Charmonium suppression at RHIC and SPS: a unified approach

L Turko, D Prorok, D Blaschke

► To cite this version:

L Turko, D Prorok, D Blaschke. Charmonium suppression at RHIC and SPS: a unified approach. Journal of Physics G: Nuclear and Particle Physics, 2010, 37 (9), pp.94053. 10.1088/0954-3899/37/9/094053 . hal-00600859

HAL Id: hal-00600859

<https://hal.science/hal-00600859>

Submitted on 16 Jun 2011

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Charmonium suppression at RHIC and SPS: an unified approach

L. Turko¹, D. Prorok¹ and D. Blaschke^{1,2}

¹Institute for Theoretical Physics, University of Wrocław, 50-204 Wrocław, Poland

²Bogoliubov Lab. for Theoretical Physics, JINR Dubna, 141980 Dubna, Russia

E-mail: lturko@ift.uni.wroc.pl, prorok@ift.uni.wroc.pl, blaschke@ift.uni.wroc.pl

Abstract. A kinetic equation approach reproduces an anomalous J/ψ suppression at RHIC and SPS by absorption in a hadron resonance gas. The rapidity dependence of the PHENIX data is also reproduced as a geometric effect due to a longer absorption path for J/ψ production at forward rapidity.

PACS numbers: 14.40.Gx, 24.10.Pa, 25.75.-q

Submitted to: *J. Phys. G: Nucl. Phys.*

1. Introduction

Recent STAR and PHENIX experiments [1, 2, 3] brought up two unexpected results. First, at forward rapidity J/ψ is more suppressed than at midrapidity. Second, the dependence of J/ψ suppression at midrapidity on the number of participants N_{part} [3, 4] coincides with the one observed at SPS Pb-Pb collisions by the NA50 experiment [5]. Two different mechanisms to explain those RHIC data are usually considered in the literature: recombination [6, 7, 8, 9] or statistical coalescence [10, 11, 12, 13] and nuclear effects [14, 15].

We present a step towards a general description of J/ψ absorption in the framework of a statistical analysis. The formalism allows [16, 17] for a unified description of the data from the NA38 and NA50 experiments at CERN and from the PHENIX experiment at RHIC. Both PHENIX results, concerning rapidity and N_{part} dependencies of J/ψ suppression in Au-Au and Cu-Cu collisions are simultaneously reproduced. More details are given in [18].

The J/ψ absorption is caused here by the effective hadronic medium consisting of a multi-component non-interacting hadron resonance gas (HRG). This medium does not exclude a suppression scenario based on the existence of the quark-gluon plasma (QGP) phase [19]. The recent lattice QCD calculations [20] locate hadronic systems considered here, with energy densities in the range 2.5 - 5.4 GeV/fm³, slightly above the expected HRG-QGP transitions temperature. This is still not the region of asymptotically free quarks and gluons. All partons are strongly correlated and J/ψ evolution in the medium consists of collisions with free and bound states in the

surrounding medium. Detailed calculations, based on Green function technique, show the equivalence of descriptions by means of hadronic or partonic degrees of freedom [21, 22].

All hadrons from the lowest up to 2 GeV mass are taken into account as constituents of the matter. The gas is in thermal equilibrium and expands longitudinally and transversally according to relativistic hydrodynamics [23]. J/ψ suppression is the result of inelastic scattering on constituents of the HRG and on nucleons in the cold nuclear matter (CNM) of the colliding ions. Both sources of J/ψ suppression, namely absorption in CNM and HRG, are considered simultaneously.

The model applied here is a straightforward generalization of the model of Refs. [16, 24] to include the non-zero rapidity case. J/ψ suppression is the result of a J/ψ final state absorption in a confined medium through interactions of the type

$$J/\psi + h \longrightarrow D + \bar{D} + X, \quad (1)$$

where h denotes a hadron, D is a charm meson and X stands for a particle which assure conservation laws (charge, baryon number, strangeness). Charmonium states can be absorbed first in nuclear matter and soon after in the hadron gas. In our phenomenological analysis we assume universal cross sections for baryons, with the appropriate thresholds for their dissociation reactions but energy-independent, $\sigma_{J/\psi N} = 4$ mb. This choice corresponds to the absorption cross section $\sigma_{\text{abs}} = 4.2 \pm 0.5$ mb for J/ψ in cold nuclear matter measured in p-A collisions by the NA50 experiment [25], shown to be compatible [15, 26] with recent d-Au data from the PHENIX experiment [27]. The absorption cross section for meson impact is taken as $\sigma_m = 2\sigma_{J/\psi N}/3$, according to quark counting rules.

