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Energy loss effect of incoming gluons from J/ψ production in p-A collisions*

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Abstract: The energy loss effect of incoming gluons from J/ψ production in p-A (or d-A) collisions is investigated by means of the E866, RHIC and LHC experimental data. The gluon mean energy loss per unit path length $\mathrm{d}E/\mathrm{d}L = 2.18 \pm 0.14$ GeV/fm is extracted by fitting the E866 experimental data for J/ψ production cross section ratios $R_{\mathrm{W(Fe)/Be}}(x_{\mathrm{F}})$. The obtained result indicates that the incoming gluons lose more energy than the incident quarks. By comparing the theoretical results with E866, RHIC, and LHC experimental data, it is found that the nuclear suppression due to the incident gluon (quark) energy loss reduces (increases) with the increase of the kinematic variable x_{F} (or y). The energy loss effect of incoming gluons plays an important role in the suppression of J/ψ production in a wide energy range from $\sqrt{s} = 38.7$ GeV to $\sqrt{s} = 5.0$ TeV, and the influence of incident quark energy loss can be ignored for high energies (such as at RHIC and LHC energy).

Keywords: J/ψ production, gluon, charm quark, energy loss

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1 Introduction

In order to quantify the properties of the quark-gluon plasma (QGP) created in heavy-ion collisions, a solid understanding of the nuclear modification of particle spectra in cold nuclear matter is fundamentally important. J/ψ production in proton-nucleus collisions provides an ideal tool to test the microscopic dynamics of medium-induced parton energy loss.

Drastic nuclear suppression effects are observed over a wide collision energy range for minimum bias p-A and d-A collisions, such as at the NA3 [1], E772 [2], E866 [3, 4], NA50 [5], HEAR-B [6], LHC [7, 8] and RHIC [9]experiments. However, it is striking that there is no consensus on the origin of J/ψ suppression in some kinematical conditions [10]. Some approaches attribute J/ψ suppression to an effective absorption cross section σ_{abs} of the $c\bar{c}$ pair [11–12]; other models attribute J/ψ suppression to the increase of the $c\bar{c}$ pair invariant mass by multiple soft rescatterings through the nucleus, leading to a reduction of the overlap with the J/ψ wave function [13].

In the nucleus rest frame, a high-energy J/ψ is formed long after the nucleus, thus what actually propagates through the nucleus is the parent $c\bar{c}$ pair. Our previous works [14–15] support that the nuclear modification of the parton distribution functions and the incident proton energy loss owing to multiple scattering on the surrounding nucleon and gluon radiation are the main initial state effects which induce the J/ψ suppression, and the energy loss of the color octet $c\bar{c}$ is the dominant final state effect when the $c\bar{c}$ pair remains colored on its entire path through the medium. In Ref. [15], by using the EPS09 nuclear parton distributions [16] together with the energy loss of the proton beam in the initial state (the center-of-mass system energy loss per collision $\Delta\sqrt{s} = 0.18$ GeV is determined from the nuclear Drell-Yan experimental data in the Glauber model [17]) and the linear quark energy loss in the final state, we extracted the charm quark mean energy loss per unit path length ($\mathrm{d}E/\mathrm{d}L = 1.49 \pm 0.37$GeV/fm with $\chi^2/ndf = 0.91$) by fitting the E866 experimental data [4] in the region $0.2 < x_{\mathrm{F}} < 0.65$.

To further investigate the microscopic dynamics of medium-induced parton energy loss, the color charge of parton energy loss has received significant interest. This issue is of fundamental importance for accurately understanding the dynamics of modifying a hard probe and the dense QCD properties of what is probed. Previ-

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ous research [18–22] predicted that gluons lose more energy than quarks because of the stronger coupling to the medium.

In the J/ψ production for p-A (or d-A) collisions, the observed suppression induced by the incident parton energy loss effect can give a better way to discriminatingly identify the energy loss of incoming gluons and quarks. Following our previous work, in the present study we investigate the incoming gluon energy loss effect by means of the E866 [4], RHIC [9] and LHC [7, 8] experimental data, and hope that our research can provide a useful reference for deep understanding of the microscopic dynamics of medium-induced parton energy loss.

The remainder of this paper is organized as follows. In Section 2, the theoretical framework of our study is introduced. Section 3 is devoted to the results and discussion. Finally, a summary is presented.

