J/ψ suppression in heavy ion collisions – interplay of hard and soft QCD processes

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Abstract

We study J/ψ suppression in AB collisions assuming that the charmonium states evolve from small, color transparent configurations. Their interaction with nucleons and nonequilibrated, secondary hadrons is simulated using the microscopic model UrQMD. The Drell-Yan lepton pair yield and the J/ψ/Drell-Yan ratio are calculated as a function of the neutral transverse energy in Pb+Pb collisions at 160 GeV and found to be in reasonable agreement with existing data.

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I. INTRODUCTION

Experimental data on the AB and E_T dependence of J/ψ-meson production from the CERN SPS [1–4] exhibit tantalizing evidence for J/ψ suppression when compared to hard QCD production. Do the J/ψ data in Pb+Pb-collisions indicate the creation of a deconfined phase of strongly interacting matter, *i.e.* a quark-gluon plasma (QGP) [5,6]? Such QGP scenarios generally rely on the experimental observation of deviations from the predictions of models of hadronic suppression. Simple analytical models of J/ψ suppression have used nuclear absorption alone [5] or absorption by nucleons and comoving secondaries [7] to fit all but the Pb+Pb data. These models generally assume a single, fixed nucleon absorption cross section for all charmonium states and that the comover interaction rate, assuming a Bjorken scaling expansion, is essentially thermal. (For theoretical reviews, see Refs. [8–10].)[1]

Charmonium final state interactions with mesons and baryons are simulated using the Ultrarelativistic Quantum Molecular Dynamics, UrQMD [15], a microscopic hadronic transport model. The charmonium nucleon cross sections employed here are calculated in a nonrelativistic potential model [16] since at SPS energies, charmonium-nucleon interactions are predominantly nonperturbative. The charmonium precursors are not eigenstates of the QCD Hamiltonian, therefore their effective sizes and interaction cross sections may vary from their production to the final state formation [16]. Thus the charmonium absorption cross sections are assumed to expand linearly with time until their asymptotic value is reached. Since the produced particles in the collision have a non-thermal distribution [17], comover interactions can rather effectively dissociate the J/ψ. Because of abundant high mass resonances, most of the meson induced J/ψ dissociation processes are exothermic [17]. They account for an important fraction of the observed suppression, larger in Pb+Pb collisions than the nuclear absorption alone.

II. THE MODEL

We apply perturbative QCD to the production of charmonium states by simulating nucleus-nucleus collisions in the impulse approximation. The nuclear dependence of parton distribution functions is neglected. The resulting space-time distribution of charmonium production points is inserted into the evolving hadronic environment calculated with UrQMD [17] since the rare quarkonium production processes are small perturbations on the heavy ion collision[2]. Our model is thus designed to account for partonic and hadronic aspects of the charmonium dynamics. The space-time distributions of hard and soft processes, *i.e.*

[1]Recently, there have been several attempts to build models of charmonium production and absorption by means of microscopic hadronic transport simulations [11–14]. Based on rather different model treatments of the charmonium dynamics and the interconnection of hard and soft processes it is claimed in all these studies that conventional hadronic scenarios are consistent with the Pb+Pb data.

[2]Since we consider only exclusive charmonium production, the QCD factorization theorem is inapplicable.

in particular charmonium production and absorption, may overlap. Thus, in our model, a charmonium state produced in a hard process can be dissociated by the interaction with a comoving hadron before this state leaves the nuclear environment and before all other hard production processes are completed (in contrast to Ref. [14]). The probability for such an event, however, is reduced due to the initially small absorption cross sections and the finite formation times of comoving mesons according to the string model (see below). To avoid double counting, interactions of $c\bar{c}$ states with produced hadrons in individual NN collisions are excluded. In AB collisions, all hard NN collisions can contribute to the $c\bar{c}$ production while all soft NN collisions can contribute to the hadronic environment in which the $c\bar{c}$ state may be dissociated. The error imposed by this concept — inherent to all microscopic and analytical models of comover absorption — is estimated to be very small.

The charmonium states are distributed according to their assumed production probability times their decay probability to J/ψ's. Thus 40% of the final states are χ's, 55% are J/ψ's, and 5% are ψ's [18]. According to the spin degeneracy, 1/3 of the χ's are χ_{c10} states and 2/3 are χ_{c11} states. Their momenta are assigned according to the parametrization [19],

$$E\frac{d\sigma}{dMdp^3} \sim (1-x_F)^{3.55}\exp(-p_T\,2.08\,\mathrm{GeV}^{-1}) \ .$$

