Production and absorption of $c\bar{c}$ pairs in nuclear collisions at SPS energies

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Abstract

We study the production of $c\bar{c}$ pairs and dimuons from hard collisions in nuclear reactions within the covariant transport approach HSD, which describes successfully both hadronic and electromagnetic observables from p + A and A + A collisions from SIS to SPS energies. The production of $c\bar{c}$ and Drell-Yan pairs is treated perturbatively employing experimental cross sections while the interactions of $c\bar{c}$ pairs with hadrons are included by conventional cascade-type two-body collisions. Adopting 6 mb for the $c\bar{c}$-baryon cross sections the data on $J/\Psi$ suppression in p + A reactions are reproduced in line with calculations based on the Glauber model. We study different models for $c\bar{c}$ dissociation on mesons in comparison with the experimental data of the HELIOS-3, NA38 and NA50 collaborations. Adopting absorption cross sections with mesons above the $D\bar{D}$ threshold in the order of 1.5 - 3 mb we find that all data on $J/\Psi$ suppression from both proton-nucleus and nucleus-nucleus collisions can be described without assuming the formation of a quark-gluon plasma in these collisions.

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1 Introduction

The study of hot and dense nuclear matter via relativistic nucleus-nucleus collisions is the major aim of high energy heavy-ion physics. Nowadays, the search for a restoration of chiral symmetry at high baryon density and temperature or for a phase transition to the quark-gluon plasma (QGP) is of specific interest. In this context Matsui and Satz [1] have proposed that a suppression of the $J/\Psi$ yield in ultra-relativistic heavy-ion collisions is a plausible signature for the formation of the quark-gluon plasma because the $J/\Psi$ should dissolve in the QGP due to color screening [1]. This suggestion has stimulated a number of heavy-ion experiments at CERN SPS to measure the $J/\Psi$ via its dimuon decay. Indeed, these experiments have shown a significant reduction of the $J/\Psi$ yield when going from proton-nucleus to nucleus-nucleus collisions [2]. Especially for Pb + Pb at 160 GeV/A an even more dramatic reduction of $J/\Psi$ has been reported by the NA50 collaboration [3, 4].

To interpret the experimental results, various models based on $J/\Psi$ absorption by hadrons have also been proposed. In Ref. [5], Gerschel and H"ufner have shown within the Glauber model that the observed suppression of $J/\Psi$ in nuclear collisions is consistent with the hadronic absorption scenario if one assumes a $J/\Psi$-nucleon absorption cross section of about 6-7 mb. Similar but more recent analyses by the NA50 collaboration [4] and Kharzeev [6] have led to the same conclusion. However, this model has failed to explain the “anomalous” suppression reported in central Pb + Pb collisions, thus leading to the suggestion of a possible formation of a quark-gluon plasma in these collisions [3, 4]. On the other hand, Gavin et al. [4, 10], based also on the hadronic absorption model, have found that although $J/\Psi$ absorption by nucleons is sufficient to account for the measured total $J/\Psi$ cross sections in both proton-nucleus and nucleus-nucleus collisions, it cannot explain the transverse energy dependence of $J/\Psi$ suppression in nucleus-nucleus collisions. To account for the nucleus-nucleus data they have introduced additionally the absorption on mesons (‘comovers’) with a cross section of about 3 mb. A similar model has also been proposed by Capella et al. [11] to describe the $J/\Psi$ and $\Psi'$ suppression in nucleus-nucleus collisions. On the other hand, Kharzeev et al. [12] claim the ‘comover’ absorption model to be inconsistent when considering all data on $J/\Psi$ production simultaneously.

In all these studies the dynamics of the collisions is based on the Glauber model, so a detailed space and time evolution of the colliding system is not included. In particular, the transverse expansion of the system and the finite hadron formation time is ignored in the Glauber models. Especially for nucleus-nucleus collisions involving heavier beams, such as the Pb + Pb collisions at 160 GeV/nucleon, the dynamics is more subtle than in proton and S induced reactions. Thus dynamical models are needed to complement our information on the reaction dynamics. In this respect Loh et al. [13] have investigated the $J/\Psi$ dissociation in a color electric flux tube in a semiclassical model based on the Friedberg-Lee color dielectric Lagrangian. They find that the $c\bar{c}$ dissociation time is in the order of 1 fm/c. A first transport theoretical analysis of $J/\Psi$ production and absorption has been performed in Ref. [14] where the $c\bar{c}$ production was based on the LUND string formation and fragmentation model [13].
Indeed, substantial differences to the Glauber approaches have been found due to a finite formation time of the $c\bar{c}$ pair and its subsequent interactions with baryons and mesons. However, due to the low statistics achieved in the numerical calculations a definite conclusion about the charmonium suppression could not be obtained in the latter study since alternative production and absorption schemes also could lead to different absorption rates.

