Additional $J/\Psi$ suppression from high density effects

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Abstract. At high energies the saturation effects associated to the high parton density should modify the behavior of the observables in proton–nucleus and nucleus–nucleus scattering. In this paper we investigate the saturation effects in the nuclear $J/\Psi$ production and estimate the modifications in the energy dependence of the cross section as well as in the length of the nuclear medium. In particular, we calculate the ratio of $J/\Psi$ to Drell–Yan cross sections and show that it is strongly modified if the high density effects are included. Moreover, our results are compared with the data from the NA50 Collaboration and predictions for the RHIC and LHC kinematic regions are presented. We predict an additional $J/\Psi$ suppression associated to the high density effects.

1 Introduction

High energy heavy-ion collisions offer the opportunity to study the properties of the predicted QCD phase transition to a locally deconfined quark–gluon plasma (QGP) (see, e.g., [1]). A dense parton system is expected to be formed in the early stage of relativistic heavy-ion collisions at RHIC (Relativistic Heavy Ion Collider) energies and above, due to the onset of hard and semihard parton scatterings. The search for experimental evidence of this transition during the very early stage of $AA$ reactions requires one to extract unambiguous characteristic signals that survive the complex evolution through the later stages of the collision. One of the proposed signatures of the QCD phase transition is the suppression of quarkonium production, particularly of the $J/\Psi$ [2]. The idea of suppression of $c\bar{c}$ mesons $J/\psi$, $\psi'$, etc., is based on the notion that $c\bar{c}$ are produced mainly via primary hard collisions of energetic gluons during the preequilibrium stage up to shortly after the plasma formation (before the initial temperature drops below the production threshold), and the mesons formed from these pairs may subsequently experience deconfinement when traversing the region of the plasma. In a QGP, the suppression occurs due to the shielding of the $c\bar{c}$ binding potential by color screening, leading to the breakup of the resonance. The $c\bar{c}$ ($J/\psi$, $\psi'$, ...) and $b\bar{b}$ ($Y$, $Y'$, ...) resonances have smaller radii than light-quark hadrons and therefore higher temperatures are needed to dissociate these quarkonium states.

Over the years, several groups have measured the $J/\Psi$ yield in heavy-ion collisions with the $J/\Psi$ suppression observed in the experimental data. In particular, the NA50 Collaboration at CERN observed a much stronger $J/\Psi$ suppression in Pb–Pb collisions at SPS energies [3]. Different mechanisms have been proposed to explain this phenomenon. It has been suggested that the suppression was due the QGP phase [4], percolation deconfinement [5] or absorption by comovers [6,7] (for a review see e.g. [8]). Recently, the origin of the anomalous behavior of the $J/\Psi$ production cross section has still been debated and several competing interpretations have so far been proposed. In general, these models consider the final state interactions of the quarkonium state with the nuclear/QGP medium. A comprehensive analysis of the different mechanisms is presented in [9]. Here, we address another search of $J/\Psi$ suppression in nuclear collisions at high energies: the modification in the nuclear wave functions of the incident nuclei associated to the high density (saturation) effects.

The probability of a thermalized QGP production and the resulting strength of its signatures strongly depends on the initial conditions associated to the distributions of partons in the nuclear wave functions. At very high energies, the growth of parton distributions should saturate. There is a possible formation of a color glass condensate [10], characterized by a bulk momentum scale $Q_s$. Moreover, the limitation on the maximum phase-space parton density that can be reached in the hadron wave function (parton saturation) and very high values of the QCD field strength squared $F_{\mu\nu}^2 \propto 1/\alpha_s$ [11] are expected in this regime. Furthermore, the number of gluons per unit phase-space volume practically saturates and at large densities grows only very slowly (logarithmically) as a function of the energy [12]. If the saturation scale is larger than the...
QCD scale $\Lambda_{\text{QCD}}$, then this system can be studied using weak coupling methods. The magnitude of $Q_s$ is associated to the behavior of the gluon distribution at high energies, and some estimates have been obtained. In general, the predictions are $Q_s \sim 1$ GeV at RHIC and $Q_s \sim 2–3$ GeV at LHC [13, 14]. From the experimental point of view, the recent results from HERA for $ep$ collisions [15,16] and from RHIC for heavy-ion collisions [17–19] suggest that these processes at high energies probe QCD in the non-linear regime of high parton density. These results motivate our analysis of the $J/\Psi$ production in nuclear processes.