The rescattering cross sections for $X(c\bar{c})+B$, assuming $B\equiv N$, are taken from Ref. [16]: $\sigma(J/\psi N) = 3.6$ mb, $\sigma(\psi' N) = 20$ mb, $\sigma(\chi_{c10}N) = 6.8$ mb, and $\sigma(\chi_{c11}N) = 15.9$ mb. Charmonium-meson cross sections ($X(c\bar{c})+\pi$, $X(c\bar{c})+\rho$, *etc.*) are reduced by a factor of 2/3 from the corresponding baryon values. All baryon and meson collisions above the respective dissociation thresholds are assumed to break up the charmonium state. Universal and energy independent cross sections are employed, ignoring any charmonium-meson resonances, perhaps too crude an assumption. From phase space arguments one can infer that the J/ψ dissociation cross sections with π's should be suppressed close to threshold while it should be enhanced for exothermic channels. However, we have found that, during the initial stage of the J/ψ comover collisions, the average interaction energy, $<E>\approx 5$ GeV, is far above threshold [17]. There are no calculations of J/ψ dissociation cross sections with mesons other than π's and ρ's [10]. In a thermal comover scenario the density of heavier mesons is suppressed by the Boltzmann factor. According to the UrQMD simulations, however, these mesons dominate the comover absorption [17]. In a forthcoming paper [20] the influence of the energy dependence of the comover interactions will be studied further.

The cross sections correspond to the geometrical transverse radii $r_T^i = \sqrt{\frac{\sigma^i}{\pi}}$ of the charmonium states. We use σ^i to estimate the respective formation times τ_F^i of the charmonium states by choosing $\tau_F^i = r_T^i/c$. During these formation times the cross sections increase linearly with t [16], starting from 0 at $t=0$.

Here it is important that we also take into account the formation time of comoving mesons (on average, $\tau_F \approx 1$ fm/c). Particles produced by string fragmentation are not allowed to interact with other hadrons – in particular with a charmonium state – within their formation time. However, leading hadrons are allowed to interact with a reduced cross section even within their formation time. The reduction factor is 1/2 for mesons which contain a leading constituent quark from an incident nucleon and 2/3 for baryons which contain a leading diquark.

For this study, we have slightly modified the angular distributions of meson-baryon interaction in the UrQMD 1.0 model since their strong forward peak underpredicts the total produced transverse energy [21]. The model now reproduces the E_T spectra in S(200 GeV)+Au and Pb(160 GeV)+Pb collisions measured by NA35 and NA49, respectively [22]. Neither the amount of baryon stopping nor the rapidity distribution of negatively charged particles which have been shown to agree with experimental pp and AB interactions [15] are significantly affected by this modification.

III. RESULTS AND DISCUSSION

Figure 1 shows the calculated number of Drell-Yan muon pairs, proportional to the number of hard collisions, in Pb+Pb collisions as a function of the produced neutral transverse energy within $1.1 < \eta < 2.3$. The NA50 data [23] have been included with the abscissa rescaled to reflect the latest change in data [4] which indicates an ≈ 20 % shift in the absolute E_T scale from previous publications [3,23]. We are aware that the new analysis does not imply a simple overall rescaling of the old data points. However, in order to reasonably compare the gross features of the experimental dimuon E_T spectrum with our model calculation, we have multiplied all E_T-values of the data by 0.8. This factor was obtained by comparing the $E_T - E_{ZDC}$ contour from Quark Matter '97 [23] and the Moriond '98 [4] proceedings. The agreement between the model and the rescaled data is to be expected since the NA49 E_T distribution [24] is described correctly [22][3]. The additional simulation is a simple and well understood model of hard scattering processes in nucleus-nucleus collisions.

Figure 2 shows the J/ψ production cross section according to UrQMD calculations for several projectile-target combinations (p(450 GeV)+C, p(200 GeV)+Cu, p(200 GeV)+W, p(200 GeV)+U, S(200 GeV)+U, and Pb(160 GeV)+Pb) in comparison to experimental data [3]. The results of the calculations are normalized to the experimental cross section in p(200 GeV)+p interactions. The 450 GeV and 160 GeV simulations are rescaled to $p_{lab} = 200$ GeV with the parametrization of Ref. [26], as done by NA50 [2,3]. Considering only nuclear dissociation results in a far smaller J/ψ suppression than seen in the data, not only for Pb+Pb collisions but also for S+U and even pA reactions. Note that the systematics of nuclear absorption shown in Fig. 2 does not reflect a universal straight line as in Glauber calculations with constant absorption cross sections. By taking the nonequilibrium charmonium-meson interactions into account, good agreement with the data is obtained. However, a strong dependence on parameters such as the charmonium and comover formation times and the dissociation cross sections remains to be studied in detail [20].