In this work we continue the studies in Ref. [14] on $c\bar{c}$ production and suppression at SPS energies within the covariant transport approach HSD\(^1\) [16] using different production and absorption models. The nonequilibrium transport calculations have been shown to describe satisfactorily both the measured hadronic observables (rapidity distributions, transverse momentum spectra etc. [10]), which are sensitive to the final stage collision dynamics, and dilepton spectra [17, 18, 19, 20], which reflect also the initial hot dense stage of the collisions. It thus gives a more realistic description of the heavy-ion reaction dynamics than that used in Refs. [4, 5, 7, 9, 10]. Within this approach we can check if the $c\bar{c}$ pair might be destroyed by nucleons before the mesons are produced as argued in Ref. [4] (cf. also Refs. [3, 5]). Furthermore, we can test if a finite lifetime of the $c\bar{c}$ pre-resonance system as suggested by Kharzeev et al. [3, 21] comes in conflict with the data since according to Ref. [22] the $J/\Psi$ - meson cross section might be negligibly small in hadronic matter due to the small size of the $J/\Psi$ and its large mass gap from open charms. However, it is expected that the $c\bar{c}$ pair is first produced in a color-octet state together with a gluon (‘pre-resonance state’) and that this more extended configuration has a larger interaction cross section with baryons and mesons before the $J/\Psi$ singlet state finally emerges. We will not address the question of whether the magnitude of the $c\bar{c}$-hadron cross sections used is correct or can be justified by nonperturbative QCD and concentrate on the question if specific reactions models can be ruled out in comparison to the data available so far.

The outline of the paper is as follows: In Section 2 we briefly describe the covariant transport approach employed and present details of the baryon and meson dynamics for S + U at 200 GeV/A and Pb + Pb at 160 GeV/A. Section 3 contains the description of charmonium and Drell-Yan production by nucleon-nucleon collisions as well as two models for the charmonium reabsorption on hadrons. In Section 4 we present a detailed comparison of our calculations with the experimental data available so far while Section 5 concludes with a summary and discussion of open problems.

2 The covariant transport approach

In this work we perform our analysis along the line of the HSD approach [10] which is based on a coupled set of covariant transport equations for the phase-space distributions $f_h(x, p)$ of hadron $h$ [10, 23], i.e.

$$\left\{ \left( \Pi_\mu - \Pi_\nu \partial^\mu U^\nu_h - M_h \partial^\mu U^S_h \right) \partial^\mu_x + \left( \Pi_\nu \partial^\mu U^\nu_h + M_h \partial^\mu U^S_h \right) \partial^\mu_p \right\} f_h(x, p)$$

\(^1\)Hadron String Dynamics
In Eq. (1) $U^S_h(x, p)$ and $U^\mu_h(x, p)$ denote the real part of the scalar and vector hadron selfenergies, respectively, while $[G^+G]_{12 \rightarrow 34 \cdots \delta_4^4(\Pi + \Pi_2 - \Pi_3 - \Pi_4 \cdots)}$ is the ‘transition rate’ for the process $1+2 \rightarrow 3+4+\cdots$ which is taken to be on-shell in the semiclassical limit adopted. The hadron quasi-particle properties in (1) are defined via the mass-shell constraint \[ \delta(\Pi_{\mu}\Pi^\mu - M_h^2) \] ,

with effective masses and momenta given by

\[
M^*_h(x, p) = M_h + U^S_h(x, p)
\]

\[
\Pi^\mu(x, p) = p^\mu - U^\mu_h(x, p)
\]

while the phase-space factors

\[
\bar{f}_h(x, p) = 1 \pm f_h(x, p)
\]

are responsible for fermion Pauli-blocking or Bose enhancement, respectively, depending on the type of hadron in the final/initial channel. The dots in Eq. (1) stand for further contributions to the collision term with more than two hadrons in the final/initial channels. The transport approach (1) is fully specified by $U^S_h(x, p)$ and $U^\mu_h(x, p)$ ($\mu = 0, 1, 2, 3$), which determine the mean-field propagation of the hadrons, and by the transition rates $G^+G \delta^4(\ldots)$ in the collision term, that describes the scattering and hadron production/absorption rates.

The scalar and vector mean fields $U^S_h$ and $U^\mu_h$ for baryons are taken from Ref. [16] and don’t have to be specified here again, since variations in the baryon selfenergies within the constraints provided by experimental data were found to have no sizeable effect on the issue of $c\bar{c}$ production and absorption. In the present approach we propagate explicitly – apart from the baryons (cf. [16]) – pions, kaons, $\eta$’s, $\eta$’s, the 1$^-$ vector mesons $\rho$, $\omega$, $\phi$ and $K^*$’s as well as the axial vector meson $a_1$. The production of mesons and baryon-antibaryon pairs is treated within the LUND string model [15] employing a formation time $\tau_F = 0.7$ fm/c which controls the baryon and meson rapidity distributions $dN/dy$ in comparison to experimental data. As meson-meson channels we include the reactions $\pi\pi \rightarrow \rho$, $\pi\pi \rightarrow K\bar{K}$, $\pi\rho \rightarrow \phi$, $\pi\rho \rightarrow a_1$ as well as the time reversed reactions using Breit-Wigner cross sections with parameters from the literature [24] and exploiting detailed balance. As noted before, this transport approach was found to describe reasonably well hadronic as well as dilepton data from SIS to SPS energies [14, 19, 20].

