Debye mass. We can thus assume that the critical isotherms for Ψ' and χ are the same. As the formation time for the Ψ' is shorter than for the χ (see Table 1) we immediately conclude that the suppression of Ψ' is stronger at a given P_T. In fact from (4) we find that normal Ψ' formation can only be recovered for Ψ' having momenta larger than 5.4 GeV. This explains why the Ψ' signal has disappeared within the present accuracy of the data. In Fig. 6 we report the ratio $R(P_T)$ for the Ψ' case and compare it with the corresponding one for J/Ψ. We consider the measurement of the detailed pattern of Ψ' suppression an important check of this approach. We want to stress that the role of the χ suppression has been crucial in our analysis. Without it we could not obtain the sizeable difference between the values of $R(P_T=0)$ in the two E_T bins and we would have been pushed to unacceptably high values of the parameter b, of the order of 50–100. Also, the Ψ' suppression would have been modest.

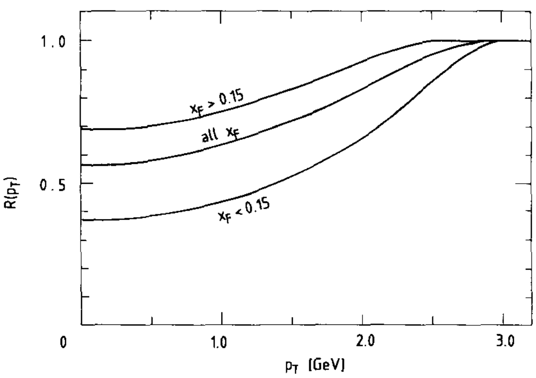

Fig. 5. J/ψ suppression pattern as a function of P_T for the x_F integrated case and for two different x_F bins

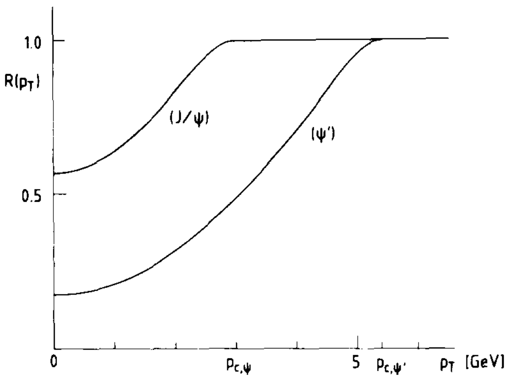

Fig. 6. Comparison of the P_T dependence of the Ψ' and J/Ψ suppression rates

The present considerations can be easily extended to the bottonium system. Using the formation times given in Table 1 and the information about the critical Debye masses we have from [8], we can for instance determine the ratio of the lifetimes for the critical isotherms. We find $T_Y/T_\Psi = 2.24$ for the ratio of critical temperatures, which gives $t_Y/t_\Psi = 0.1$ for the lifetimes of the isotherms. This large difference would show up as a sizeable difference in the critical momenta for the recovery of normal resonance production.

An important question is how to extrapolate these results to heavier nuclei, but we do not have a clear answer to it. For there are many intrinsic scales in the problem, the energy, the temperature, the nucleus size and it is hard to define a scaling law as a function of the nucleus's radius only. The simplest guess, however, would be to rescale the plasma lifetimes, the transverse energy of the high E_T bin and the initial transverse plasma's size with the radius of the nucleus, i.e. with $A^{1/3}$. Assuming the same x_F distribution, the suppression at $P_T = 0$ would change from about 50% (oxygen) to 80% (sulfur) and the critical transverse momentum above which normal resonance production is recovered would shift from 3 GeV (oxygen) up to 4 GeV (sulfur).

Higher statistics data are needed to reveal some of the effects discussed, like the two-step suppression pattern and the P_T dependence of the suppression for the Ψ'. An extrapolation from oxygen to sulfur based on a naive scaling law indicates the existence of appreciable differences. Finally we want to stress again that the general feature of the momentum dependence of J/Ψ suppression is probably not a unique signature for plasma formation. To a large extend it reflects the geometry of the nucleus-nucleus collision. We thus believe that a detailed analysis of the suppression pattern for different resonances will be necessary to give further support to the underlying hydrodynamic picture of a rapidly cooling quark-gluon plasma studied in this paper.

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Note added in proof. The preliminary data on the P_T dependence of the suppresion pattern in different x_F bins presented by NA 38 at the Nordkirchen conference [1] are still not completly analyzed. The values quoted by us in Eq. (2) for $R(0)$ in the $x_F < 0.15$ and $x_F > 0.15$ bins should thus be taken as indicative only.

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