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Excited charmonium suppression in proton–nucleus collisions as a consequence of comovers

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ABSTRACT

Recent results from proton(deuteron)–nucleus collisions at RHIC and LHC energies have shown an unexpected suppression of excited quarkonium states as compared to their ground states. In particular, stronger suppression of the $\psi(2S)$ relative to the J/ψ has been detected. Similar observations were made at lower energies and were easily explained by nuclear absorption. At higher energies, a similar explanation would violate the Heisenberg principle, since the calculations based on the uncertainty principle lead to a charmonium formation time expected to be larger than the nuclear radius, which results in identical nuclear break-up probability for the $\psi(2S)$ and J/ψ. On the contrary, this behavior is naturally explained by the interactions of the quarkonium states with a comoving medium. We present our results on J/ψ and $\psi(2S)$ production for d + Au collisions at $\sqrt{s} = 200$ GeV and for p + Pb collisions at $\sqrt{s} = 5.02$ TeV.

Charmonium mesons have captured our attention for decades. Due to the high scale provided by their large masses, they are considered to be outstanding probes of Quantum Chromodynamics (QCD). The interest in this field concerns the issue of their production mechanisms in proton–proton collisions together with their interaction with the nuclear matter created in ultrarelativistic heavy-ion collisions.

This is so since lattice QCD calculations predict that, at sufficiently large energy densities, hadronic matter undergoes a phase transition to a plasma of deconfined quarks and gluons, the so-called quark–gluon plasma (QGP), where the QCD binding potential is screened. Given the existence of several quarkonium states, each of them with different binding energies, they are expected to sequentially melt into open charm or bottom mesons above certain energy density thresholds. Thus, the production and absorption of quarkonium in a nuclear medium provide quantitative inputs for the study of QCD at high density and temperature.

The interest on quarkonium production is not restricted to the study of deconfinement. Puzzling features in proton(deuteron)–nucleus collision data, where the deconfinement cannot be reached, reveal new aspects of charmonium physics in nuclear reactions, namely the role of cold nuclear matter effects.

In particular, the measurement of production rates for multiple quarkonium states, with different physical sizes and binding energies, offers an excellent tool for probing the time scale of the evolution of heavy quark–antiquark pairs into bound color singlet quarkonium states which represents a challenge within QCD.

As a matter of fact, recent unexpected results on $\psi(2S)$ production in d + Au and p + Pb collisions from PHENIX [1] and ALICE [2,3] Collaborations have shown an important suppression of its yield with respect to proton–proton production. Furthermore, this suppression is stronger than the one previously obtained for the J/ψ production. Former measurements of J/ψ and $\psi(2S)$ production rates in proton–nucleus collisions at lower energies by E866/NuSea [4] and by NA50 [5] Collaborations also show a stronger suppression of the excited state near $x_F \approx 0$. At those lower energies, this dissimilarity has been interpreted as the effect of $c\bar{c}$ break-up in interactions with the primordial nucleons, the so-called nuclear absorption. When the time spent traversing the nucleus by the $c\bar{c}$ pair becomes longer than the charmonia formation time, the larger $\psi(2S)$ meson will be further suppressed by a stronger nuclear break-up effect.

However, at higher energies, the charmonium formation time is expected to be larger than the nucleus radius [6]. Following the uncertainty principle, the formation time is related to the time needed – in their rest frame – to distinguish the energy levels of the $1S$ and $2S$ states, $\tau_f = \frac{2M_{c\bar{c}}}{(M_{2S}^2 - M_{1S}^2)} = 2 \times 3.3\ \text{GeV}/4\ \text{GeV}^2 = 0.35$ fm for the ψ. Moreover, this formation time has to be considered in the rest frame of the target nucleus, i.e. the Au beam at RHIC and the Pb beam at LHC. In this case, the formation time is

