

J/Ψ suppression in nuclear collisions at SPS energies*

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Abstract

We have carried out a first calculation of J/Ψ production from nuclear collisions within the covariant transport approach HSD, which has been very successful in describing both hadronic and electromagnetic observables from heavy-ion collisions at intermediate and high energies. The production of J/Ψ 's is based on the Lund string fragmentation model, while its interactions with hadrons are included by conventional cascade-type two-body collisions. Adopting 6 mb for the J/Ψ -baryon cross sections and 3 mb for the J/Ψ -meson cross sections above the $D\bar{D}$ threshold, we find that data on J/Ψ suppression from both proton-nucleus and nucleus-nucleus collisions (including Pb + Pb) can be explained without assuming the formation of a quark-gluon plasma in these collisions. Our microscopic studies thus confirm the suggestion of Gavin *et al.* that J/Ψ suppression observed in nuclear collisions is largely due to absorption by comovers, i.e., the produced mesons.

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Because of color screening a J/Ψ dissolves in a quark-gluon plasma. Matsui and Satz [1] thus proposed that a suppression of the J/Ψ yield in ultra-relativistic heavy-ion collisions is a plausible signature for the formation of the quark-gluon plasma in these collisions. This suggestion has stimulated a number of heavy-ion experiments at CERN SPS to measure the J/Ψ production via its dimuon decay. Indeed, these experiments have shown a significant reduction of the J/Ψ yield when going from proton-nucleus to nucleus-nucleus collisions [2, 3]. Especially for Pb + Pb at 160 GeV/u an even more dramatic reduction of J/Ψ has been reported by the NA50 collaboration [4].

To understand the experimental results, models based on J/Ψ absorption by hadrons have also been proposed. In Ref. [5], Gerschel and Hüfner have shown that the observed suppression of J/Ψ in nuclear collisions is consistent with the hadronic absorption scenario if one assumes that the J/Ψ -nucleon absorption cross section is about 6-7 mb. On the other hand, Gavin *et al.* [6], based also on the hadronic absorption model, have found that although J/Ψ absorption by nucleons is sufficient to explain the proton-nucleus data, it can not account for the suppression seen in nucleus-nucleus collisions. Introducing J/Ψ absorption by the produced mesons, which they call the ‘comovers’, with a cross section of about 3 mb, they can also obtain a satisfactory account of the nucleus-nucleus data. They attribute the difference between their conclusion and that of Ref. [5] to the different consideration in the thickness of nuclear matter where the produced J/Ψ has to pass through. In both 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 is ignored in these studies. Especially for nucleus-nucleus collisions involving heavier beams, such as the recent Pb+Pb collisions at 160 GeV/nucleon, the dynamics is more complex than in proton and S induced reactions. Although the hadronic absorption model of Ref. [6] has been shown to also explain the data [7], an improved study based on a more realistic dynamic model will be very useful in clarifying the underlying assumptions.

In this work we will carry out a study of J/Ψ production and suppression at SPS energies using the covariant transport approach HSD [8]. This nonequilibrium model has been shown to describe satisfactorily both the measured hadronic observables (rapidity distributions, transverse momentum spectra etc. [8]), which are sensitive to the

final stage collision dynamics, and dilepton spectra [9, 10, 11], 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 those used in Refs. [5, 6, 7]. Within this approach we can check if the simple hadronic absorption model used in both Ref. [5] and Refs. [6, 7] can indeed explain quantitatively the observed J/Ψ suppression. Furthermore, we can check if the J/Ψ is destroyed by nucleons before mesons are produced, since this assumption has been used in Ref. [12] to argue that J/Ψ absorption by mesons should be neglected, and the large suppression observed in Pb+Pb collisions might partly be due to the quark-gluon plasma. We will not address the question of whether the magnitude of the J/Ψ -hadron cross sections used is correct or can be justified by nonperturbative QCD. According to Ref. [13], these cross sections might be negligibly small in hadronic matter due to the small size of the J/Ψ and its large mass gap from open charms. However, it might well be true that the $c\bar{c}$ pair is first produced in a color-octet state together with a gluon and that this more extended configuration has a larger interaction cross section with baryons and mesons (i.e., 6 mb and 3 mb, respectively) before the J/Ψ singlet state finally emerges.