In order to justify the magnitude of hadronic absorption cross sections employed in the present work, a strong medium dependence is required which could for instance stem from spectral broadening of light mesons at the chiral restoration transition (mesonic Mott effect) [28, 29].

An A-A collision at impact parameter b generates an almond shaped overlap region S_{eff} . The time $t = 0$ corresponds to the moment of the maximal overlap of the nuclei. After about half of the time the nuclei need to cross each other, matter appears in the central region. Soon thereafter matter thermalizes and this moment, t_0 , is estimated at about 1 fm. In the real situation the width of the matter at t_0 is also of the order of 1 fm. Then matter starts to expand and cool according to relativistic hydrodynamics (for details see [16, 17, 23, 24]) until reaching the freeze-out temperature $T_{\text{f.o.}}$ and subsequently freely streaming towards the detectors.

A $c\bar{c}$ pair is created in a hard nucleon-nucleon collision during the passage of the colliding nuclei through each other. It will evolve to a charmonium eigenstate during the formation time which is of the order of t_0 while experiencing cold nuclear matter (CNM) effects. These are due to nuclear modification of the initial state gluon distributions and partial extinction while passing through the colliding nuclei and will be appropriately parametrized using data from pA collisions. We are interested here to describe the “anomalous suppression” effect by subsequent final state interactions with the expanding HRG formed between the receding nuclei. Since these nuclei which border the HRG on both sides in the longitudinal direction move almost with the speed of light, even J/ψ s which contribute to the particle spectra measured in the forward (backward) rapidity region can not escape the hadronic medium. Due to the different production process, the J/ψ velocities can be considered as independent from the velocity distribution of the HRG medium. This results in considerable impact

velocities, in particular for forward (backward) produced J/ψ s traversing counter-propagating HRG flow.

The transverse expansion starts in the form of a rarefaction wave moving inward S_{eff} . The evolution is decomposed into a longitudinal expansion inside a slice bordered by the front of the rarefaction wave and the transverse expansion. The rarefaction wave moves radially inward with the sound velocity c_s . Since the temperature (and hadron gas density) decreases rapidly outside the wave, we shall ignore possible J/ψ scattering there. We denote by t_{esc} the moment of crossing the border of the rarefaction front.

Inside the region bordered by the front of the rarefaction wave the hydrodynamic evolution ceases when the freeze-out temperature is reached, here we take $T_{f.o.} = 150$ MeV what is suggested by the statistical model analysis of the PHENIX data [30, 31]. So J/ψ is subject to absorption for the time $t_{final} = \min\{\langle t_{esc} \rangle, t_{f.o.}\}$ where $\langle t_{esc} \rangle$ is the mean time until it escapes the hadron gas region and $t_{f.o.}$ is the time when it passes the kinetic freeze-out surface for its absorption reactions. The rapidity dependence of t_{final} is crucial for the description of J/ψ RHIC absorption processes. This is an increased functions of rapidity as is illustrated by figure 1-Left.

2. J/ψ absorption

The J/ψ absorption processes in CNM (nuclear absorption - NA) and HRG take place subsequently. Due to this separation in time the J/ψ suppression factor for given rapidity in a heavy-ion collision with impact parameter b assumes the form

$$R_{AA}(y, b) = S_{NA}(y, b) \cdot S_{HRG}(y, b) , \quad (2)$$

where $S_{NA}(y, b)$ and $S_{HRG}(y, b)$ are J/ψ suppression factors in CNM and HRG, respectively. For S_{NA} we employ the usual approximation

$$S_{NA} \cong \exp \{ -\sigma_{\psi N} \rho_0 \langle L \rangle \} , \quad (3)$$

where $\rho_0 = 0.16 \text{ fm}^{-3}$ is the nuclear matter density and $\langle L \rangle$ is the mean absorption path length of the J/ψ through the colliding nuclei obtained from the Glauber model. Within this approximate expression, S_{NA} does not depend on rapidity.

The HRG suppression factor $S_{HRG}(y, b)$ is defined as

$$S_{HRG}(y, b) = \frac{\int d^2 p_T \int d^3 r \mathcal{F}(\vec{r}, y, \vec{p}_T, t)|_{t=\infty}}{\int d^2 p_T \int d^3 r \mathcal{F}(\vec{r}, y, \vec{p}_T, t)|_{t=t_0}} , \quad (4)$$

where the initial time $t_0 = 1 \text{ fm}/c$ denotes the moment of the thermalization of the created hadronic matter and the beginning of the hydrodynamical expansion.