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increased by the Lorentz boost factor, $t_f = \gamma\ \tau$. The boost factor γ is obtained from the rapidity of the pair corrected by the nucleus beam rapidity, $\gamma = \cosh(y - y^{\rm Au}_{beam})$ where $y^{\rm Au}_{beam} = -\ln(\frac{\sqrt{s}}{m_N}) = -5.36$ for RHIC, resulting in a boost factor bigger than 100 at mid and forward rapidities [6]. Consequently, in the mid and forward rapidity regions at RHIC, t_f is significantly larger than the Au radius, $t_f = 36.7$ fm for $y = 0$ and larger for forward rapidities. At the LHC, for a lead beam of 1.58 TeV in pPb mode,[1] $y^{\rm Pb}_{beam} = -8.11$, which results in a boost of more than 1000 at LHC mid rapidities [7]. This implies that the charmonium formation time will be larger than the Pb radius practically in the whole rapidity region. This means that the $c\bar{c}$ is nearly always in a pre-resonant state when traversing the nuclear matter, which results in identical break-up probability for the $\psi(2S)$ and J/ψ, since these states cannot be distinguished at the time they traverse the nucleus.[2]

Other usual explanations, as the one based on the shadowing of the heavy pairs due to the modification of the gluon parton distribution functions in the nucleus, cannot be invoked here, since the nuclear parton shadowing effects are indistinguishable between $\psi(2S)$ and J/ψ [6].

Here, we will demonstrate that the final state interactions of the $c\bar{c}$ pair with the dense medium created in the collision can cause the puzzling anomalies seen in quarkonium production, i.e. the stronger $\psi(2S)$ suppression relative to the J/ψ, within the so-called comover scenario. In a comover framework, the suppression arises from scattering of the nascent ψ with produced particles – the comovers – that happen to travel along with the $c\bar{c}$ pair [8,9]. By comover interaction one means the interaction of the J/ψ and $\psi(2S)$ particle with the produced medium: the quarkonium particle is comoving with the soft particles produced in the collision, their formation times being both boosted by Lorentz dilation. This implies that the comovers can continue to interact well outside of the nuclear volume, playing an important role.

Let us recall two common features of the comover approaches. First, the comover dissociation affects strongly the $\psi(2S)$ relative to the J/ψ, due to the larger size of the first. Second, the comover suppression is stronger where the comover densities are larger, i.e. it increases with centrality and, for asymmetric collisions as proton(deuteron)–nucleus, it will be stronger in the nucleus-going direction.

In the following, we will show that taking into account the above features we obtain a surprisingly good and coherent quantitative description of the available deuteron–nucleus and proton–nucleus data at RHIC and LHC energies. We will apply the well-established comover interaction model (CIM) [9–14]. In this model, the rate equation that governs the density of charmonium at a given transverse coordinate s, impact parameter b and rapidity y, $\rho^{\psi}(b,s,y)$, obeys the simple expression

$$\tau \frac{\mathrm{d}\rho^{\psi}}{\mathrm{d}\tau}(b,s,y) = -\sigma^{co-\psi}\,\rho^{co}(b,s,y)\,\rho^{\psi}(b,s,y), \qquad (1)$$

where $\sigma^{co-\psi}$ is the cross section of charmonium dissociation due to interactions with the comoving medium of transverse density $\rho^{co}(b,s,y)$.

In order to obtain the survival probability $S^{co}_{\psi}(b,s,y)$ of a ψ interacting with comovers, this equation is to be integrated between initial time τ_0 and freeze-out time τ_f. We consider longitudinal boost invariance and neglect transverse expansion since we have estimated that the transverse expansion, unlike the longitudinal one, is a very smooth process that takes place later.[3] Thus, assuming a dilution in time of the densities due to longitudinal motion which leads to a τ^{-1} dependence on proper time, the equation can be solved analytically. The result depends only on the ratio τ_f/τ_0 of final over initial time. Using the inverse proportionality between proper time and densities, we put $\tau_f/\tau_0 = \rho^{co}(b,s,y)/\rho_{pp}(y)$, i.e. we assume that the interaction stops when the densities have diluted, reaching the value of the $\mathrm{p+p}$ density at the same energy. Thus, the solution of Eq. (1) is given by

$$S^{co}_{\psi}(b,s,y) = \exp\left\{-\sigma^{co-\psi}\,\rho^{co}(b,s,y)\ln\left[\frac{\rho^{co}(b,s,y)}{\rho_{pp}(y)}\right]\right\}, \qquad (2)$$

where the argument of the log is the interaction time of the ψ with the comovers.

