Energy loss of charm quarks from J/ψ production in cold nuclear matter[*]

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Abstract: J/ψ suppression in p-A collisions is studied by considering the nuclear effects on parton distribution, energy loss of beam proton and the finial state energy loss of color octet $c\bar{c}$. The leading-order computations for J/ψ production cross-section ratios $R_{\mathrm{W/Be}}(x_{\mathrm{F}})$ are presented and compared with the selected E866 experimental data with the $c\bar{c}$ remaining colored on its entire path in the medium. It is shown that the combination of the different nuclear effects accounts quite well for the observed J/ψ suppression in the experimental data. It is found that the J/ψ suppression on $R_{\mathrm{W/Be}}(x_{\mathrm{F}})$ from the initial state nuclear effects is more important than that induced by the energy loss of color octet $c\bar{c}$ in the large x_{F} region. Whether the $c\bar{c}$ pair energy loss is linear or quadratic with the path length is not determined. The obtained $c\bar{c}$ pair energy loss per unit path length $\alpha = 2.78 \pm 0.81$ GeV/fm, which indicates that the heavy quark in cold nuclear matter can lose more energy compared to the outgoing light quark.

Key words: J/ψ production, charm quark, energy loss

PACS: 24.85.+p, 25.40.-h, 12.38.-t   **DOI:** 10.1088/1674-1137/38/12/124103

1 Introduction

J/ψ suppression observed in heavy-ion collisions at RHIC and LHC, is considered as a most reliable signature for the formation of Quark-Gluon Plasma (QGP) in the present time. In order to quantify the properties of the QGP created in heavy-ion collisions, a solid understanding of the basic mechanisms responsible for the suppression of J/ψ production due to the nuclear modification of particle spectra in cold nuclear matter is required. The study about the nuclear effects on J/ψ suppression in p-A collisions can give a good baseline for clarifying the conventional nuclear suppression mechanism in heavy-ion collisions.

The nuclear dependence of J/ψ production cross sections as a function of the Feynman variable x_{F} has been studied by several proton-induced fixed target experiments, such as NA3 [1], E772 [2], E866 [3, 4], NA50 [5] and HEAR-B [6]. The E866 collaboration [3, 4] published the precise measurement of the J/ψ suppression for 800 GeV protons incident on iron and tungsten nuclear targets, relative to beryllium nuclear targets with very broad coverage $-0.1 < x_{\mathrm{F}} < 0.95$. The observed suppression is smallest for $x_{\mathrm{F}} \leqslant 0.25$, and increases at larger values of x_{F}.

J/ψ production is generally believed to occur in two different steps where a charm-quark pair is produced first through the interaction of a projectile on a target parton, then followed by the non-perturbative formation of a colorless asymptotic state. As for the non-perturbative formation of J/ψ, some approaches attribute to an effective absorption cross section σ_{abs} of the $c\bar{c}$ pair [7, 8]. In fact, if the distance L_0 which the $c\bar{c}$ pair travels during the proper color neutralization time τ_0 exceeds the length L_{A} of its path in the medium, the $c\bar{c}$ will remain colored on its entire path in the medium and the J/ψ hadronization will occur outside the nucleus. In this case, the so-called nuclear absorption σ_{abs} becomes irrelevant and the energy loss of color octet $c\bar{c}$ due to the medium-induced gluon radiation is the main final state effect. Otherwise, the J/ψ hadronization will occur inside the nucleus and nuclear suppression partly arises from the absorption cross section σ_{abs} of the charm-quark pair. If the color octet $c\bar{c}$ is produced at a random point inside a nucleus of radius R_{A}, then $L_{\mathrm{A}} = 3R_{\mathrm{A}}/4$. With a proper colour neutralization time $\tau_0 = 0.25$ fm, the relation $L_0 \geqslant L_{\mathrm{A}}$ for $x_{\mathrm{F}} \geqslant 0.2$ at $\sqrt{s} = 20$ GeV and for $x_{\mathrm{F}} \geqslant 0$ at $\sqrt{s} = 40$ GeV [9], which implies that the $c\bar{c}$ will remain

colored on its entire path for the E866 experimental data in the kinematical range $x_{\rm F} \geqslant 0$. Therefore, J/ψ production in p-A collisions seems the ideal tool for exploring the energy loss of charm quarks in cold nuclear matter. Recently, Arleo and Peigné studied the effects of energy loss in cold nuclear matter on J/ψ suppression in p-A collisions. Their results strongly support energy loss as a dominant effect in quarkonium suppression. However, this approach cannot distinguish between initial and final state energy loss contributions [10].