In HSD a J/Ψ (or better $c\bar{c}$ pair) is produced from string fragmentation [14] in the initial stage of a nuclear collision. Since the probability of producing a J/Ψ is very small, a perturbative approach is used in our study: i.e., whenever an $s\bar{s}$ pair (Φ -meson) is produced in the string decay, a J/Ψ is produced with a probability factor W , which is given by the ratio of the J/Ψ to Φ cross section at a center-of-mass energy \sqrt{s} of the baryon-baryon collision, i.e.,

$$W = \frac{\sigma_{BB \rightarrow J/\Psi + X}(\sqrt{s})}{\sigma_{BB \rightarrow \Phi + X}(\sqrt{s})}. \quad (1)$$

We then follow the motion of the J/Ψ in hadronic matter throughout the collision dynamics by treating its collisions with hadrons in the same way as for other hadron-hadron collisions [8]. We use as in Refs. [6, 7] 6 mb for J/Ψ -baryon collisions ($J/\Psi + B \rightarrow \Lambda_c + \bar{D}$) and 3 mb for J/Ψ -meson collisions ($J/\Psi + m \rightarrow D\bar{D}$) once the energies are above the threshold for these reactions. Since the J/Ψ production is treated perturbatively, light hadrons are not affected by these collisions in their propagation, however, the J/Ψ is destroyed.

Since in experiment the J/Ψ is measured in nuclear collisions from its decay into

dimuons, we calculate explicitly the dimuon invariant mass spectra from the collisions. This includes not only the decay of the J/Ψ but also the decay of other vector mesons (ρ , ω , and ϕ) as well as the Dalitz decay of π , η , ω , etc. Details on calculating the dilepton spectra from heavy-ion collisions up to invariant masses of about 1.5 GeV can be found in Refs. [9, 10]. Since both the Drell-Yan and open charm contributions are important for dileptons with invariant masses above 1.5 GeV, the latter being known e.g. for $p + W$ reactions [15], we have simulated their yield by a background term which is fitted to the dimuon yield for $p + W$ at 200 GeV/u.

We have carried out calculations for $p+W$, $S + W$ and $Pb + Pb$ collisions at 200 GeV/u as well as $Pb+Pb$ collisions at 160 GeV/nucleon. All results presented below are obtained at an impact parameter of 2 fm. In Fig. 1 we show the dilepton invariant mass spectra for the three reactions 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. [16]. Since there are no data from the HELIOS-3 collaboration for $Pb+Pb$ at 200 GeV/u, the $S+W$ data at 200 GeV/u are employed for the comparison with the calculated results for $Pb+Pb$. It is seen from Fig. 1 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 analysed in Ref. [10] - also the J/Ψ region is described reasonably well. For $S+W$ in the invariant mass range from $1.3 \text{ GeV} \leq m \leq 2.5 \text{ GeV}$ we miss about a factor of 2 in the dilepton yield, which might be due to the contribution from $\pi a_1 \rightarrow \mu^+ \mu^-$ [17] and/or an enhancement of open charm channels in the nucleus-nucleus case; these channels are not included in the present transport approach and require further analysis. When comparing the theoretical spectrum for $Pb+Pb$ with the data for $S+W$ in the J/Ψ mass region (Fig. 1c), we find a drastic suppression as compared to the $S + W$ reaction. We, therefore, may already conclude that the simple calculations of Refs. [6, 7] are quite reasonable and the observed large suppression of J/Ψ production in nuclear collisions (especially $Pb + Pb$) can be accounted for by hadronic absorption.