2 Formalism for J/ψ production differential cross sections

In the the color evaporation model (CEM) [23], for J/ψ production in p-A collisions, 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 $\mathrm{c\bar{c}}$ pair mass is then $2m_{\mathrm{D}}$. The hadroproduction of a heavy quark at leading order (LO) in perturbative QCD is the sum of contributions from $\mathrm{q\bar{q}}$ annihilation and gg fusion. The charmonium production cross section $\mathrm{d}\sigma_{\mathrm{p-p}}/\mathrm{d}x_{\mathrm{F}}$ is a convolution of the $\mathrm{q\bar{q}}$ and gg partonic cross sections with the parton distribution functions f_i in the incident proton and f'_i in the target proton, and is expressed as [24]:

$$\begin{aligned}\frac{\mathrm{d}\sigma_{\mathrm{p-p}}}{\mathrm{d}x_{\mathrm{F}}}(x_{\mathrm{F}})=\rho_{\mathrm{J}/\psi}\int_{2m_{\mathrm{c}}}^{2m_{\mathrm{D}}}\mathrm{d}m\frac{2m}{\sqrt{x_{\mathrm{F}}^2s+4m^2}}\\ \times\Bigg[f_{\mathrm{g}}(x_1,m^2)f'_{\mathrm{g}}(x_2,m^2)\sigma_{\mathrm{gg}}(m_{\mathrm{c}}^2)\\ +\sum_{\mathrm{q=u,d,s}}\{f_{\mathrm{q}}(x_1,m^2)f'_{\mathrm{\bar{q}}}(x_2,m^2)\\ +f_{\mathrm{\bar{q}}}(x_1,m^2)f'_{\mathrm{q}}(x_2,m^2)\}\sigma_{\mathrm{q\bar{q}}}(m_{\mathrm{c}}^2)\Bigg].\end{aligned} \quad (1)$$

Here, in the rest frame of the target nucleus, $x_{1(2)}$ is the projectile proton (target) parton momentum fractions, $x_{\mathrm{F}}=x_1-x_2$, $\sqrt{s}$ is the center of mass energy of the hadronic collision, $m^2=x_1x_2s$, $m_{\mathrm{c}}=1.2$ GeV and $m_{\mathrm{D}}=1.87$ GeV are respectively the charm quark and D meson mass, $\sigma_{\mathrm{gg}}(\sigma_{\mathrm{q\bar{q}}})$ is the LO $\mathrm{c\bar{c}}$ partonic production cross section from the gluon fusion (quark-antiquark annihilation), and $\rho_{\mathrm{J}/\psi}$ is the fraction of the $\mathrm{c\bar{c}}$ pair which produces the J/ψ state.

In J/ψ production from p-A (or d-A) collisions, owing to multiple scattering on the surrounding nucleon and gluon radiation while the incident parton propagates through the nucleus, the incoming gluon (quark) can lose its energy ΔE_{g} (ΔE_{q}). The energy loss of the incoming gluon (quark) results in an average change in its momentum fraction prior to the collision,

$$\Delta x_{1\mathrm{g}}=\Delta E_{\mathrm{g}}/E_{\mathrm{p}},\Delta x_{1\mathrm{q}}=\Delta E_{\mathrm{q}}/E_{\mathrm{p}}. \quad (2)$$

According to the parametrization for parton energy loss [25–26], the mean energy loss of an incoming gluon (quark) can be expressed as:

$$\Delta E_{\mathrm{g}}=\alpha L_A,\Delta E_{\mathrm{q}}=\beta L_A. \quad (3)$$

Here, $L_A=3R_A/4$ ($R_A=1.12A^{1/3}$) [27], and α, β are the parameters that can be extracted from the experimental data by adopting the χ^2 analysis method.

When the J/ψ hadronization occurs outside the nucleus, nuclear absorption should play little or no role and the energy loss of the color octet $\mathrm{c\bar{c}}$ is the dominant final state effect. In view of the shift in x_{F} due to the energy loss of color octet $\mathrm{c\bar{c}}$ ($\Delta E_{\mathrm{c\bar{c}}}$), the momentum fraction of the incident gluon (quark) is actually:

$$x'_{1\mathrm{g}}=x'_1+\Delta x_{1\mathrm{g}},x'_{1\mathrm{q}}=x'_1+\Delta x_{1\mathrm{q}}, \quad (4)$$

with $x'_1=\frac{1}{2}[\sqrt{x'^2_{\mathrm{F}}(1-\tau)^2+4\tau}+x'_{\mathrm{F}}(1-\tau)]$, $x'_{\mathrm{F}}=x_{\mathrm{F}}+\Delta E_{\mathrm{c\bar{c}}}/E_{\mathrm{p}}$[15], $\tau=m^2/s$. The J/ψ differential production cross section in p-A collisions $\mathrm{d}\sigma_{\mathrm{p-A}}/\mathrm{d}x_{\mathrm{F}}$ is written as:

