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THE PLASMA MODEL FOR J/ψ SUPPRESSION IN HEAVY ION COLLISIONS

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The formation of a quark-gluon plasma in ultra-relativistic heavy ion collisions is expected to lead to a substantial reduction of the J/ψ yield. We outline the basic features of the plasma model, discuss the expected transverse energy and momentum dependence of the suppression pattern and give a comparison with experimental data.

1. INTRODUCTION

The QCD heavy quark potential undergoes a characteristic change during the phase transition from ordinary hadronic matter to a quark-gluon plasma: the confining $q\bar{q}$ potential of the hadronic phase gets replaced by a Debye-screened Coulomb potential in the plasma phase. For large enough temperatures the Debye screening mass, $\mu(T)$, is proportional to T. Thus even for very heavy quarks there exists a critical temperature, T_D, above which there are no bound states in such a strongly screened potential. The strong screening of the heavy quark potential in a quark-gluon plasma is expected to provide an efficient mechanism for the disintegration of $c\bar{c}$ pairs immersed in such an environment[1].

Does this observation provide us with an unambiguous signal for plasma formation in heavy ion collisions? To answer this question we have to analyze the quantitative predictions based on the hypothesis of heavy quark disintegration due to screening of the $q\bar{q}$ potential in the plasma phase. However, we also have to understand other, more conventional mechanisms that can lead to a disintegration of heavy quark bound states. Both aspects have been studied in detail during the past year[2]. It now became clear that $q\bar{q}$ bound state suppression is not an exclusive feature of plasma formation, but rather signals the formation of a high density partonic system[3] responsible for the disintegration of heavy $q\bar{q}$ pairs. Models based on the assumption of plasma formation in heavy ion collisions[4–7] provide a satisfactory description of the existing experimental data on J/ψ suppression in $O-U$ and $S-U$ collisions[8]. However, nuclear absorption models[7,9] can also predict a large amount of J/ψ suppression and combined with a model for initial state interactions[10] they as well lead to a satisfactory description of the data. At present both approaches have their shortcomings: the nuclear absorption model has to deal with large initial hadron densities and ignores the fact that several nucleons occupy the volume of a single pion. This makes the approach conceptually questionable. The plasma model on the other hand is rather sensitive to the plasma lifetime which itself has to be of the order of the equilibration time of the system. Quantitative predictions based on this approach thus require a fine tuning of time scales.

The nuclear absorption model and effects of initial state scattering have been discussed by S. Gavin[11] and J.-P. Blaizot[2] at this conference. Here we want to discuss the predictions of the plasma model[12] for J/ψ suppression and compare its predictions with existing data from NA38. We briefly comment about the incorporation of initial state interactions in the framework of the plasma model.

2. J/ψ SUPPRESSION IN A QUARK-GLUON PLASMA

A quantitative description of the expected suppression pattern in the plasma model requires a specification of the inital conditions, i.e. the density or temperature profile at some initial time t_i at which the system is assumed to be in thermal equilibrium, and a model for the subsequent time evolution of the plasma phase. Let us assume that at t_i the temperature profile is given by

$$T(r) \; = \; T_i\left(1 - \left(\frac{r}{R_A}\right)^2\right)^{b/3} \quad , \tag{1}$$

with $R_A \simeq 1.2A^{1/3}$ denoting the radius of the projectile nucleus and b parametrizing the transverse density distribution in the projectile and target nucleus[4]. At later times the plasma is assumed to cool rapidly due to isentropic longitudinal expansion. At time $t \geq t_i$ the temperature is then related to the one at time t_i by $T_i^3 t_i \; = \; T^3 t$. In particular this fixes the plasma lifetime as*

$$t_f \; = \; t_i\left(\frac{T_i}{T_D}\right)^3 \quad . \tag{2}$$

This relation can be used to determine the initial energy density in the plasma phase as a function of the plasma lifetime. The energy density in a quark-gluon plasma is well approximated by the ideal gas expression

$$\epsilon(r) \; = \; \alpha\frac{\pi^2}{15}T^4(r) \quad , \tag{3}$$

with α counting the effective number of degrees of freedom in the plasma phase, i.e. $\alpha = N^2 - 1 + \frac{7}{4}Nn_f = 18.5$, for SU($N$), $N = 3$, and $n_f = 2$ light quarks. This energy density is distributed over a disk of transverse radius R_A and longitudinal extent l. Using eq.(1) and (2) we find[6]

$$E/A^{2/3} \; = \; \frac{\pi^3}{15}\frac{3\alpha}{4b+3}1.44lT_c^4\left(\frac{t_f}{t_i}\right)^{4/3}\left[1 - \left(\frac{t_i}{t_f}\right)^{(4b+3)/3b}\right] \quad , \quad t_f \geq \tau_\chi \simeq 2fm \tag{4}$$