The rapidity-momentum J/ψ distribution results from the kinematical change of variables $d^3 p \rightarrow d^2 p_T dy$ and is given by $\mathcal{F}(\vec{r}, y, \vec{p}_T, t) = M_T \cosh(y) \times f(\vec{r}, \vec{p}, t)$, where $f(\vec{r}, \vec{p}, t)$ is the formal solution of a kinetic equation (for details see [16, 24, 18]).

For the description of the evolution of the matter, relativistic hydrodynamics is employed. For $n_B = 0$ and a uniform initial temperature distribution with a sharp edge at the border established by the nuclear surfaces, the full solution of the (3+1)-dimensional hydrodynamic equations is known [23]. The radial velocity is zero inside the region bordered by the rarefaction wave and $v_z(\vec{s}, z, t) = z/t$, the four-velocity $u^\nu(\vec{r}, t)$ simplifies to

$$u^\nu(\vec{r}, t) = \frac{1}{\tau}(t, 0, 0, z) . \quad (5)$$

The temperature also does not depend on the radial coordinate s within the region bordered by the rarefaction wave,

$$T(\vec{r}, t) = T(z, t) = T(0, \tau) = T_0 \cdot \tau^{-a} \quad (6)$$

and the power a is the sound velocity squared at T_0 , $a = c_s^2(T_0)$ [16, 17].

It turned out that $T(\tau)$ has the form given by (6) with a varying in the range $a = 0.148 - 0.156$ for ϵ_0 in the range $\epsilon_0 = 5.5 - 0.5 \text{ GeV/fm}^3$.

For a J/ψ which is at $\vec{s}_0 \in S_{eff}$ at the moment t_0 and has the velocity $\vec{v} = \vec{v}_T + \vec{v}_L = \vec{p}_T/E + \vec{p}_L/E$ we denote by t_{esc} the moment of crossing the border of the rarefaction front.

Figure 1.

Left: An example of t_{final} in a function of rapidity for $p_T = 2 \text{ GeV}$ and the 0 – 20% centrality bin for Au-Au (solid) and Cu-Cu (dashed) collisions. More details are given in [18]. **Right:** J/ψ (dashed and dot-dashed lines) inside hadronic gas absorption region and the time evolution of the rarefaction front radius s at different z (continuous lines with labels denoting z in fm). Numerical values correspond to Au-Au collisions. More details are given in [18]

The continuous lines in figure 1-Right, labeled by different values of the longitudinal variable z , show the time evolution of the rarefaction front radius s at the position z . The dashed and dash-dotted lines in figure 1-Right are (s, t) trajectories of J/ψ particles originating from the same point in the region S_{eff} , but with different values of transverse velocity $\vec{v}_T$. The dot-dashed line corresponds here to the lower value of v_T .

The final expression for $S_{\text{HRG}}(y, b)$ reads

$$S_{\text{HRG}}(y, b) = \frac{1}{\int dp_T M_T g_0(p_T)} \int dp_T M_T g_0(p_T) \times \exp \left\{ - \int_{t_0}^{t_{\text{final}}} dt \sum_{i=1}^l \int \frac{d^3 q}{(2\pi)^3} f_i(\vec{q}, t) \sigma_i v_{\text{rel}, i} \frac{p_\nu q_i^\nu}{E E'_i} \right\}, \quad (7)$$

where $t_{\text{final}} = \min\{\langle t_{esc} \rangle, t_{f.o.}\}$, $\langle t_{esc} \rangle(b, v)$ is an average time of leaving the hadron medium (i.e. crossing the rarefaction wave front) by J/ψ with the velocity v produced in a collision at impact parameter b and $t_{f.o.}$ is the freeze-out moment resulting from the longitudinal Bjorken expansion.

Equation (7) is in fact an approximation of the more involved exact formula. The approximation means that the average of integrals over trajectories has been replaced by the integration over the averaged trajectory, similarly as in (3). Our preliminary results of estimations of the exact formula suggest that the approximation influences only the normalization and in such a way that this can be compensated by the rescaling of the absorption cross-section to the lower values.

3. Results

In figure 2 and 3 we show the J/ψ nuclear modification factor R_{AA} for different centralities versus rapidity in Au-Au and Cu-Cu collisions vs. PHENIX data. There is an overall agreement with the data.

Figure 2. J/ψ nuclear modification factor versus rapidity in Au-Au collisions for constant $\sigma_{J/\psi N} = 4$ mb. PHENIX data are from [1]. Errors shown are the quadratic sum of statistical and uncorrelated systematic uncertainties.