In our preceding article [11], by combining three representative sets of nuclear parton distributions with the energy loss effect of the incident proton determined by the nuclear Drell-Yan reaction [12], a leading order phenomenological analysis is performed on J/ψ production cross section ratios $R_{\rm W/Be}(x_{\rm F})$ for the E866 experimental data. The nuclear absorption effects in the final state are taken into account in the Glauber model framework. It is shown that the energy loss effect, resulting in the suppression on $R_{\rm W/Be}(x_{\rm F})$, is more important than the nuclear effects on parton distributions in the high $x_{\rm F}$ region. It is found that the J/ψ-nucleon inelastic cross section $\sigma_{\rm abs}^{\rm J/\psi}$ depends on the kinematical variable $x_{\rm F}$, and increases as $x_{\rm F}$ in the region $x_{\rm F} > 0.2$. In view of the different idea for the $c\bar{c}$ pair color neutralization, the present work will focus on the final state effects owing to the energy loss of color octet $c\bar{c}$. By means of the phenomenological analysis at the leading order for J/ψ production cross-section ratios for the E866 experimental data with the kinematical domain for a compact color octet $c\bar{c}$ propagating through the nuclear target, the energy loss effect of the charm-quark pair is researched. It is hoped that our study gives some hint of the energy loss effects on the suppression of J/ψ production in heavy-ion collisions.

The remainder of the paper is organized as follows. In Section 2, a brief formalism for the differential cross section in J/ψ production is given. Section 3 is devoted to the results and discussion. Finally, a summary is presented.

2   The formalism for J/ψ production differential cross sections

In the color evaporation model (CEM), quarkonium production is treated identically to open heavy-quark production except that the invariant mass of the heavy quark pair is restricted to be less than twice the mass of the lightest meson that can be formed with one heavy constituent quark. For charmonium, the upper limit on the $c\bar{c}$ pair mass is then two times the mass of the D meson mass, $m_{\rm D}$. The hadroproduction of a heavy quark at the leading order (LO) in perturbative QCD is the sum of contributions from $q\bar{q}$ annihilation and gg fusion.

The charmonium production cross section $d\sigma_{\rm pp}/dx_{\rm F}$ is a convolution of the $q\bar{q}$ and gg partonic cross sections with the parton densities in the incident proton and the target proton [13]:

$$\frac{d\sigma_{\rm pp}}{dx_{\rm F}}(x_{\rm F}) = \rho_{\rm J/\psi} \int_{2m_{\rm c}}^{2m_{\rm D}} dm \frac{2m}{\sqrt{x_{\rm F}^2 s + 4m^2}}$$

$$\times [f_{\rm g}(x_1, m^2) f_{\rm g}'(x_2, m^2) \sigma_{\rm gg}(m^2)$$

$$+ \sum_{\rm q=u,d,s} \{ f_{\rm q}(x_1, m^2) f_{\bar{\rm q}}'(x_2, m^2)$$

$$+ f_{\bar{\rm q}}(x_1, m^2) f_{\rm q}'(x_2, m^2) \} \sigma_{\rm q\bar{q}}(m^2)], \quad (1)$$

where $x_{1(2)}$ is the projectile proton (target) parton momentum fractions, $x_{\rm F} = x_1 - x_2$, $\sqrt{s}$ is the center of mass energy of the hadronic collision, $m^2 = x_1 x_2 s$, $m_{\rm c} = 1.2$ GeV and $m_{\rm D} = 1.87$ GeV are respectively the charm quark and D meson mass, and $\sigma_{\rm gg}(\sigma_{\rm q\bar{q}})$ is the LO $c\bar{c}$ partonic production cross section from the gluon fusion (quark-antiquark annihilation). $\rho_{\rm J/\psi}$ is the fraction of $c\bar{c}$ pair, which produces the J/ψ state, f_i and f_i' stand respectively for the parton distribution function in the incident proton and in the target proton.

