Charmonium Production off Nuclei: from SPS to RHIC

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The physics of charmonium suppression in nuclear collisions drastically changes between the energies of SPS and RHIC. Mechanisms suppressing charmonia at the SPS are reviewed, neither of which is important at RHIC. On the other hand, coherence, or shadowing of $c$ quarks and gluons barely seen at SPS, becomes a dominant effect at RHIC providing a much stronger suppression. The onset of coherence at Fermilab energies explains why the observed cross section ratio falls steeply at large Feynman $x_F$. In nuclear collisions the variation of charmonium suppression with $x_F$ suggests a sensitive probe to look for the QGP.

1. Introduction

Charmonium production in heavy ion collisions at high energies is subject to a two-step suppression well separated in time,

$$S_{AB}^{\Psi} = S_{\text{nucl}} S_{\text{FSI}}.$$  \hspace{1cm} (1)

The early stage presented by the first factor is due to multiple interaction with the colliding nucleons. It includes absorption and shadowing. At the late stage the formed charmonium attenuates through the cloud of matter produced in the collision, providing the second suppression factor in (1). Actually, this is the factor probing the properties of the created matter and is the main goal of measurements \[\text{[1]}\]. However, it is impossible to single the final state interaction (FSI) factor out of the overall suppression in Eq. (1) unless the first factor, $S_{\text{nucl}}$, providing the main contribution, is reliably known. Surprisingly, this problem is not settled yet even for $pA$ collisions.

2. Pitfalls and perspectives for the QGP search at the SPS

We give here a brief list of effects contributing to nuclear suppression of the charmonium production rate in $pA$ and $AB$ collisions at SPS energies.

1. Absorption. The model for the factor $S_{\text{nucl}}$ widely used at the SPS is based on a simple idea that the charmonium is produced instantaneously inside the nucleus and then attenuates with a constant absorption cross section treated as a fitted parameter. This model is missing important effects and predicts a suppression which is independent of Feynman $x_F$, while the data show that $S_{\text{nucl}}(x_F)$ falls dramatically with $x_F$ \[\text{[2,3]}\].

2. Formation time. Apparently, the produced $\bar{c}c$ pair takes time to develop the charmonium wave function. According to the uncertainty principle one cannot momentarily disentangle the different levels and conclude which state has been produced. It takes a time, called the formation time (length), which is inversely related to the
charmonium mass splitting. Corrected for Lorentz time dilation it can be estimated to be $t_f = 2E_\Psi/(M_{\Psi'}^2 - M_{J/\Psi}^2)$. The NA38/50 experiments detect charmonia with $E_\Psi \approx 50\text{ GeV}$, therefore $t_f \gg R_A$ and the formation effects are important. A quantum-mechanical description of the evolution of a $\bar{c}c$ wave packet in an absorptive medium was suggested in [4], and in a hadronic representation in [5]. A beautiful quantum effect has been found: in spite of naive expectations the $\Psi'$ attenuation should be similar or even less than that of $J/\Psi$, provided that the energy is sufficiently high [4]. At the same time, in $BA$ collisions, $\Psi'$ is more suppressed due to the inverse kinematics for nuclei $A$ and $B$ [5]. At the same time the effective absorption cross for $J/\Psi$ varies with energy and nuclear thickness and cannot be treated as a universal parameter [4].

3. Energy loss. This mechanism was suggested in [7] right after the NA3 collaboration published the first data demonstrating a steep drop of the cross section ratio at large $x_F$. The incoming hadron experiences an inelastic collision on the surface of the nucleus, followed by hadronization and energy loss of the projectile partons. As a result, they arrive at the point of $\Psi$ creation with diminished energy. Therefore, the value of $x_F$ in this elementary process must be shifted to a higher value resulting in extra suppression. A similar, but weaker nuclear suppression was also predicted in [7] for the Drell-Yan reaction, confirmed by the E772/E866 experiments. The recent analysis [8] of this data led to the rate of energy loss per unit of length $dE/dz = -2.3 \pm 0.52 \pm 0.5 \text{ GeV/fm}$ in agreement with the value used in [7]. The mechanism of energy loss alone is able to describe the main features of the NA3 data, later confirmed by the E537 experiment [9].