The main new effect of the PHENIX data, that J/ψ suppression is stronger at forward rapidity than at midrapidity is shown in figure 4 for the N_{part} dependence. It arises in the present approach as a result of the geometry of the kinetic freeze-out surface for the J/ψ which extends much more in the longitudinal direction for sufficiently long times, $t \geq R_A - b/2$. This entails a longer absorption path for J/ψ

Figure 3. Same as Fig. 2 but for Cu-Cu collisions with PHENIX data from [2].

production at forward rapidity.

Note that the present model simultaneously accounts for the anomalous J/ψ suppression in the centrality dependence of the NA50/NA60 experiments at CERN, see [16, 17].

The present model may be seen as a preparatory step towards a unified description of charmonium suppression kinetics in SPS and RHIC experiments within a quantum statistical approach to the sQGP to be developed. The geometrical effect on the rapidity dependence described in the present work shall be a part of such a description.

Acknowledgments

We thank Susumu Oda for providing us with the J/ψ rapidity data for various centralities of Cu-Cu collisions and Krzysztof Redlich for valuable discussions. This work was supported in part by the Polish Ministry of Science and Higher Education.

References

- [1] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **98**, 232301 (2007).
- [2] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **101**, 122301 (2008).

Figure 4. J/ψ nuclear modification factor versus centrality in Au-Au (left) and Cu-Cu (right) collisions for constant $\sigma_{J/\psi N} = 4$ mb. Lines are predictions of the model for midrapidity (solid) and forward rapidity (dashed). PHENIX data are from [1, 2]. Errors shown are the quadratic sum of statistical and uncorrelated systematic uncertainties.

- [3] B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. Lett. **98**, 192301 (2007).
- [4] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **94**, 082301 (2005).
- [5] L. Ramello *et al.* [NA50 Collaboration], Nucl. Phys. A **715**, 243 (2003).
- [6] R. L. Thews, M. Schroedter and J. Rafelski, Phys. Rev. C **63**, 054905 (2001).
- [7] L. Grandchamp and R. Rapp, Nucl. Phys. A **709**, 415 (2002).
- [8] A. Capella *et al.*, Eur. Phys. J. C **58**, 437 (2008).
- [9] X. Zhao and R. Rapp, Eur. Phys. J. C **62**, 109 (2009).
- [10] P. Braun-Munzinger and J. Stachel, Phys. Lett. B **490**, 196 (2000).
- [11] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Phys. Lett. B **571**, 36 (2003).
- [12] A. P. Kostyuk, M. I. Gorenstein, H. Stoecker and W. Greiner, Phys. Rev. C **68**, 041902 (2003).
- [13] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, J. Phys. G **35**, 104155 (2008).
- [14] D. Kharzeev, E. Levin, M. Nardi and K. Tuchin, Phys. Rev. Lett. **102**, 152301 (2009).
- [15] E. G. Ferreiro, F. Fleuret, J. P. Lansberg and A. Rakotozafindrabe, Phys. Lett. B **680**, 50 (2009).
- [16] D. Prorok and L. Turko, Phys. Rev. C **64**, 044903 (2001).
- [17] D. Prorok, L. Turko and D. Blaschke, AIP Conf. Proc. **1038**, 73 (2008).
- [18] D. Prorok, L. Turko and D. Blaschke, arXiv:0901.0166 [hep-ph].
- [19] T. Matsui and H. Satz, Phys. Lett. **B178**, 416 (1986).
- [20] A. Bazavov *et al.*, Phys. Rev. D **80**, 014504 (2009).
- [21] R. Rapp, D. Blaschke and P. Crochet, arXiv:0807.2470
- [22] D. Blaschke, [arXiv:0912.4479 [hep-ph]].
- [23] G. Baym, B. L. Friman, J. P. Blaizot, M. Soyeur and W. Czyż, Nucl. Phys. **A407**, 541 (1983).
- [24] J. P. Blaizot and J. Y. Ollitrault, Phys. Rev. D **39**, 232 (1989).
- [25] B. Alessandro *et al.* [NA50 Collaboration], Eur. Phys. J. C **48**, 329 (2006).
- [26] V. N. Tram and F. Arleo, Eur. Phys. J. C **61**, 847 (2009).
- [27] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. C **77**, 024912 (2008).
- [28] G. R. G. Burau, D. B. Blaschke and Y. L. Kalinovsky, Phys. Lett. B **506**, 297 (2001).
- [29] D. B. Blaschke and K. A. Bugaev, Prog. Part. Nucl. Phys. **53**, 197 (2004).
- [30] J. Rafelski, J. Letessier and G. Torrieri, Phys. Rev. C **72**, 024905 (2005).
- [31] D. Prorok, Acta Phys. Polon. B **40**, 2825 (2009).