As for p-A collisions, if only considering the nuclear effects of parton distribution functions, J/ψ differential production cross section $d\sigma_{\rm pA}/dx_{\rm F}$ is given by replacing parton distribution functions of the target proton with the bound nucleon parton distribution functions in Eq. (1).

With regard to the energy loss of the projectile proton in the nuclear target, it is supposed that after the projectile proton has n collisions with nucleons in the nucleus, the center of mass system energy $\sqrt{s'}$ of the nucleon-nucleon collision producing $c\bar{c}$ is reduced to

$$\sqrt{s'} = \sqrt{s} - (n-1)\Delta\sqrt{s}, \quad (2)$$

where $\Delta\sqrt{s}$ is the center of mass system energy loss (see Refs. [11, 12] for more detail discussion). The J/ψ production cross section in the nth collision can be rewritten as

$$\frac{d\sigma_{\rm pA}^{(n)}}{dx_{\rm F}}(x_{\rm F}) = \frac{d\sigma_{\rm pA}}{dx_{\rm F}'}(x_{\rm F}'). \quad (3)$$

Here the rescaled quantities are defined as

$$x_{\rm F}' = r_{\rm s} x_{\rm F}, \qquad r_{\rm s} = \frac{\sqrt{s}}{\sqrt{s'}}. \quad (4)$$

Now let us take account of the energy loss of the color octet $c\bar{c}$ in the color neutralization process. If the octet $c\bar{c}$ pair can lose its energy ΔE, the observed J/ψ at a given $x_{\rm F}$ comes from a $c\bar{c}$ pair originally produced at the higher value $x_{\rm F} + \Delta x_{\rm F}$ [10], with

$$\Delta x_{\rm F} = \frac{\Delta E}{E_{\rm p}'}, \quad (5)$$

where E'_p is the incoming proton energy corresponding to the center of mass system energy $\sqrt{s'}$, which has been modified by the initial state proton energy loss effect.

Combining the above ingredients on initial and final state effects, the J/ψ production cross section in proton-nucleus collisions can be expressed as

$$\left\langle \frac{d\sigma}{dx_F} \right\rangle = \sum_{n=1}^{A} P(n) \frac{d\sigma_{pA}^{(n)}}{dx_F}(x_F). \tag{6}$$

Here $P(n)$ is the probability of a projectile proton having n collisions in nuclei [11, 12].

3   Results and discussion

The E866 collaboration [3, 4] published the precise measurement on the differential cross-section ratios $R_{W/Be}(x_F)$,

$$R_{W/Be}(x_F) = \frac{\left\langle \dfrac{d\sigma^{p-W}}{dx_F} \right\rangle}{\left\langle \dfrac{d\sigma^{p-Be}}{dx_F} \right\rangle}, \tag{7}$$

for proton-induced tungsten to beryllium target for J/ψ production with very broad coverage $-0.1 < x_F < 0.95$. With a proper color neutralization time $\tau_0 = 0.25$ fm [9], the distance that the octet $c\bar{c}$ pair travels during this time exceeds the length of its path through the medium for the kinematical domain $x_F > 0$, which implies that the $c\bar{c}$ will remain colored on its entire path in the medium. The experimental data on $R_{W/Be}(x_F)$ will be used to study the energy loss incurred by the octet $c\bar{c}$ pair propagating through the nucleus.

If only considering the nuclear effects of parton distribution functions, the calculated J/ψ production cross section ratios $R_{W/Be}(x_F)$(dotted line) are compared with the E866 experimental data in Fig. 1 by using EPS09 nuclear parton distribution functions [14] together with the CTEQ6L parton density in the proton [15]. The calculated result shows that the nuclear suppression from the nuclear effects on the parton distribution functions becomes larger as the increase of x_F in the range $x_F > 0$. The nuclear suppression is approximately from zero to 17% for $R_{W/Be}(x_F)$ in the range $0 \leqslant x_F \leqslant 0.95$.