4. Gluon enhancement in nuclei. There is some model-dependent evidence [9] that the gluon density is enhanced in heavy nuclei by about $10 - 20\%$ at large $x_2 \sim 0.1$. Accidentally, this is just the value corresponding to the kinematics of the NA38/50 experiments. Therefore, theoretical predictions should be corrected for this factor $\sigma_{pA}/\sigma_{pN} \propto G_A(x_2)/G_N(x_2) \approx 1.1 - 1.2$.

5. Excitation of nuclear matter in AB collisions. It is commonly assumed that charmonium produced in heavy ion collisions propagates and attenuates in conventional cold nuclear matter. However, each nucleon met by the $\Psi$ has already interacted at least once with other nucleons and must be in an excited state. First of all, inelastic $NN$ collisions are followed by gluon radiation which also contributes to the break-up of the $\Psi$ [10]. Second, inelastic $NN$ collisions are mediated by color exchange. Therefore, all the nucleons met by the $\Psi$ are in colored states and interact stronger than colorless ones [11]. These effects are able to explain the observed suppression of the total cross section of charmonium production, including lead-lead, but do not leave much room for the FSI suppression which manifests itself in central collisions at large $E_T$.

6. Scanning the QGP. Although the observed $E_T$ dependence of charmonium suppression cannot be reproduced by simplest models, still more sophisticated approaches are more successful, and manifestation of the FSI suppression is disputable (e.g. see [12]). A new sensitive probe for FSI, scanning the produced matter by varying $x_F$ of the charmonium, has been suggested recently [13]. One can see it on the plot Fig. illustrating the time – longitudinal coordinate distribution of the created medium. Interaction with the medium most dense at central rapidities causes a specific minimum at $x_F = 0$ in the nuclear suppression factor. This would be an indisputable signature of FSI, which is also very sensitive to QGP production.
3. From Fermilab to RHIC.

A new phenomenon, quantum coherence, or quark and gluon shadowing is expected to become dominant at RHIC. However, before jumping to RHIC energies, one must understand (as observed at Fermilab [14]) the $x_F$ dependence of $\Psi$ suppression, which demonstrates the onset of coherence. The first full QCD (parameter free) calculation of the dependence of nuclear suppression on $x_F$ is performed in [15]. The results are compared with data [14] in Fig. 3 where contributions of different mechanisms are explicitly shown. The curves correspond to: absorption and shadowing for the produced $\bar{c}c$ (thin solid curve); gluon shadowing added (dotted); energy loss included (dashed); gluon anti-shadowing added (thick solid). One can see that gluon shadowing is the main source of nuclear suppression at small $x_2$.

Energy loss violating $x_2$ scaling still noticeable at Fermilab completely vanishes at RHIC. Predictions [17] for nuclear suppression in $p-Au$ and $Au-Au$ collisions at RHIC are depicted in Fig. 4. On top of that one should expect a FSI suppression which is strongest at $x_F = 0$.

An opposite effect of FSI enhancement of $\Psi$ due to fusion of produced $\bar{c}c$’s has been predicted recently [16,17]. However, if gluon shadowing suppresses direct $\Psi$ by nearly an order of magnitude, it should be square of that for the fusion mechanism. It may eliminate fusion even at LHC due to gluon saturation. Apparently, this problem needs further study. Nevertheless, whatever happens, FSI suppression or enhancement, it will show up only on top of the nuclear suppression which has to be well understood.

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Figure 3. Comparison of the results of parameter free calculations in [15] with the E866 data [14]. See text for explanations for the curves.

Figure 4. Predictions of [15] for the $x_F$ dependence of nuclear suppression in proton-gold and gold-gold collisions at $\sqrt{s} = 200 \text{ GeV}$.

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