* Monte Carlo simulations for QCD indicate that $\mu(T)$ is large even close to the phase transition temperature T_c. Recent results from simulations in the pure gauge sector give $\mu(T)/T \simeq 2.5$ at $T \simeq 1.2$[13], and simulations for QCD with light quarks indicate that the screening mass increases further, $\mu(T)/T \simeq 3.5$ at $T \simeq 1.1$ for two light quark flavours of mass $m_q/T = 0.1$[14]. This suggests that T_D is close to the transition temperature T_c. In fact potential model calculations[15] suggest that for the charmed quark system only J/ψ may survive as a bound state above T_c up to $T_D \simeq 1.3T_c$, while all higher states (χ, ψ', ..) get dissolved already at T_c.

for the total energy in the plasma phase. Here τ_χ denotes the formation time of χ-resonances, which contribute about 40% to the total J/ψ yield. We note that E is proportional to the transverse size of the projectile nucleus, $E \sim A^{2/3}$, and the fourth power of the phase transition temperature T_c. The critical temperature as well as several other parameters entering this relation are only approximately known. The same is true for the relation between the energy calculated this way and the transverse energy, E_T, determined experimentally. The relation between plasma lifetime t_f and transverse energy E_T thus involves a more or less arbitrary conversion factor K,

$$E_T/A^{2/3} = K\left(\frac{t_f}{t_i}\right)^{4/3}\left[1-\left(\frac{t_i}{t_f}\right)^{13/3}\right] GeV \ , \qquad (5)$$

which at present has to be determined from the experimental data. In eq.(5) we used $b = 1/3$ for the parametrization of the temperature profile[5,6].The main uncertainty in K results from the phase transition temperature, which enters as T_c^4. Using conventional estimates for the initial time t_i ($t_i \simeq 1fm$) and the formation length l ($l \simeq 2fm$, for the 2 central rapidity bins covered by NA38), we obtain[6] $K = 2.8x$, with $x = (T_c/200fm)^4$.

With increasing transverse energy the plasma lifetime increases and so does the initial temperature T_i. From eq.(1) we see that this results in an increasing transverse size of the region initially being in the plasma phase. We thus expect an increasing amount of J/ψ suppression with increasing transverse energy. In fact, if we consider for the moment only $c\bar{c}$ pairs with $p_T = 0$, the amount of the suppression is simply related to the transverse size of the plasma region relative to the size of the projectile nucleus. Fig.1a shows the predicted amount of suppression, $S(p_T = 0)$, for various values of the scale parameter K.[6]

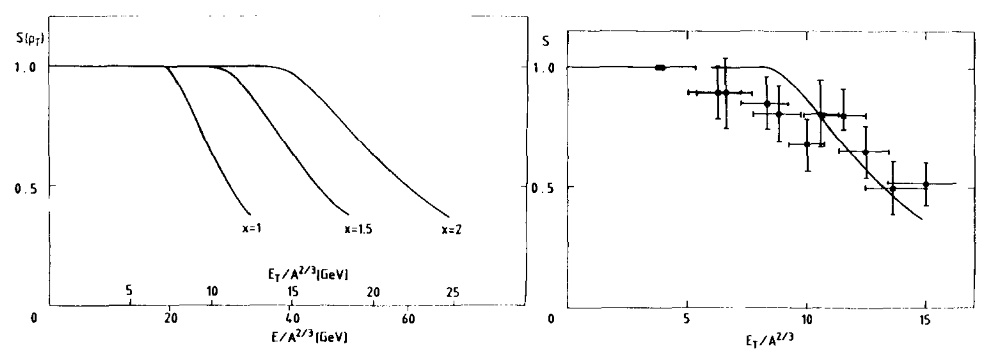

FIGURE 1
Survival probability for J/ψ with $p_T = 0$ versus $E_T/A^{2/3}$ for various values of $K = 2.8x$. In fig.1a we show results for $x = 1$ (a), $x = 1.5$ (b) and $x = 2$ (c). In fig.1b the prediction for $x = 1.2$ is compared with experimental data for the p_T-integrated survival probability for oxygen-uranium (●) and sulphur-uranium (■). Data are taken from reference 8 and normalized to the lowest E_T-bin.

A comparison with experimental data for the p_T-integrated suppression rate allows a determination of K. This is shown in fig.1b. The experimental data have been normalized to the lowest E_T-bin. This should eliminate a great part of the suppression effects due to nuclear absorption. The plasma model reproduces quite well the slope of the E_T dependence for the large E_T events. For $K = 3.36$ we find that there is no J/ψ suppression below $E_T/A^{2/3} = 8.2 GeV$, i.e. below $E_T = 52$ (82) GeV for oxygen (sulphur).