Further, taking into account the energy loss of the beam proton in the initial state, our calculations use the center-of-mass system energy loss of per collision $\Delta\sqrt{s} = 0.18$ GeV determined from the nuclear Drell-Yan experimental data in the Glauber model [12]. It is shown that the nuclear suppression on $R_{W/Be}(x_F)$ from the energy loss of the beam proton in the initial state increases gradually in the region $0 \leqslant x_F \leqslant 0.8$, and becomes much steeper in the region $x_F > 0.8$. The nuclear suppression due to the beam proton energy loss effect is approximately 4% to 17% in the range $0 \leqslant x_F \leqslant 0.8$ and 17%

to 44% in the range $0.8 \leqslant x_F \leqslant 0.95$. As can be seen by the dashed line in Fig.1, the total suppression from the two kinds of initial state nuclear effects is roughly 4% to 30% and 30% to 60% in the ranges $0 \leqslant x_F \leqslant 0.8$ and $0.8 \leqslant x_F \leqslant 0.95$, respectively.

Next we study the energy loss ΔE incurred by the octet $c\bar{c}$ pair propagating through the nucleus. In order to compare with the energy loss of light quark in cold nuclear matter, two different parametrizations for energy loss were proposed with the help of similarity cases in the nuclear Drell-Yan process [16, 17]. One is written as

$$\Delta E = \alpha L_A, \tag{8}$$

which denotes that the energy loss of the $c\bar{c}$ pair is liner with the path length L_A. Another one is presented as

$$\Delta E = \beta L_A^2. \tag{9}$$

Obviously, the energy loss is quadratic with the path length. Here, α and β are the parameters that can be extracted from experimental data.

In order to determine the parameter α and β in the energy loss expressions, the calculated J/ψ production cross-section ratios $R_{W/Be}(x_F)$ are compared with the selected experimental values by using the CERN sub-routine MINUIT [18] and minimizing χ^2,

$$\chi^2 = \sum_i^N \left[\frac{R_{W/Be,i}^{data} - R_{W/Be,i}^{theo}}{\sigma_i^{err}} \right]^2, \tag{10}$$

where $R_{W/Be,i}^{data}$ and $R_{W/Be,i}^{theo}$ indicate separately the experimental data and theoretical values of the cross-section ratios $R_{W/Be}$, σ_i^{err} is the uncertainty of the experimental points. Our analysis has in total 27 data points from the E866 experiment in the kinematical range $x_F > 0$. One standard deviation of the optimum parameter corresponds to an increase of χ^2 by 1 unit from its minimum χ^2_{min}. The fit of the selected data makes $\alpha = 3.42 \pm 0.15$ with the relative uncertainty $\delta\alpha/\alpha \simeq 4\%$ and $\chi^2/\mathrm{ndf} = 20.56$. Regarding the quadratic energy loss expression of the $c\bar{c}$ pair, the value of parameter β as well as its corresponding error extracted from the fit of the experimental data is $\beta = 0.55 \pm 0.03$ with the relative uncertainty $\delta\alpha/\alpha \simeq 5\%$ and $\chi^2/\mathrm{ndf} = 20.52$.