Before discussing the question of charmonium production we show in Fig. 1 the time evolution of the baryon density $\rho_B(x, y, z; t)$ as a function of $z$ and time $t$ for $x = y = 0$ in a central collision of Pb + Pb at 160 GeV/A in the nucleon-nucleon center-of-mass
frame. The two Pb-ions start to overlap at $t \approx 1\text{ fm}/c$, get compressed up to a maximum density of about $2.5\text{ fm}^{-3}$ at $t \approx 2.5\text{ fm}/c$ and expand in longitudinal ($z$) direction later on indicating a sizeable amount of transparency. We note that the space-time evolution in Fig. 1 is controlled by the experimental rapidity distributions $dN/dy$ for protons and negatively charged particles from NA49 [23]; the streaming of hadrons or more precisely their distribution in velocity $\beta$, i.e. $dN/d\beta$ can also be directly extracted from the experimental data using $dN/d\beta = \frac{1}{2}dN/dy(\beta)\left(\frac{1}{1+\beta} + \frac{1}{1-\beta}\right)$.

The produced mesons in this reaction (in a central cylinder of radius $R = 3\text{ fm}$ and volume $V \approx 15\text{ fm}^3$) appear at about $t \approx 2\text{ fm}/c$ as can be extracted from Fig. 2 (lower part) where the densities of pions, $\rho, \omega$ and $\eta$ mesons are displayed separately as a function of time. The maximum in the meson density ($\approx 1\text{ fm}^{-3}$ for pions) at $t \approx 3.2\text{ fm}/c$ appears with a delay of $\tau_F = 0.7\text{ fm}/c$ with respect to the maximum baryon density (cf. Fig. 1). For comparison we also show in Fig. 3 the meson densities for a central S + U collision at 200 GeV/A within the same volume. When comparing to the central Pb + Pb collision at 160 GeV/A we observe a lower meson density for the S + U case in the central overlap region; especially the $\rho$-meson density is lower by about a factor of 2. Nevertheless, high baryon and meson densities are encountered in these reactions for $t \geq 2\text{ fm}/c$ where a $c\bar{c}$ pair – that can be produced from 1 - 3.5 fm/c – has to pass through.

This situation is summarized schematically in Fig. 3 for a p + Pb (upper part) and S + U collision at 200 GeV (middle part) as well as for a central Pb + Pb collision at 160 GeV/A (lower part) for freely streaming baryons (thick lines). In all cases the initial string formation space-time points are indicated by the full dots; the mesons (indicated by arrows) hadronize after a time delay $\tau_F = 0.7\text{ fm}/c$ as shown by the first hyperbola. A $c\bar{c}$ pair produced in the initial hard nucleon-nucleon collision cannot be absorbed by mesons in the dark shaded areas in space and time; however, in case of Pb + Pb, where $c\bar{c}$ pairs should be produced within the inner rectangles, a sizeable fraction will also be produced in a dense mesonic environment. This fraction of pairs produced at finite meson density for S + U is much reduced as can be seen from Fig. 3 (middle part).

The upper hyperbolas in Fig. 3 represent the boundaries for the appearance of mesons from the second interaction points (full dots) which appear somewhat later in time; they stand for a representative further nucleon - nucleon collision during the reaction.

3 Charmonium and Drell-Yan production

Since the probability of producing a $c\bar{c}$ or Drell-Yan pair is very small, a perturbative approach is used for technical reasons. Whenever two nucleons collide a $c\bar{c}$ pair is produced with a probability factor $W$, which is given by the ratio of the $J/\Psi$ (or $\Psi'$) to $NN$ cross section at a center-of-mass energy $\sqrt{s}$ of the baryon-baryon collision,

$$W = \frac{\sigma_{BB \to J/\Psi + X}(\sqrt{s})}{\sigma_{BB \to BB + X}(\sqrt{s})}. \quad (5)$$
The parametrization used for the $J/\Psi$ cross section is

$$
\sigma_{BB \rightarrow J/\Psi + X}(\sqrt{s}) = 160 \left(1 - \frac{a}{\sqrt{s}}\right)^2 \frac{\sqrt{s}}{a} \text{ [nb]}
$$

(6)

with $a = 7.47$ GeV which is shown in Fig. 4 (solid line) in comparison to the experimental data displayed in Ref. [26]. For the systems to be studied, in the energy regime $\sqrt{s} \leq 30$ GeV, the estimated uncertainty of our parametrization is about 20%. We note that the parametrization used conventionally [26] is

$$
\sigma_{pp \rightarrow J/\Psi + X}(\sqrt{s}) = d \left(1 - \frac{c}{\sqrt{s}}\right)^{12}
$$

(7)

with $c = 3.097$ GeV, $d = 2 \cdot 37/B_{\mu\mu}$ nb while $B_{\mu\mu} = 0.0597$ is the branching ratio of the $J/\Psi$ to dimuons. The expression (7) (dashed line in Fig. 4) is in a good agreement with our formula (6) for $10 \text{ GeV} \leq \sqrt{s} \leq 30$ GeV which is the energy regime of interest.

The rapidity distribution of the $c\bar{c}$-pair is approximated by a Gaussian in the nucleon-nucleon center-of-mass of width $\sigma \approx 0.6$ as in Ref. [27] while the transverse momentum distribution is fitted to experimental data (see below). For $\Psi'$ production we employ the same model, however, scale the experimental cross section by a factor of 0.122 relative to the $J/\Psi$ production cross section.

