We study the production of $c\bar{c}$ pairs and dimuons from hard collisions in nuclear reactions within the covariant transport approach HSD. Adopting 6 mb for the $c\bar{c}$-baryon cross section the data on $J/\Psi$ suppression in $p + A$ reactions are reproduced in line with calculations based on the Glauber model. Furthermore, using $J/\Psi$ 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 NA38/NA50 can be described without assuming the formation of a quark-gluon plasma. Alternatively, we also investigate an 'early'-comover absorption scenario where the $c\bar{c}$ pairs are dissociated in the color electric fields of neighboring strings. Again we find good agreement with the experimental data with an estimate for the string radius of $R_s \approx 0.2 - 0.25 \text{ fm}$.

1 Introduction

More than a decade ago Matsui and Satz\cite{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. 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\cite{2}. Especially for $\text{Pb} + \text{Pb}$ at 160 GeV/A an even more dramatic reduction of $J/\Psi$ has been reported by the NA50 collaboration\cite{3,4,5}.

To interpret the experimental results, various models based on $J/\Psi$ absorption by hadrons have also been proposed\cite{6,7,8}. However, these models have failed to explain the “anomalous” suppression reported in central $\text{Pb} + \text{Pb}$ collisions, thus leading to the suggestion of a possible formation of a quark-gluon plasma in these collisions\cite{9,10}. On the other hand, Gavin and Vogt\cite{11} 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

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3 mb. A similar model has also been proposed by Capella et al. to describe the $J/\Psi$ and $\Psi'$ suppression in nucleus-nucleus collisions.

In all these studies the dynamics of the collisions is based on the Glauber model, thus a detailed space and time evolution of the colliding system is not included. In the following we want to report on our theoretical analysis of $J/\Psi$ production and absorption within a transport theoretical analysis. On the one hand we will show our detailed microscopic analysis of the (hadronic) comover scenario. As an alternative we also consider the effect of $c\bar{c}$ dissociation in the prehadronic phase of the heavy-ion collision, which can be regarded as an 'early'-comover absorption scenario, and not as absorption by 'late' hadronic comovers. This is motivated by the fact, that the very early collision phase is not described by hadrons but by highly excited strings. As each individual string carries a lot of internal energy (to produce the later secondaries) in a small and localized space-time volume the quarkonia state might get completely dissociated by the intense color electric field inside a single string.

2 Ingredients of the transport calculations

Within our transport calculation we can exploit various assumptions (models) for the $c\bar{c}$ formation and propagation and also take into account the Drell-Yan process explicitly. This represents a sophisticated extension of the first analysis carried out in Ref. A detailed description of the transport approach as well as its ingredients is given in Refs. The generation of Drell-Yan events is performed with the PYTHIA event generator version 5.7 using GRV LO or MRS mode 43 structure functions from the PDFLIB package.

According to our dynamical prescription the Drell-Yan pairs can be created in each hard $pp$, $pn$ 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. In case of MRS mode 43 structure functions, which include NLO corrections, a K-factor of about 1.6 had to be introduced (cf. Ref. We have compared our results within the production scheme given above with that used in Refs. 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. is less then 10%. As the production scheme is considered to be 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. We emphasize that the $A_P \times A_T$ scaling of the initial $c\bar{c}$ production is an input of our calculation and
We then 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. 21. 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 (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. 22. Within the comover scenario 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 our alternative approach we discard the possible absorption on late mesonic comovers, but instead focus on the possible $c\bar{c}$ dissociation by the strings in the prehadronic phase 23. The absorption on the surrounding nucleons will be treated like for model II. In the early stages of the reaction the $c\bar{c}$ states move not in a hadronic environment but in an environment of color electric strings of 'wounded' nucleons: Several hundred strings are formed during a central Pb-Pb collision at SPS energies. In Fig. 1 a characteristic representation of the hadrons and the strings during the high density phase in a central Pb + Pb collision at 160 AGeV is shown. The high energy hadron-hadron collisions are described by the FRITIOF model 24 resulting in two excited strings. The dynamical evolution of the strings is now included explicitly (for details see Ref. 23). The fragmentation of the strings into hadrons starts after the formation time, which is set to $t_f = 0.8$ fm/c. We now assume that a $c\bar{c}$ state immediately dissociates whenever it moves into the region of the color electric field of a string. In this sense strings are completely 'black' for $c\bar{c}$ states. It was found in Ref. 12 that the additional force acting on the charm quarks in the color electric field is given by $2 \times \sigma \approx 2 GeV/fm$, where $\sigma$ denotes the phenomenological string constant of a chromo electric flux, which is sufficient to immediately break up a $c\bar{c}$ state. One can also argue that the field energy density contained in a string is given by $\sigma/(\pi R_S^2)$. For $R_S \approx 0.3 fm$ one accordingly has a local high color electric energy density of $\approx 4 GeV/fm^3$, which
Figure 1: Graphical representation of the hadrons (left) and the strings (right) during the high density phase in a central Pb + Pb collision at 160 AGeV in the center-of-mass system. Three time steps are shown at $t_{cm} = (t_0, t_0 + 0.6, t_0 + 1.2) \text{ fm/c}$; the axis labels are given in fm.

substantially screens the binding potential of the charmonium state. For practical reasons the dissociation by a string is modeled when the center-of-mass of the $c\bar{c}$ state is located inside the string of radius $R_s$. (Absorption by strings spanned between the parent particles of the $c\bar{c}$ pair is excluded, since this effect already is included in the production cross section.) The string radius $R_s$ represents an unknown parameter.

