Charmonium dissociation in hot and dense matter

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Abstract

We investigate $J/\psi$ suppression in ultrarelativistic heavy ion collisions within a generalized Glauber model and compare results of a hadronic comover scenario with those of a quark plasma scenario where conditions for Mott dissociation of charmonium are fulfilled locally at the short time scales before hadronization. We study possible consequences for the theoretical description to be drawn from the observation of “anomalous” thresholds in the $J/\psi$ suppression pattern by the NA50 collaboration.

1 Generalized Glauber model for $AB$ collisions

Recently, the NA50 collaboration at CERN has observed an “anomalous” threshold effect for $J/\psi$ production in $Pb - Pb$ collisions at 158 $A$ GeV/c [1,2]. After the debate whether the $J/\psi$ suppression itself already signals quark-gluon plasma formation [3] or may be explained by hadronic absorption [4], the present observation seems to support a plasma scenario predicting anomalous $J/\psi$ suppression thresholds to occur due to the Mott effect [5] which excludes charmonium bound state formation in a medium at densities and/or temperatures just above those which have been reached in previous $AB$ collisions at 200 $A$ GeV/c ($A = ^{16}O$, $^{32}S$, $B = ^{238}U$). In order to explain both the normal and the anomalous $J/\psi$ suppression pattern in $AB$ collisions quantitatively, generalizations of the Glauber model have been considered which include density thresholds for charmonium production [6,7]. On the other hand, it has been checked whether more conventional scenarios of $J/\psi$ absorption by comoving matter can give a reasonable description of the $Pb - Pb$ data [8,9]. In this contribution we report on the present status of the interpretation of the new data for the $E_T$ dependence of $J/\psi$ suppression within a generalized Glauber model approach which besides of charmonium attenuation by projectile and target nucleons also includes absorption by comoving hadronic and/or partonic matter as produced in the course of the collision. Within this approach, the survival probability of a charmonium state produced in a collision of the nuclei $A$ and $B$ at impact parameter $b$ is given by [10]

$$S(b) = \left[\frac{d\sigma_{\text{prod}}}{db}\right]^{-1} \int_0^\infty d^2 b_A \frac{d^2 \sigma_{\text{prod}}}{db b_A} P_{\text{abs}}^{\text{nuc},A}(b_A) P_{\text{abs}}^{\text{nuc},B}(b - b_A) P_{\text{com}}(b, b_A), \quad (1)$$

where the absorption by projectile and target nucleons with density distributions $\rho_i(z_i, b)$ is given by

$$P_{\text{abs}}^{\text{nuc},i}(b) = \int_{-\infty}^{\infty} dz_i \rho_i(z_i, b) \left[1 - \int_{z_i}^{\infty} dz \rho_i(z, b) \sigma_{\text{abs}}^{(c)}(z)\right]^{i-1}; \quad i = A, B, \quad (2)$$

and $\sigma_{\text{abs}}^{(c)}N$ is a phenomenological cross section adjusted in order to describe the mass number dependence of charmonium hadroproduction in $pA$ and $\pi A$ collisions where no dense medium is expected to be formed [4,9]. The impact parameter dependence can be translated to an $E_T$ dependence using the $E_T - b$ correlation function which is also

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obtained within the Glauber model approach from a fit to the experimental dimuon $E_T$ distribution. The additional absorption by hot, dense matter produced in the central region of an ultrarelativistic nucleus-nucleus collision is accounted for by

$$P_{\text{abs,com,}h}(\mathbf{b}, \mathbf{b}_A) = \exp \left[ - \int_{t_0}^{t_f} dt \tau^{-1}(\mathbf{b}, \mathbf{b}_A, t) \right],$$

where $\tau(\mathbf{b}, \mathbf{b}_A, t)$ is the relaxation time for the initial distribution of $c\bar{c}$ pairs due to inelastic collisions with hadrons or partons of the hot and dense medium. We present results of model calculations with and without a critical threshold behaviour in the relaxation time in order to discuss whether or not the experimental signal of anomalous $J/\psi$ suppression can be interpreted as a signature of quark-gluon plasma formation.

2 Charmonium dissociation in hadronic matter

In dense hadronic matter charmonium formation is suppressed by charm dissociation into open charm hadrons. We have calculated the cross sections $\sigma_h$ of such quark rearrangement (string-flip) processes using a confining quark potential model [11] and obtained the relaxation time $\tau_h = (\sigma_h v_{rel} n_h)^{-1}$ including a parametric dependence on the hadron properties (masses and r.m.s. radii). In Fig. 1 we contrast a conventional description in terms of nuclear absorption (full lines, $\sigma_{\text{abs}} = 7.3$ mb) with different hadronic comover absorption scenarios: dotted lines- $\sigma_h = \text{const}$, $n_h(t) = n$, dashed lines- $\sigma_h = \text{const}$, $n_h(t) = n t_0/t$ and dash-dotted lines- $\sigma_h = \text{const}$, $n_h(t) = n_0/t$. Our results [12] for the additional absorption due to comoving hadrons show a continuous dependence on the impact parameter. No acceptable description of both sets of data ($S-U$ and $Pb-Pb$) is possible and a hadronic comover scenario has to be disfavoured, see also [9].