The main ingredient in order to compute the survival probability S^{co}_{ψ} of the quarkonium due to interactions with the comoving medium is the density of comovers ρ^{co}. This density is not a free parameter, since it has the constraint that the total rapidity distribution dN/dy of the observed particles must be reproduced. We take it as proportional to the number of collisions,

$$\rho^{co}(b,s,y) = n(b,s)\,S^{sh}_{co}(b,s)\,\frac{3}{2}(dN^{pp}_{ch}/dy), \qquad (3)$$

where $n(b,s)$ corresponds to the number of binary nucleon–nucleon collisions per unit transverse area at a given impact parameter, S^{sh}_{co} refers to the shadowing of the parton distribution functions in a nucleus that affects the comover multiplicity, ch refers to the charged particle density in $\mathrm{p+p}$ and the factor $3/2$ takes into account the neutral comovers. In order to compute the comover densities in nuclear collisions we have introduced the shadowing corrections that affect the comover multiplicities [15–17]. Within this approach, a good description of the centrality dependence of charged multiplicities in nuclear collisions is obtained both at RHIC [18] and LHC energies [15].

Finally, the comover density in $\mathrm{p+p}$ collisions is given by $\rho_{pp}(y) = \frac{3}{2}(dN^{pp}_{ch}/dy)/\pi R_p^2$, where R_p is the proton radius. We apply the experimental values and theoretical extrapolations [15] for the charged particle multiplicities in proton–proton collisions. We get, at mid rapidity, the values $\rho_{pp}(0) = 2.24\ \mathrm{fm}^{-2}$ at $\sqrt{s} = 200$ GeV [13] and $\rho_{pp}(0) = 3.37\ \mathrm{fm}^{-2}$ at $\sqrt{s} = 5.02$ TeV, which correspond to the values of charged particle multiplicities $\mathrm{d}N^{ch}_{pp}/\mathrm{d}\eta = 2$ at $\sqrt{s} = 200$ GeV and $\mathrm{d}N^{ch}_{pp}/\mathrm{d}\eta = 4.5$ at $\sqrt{s} = 5.02$ TeV.

With the numbers quoted above, one obtains for the comover multiplicities the values $\mathrm{d}N^{co}_{dAu}/\mathrm{d}\eta = 15.75$ for minimum bias $\mathrm{d+Au}$ collisions at $\sqrt{s} = 200$ GeV at mid rapidity, and $\mathrm{d}N^{co}_{pPb}/\mathrm{d}\eta = 26.4$ at mid rapidity, $\mathrm{d}N^{co}_{pPb}/\mathrm{d}\eta = 22.5$ in the p-going direction, $2.03 < y < 3.53$, and $\mathrm{d}N^{co}_{pPb}/\mathrm{d}\eta = 31.2$ in the Pb-going direction, $-4.46 < y < -2.96$, for minimum bias $\mathrm{p+Pb}$ collisions at $\sqrt{s} = 5.02$ TeV. These values are consistent with the experimental charged particle multiplicities [19,20].

The only adjustable parameter of the comover interaction model is the cross section of charmonium dissociation due to interactions with the comoving medium, $\sigma^{co-\psi}$. It was fixed [10] from fits to low-energy experimental data to be $\sigma^{co-J/\psi} = 0.65$ mb for the J/ψ and $\sigma^{co-\psi(2S)} = 6$ mb for the $\psi(2S)$. The magnitude of the charmonium absorption cross section in medium is theoretically not well under control. Different theoretical calculations of

[1] Due to the LHC design, the colliding beams have different energies per nucleon, $E_{\rm p} = 4$ TeV, $E_{\rm Pb} = 1.58$ TeV, and cannot be tuned separately. As a consequence, the center of mass of the nucleon–nucleon collision is shifted by $\Delta y = 0.465$ with respect to the laboratory frame in the direction of the proton beam [2].

[2] Moreover, this nuclear absorption can be taken as negligible at the LHC energies.

[3] The effect of a small transverse expansion can presumably be taken into account by a small change of the final state interaction cross sections.