Due to the linear expansion of the charmonium cross sections with time, the J/ψ and

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[3]However, the agreement between the model and the NA38 experiment becomes poor for S+U collisions. The UrQMD calculation appears to overestimate the neutral transverse energy by about 25% in the range $1.7 < \eta < 4.1$ [1,25] although the calculated E_T spectrum of the similar S+Au system agrees well with the NA35 data [24]. The UrQMD calculation thus indicates an inconsistency between the E_T measurements by NA35, NA49 and NA50 on the one hand and NA38 on the other [22].

ψ' cross sections are similar in the very early stages, leading to a weak A-dependence of the $\psi'/J/\psi$ ratio in pA collisions at central rapidities, apparently consistent with the data. However, for a deeper understanding of this ratio quantum interference effects [27] as well as refeeding processes, $\pi J/\psi \rightarrow \psi'\pi$ [28,29], must be considered. The $\psi'/J/\psi$ ratio will be studied further later [20].

Figure 3 shows the J/ψ to Drell-Yan ratio as a function of E_T for Pb+Pb interactions at 160 GeV compared to the NA50 data [4]. The normalization of $B_{\mu\mu}\sigma(J/\psi)/\sigma(\mathrm{DY}) = 46$ in pp interactions at 200 GeV has been fit to S+U data within a geometrical model [5]. The application of this value to our analysis is not arbitrary: the model of Ref. [5] renders the identical E_T-integrated J/ψ survival probability, $S = 0.49$, as the UrQMD calculation for this system. An additional factor of 1.25 [8] has been applied to the Pb+Pb calculation in order to account for the lower energy, 160 GeV, since the J/ψ and Drell-Yan cross sections have different energy and isospin dependencies. The gross features of the E_T dependence of the J/ψ to Drell-Yan ratio are reasonably well described by the model calculation. No discontinuities in the shape of the ratio as a function of E_T are predicted by the simulation.

IV. CONCLUSION

We have examined charmonium production and absorption processes in pA and AB collisions at SPS energies. The microscopic simulation of hard processes in the impulse approximation and the hadronic transport description of AB collisions with the UrQMD model simultaneously provide reasonable E_T dependencies of the Drell-Yan rates as well as baryon and meson rapidity distributions. We have modelled J/ψ absorption according to the scenario described in Ref. [16]. Cross sections evolving from color transparent small configurations to asymptotic states derived from quantum diffusion and the dynamical χ polarization (color filtering) are taken into account.

The calculated J/ψ production cross sections for minimum bias pA, S+U and Pb+Pb collisions agree with experiment. Dissociation by nonequilibrium comovers accounts for about half of the total absorption in S+U and Pb+Pb reactions. The contribution of the interaction with comovers in pA reactions is small but not negligible. The suppression of charmonium states is sensitive to the comover momentum distributions. The effective dissociation by comovers seems to indicate a nonequilibrated hadronic environment. The observed E_T dependence of the J/ψ to Drell-Yan ratio in Pb+Pb collisions is reproduced by the model. The calculated result is smooth, without abrupt discontinuities, in agreement with new high statistics data [30]. We conclude that within our model, the data on charmonium cross sections at the SPS can be explained without invoking exotic mechanisms.

FIGURES

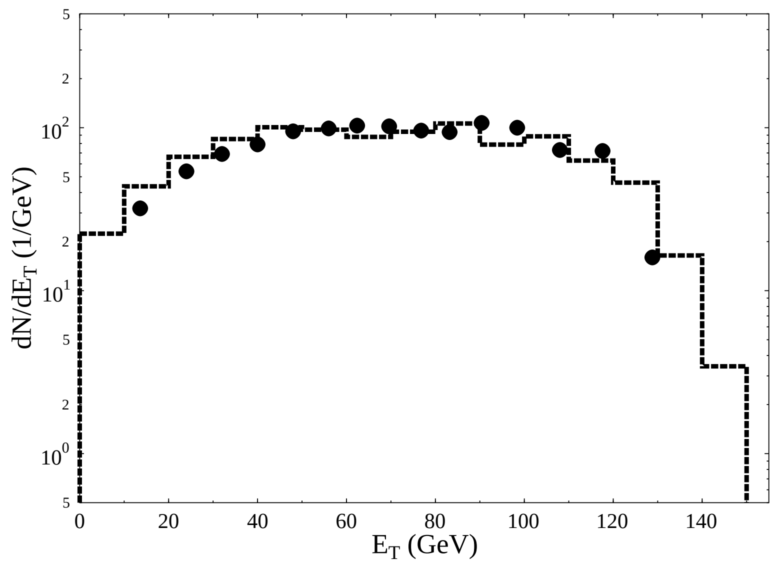

FIG. 1. Number of Drell-Yan pairs in Pb+Pb interactions as a function of the neutral transverse energy within $1.1 < \eta < 2.3$. The calculation is normalized to the data. Shown is the UrQMD result and experimental data from NA50 [23] with the E_T of the data rescaled by 0.8. The modification is motivated by a comparison of the recently published $E_T - E_{ZDC}$ contour plot [4] with the previously published analysis [3,23].