3 Mott dissociation of $c\bar{c}$ in partonic matter

According to the MOTT effect, above critical densities characteristic for the bound states under consideration, these states vanish from the spectrum since they merge the continuum of scattering states. In the case of charmonium, quark rearrangement processes occur
which result in a dissociation of the heavy flavour [13] when critical parton densities \( n_{\text{MOTT}}^{\chi} \) are exceeded. For a \( c\bar{c} \) pair born into a dense partonic environment, a MOTT criterion has been formulated in [7] which accounts for the proper time dependence of both the size of the \( c\bar{c} \) wave function and the parton density [14] at given impact parameter and Lorentz factor \( \gamma \) in the parton center-of-mass system, see Fig. 2. Accounting for a 30% feeding of the \( J/\psi \) channel from \( \chi \) decays, we obtain for the additional absorption due to MOTT dissociation of charmonium in dense partonic matter

\[
P_{\text{abs}}^{\text{com,MOTT}}(b, b_A) = 0.3 \Theta[\gamma^2 n_{\text{MOTT}}^{\chi} - n(b, b_A)] + 0.7 \Theta[\gamma^2 n_{\text{MOTT}}^{\psi} - n(b, b_A)] , \quad (4)
\]

\( n(b, b_A) = A_T A(b_A)(1 - (1 - \sigma_{\text{inel}} T_B(b - b_A))^{B}) + B T_B(b - b_A)(1 - (1 - \sigma_{\text{inel}} T_A(b))^{A}) \)

being the density of participants in the transverse plane and \( T_{A,B}(b) \) the normalized nuclear thickness functions. From the r.m.s. transverse radii of \( \chi \) and \( J/\psi \) we expect that

Figure 3: Suppression ratio for \( J/\psi \) in S-U (left panel) and Pb-Pb (right panel) collisions.

\( n_{\text{MOTT}}^{\psi} \approx 2 n_{\text{MOTT}}^{\chi} \) and the parameter \( n_{\text{MOTT}}^{\chi} \) is chosen such that the threshold for anomalous suppression which is interpreted as a consequence of the MOTT effect is reproduced. Our results are shown in Fig. 3 and demonstrate that a threshold behaviour can indeed be
obtained for the $Pb - Pb$ collisions whereas it is not present in the $S - U$ case. However, the most recent data of the 1996 run [2] exhibit a much steeper decrease of the $J/\psi$ suppression ratio than can be explained within a generalization of the Glauber model even by the extreme MOTT scenario as presented here and in [7].

4 Conclusions

We have analyzed data for the $E_T$ dependence of $J/\psi$ suppression in $S - U$ and $Pb - Pb$ collisions at CERN-SpS within a generalized Glauber model approach which accounts for the fact that after its creation the $c\bar{c}$ pair suffers not only normal absorption by projectile and target nucleons but also additional absorption while traversing the dense hadronic and/or partonic matter which is formed in the collision. It has been shown that a hadronic comover scenario cannot explain both the $S - U$ and the $Pb - Pb$ data since it has a continuous centrality dependence. The scenario of MOTT dissociation in dense partonic matter when implemented in the Glauber approach exhibits a threshold behaviour with increasing centrality of the collision and seems to describe both the $S - U$ and the 1995 $Pb - Pb$ data. The new 1996 $Pb - Pb$ data, however, show a sudden drop in the $J/\psi$ production above $E_T \sim 50$ GeV which, when established in the final analysis of the data, indicates the transition to a new regime in the $Pb - Pb$ collisions that can no longer be modeled adequately within a Glauber type approach. Studies which implement the change of time scales due to a quark-gluon-plasma phase transition [5,15] on the other hand seem to have the potential to explain the observed anomalous threshold behaviour of $J/\psi$ suppression. These theoretical studies have to be further developed by improving the microscopic description of charmonium dissociation kinetics and by combining them with numerical simulations of $AB$ collisions. Further experimental studies with higher statistics and also with inverse kinematics should be performed in order to settle the details of the anomalous suppression pattern as a possible signal of quark-gluon-plasma formation in heavy-ion collisions.

2. E. Scomparin (NA50 Collaboration), talk at this conference.