In extension to Ref. [14] the Drell-Yan process is taken into account explicitly. The generation of Drell-Yan events was performed with the PYTHIA event generator [28] version 5.7 using GRV LO [29] or MRS A [30] structure functions from the PDFLIB package [31] with $k_T = 1.0$ GeV. In the kinematical domain $1.5 \leq M \leq 5.5$ GeV, $3 \leq y_{lab} \leq 4$ and $-0.5 \leq \cos \theta_{CS} \leq 0.5$, where $\theta_{CS}$ is the polar angle in the Collins-Soper reference frame, this yields a dimuon cross section of 270 pb in pp collisions at 200 GeV and 261 pb in pn collisions, respectively, as in Refs. [2, 27].

According to our dynamical prescription the Drell-Yan pairs can be created in each hard $pp, pn, np$ or $nn$ collision ($\sqrt{s} \geq 10$ GeV). Since PYTHIA calculates the Drell-Yan process in leading order only (using GRV LO structure functions) we have multiplied the Drell-Yan yield for $NN$ collisions by a K-factor of 2.0 (cf. Refs. [2, 27]). In case of MRS A structure functions, which include NLO corrections, a K-factor of about 1.6 had to be introduced (cf. [26]). The energy distribution of the hard $NN$ collisions $dN/d\sqrt{s}$ for nucleus-nucleus collisions in our transport approach shows a pronounced peak around $\sqrt{s_0} = \sqrt{2m_N(T_{\text{kin}} + 2m_N)}$ where $T_{\text{kin}}$ is the kinetic energy per nucleon in the laboratory frame. Thus the main contribution to the dimuon yield – summed over all $NN$ events – comes from $NN$ collisions with $\sqrt{s} \simeq \sqrt{s_0}$. However, there are also Drell-Yan pairs from $NN$ collisions with $\sqrt{s}$ larger or smaller than $\sqrt{s_0}$.

We have compared our results within the production scheme given above with that used in Refs. [4, 8, 27], where the Drell-Yan yield from $p + A$ and $A + A$ collisions is calculated as the isotopical combination of the yield from $pp$ and $pn$ at fixed $\sqrt{s_0}$ scaled by $A_p \times A_T$. We found that the variation from the scheme used in Refs. [2, 3, 27] is less then 10%. We, furthermore, note that the difference in the dimuon spectrum using different structure functions (GRV LO or MRS A) is less than 5%. In the present
analysis we have discarded dimuon production from open charm channels because a recent analysis by Braun-Munzinger et al. [32] on the basis of the same PYTHIA event generator has shown that the open charm contributions at low and high invariant masses are of minor importance.

Since the production scheme is the same for $c\bar{c}$-pairs, their total cross section (without reabsorption) also scales with $A_p \times A_T$; the ratio of the $J/\Psi$ to the Drell-Yan cross section thus provides a direct measure for the $J/\Psi$ suppression.

In order to obtain some information about the primary distribution of the produced 'pre-resonance' states in coordinate space we show in Fig. 5 the $c\bar{c}$ distribution in the $(x, z)$-plane integrated over $y$ for a central collision of Pb + Pb at 160 GeV/A. The collision of the two nuclei proceeds along the $z$-direction and the actual $z$-axis has been stretched by the Lorentz factor $\gamma_{cm} \approx 9.3$ to compensate for the Lorentz contraction in beam direction. It is clearly seen from Fig. 5 that the production of the charmonium state by hard nucleon-nucleon collisions is enhanced in the center and drops rapidly in the surface region of the overlapping nuclei.

We follow the motion of the $c\bar{c}$ pair in hadronic matter throughout the collision dynamics by propagating it as a free particle. In our simulations the $c\bar{c}$ pair, furthermore, may be destroyed in collisions with hadrons using the minimum distance concept as described in Sec. 2.3 of Ref. [33]. For the actual cross sections employed we study two models (denoted by I and II) which both assume that the $c\bar{c}$ pair initially is produced in a color-octet state and immediately picks up a soft gluon to form a color neutral $c\bar{c} - g$ Fock state $|\bar{1}\rangle$ (color dipole). This extended configuration in space is assumed to have a 6 mb dissociation cross section in collisions with baryons ($c\bar{c} + B \rightarrow \Lambda_c + \bar{D}$) as in Refs. [4, 5, 6] during the lifetime $\tau$ of the $c\bar{c} - g$ state which is a parameter. In the model I we assume $\tau = 10$ fm/c which is large compared to the nucleus-nucleus reaction time such that the final resonance states $J/\Psi$ and $\Psi'$ are formed in the vacuum without further interactions with hadrons. In the model II we adopt $\tau = 0.3$ fm/c as suggested by Kharzeev [6] which implies also to specify the dissociation cross sections of the formed resonances $J/\Psi$ and $\Psi'$ on baryons. For simplicity we use 3 mb following Ref. [21]. The cross section for $c\bar{c} - g, J/\Psi$, or $\Psi'$ dissociation on mesons ($c\bar{c} + m \rightarrow D\bar{D}$) is treated as a free parameter ranging from 0 to 3 mb.