The solid line in Fig. 1 shows the calculated $R_{W/Be}(x_F)$ for J/ψ production, compared with the E866 data, given by using the EPS09 nuclear parton distributions together with the energy loss of the beam proton in initial state and the linear color octet $c\bar{c}$ energy loss. The theoretical value of the cross section on $R_{W/Be}(x_F)$ from the linear energy loss has almost no difference with that given by the quadratic energy loss. The total nuclear suppression on $R_{W/Be}(x_F)$ from the three nuclear effects increases gradually from 11% to 60% in the region $0 \leqslant x_F \leqslant 0.8$, and gets rapidly bigger from 60% to 96% in the region $0.8 \leqslant x_F \leqslant 0.95$.
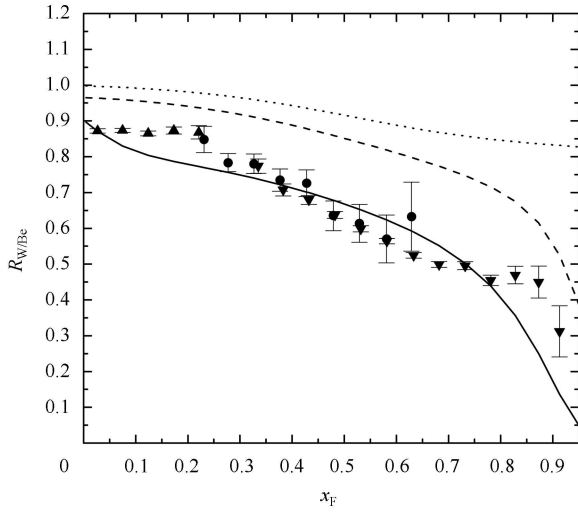
Fig. 1. The calculated J/ψ production cross-section ratios $R_{W/Be}(x_F)$ with three nuclear effects (solid line), the nuclear effects on the parton distribution functions and energy loss of beam proton (dashed line), and only the nuclear effects on the parton distribution functions (dotted line). The solid triangles (circles and inverted triangles) are the E866 experimental data [3, 4] in the region $0 < x_F < 0.3$ ($0.2 < x_F < 0.65$ and $0.3 < x_F < 0.95$).

However, whether the linear color octet $c\bar{c}$ energy loss or the quadratic energy loss, the value of χ^2/ndf extracted from the selected data on $R_{W/Be}$ is too high in spite of the small relative uncertainty. From Fig. 1, we can find intuitively that the numerical calculations of the cross-section ratios $R_{W/Be}(x_F)$ deviate far from the experimental data in small ($x_F < 0.2$) and large ($x_F > 0.8$) x_F regions. For the quantitative evaluation of the possible origins for the big χ^2/ndf value, the χ^2 analysis on the experimental data is performed by means of the different combination of three x_F regions for the small ($0 < x_F < 0.3$), middle ($0.2 < x_F < 0.65$) and big ($0.3 < x_F < 0.95$) x_F regions. The values of parameters α, β and χ^2 per degrees of freedom are calculated and summarized in Table 1 by fitting the selected experimental data on $R_{W/Be}$ as a function of x_F. As can be seen from Table 1, the big χ^2/ndf value really stems from the experimental measurement in the small($0 < x_F < 0.3$) and big ($0.3 < x_F < 0.95$) x_F regions. If only using the experimental data in middle x_F regions, the χ^2/ndf value is approximately equal to one for the linear and quadratic color octet $c\bar{c}$ energy loss. The obtained $\alpha = 2.78 \pm 0.81$ with the relative uncertainty $\delta\alpha/\alpha \simeq 29\%$, and $\beta = 0.44 \pm 0.13$ with $\delta\beta/\beta \simeq 29\%$.

Regarding the energy loss of a charm quark, if it is assumed that the charm and anti-charm quark lose the same energy, the obtained energy loss per unit length is $\alpha = 1.39$ GeV/fm. For an outgoing light quark, however, the theoretical energy loss is 0.38 GeV/fm by the

global fit of the experimental data in semi-inclusive deep inelastic scattering of leptons on the nucleus [19]. It is indicated that the heavy quark in cold nuclear matter loses more energy compared to the light quark.

Table 1. The values of parameters α, β and χ^2/ndf extracted from the selected data on $R_{W/Be}$ as a function of x_F.

x_F	No.data	$\alpha(\chi^2/\text{ndf})$	$\beta(\chi^2/\text{ndf})$
0.20–0.65	9	2.78±0.81(1.01)	0.44±0.13(1.03)
0.30–0.95	13	4.44±0.21(13.29)	0.71±0.03(12.32)
0.20–0.95	22	4.35±0.20(8.78)	0.70±0.03(8.35)
0.00–0.95	27	3.42±0.15(20.56)	0.55±0.03(20.52)