In this work, we analyze in detail the $J/\Psi$ production in $pA$ and $AA$ processes. A detailed study of the $J/\Psi$ production in $pA$ collisions is justified by the fact that a systematic study of $pA$ and $AA$ scatterings at the same energies is essential to gain insight into the structure of the dense medium effects. Such effects, as the energy loss and high density effects, are absent or small in $pp$ collisions, but become increasingly prominent in $pA$ collisions, and are of major importance in $AA$ reactions. By comparing $pA$ and $AA$ reactions involving very heavy nuclei, one may be able to distinguish basic hadronic effects that dominate the dynamics in $pA$ collisions, from a quark–gluon formation predicted to occur in heavy-ion AA collisions. Furthermore, our analysis is motivated by the fact that the quarkonium production at RHIC and LHC energies is dominated by initial state gluons. As the probability for making a heavy quark pair is proportional to the square of the gluon distribution, any depletion in number of gluons will make a significant difference in the number of the $J/\Psi$ produced [20]. Here we assume the presence of initial state effects in the nuclear wave functions and final state interactions of the $\phi$ pair with the nuclear medium. Our main goal is to estimate the magnitude of quarkonium suppression in hadronic matter associated to these effects. Our results demonstrate that the high density effects imply an additional $J/\Psi$ suppression when compared with the scenario where only final state interactions are estimated. As the formation of a QGP is not assumed, our predictions are now a lower bound for the $J/\Psi$ suppression in high energy nuclear collisions.

This paper is organized as follows. In the next section, we present the color evaporation model (CEM), which is used as a model for the $J/\Psi$ production in proton–nucleus ($pA$) and nucleus–nucleus ($AA$) collisions. In Sect. 3 we present a brief review of the AG parameterization [21], used to include the high density effects in the calculation. Moreover, we present our predictions for the energy dependence of the $J/\Psi$ cross section in Sect. 4. In Sect. 5 the generalization of the CEM to the inclusion of the final state interactions proposed in [22] is discussed and our results for the medium length dependence of the cross sections are presented in Sect. 6. Our main conclusions are also summarized.

## 2 $J/\Psi$ production in the collinear factorization

Vector-meson production has proven to be a very interesting process in which one may test the interplay between the perturbative and non-perturbative regimes of QCD (for a review, see for example [23,24]). One of the main uncertainties in quarkonium production is related to the transition from the colored state to a colorless meson. Initially, the $q\bar{q}$ pair will in general be in a color octet state. It subsequently neutralizes its color and binds into a physical resonance. Color neutralization occurs by interaction with the surrounding color field. An alternative view of the $J/\Psi$ production process is to use the color evaporation model (CEM), which describes a large range of data in hadro- and photoproduction, as shown in [25]. In CEM, quarkonium production is treated identically to open heavy quark production with the exception that, in the case of quarkonium, the invariant mass of the heavy quark pair is restricted to be below the open meson threshold, which is twice the mass of the lowest meson mass that can be formed with the heavy quark. For charmonium the upper limit on the $c\bar{c}$ mass is then $2m_D$. The hadronization of the charmonium states from the $c\bar{c}$ pairs is non-perturbative, usually involving the emission of one or more soft gluons. Depending on the quantum numbers of the initial $c\bar{c}$ pair and the final state charmonium, a different matrix element is needed for the production of the charmonium state. The averages of these non-perturbative matrix elements are combined into the universal factor $F[n, J^{PC}]$, which is process- and kinematics-independent and describes the probability that the $c\bar{c}$ pair binds to form a quarkonium $J/\Psi(n, J^{PC})$ of given spin $J$, parity $P$, and charge conjugation $C$. Once $F$ has been fixed for each state ($J/\Psi$ or $\phi$), the model successfully predicts the energy and momentum dependence [26,27].

Considering the $J/\Psi$ production and the collinear factorization approach, the CEM predicts that the cross section in the collision of hadrons $A$ and $B$ is given by

$$\sigma_{AB \rightarrow J/\Psi X} = K \sum_{a,b} \int \frac{dq^2}{Q^2} \left( \frac{\sigma_{ab \rightarrow c\bar{c}}(Q^2)}{Q^2} \right)$$

$$\times \int dx_F \phi_a/\Lambda(x_a)\phi_b/\beta(x_b)x_a x_b F_{c\bar{c} \rightarrow J/\Psi}(q^2),$$

where $\sum_{a,b}$ runs over all parton flavors, $Q^2 = q^2 + 4m_c^2$, $\phi_a/\Lambda(x_a)$ is the distribution function of parton $a$ in hadron $A$, $x_F = x_a - x_b$ and $x_a x_b = Q^2/s \equiv \tau$. The expressions of the elementary partonic cross sections can be taken from [28], and to take into account the next-to-leading order corrections to the cross section we consider the phenomenological constant $K$-factor. The factor $F_{c\bar{c} \rightarrow J/\Psi}(q^2)$ describes the transition probability for the $c\bar{c}$ state of the relative square momentum $q^2$ to evolve into a physical $J/\Psi$ meson. In general, it is parameterized by

$$F_{c\bar{c} \rightarrow J/\Psi}(q^2) = N_{J/\Psi} \theta(q^2)\theta(4m_D^2 - 4m_c^2 - q^2),$$

where $N_{J/\Psi}$ is a normalization factor which is obtained from a fit of the experimental data for $J/\Psi$ produc-