In order to test the transverse momentum dependence of the $J/\Psi$ production we have performed calculations for $p + U$ and $S + U$ at 200 GeV/A (using model I with $\sigma_{abs}^{\text{baryons}} = 6$ mb and $\sigma_{abs}^{\text{mesons}} = 1$ mb) which are scaled in magnitude to the respective data for the same systems from Ref. [2]. Our calculated results are shown in Fig. 5 for both systems in terms of the histograms while the solid lines represent fits to the experimental transverse momentum distributions. Since this $p_T$ dependence is described fairly well we expect the $c\bar{c}$ event distributions to be quite realistic.

4 Analysis of experimental data

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The formation time $\tau_F$ for the $c\bar{c}$-pair is assumed to be zero in our present approach in contrast to Ref. [14].
4.1 HELIOS-3 data

Since the $J/\Psi$ and $\Psi'$ are measured in nuclear collisions through their decay into dimuons, we calculate explicitly the dimuon invariant mass spectra from these collisions. This includes not only the decay of the $J/\Psi, \Psi'$ but also the decay of other mesons ($\eta, \rho, \omega, \phi$) as well as the Dalitz decay of the $\eta, \omega, \eta'$ etc. Details on calculating the dimuon spectra from heavy-ion collisions up to invariant masses of about 1.3 GeV can be found in Refs. [17, 18, 20]. Since the Drell-Yan contribution is important for dileptons with invariant masses above 1.5 GeV [27] we have included these channels by computing for each 'hard' nucleon-nucleon collision ($\sqrt{s} \geq 10$ GeV) their contribution via PYTHIA 5.7 [28] as described above.

We have carried out calculations for p + W and central S + W collisions at 200 GeV/A as in Ref. [14] in order to check on an absolute scale if the production and absorption schemes employed in the HSD approach are included properly. In Fig. 7 we show the dilepton invariant mass spectra for p + W and S + W at 200 GeV/A normalized to the number of charged particles in the pseudorapidity bin $3.7 \leq \eta \leq 5.2$ and compare them with the experimental data from Ref. [34] including their acceptance and mass resolution. Again we have employed model I with $\sigma_{\text{baryons}} = 6$ mb and $\sigma_{\text{mesons}} = 1$ mb (see below). It is seen from Fig. 7 that in the p + W and S + W cases the theoretical results agree well with the data on an absolute scale which implies that apart from the low mass dimuon spectrum - which has been analyzed in Ref. [18] - also the $J/\Psi$ and $\Psi'$ region is described reasonably well. At low dimuon masses the explicit contributions from the mesons $\eta, \omega, \phi$ are displayed in terms of the thin lines while for invariant masses above 1.5 GeV the Drell-Yan (DY), $J/\Psi$ and $\Psi'$ contributions are shown explicitly. The full solid curve represents the sum of all contributions (without open charm channels). It is intersected from $M \approx 1.2$ GeV to 1.5 GeV because the continuation of the Drell-Yan contribution to lower energies is not clear as well as the tail of the $\rho$-meson contribution at higher $M$. Furthermore, open charm channels (from $D$ and $\bar{D}$ mesons) have not been included yet (cf. Ref. [22]). We note that for S + W in the invariant mass range from 1.6 GeV $\leq M \leq 2.5$ GeV the dimuon yield is almost twice that for p + W within the present normalization and that our calculations reproduce also the intermediate mass range on the basis of PYTHIA 5.7 reasonably well. Thus our calculations can be regarded as fully microscopic studies on dilepton production for invariant masses 0.2 GeV $\leq M \leq 5$ GeV including both the relevant 'soft' and 'hard' processes.

4.2 Proton-nucleus reactions

Since the absorption of $c\bar{c}$-pairs on secondary mesons in proton-nucleus collisions is practically negligible [14], these reactions allow to fix 'experimentally' the $c\bar{c}$-baryon dissociation cross section. Furthermore, the Glauber approach for $c\bar{c}$ absorption in this case should be approximately valid at energies of about 200 – 450 GeV such that the transport calculations can be tested additionally in comparison e.g. to the model calculations of Refs. [3, 4, 8, 10, 21].
In Fig. 8 we show the results of our calculations for the $J/\Psi$ ‘survival probability’ (open squares) using 6 mb for the absorption cross section of the $c\bar{c}$-pairs on nucleons in comparison to the data [4]. The experimental ‘survival probabilities’ $S_{exp}^{J/\Psi}$ in this figure as well as in the following comparisons are defined by the ratio of experimental $J/\Psi$ to Drell-Yan cross sections as

$$S_{exp}^{J/\Psi} = \left( \frac{B_{\mu\mu} \sigma_{AB}^{J/\Psi}}{\sigma_{DY}^{2.9-4.5 \text{ GeV}}} \right) \left/ \left( \frac{B_{\mu\mu} \sigma_{pd}^{J/\Psi}}{\sigma_{DY}^{pd}} \right) \right.$$  

where $A$ and $B$ denote the target and projectile mass while $\sigma_{AB}^{J/\Psi}$ and $\sigma_{DY}^{AB}$ stand for the $J/\Psi$ and Drell-Yan cross sections from $AB$ collisions, respectively, and $B_{\mu\mu}$ is the branching ratio of $J/\Psi$ to dimuons. The theoretical ratio is defined as