By making use of the linear color octet $c\bar{c}$ energy loss determined from the E866 experimental data in the region $0.2 < x_F < 0.65$, we revisit the final state energy loss effect on the J/ψ production cross-section ratio $R_{W/Be}(x_F)$. The theoretical results are compared with the relative experimental data in Fig. 2. It is shown that the nuclear effects in the initial state provide roughly the J/ψ suppression from 4% to 15%, 15% to 60% in the ranges $0 < x_F < 0.5$ and $0.5 < x_F < 0.95$, respectively. The contributions from nuclear effects in the final state are approximately from 6% to 15% and 15% to 34% in the corresponding x_F ranges. Therefore, it is demonstrated that the J/ψ suppression on $R_{W/Be}(x_F)$ induced by the energy loss of color octet $c\bar{c}$ is more important than that of the initial state nuclear effects in the $x_F < 0.5$ region, but the exact reverse is the case in the $x_F > 0.5$ region.
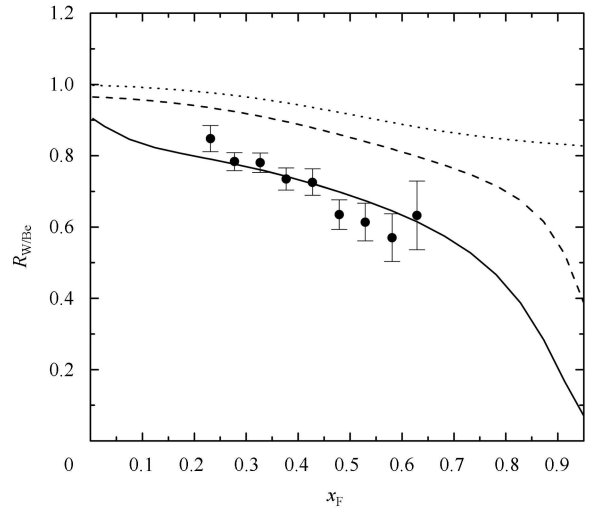

Fig. 2. The J/ψ production cross-section ratio $R_{W/Be}(x_F)$. The filled circles are the E866 experimental data [3, 4] in the region $0.2 < x_F < 0.65$. The comments are the same as Fig. 1.

In fact, except for the three kinds of nuclear effects that we consider, the other cold nuclear matter effects,

such as nuclear absorption and gluon saturation, might affect J/ψ suppression in nuclei. As for J/ψ production in the E866 experiment, however, the gluon saturation effect is rather small [10], and the nuclear absorption is expected to be negligible. It is also worth noting that the initial state energy loss effect is evaluated by means of the energy loss of the incident proton determined by the nuclear Drell-Yan reaction [12]. Therefore, it is thought that the obtained result on the final state energy loss effect should be solid despite the contradiction with previous theoretical expectation that heavy quark energy loss should be suppressed relative to the light quark due to the "dead-cone" effect [20].

4　Summary

J/ψ production in p-A collisions is an ideal tool for exploring the energy loss of charm quarks in cold nuclear matter. In this paper, the nuclear effects for J/ψ production in p-A collisions are investigated by considering the nuclear effects on parton distribution, energy loss of beam proton and the finial state energy loss of color octet $c\bar{c}$ pair, respectively. We perform a leading order phenomenological analysis on the J/ψ production cross-section ratio $R_{W/Be}(x_F)$ and compare with the E866 experimental data for the $c\bar{c}$ remaining colored on its entire path in the nuclear medium. It is found that the theoretical results by combining the different nuclear effects have a good agreement with the experimental data. The present experimental data do not distinguish between the linear and quadratic dependence of $c\bar{c}$ pair energy loss. The J/ψ suppression on $R_{W/Be}(x_F)$ from the initial state nuclear effects is more important than that induced by the energy loss of color octet $c\bar{c}$ in the large x_F region. By means of the selected experimental data, we obtain the $c\bar{c}$ pair energy loss per unit path length $\alpha = 2.78\pm0.81$ GeV/fm, which indicates that the heavy quark can lose more energy compared to the outgoing light quark in cold nuclear matter. It is desired that our research results can provide a useful reference for deeply understanding the J/ψ suppression in heavy-ion collisions. We will extend our research method to the J/ψ production in p-Pb from the LHCb collaboration [21] in the future.

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