To understand more clearly the J/Ψ absorption in hadronic matter, we show in Fig. 2 the time evolution of the J/Ψ abundance for $p + W$ and $S + W$ at 200 GeV/u as well as for $Pb + Pb$ at 160 GeV/u. The solid curves show results with absorption

by both baryons and mesons while the dashed curves only reflect the absorption by baryons. The dotted lines show the actual number of J/Ψ 's in the simulation without including any reabsorption. We see that J/Ψ absorption by mesons is important in both S+W and Pb+Pb collisions as suggested in Refs. [6, 7]; this is in contradiction to the assumptions of Ref. [12]. On the other hand, there is no sizeable effect from J/Ψ -meson collisions for p+W due to the low meson densities involved. The enhancement of J/Ψ suppression in Pb + Pb collisions compared to S + W reactions is basically due to a longer reaction time with comovers as seen from Fig. 2b) and c).

For Pb+Pb collisions, the propagation length L of the J/Ψ in nuclear matter estimated by the Glauber theory is found to saturate with impact parameter $b \leq 9$ fm [4, 18], i.e., $L \approx 10.5 - 11.5$ fm. Thus when plotting the J/Ψ suppression factor versus L , a sudden and dramatic reduction is found experimentally [4]. As argued by Gavin and Vogt [6], this reduction is an artefact of the representation and should become smooth as a function of the transverse energy produced which increases drastically with decreasing impact parameter. We have investigated the latter question in more detail and show in Fig. 3 the calculated J/Ψ suppression factor for Pb + Pb at 160 GeV/u as a function of the transverse energy produced normalized to the transverse energy E_T^{max} for $b = 0$ fm. The corresponding values for the impact parameter are in steps of 1 fm starting from $b = 11$ fm to $b = 1$ fm. Indeed, as in the analysis by Gavin and Vogt [7] the J/Ψ suppression is found to be smooth in the transverse energy and approximately agrees with the preliminary data from [4].

In order to explore if the energy density in these reactions might be large enough to create a quark-gluon plasma in some region of space and time, we show as a function of time (Fig. 4) the volume with energy density above 2, 3, and 4 GeV/fm³ for S + W at 200 GeV/u and Pb + Pb at 160 GeV/u for a reaction at $b = 2$ fm. We do not show the result for p+W at 200 GeV because the corresponding volumes are zero in the latter case. In these calculations the energy density is computed as

$$E(x) = (\Delta V(x)\gamma(x))^{-1} \left\{ \sum_{\substack{\text{baryons} \\ i \in \Delta V}} \sqrt{p_i^2 + m_i^2} + \sum_{\substack{\text{mesons} \\ j \in \Delta V}} \sqrt{p_j^2 + m_j^2} \right\}, \quad (2)$$

where all mesons, but only baryons that have scattered at least once, have been counted. In eq. (2), $\gamma(x)$ is the Lorentz-factor associated with the cell $\Delta V(x)$, which is taken to

be 1 fm^3 ⁽¹⁾, in the nucleus-nucleus center of mass.

It is seen that in Pb+Pb collisions there is an appreciable volume of high energy density above $3 \text{ GeV}/\text{fm}^3$ ($\approx 300 \text{ fm}^3$) for time scales of a few fm/c, where a quark-gluon plasma (QGP) might be formed in the reaction². This region of high energy density is about 20 % of the volume of Pb and - from our point of view - should not be adequately described by a hadronic transport theory. The actual volume of high energy density (above $3 \text{ GeV}/\text{fm}^3$) for S + W is only about 50 fm^3 , but the volume per participating projectile nucleon is roughly the same. Thus central S + W and Pb + Pb collisions should show similar features when normalizing by the number of charged particles in a more forward rapidity bin. As an example we mention the normalized dimuon spectra (within the HELIOS-3 acceptance) for the two reactions in Fig. 1b) and 1c), which within 10 - 20 % are practically the same for invariant masses below 2 GeV.