$$S_{theor}^{J/\Psi} = \frac{M_{J/\Psi}}{N_{J/\Psi}},$$

where $N_{J/\Psi}$ is the multiplicity of initially produced $J/\Psi$’s while $M_{J/\Psi}$ is the multiplicity of $J/\Psi$’s that survive the hadronic final state interactions. We note that due to the large statistical error bars of the experimental data absorption cross sections $\sigma_{abs}^{baryons}$ of 6 ± 1 mb are compatible also. These values are slightly smaller than those of Kharzeev et al. [12] in the Glauber model claiming 7.3 ± 0.6 mb, but in the same range as those used in the Glauber models of Ref. [5]. We do not expect to get exactly the same values as in the Glauber model because the transverse expansion of the scattered nucleons as well as of the $c\bar{c}$-pairs is neglected there. Due to the ‘optimal’ reproduction of the available data with a cross section of about 6 mb we will use this value also for nucleus-nucleus collisions in the following.

4.3 Transverse energy distributions

In order to perform a detailed comparison to the data of the NA38 and NA50 Collaborations for $S + U$ at 200 GeV/A and Pb + Pb at 160 GeV/A we first have to fix the experimental event classes as a function of the neutral transverse energy $E_T$ in order to allow for an event by event analysis. In this respect we compute the differential cross section

$$\frac{d\sigma}{dE_T} = 2\pi \int_0^\infty b \, db \frac{dN}{dE_T}(b)$$

as a function of the impact parameter $b$, where $\frac{dN}{dE_T}(b)$ is the differential $E_T$ distribution for fixed $b$. Since the detector response is not known to the authors the $E_T$ distribution is rescaled to reproduce the tail in the experimental $E_T$ distributions which results in the dashed histograms in Fig. 9 that increase for low $E_T$.

In the actual experiments, however, only events are recorded with a $\mu^+\mu^-$ pair of invariant mass $M \geq 1.5$ GeV and rapidity $3 \leq y_{lab} \leq 4$ for NA38 or $M \geq 2.9$ GeV and rapidity $2.93 \leq y_{lab} \leq 3.93$ for NA50. A respective selection in the transport
calculation is obtained by

$$\frac{d\sigma^{\mu\mu}_{\text{theor}}}{E_T} = 2\pi N_0 \int_0^\infty bdb \frac{dN}{dE_T}(b) \sum_i W_i^{\mu\mu}(b),$$  \hspace{1cm} (11)$$

where $W_i^{\mu\mu}(b)$ are the weights for produced $\mu\mu$ pairs within the experimental cuts. $N_0$ is a normalization factor to adjust to the experimental number of events. The calculated distributions (11) are shown in Fig. 9 in terms of the solid histograms which reasonable reproduce the experimental distributions (grey histogram for S + U, full dots for Pb + Pb). The average values for $E_T$ in the 5 bins are indicated in Fig. 9 by the open squares and coincide with the corresponding experimental values from Ref. [3].

4.4 NA38 and NA50 data

We are now in the position to perform a comparison to the experimental survival probabilities for $J/\Psi$ and $\Psi'$ production in the respective transverse energy bins. We first compute the results for S + U at 200 GeV/A and Pb + Pb at 160 GeV/A within the model I varying the dissociation cross section on mesons of the $c\bar{c} - g$ object from 0 to 1.5 mb while keeping the absorption cross section on baryons fixed at 6 mb. The calculated $S_{J/\Psi}$ are displayed in Fig. 10 in comparison to the data for both systems; the dashed lines are obtained for $\sigma_{\text{abs}}^{\text{mesons}} = 0$ mb while the solid lines correspond to $\sigma_{\text{abs}}^{\text{mesons}} = 1.5$ mb. Whereas the data for S + U appear to be approximately compatible with our calculations without any dissociation by mesons the Pb + Pb system shows an additional suppression. This finding is in agreement with the results of Glauber models [6, 12]. On the other hand, the Pb + Pb data are well reproduced with a cross section of 1.5 mb (in model I) for the $J/\Psi$ absorption on mesons which, however, then slightly overestimates the suppression for the S + U data for the 3 middle $E_T$ bins. Our calculations thus do not indicate a strong argument in favor of a QGP phase in the Pb + Pb reaction to interpret the $J/\Psi$ suppression within the model I.

The latter conclusion is different from the Glauber calculations of Refs. [6, 12] and should be due to the simplified assumptions about the actual meson abundance with which the $c\bar{c}$ pair can be dissociated. Note again that mesons appear in our dynamical approach only after $\tau_F = 0.7$ fm/c after the first ‘hard’ collision. As has been pointed out by Gavin et al. [9] especially the $J/\Psi$ in the comoving frame should be dissociated by $\rho$ and $\omega$ mesons and less by pions due to the large gap in energy for $D\bar{D}$ dissociation. We have investigated this suggestion more quantitatively within our microscopic approach and find the following hadronic decomposition for $J/\Psi$ absorption on mesons: S + U (central): pions (35%), $\rho$’s (42%), $\omega$’s (15%), $\eta$’s (8%); Pb + Pb (central): pions (37%), $\rho$’s (42%), $\omega$’s (13%), $\eta$’s (8%). Thus the hadronic decomposition practically does not change when going from S + U to the heavier Pb + Pb system. As a side remark we note that the dilepton yield from central S + Au and Pb + Au collisions normalized to the charged particle multiplicity in the rapidity bin $2.1 \leq y \leq 3.1$ – experimentally appears to be the same [35] which is in line with our findings.