A $c\bar{c}$ pair with momentum $\vec{p}$ will form a J/ψ at a time

$$t = \tau_{J/\psi}\sqrt{1 + (\vec{p}/m)^2} \quad , \tag{6}$$

where $\tau_{J/\psi} \simeq 0.9$fm denotes the J/ψ formation time in the $c\bar{c}$ rest frame[15]. J/ψ's with large momentum thus form at a late stage in the plasma rest frame. At this time the region covered with a hot plasma is reduced and we thus expect less suppression of large momentum J/ψ. In particular, J/ψ's with a momentum larger than $p_c = m\sqrt{(t_f/\tau_{J/\psi})^2 - 1}$ will form at $t > t_f$. They are not affected by the plasma at all and thus can form normal resonances.

With the scale factor K being fixed through the E_T dependence of the suppression pattern the p_T dependence is a parameter-free prediction of the plasma model. For any given value of $E_T/A^{2/3}$ the plasma lifetime is given. This fixes p_c and the complete p_T-dependence of the suppression pattern.

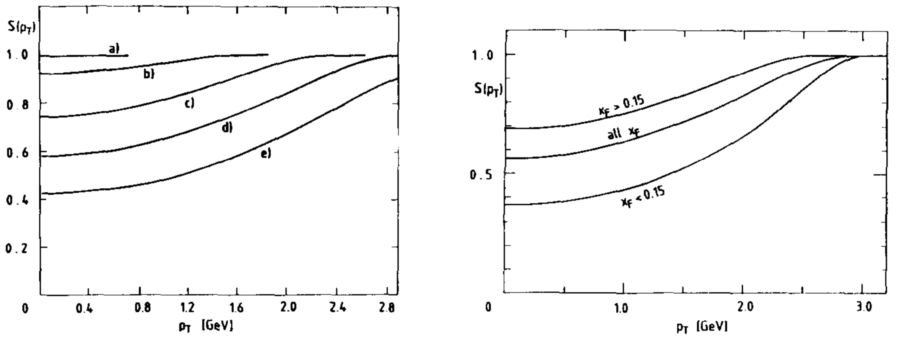

FIGURE 2
Survival probability for J/ψ versus p_T for 5 different values of $E_T/A^{2/3}$. Fig.2a shows results for $E_T/A^{2/3} \leq 8.2 GeV$ (a) and $E_T/A^{2/3} = 9.4$ (b), 11.0 (c), 12.6 (d) and 14.2 (e) GeV. In fig.2b we show the x_F dependence for fixed $E_T/A^{2/3}$ and fixed p_T.

In fig.2a we show the p_T-dependence for 5 different values of $E_T/A^{2/3}$ using $x = 1.2$.[6] These transverse energy values have been chosen such that they fall into the different E_T-bins selected by the NA38 collaboration for their oxygen data samples[8]. The pattern shown in fig.2a actually reproduces quite well the one observed by the NA38 collaboration. Also shown is the expected dependence[5] on x_f for fixed p_T and E_T. With decreasing x_F an increasing amount of suppression is expected in the plasma model. This is of particular interest as it is different from the x_f-dependence observed in hadron-nucleus collisions[16].

3. INITIAL STATE INTERACTIONS

The plasma model discussed in the previous section is entirely based on the assumption that modifications of the J/ψ yield in different E_T bins are due to final state interactions, i.e. the disintegration is due to screening of the heavy quark potential while the momentum dependence of the suppression pattern is mainly due to time dilatation effects altering the "growth" of the $c\bar{c}$ system in the plasma rest frame. The short plasma lifetime leads to a strong momentum dependence of the suppression pattern. If there are indeed strong effects due to initial state interactions that alter the momentum distribution of the $c\bar{c}$ pair[10] these have to be taken into account in a similar way, as has been done in the absorption models[10,11]. This would lead to an even stronger p_T dependence in the plasma model. To some extent, however, this could be compensated for by an increase of the plasma lifetime and a modification of the temperature profile ($b \rightarrow 1$) in the model calculations. At present it is not clear to which extent the momentum dependence is already explained by initial state interactions alone. If so there would be no room for an additional p_T dependence coming from the plasma formation. It thus seems that a more systematic study of the rescattering effects of gluons in the initial state on the the momentum distribution of produced $c\bar{c}$ pairs is needed before a further analysis of the disintegration mechanism in the final state can be performed. Here it will be of particular interest to study in addition to the modification of the p_T-distribution also the influence on the x_F-distribution.

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