3 Comparison to experimental data

Since the absorption of $c\bar{c}$-pairs on secondary mesons in proton-nucleus collisions is practically negligible, these reactions allow to fix ‘experimentally’
the $c\bar{c}$-baryon dissociation cross section on nucleons. Our analysis in Ref. [15] yields $\sigma_{\text{abs}}^{\text{baryons}} \approx 6$ mb. The experimental survival probability is defined by the ratio of experimental $J/\Psi$ to Drell-Yan cross section as

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

where $A$ and $B$ denote the target and projectile mass while $\sigma_{AB}^{J/\Psi}$ and $\sigma_{AB}^{DY}$ 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. We note that due to the large statistical error bars of the experimental data absorption cross sections $\sigma_{\text{abs}}^{\text{baryons}}$ of $6 \pm 1$ mb are compatible also. These values are slightly smaller than those of Kharzeev et al. [13] in the Glauber model claiming $7.3 \pm 0.6$ mb, but in the same range as those used in the Glauber models of Ref. [5].

The comparison to $J/\Psi$ suppression in nucleus-nucleus collisions is performed on an event-by-event basis using the neutral transverse energy $E_T$ (cf. Ref. [15]) as a trigger as in the experiments of the NA38 and NA50 collaborations. 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 $J/\Psi$ survival probabilities are displayed in Fig. 2 (l.h.s.) in comparison to the data from Ref. [3] 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, 13]. 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.

We, furthermore, compute the $J/\Psi$ suppression 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 $\tau = 0.3$ 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 $\sigma_{\text{abs}}^{\text{baryons}} = 6$ mb for the ‘pre-resonance’ state and at 3 mb for the formed $J/\Psi$ resonance. The calculated survival probabilities are displayed in Fig. 2 (r.h.s.) 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
Figure 2: The $J/\Psi$ survival probability 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 Ref. 3 within the model I assuming a long lifetime for the $c\bar{c} - g$ system (l.h.s.) as well as within model II (r.h.s.) for a respective lifetime of 0.3 fm/c. The absorption cross section on mesons is varied from 0 (dashed line) to 1.5 mb or 3.0 mb, respectively (solid lines).

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 model of Gavin et al. 9,10.

We now describe our results within the ‘early’-comover scenario. For p + U and $R_s = 0.4$ fm only 2% of the $J/\Psi$’s are absorbed by strings. The absorption is thus dominated, as expected intuitively, by the $c\bar{c}$-baryon dissociation on nucleons. This turns out to be completely different for heavy-ion collisions, where the absorption on strings becomes a much more important effect.

In Fig. 3 our results are shown for S + U and Pb + Pb as a function of the transverse energy and for different string radii $R_s = 0.1, ..., 0.4$ fm. A strong dependence on the string radius $R_s$ is observed with $R_s \approx 0.2$ fm giving the best fit to the experimental data 3,25. For this string radius 40% of the absorbed $J/\Psi$’s are dissociated by strings in central collisions of Pb + Pb.

In principle the mesonic comover absorption scenario could be included in addition; however, since most of the $c\bar{c}$ pairs are already absorbed by strings and baryons in the early stage of the reaction, the effect of meson comovers
Figure 3: The $J/\Psi$ survival probability $S_{J/\Psi}$ for $S + U$ at 200 A·GeV (upper part) and Pb + Pb at 160 A·GeV (lower part) as a function of the transverse energy $E_T$ in comparison to the experimental data from Ref. 3 (full squares). The full circles in the lower part show the new NA50 data from Ref. 25. The calculated results are shown for the string radii $R_s = 0.1, 0.2, 0.3$ and 0.4 fm.

is expected to be much less compared to the pure hadronic comover scenario (model II) discussed above.

4 Summary

In this contribution we have summarized the results of microscopic transport studies of $J/\Psi$ and Drell-Yan production in proton-nucleus and nucleus-nucleus collisions within different scenarios.

Our first set of calculations show that the absorption of ‘pre-resonance’ $c\bar{c} - g$ states by both nucleons and produced mesons (the standard, i.e. late hadronic ‘comover’-scenario) can explain reasonably not only the inclusive $J/\Psi$ cross sections but also the transverse energy ($E_T$) dependence of $J/\Psi$ suppres-
sion 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.

In our second set of calculations we found that the early absorption by strings (the ‘early’-comover scenario) is an important and dominant effect in the first few fm/c of the collision phase before secondary particles are produced. Adopting a string radius of 0.2-0.25 fm we got a similar good quantitative agreement with p+A data and the NA38 and NA50 data by taking into account the absorption by strings as well as nucleons. This radius seems to be rather small, but for two reasons it should be seen as a lower bound for $R_s$. First of all, we have assumed that the strings are completely ’black’ for $c\bar{c}$ states, and secondly, the $c\bar{c}$ pair dissociates whenever it moves into the region of the color electric field of a string. With the requirement that the center of the $c\bar{c}$ state should be inside the string for the dissociation process to start, one should add the $c\bar{c}$ radius to our value of $R_s$; this then gives a string radius of $R_s \approx 0.4 - 0.5$ fm.

As a result of our transport studies we do not find a necessary argument to require the formation of a quark-gluon-plasma in Pb + Pb collisions at the SPS.

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