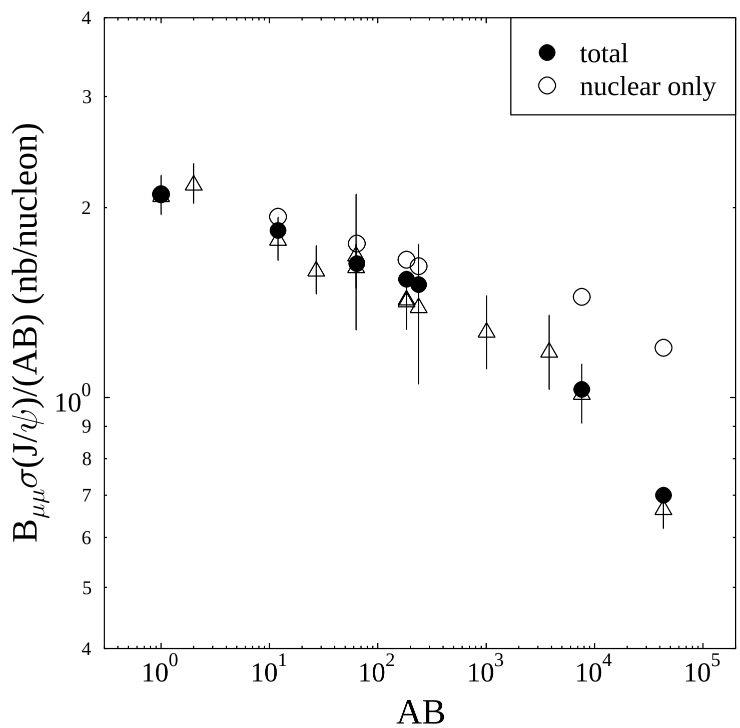

FIG. 2. J/ψ-production cross sections times dimuon branching ratio in the kinematical domain $0 < y_{cm} < 1$ and $|\cos\theta_{CS}| < 0.5$, and rescaled, if necessary, to $p_{\rm lab} = 200$ GeV as a function of AB. The data (open triangles) are from [3]. Open circles denote the production cross sections if only nuclear absorption is considered.

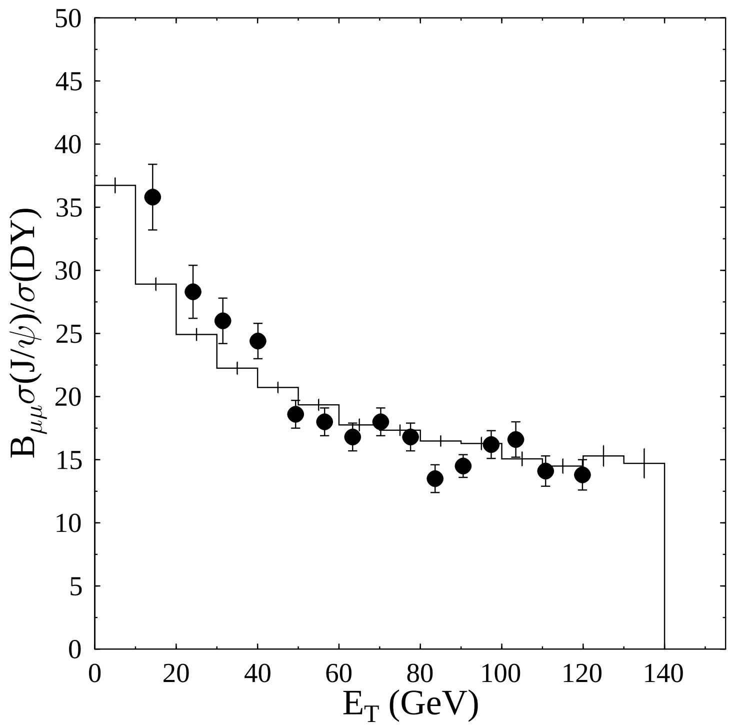

FIG. 3. The ratio of J/ψ to Drell-Yan production as a function of E_T for Pb+Pb at 160 GeV. The experimental data are from Ref. [4]. The normalization factor, from pp interactions at 200 GeV, $B_{\mu\mu}\sigma(J/\psi)/\sigma(\mathrm{DY}) = 46$ is taken from Ref. [5]. This value, however, has been indirectly determined in the framework of a different model. An additional factor of 1.25 [8] has been applied to the Pb+Pb calculation in order to account for the lower energy. Note that no scaling factor has been applied to the x-axis for either the calculations or the data.

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