Since in p+W collisions mesons do not contribute substantially to J/Ψ absorption and the energy density is not high either, the fact that the theoretical results agree with the data can be used to justify the use of 6 mb for the J/Ψ -baryon cross sections. Furthermore, the agreement between the theoretical results with the S+W data, where quark-gluon plasma effects should be of minor importance, indicates that the 3 mb used for the J/Ψ -meson cross sections is also reasonable.

We note, furthermore, that our analysis yields a maximum suppression of J/Ψ 's at high baryon and meson density, which also directly correlates with a high energy density. Thus alternative assumptions about J/Ψ suppression, that rise almost linearly with the energy density, cannot be ruled out at the present stage.

In conclusion, we have carried out a first microscopic transport study of J/Ψ production and absorption in nuclear collisions. Including only absorption by hadrons, we confirm the results of Refs. [6, 7] based on a simple Glauber model that the observed suppression in both proton-nucleus and nucleus-nucleus collisions can be explained. In particular, the absorption of J/Ψ 's by produced mesons is important in nucleus-nucleus collisions and especially for Pb + Pb, where the J/Ψ -hadron reactions extend

¹The results in Fig. 4 are independent of the cell size $\Delta V(x)$ from 0.15 to 1.5 fm^3 .

²The critical energy density for a phase transition to the QGP is not accurately known; the value of $3 \text{ GeV}/\text{fm}^3$ is chosen for convenience.

to much larger times as compared to the S + W reaction. The scaling of the $c\bar{c}$ pair suppression with the geometrical path L according to Glauber theory is found to be misleading, since the dependence on the meson density, and thus on the transverse energy produced, is smooth.

Since the hadronic J/Ψ reabsorption is proportional to the hadron density and thus also approximately proportional to the energy density, we presently cannot rule out a possible dissociation of the $c\bar{c}$ pair within local QGP droplets, which are expected to be formed at least for energy densities above $3 \text{ GeV}/\text{fm}^3$. It might also happen that the $c\bar{c}$ pairs have a finite probability to escape from the QGP-phase; such a scenario would be hard to distinguish experimentally from the hadronic reabsorption model. At the present stage we can only exclude a full J/Ψ dissociation in the QGP-phase, if the critical energy density for the phase transition is below about $1.5 \text{ GeV}/\text{fm}^3$, because the suppression factors calculated for S + W at 200 GeV/u and Pb + Pb at 160 GeV/u are then larger than those seen experimentally so far. In order to discriminate between the different model assumptions we need better information on the $c\bar{c}$ cross sections with hadrons; a task we here have to delay for future work.

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Figure Captions

Fig. 1: Dimuon invariant mass spectra from p+W, S+W, and Pb+Pb collisions at 200 GeV/nucleon in comparison to the data of the HELIOS-3 collaboration [16]. For the case of Pb + Pb (c) we compare to the data for S+W since no equivalent experimental spectra are available.

Fig. 2: Time dependence of the J/Ψ abundance for p+W, S+W at 200 GeV/u and Pb+Pb collisions at 160 GeV/u. The dotted lines show the total number of produced J/Ψ 's without reabsorption; the dashed lines display the J/Ψ number when including absorption by baryons while the full lines show the results of our calculation when including absorption by both baryons and mesons as described in the text. The J/Ψ number calculated is proportional to the actual multiplicity for S + W and Pb + Pb, whereas the statistics have been increased for p + W by a factor 100.

Fig. 3: The J/Ψ suppression factor for Pb + Pb at 160 GeV/u as a function of the transverse energy normalized to the maximum transverse energy E_T^{max} at $b = 0$ fm. The individual dots stand for a fixed impact parameter b which decreases in steps of 1 fm from 11 fm to 1 fm.

Fig. 4: Time evolution of the reaction volume with an energy density above 2, 3, and 4 GeV/fm³ for S+W at 200 GeV/u and Pb + Pb at 160 GeV/u.