$^3$The S+U data are best described with $\sigma_{\text{abs}}^{\text{baryons}} \approx 6.5$ mb.
A remarkable difference, however, is found when comparing the number of absorbed $J/\Psi$'s by mesons in central collisions for $S + U$ and $Pb + Pb$ as a function of time. In order to compare the two absorption rates $dN^{mes}_{abs}(t)/dt$ on a relative scale we have multiplied the absorption rate for the system $S + U$ by the ratio of projectile nucleons $(208/32)$ in Fig. 11. Here the heavier system $Pb + Pb$ shows higher absorption rates from the beginning (at $t = 2 \text{ fm/c}$), which correlates with the central meson densities shown in Fig. 2, and also the $J/\Psi$ absorption on mesons lasts longer in accordance with the calculations in Ref. [14]. The latter effect can also be extracted from the schematic picture in Fig. 3 where the number of produced $c\bar{c}$-pairs at finite meson density is expected to be much larger for $Pb + Pb$ than for $S + U$.

We, furthermore, compute the ratio $S_{J/\Psi}$ for $S + U$ at 200 GeV/A and $Pb + Pb$ at 160 GeV/A within the model II for a $c\bar{c} - g$ lifetime $\tau = 0.3 \text{ fm/c}$ varying the dissociation cross section of the $c\bar{c}$-pair with mesons from 0 - 3 mb while keeping the absorption cross section on baryons fixed at $\sigma_{abs}^{baryons} = 6 \text{ mb}$ for the ‘pre-resonance’ state and at 3 mb for the formed $J/\Psi$ resonance. The calculated ratios are displayed in Fig. 12 in comparison to the data; again the dashed lines correspond to the calculations without any charmonium absorption on mesons whereas the solid lines represent our calculations for a meson absorption cross section of 3 mb. In the absorption model II the data for $S + U$ are no longer compatible with our calculations without any dissociation by mesons. The $S + U$ data here need an absorption by mesons in the range of 3 mb as in the phenomenological model of Gavin et al. [9, 10]. With $\sigma_{abs}^{mesons} \approx 3 \text{ mb}$ for the absorption on mesons, however, the $Pb + Pb$ data appear to be compatible, too. For future experimental studies we display in Fig. 12 the calculated ratio $S_{J/\Psi}^{theor}$ (within model II) for more peripheral reactions (open diamonds) that correspond to an $E_{T}$-bin from $5 \div 10 \text{ GeV}$ in case of $S + U$ at 200 GeV/A and to an $E_{T}$-bin from $10 \div 20 \text{ GeV}$ in case of $Pb + Pb$ at 160 GeV/A.

We additionally investigate if the $\Psi'$ suppression measured by NA38 and NA50 for $S + U$ and $Pb + Pb$ can be described simultaneously within our approach without including any additional assumptions. Since the $\Psi'$ suppression in proton-nucleus reactions is practically the same [20] we employ also a dissociation cross section of 6 mb on baryons while the absorption cross section on mesons is treated again as a free parameter. Our numerical results for both systems on the $\Psi'$ survival probability within the absorption model I are displayed in Fig. 13 in comparison with the data from [4]. Due to the higher $\Psi'$ suppression in these reactions the absorption on mesons requires cross sections from 2.5 - 3.5 mb. We note that we cannot describe the experimental ratios $S_{exp}^{\Psi'}$ for central $S + U$ collisions (high $E_{T}$) within the present treatment which might be due to the neglect of $\Psi' \rightarrow J/\Psi + X$, or $\tau \Psi' \rightarrow J/\Psi + X$ reaction channels. This also holds for calculations within the model II where $\sigma_{abs}^{mesons} \simeq 4 - 5 \text{ mb}$ has to be assumed. Furthermore, the actual statistics reached for $\Psi'$ production and absorption events is too low to allow for final conclusions here.
5 Summary

In this paper we have carried out a microscopic transport study of $J/\Psi$, $\Psi'$ and Drell-Yan production in proton-nucleus and nucleus-nucleus collisions. Our calculations show that the absorption of ‘pre-resonance’ $c\bar{c} - g$ states by both nucleons and produced mesons can explain reasonably not only the inclusive $J/\Psi$ cross sections but also the transverse energy ($E_T$) dependence of $J/\Psi$ suppression measured in nucleus-nucleus collisions. In particular, the absorption of $J/\Psi$’s by produced mesons is found to be important especially for Pb + Pb reactions, where the $J/\Psi$-hadron reactions extend to longer times as compared to the S + W or S + U reactions. This is in contrast with results based on a simple Glauber model, which neglects both the transverse expansion of the hadronic system and the finite meson formation times, where the $c\bar{c} - N$ absorption is roughly sufficient even for S-induced collisions. As a consequence we do not find a necessary argument to require the formation of a quark-gluon-plasma in Pb + Pb collisions at 160 GeV/A. This could only be done through experimental or theoretical evidence that the charmonium-meson cross sections employed ($\approx 1.5 – 3 \text{ mb}$) in our analysis are too large. Since the $c\bar{c}$ dissociation on mesons is expected to be dominated by flavor exchange reactions the present cross sections in our opinion, however, should be reasonable.

We close our study by noting that in the phase of high baryon and meson density both the meson densities (cf. Fig. 3) as well as the associated energy densities are very high such that a purely hadronic reaction scheme might be questionable. Further experimental data with good statistics also for p + A collisions with light nuclei are expected to provide more accurate constraints.

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Figure 1: The baryon density $\rho_B(x = 0, y = 0, z; t)$ for a Pb + Pb collision at 160 GeV/A and impact parameter $b = 1$ fm.
Figure 2: The density of $\pi, \rho, \omega$ and $\eta$ mesons in a central cylinder of radius $R = 3$ fm and volume $V \approx 15$ fm$^3$ for a S + U collision at 200 GeV/A and a Pb + Pb collision at 160 GeV/A for $b = 1$ fm.
Figure 3: Schematic representation of p + Pb collision at 200 GeV (upper part), S + U collision at 200 GeV/A (middle part) and a Pb + Pb collision at 160 GeV/A (lower part) in space-time. The full dots represent early hard collision events (for Drell-Yan and $c\bar{c}$ pairs) while mesons ($\pi, \eta, \rho, \omega$, etc. – arrows) only appear after a respective formation time $\tau_F \approx 0.7 \text{ fm/c}$. The overlap area (inner rectangle) specifies the space-time region of hard production events.
Figure 4: The parametrization (6) for the elementary $J/\Psi$ cross section in pp collisions (solid line) in comparison to the experimental data from Ref. [26]. The dashed line represents the parametrization (7).
Figure 5: The production probability for $c\bar{c}$-pairs in a central Pb + Pb collision at 160 GeV/A in the $(x, z)$-plane integrated over $y$. The $z$-axis is scaled by the Lorentz factor $\gamma_{cm} = 9.3$ to compensate for the Lorentz contraction in beam direction.
Figure 6: The transverse momentum distribution of $J/\Psi$ mesons in $p + U$ (upper part) and $S + U$ collisions (lower part) at 200 GeV/A from the HSD calculations (histograms). The solid lines are fits to the experimental data from Ref. [2].
Figure 7: Dimuon invariant mass spectra from p + W and S + W collisions at 200 GeV/nucleon in comparison to the data of the HELIOS-3 collaboration [34]. In the low mass region the individual contributions from the $\eta$ Dalitz decay, $\omega$ and $\Phi$ decay are shown by the thin lines. The Drell-Yan contribution (denoted by DY) is calculated only for invariant masses $M \geq 1.5$ GeV. The explicit contributions from $J/\Psi$ and $\Psi'$ decays are indicated by thin lines for $M \geq 2.7$ GeV. The thick solid lines represent the sum of all dimuon channels (except for open charm contributions).
Figure 8: The $J/\Psi$ ‘survival probability’ $S^{J/\Psi}$ for $p + A$ reactions at 200 GeV assuming a 6 mb cross section for the $c\bar{c}$ dissociation on baryons (open squares) in comparison to the experimental data from [4] within the model I.
Figure 9: The distributions in the neutral transverse energy for S + U at 200 GeV/A and Pb + Pb at 160 GeV/A; dashed histograms: result of the transport calculations without any constraints on the experimental acceptance (10); experimental distributions: grey histogram for S + U, full dots for Pb + Pb; solid histograms: HSD calculation for the $E_T$ distribution according to Eq. (11). The open squares denote the average $E_T$ in the experimental $E_T$ bins.
Figure 10: The ratio $S^{J/\Psi}$ for S + U at 200 GeV/A (upper part) and Pb + Pb at 160 GeV/A (lower part) as a function of the transverse energy in comparison to the experimental data from [3] within the model I assuming a long lifetime for the $c\bar{c} - g$ system. The absorption cross section on mesons is varied from 0 (dashed lines) to 1.5 mb (solid lines).
Figure 11: The $J/\Psi$ absorption rate $dN_{\text{mes}}^{\text{abs}}(t)/dt$ on mesons for central collisions of S + U at 200 GeV/A and Pb + Pb at 160 GeV/A. The absorption rate for S + U has been multiplied by a factor 208/32 to compensate for the different number of projectile nucleons.
Figure 12: The ratio $S_{J/\Psi}$ for S + U at 200 GeV/A (upper part) and Pb + Pb at 160 GeV/A (lower part) as a function of the transverse energy in comparison to the experimental data from [3] within the model II (see text). The absorption cross section on mesons is varied from 0 (dashed lines) to 3 mb (solid lines); the dissociation cross section on baryons for the pre-resonance $c\bar{c} - g$ system was taken as 6 mb while for the $J/\Psi$ singlet cross section with baryons 3 mb were adopted. The open diamonds represent the calculated ‘survival probabilities’ $S_{J/\Psi}$ (within model II) for more peripheral reactions (see text).
Figure 13: The ratio $S_{\Psi'}$ for S + U at 200 GeV/A (upper part) and Pb + Pb at 160 GeV/A (lower part) as a function of the transverse energy in comparison to the experimental data from [3] within the model I assuming a long lifetime for the $c\bar{c} - g$ system. The absorption cross section on mesons is varied from 2.5 to 3.5 mb.