$$\begin{aligned}\frac{\mathrm{d}\sigma_{\mathrm{p-A}}}{\mathrm{d}x_{\mathrm{F}}}(x_{\mathrm{F}})=\rho_{\mathrm{J}/\psi}\int_{2m_{\mathrm{c}}}^{2m_{\mathrm{D}}}\mathrm{d}m\frac{2m}{\sqrt{x_{\mathrm{F}}^2s+4m^2}}\\ \times\Bigg[f_{\mathrm{g}}(x'_{1\mathrm{g}},m^2)f'_{\mathrm{g}}(x'_2,m^2)\sigma_{\mathrm{gg}}(m^2)\\ +\sum_{\mathrm{q=u,d,s}}\{f_{\mathrm{q}}(x'_{1\mathrm{q}},m^2)f'_{\mathrm{\bar{q}}}(x'_2,m^2)\\ +f_{\mathrm{\bar{q}}}(x'_{1\mathrm{q}},m^2)f'_{\mathrm{q}}(x'_2,m^2)\}\sigma_{\mathrm{q\bar{q}}}(m^2)\Bigg].\end{aligned} \quad (5)$$

Here, in consideration of the shift in x_{F} due to the energy loss of color octet $\mathrm{c\bar{c}}$, the target parton momentum fraction is actually $x'_2=\frac{1}{2}[\sqrt{x'^2_{\mathrm{F}}(1-\tau)^2+4\tau}-x'_{\mathrm{F}}(1-\tau)]$.

Further, considering the energy loss of the incident gluon, incoming quark and the color octet $\mathrm{c\bar{c}}$, the leading order for J/ψ production cross section as a function of y should be written as:

$$\frac{\mathrm{d}\sigma_{\mathrm{p-A}}}{\mathrm{d}y}(y)=\frac{\mathrm{d}\sigma_{\mathrm{p-p}}}{\mathrm{d}y}(y'). \quad (6)$$

Here,

$$\begin{aligned}\frac{\mathrm{d}\sigma_{\mathrm{p-p}}}{\mathrm{d}y}(y') = \rho_{\mathrm{J/\psi}}\int_{2m_{\mathrm{c}}}^{2m_{\mathrm{D}}}\mathrm{d}m\frac{2m}{s} & \\ \times\Bigg[f_{\mathrm{g}}(x'_{1\mathrm{g}},m^2)f'_{\mathrm{g}}(x'_2,m^2)\sigma_{\mathrm{gg}}(m_{\mathrm{c}}^2) & \\ +\sum_{\mathrm{q=u,d,s}}\{f_{\mathrm{q}}(x'_1,m^2)f'_{\bar{\mathrm{q}}}(x'_2,m^2) & \\ +f_{\bar{\mathrm{q}}}(x'_{1\mathrm{q}},m^2)f'_{\mathrm{q}}(x'_2,m^2)\}\sigma_{\mathrm{q\bar{q}}}(m_{\mathrm{c}}^2)\Bigg], & \quad (7)\end{aligned}$$

with

$$y' = y+\ln\left(\frac{E+\Delta E_{\mathrm{c\bar{c}}}}{E}\right), \quad (8)$$

$$x'_{1\mathrm{g}} = \frac{m}{\sqrt{s}}\mathrm{e}^{y'}+\Delta E_{\mathrm{g}}/E_{\mathrm{p}}, \qquad x'_{1\mathrm{q}} = \frac{m}{\sqrt{s}}\mathrm{e}^{y'}+\Delta E_{\mathrm{q}}/E_{\mathrm{p}}, \quad (9)$$

and

$$x'_2 = \frac{m}{\sqrt{s}}\mathrm{e}^{-y'}. \quad (10)$$

3 Results and discussion

In order to determine the value of the incoming gluon energy loss parameter α, we give a phenomenological analysis at leading order for the J/ψ production cross section ratios $R_{\mathrm{W(Fe)/Be}}(x_{\mathrm{F}})$:

$$R_{\mathrm{W(Fe)/Be}}(x_{\mathrm{F}}) = \frac{\mathrm{d}\sigma_{\mathrm{p-W(Fe)}}}{\mathrm{d}x_{\mathrm{F}}}\Big/\frac{\mathrm{d}\sigma_{\mathrm{p-Be}}}{\mathrm{d}x_{\mathrm{F}}}, \quad (11)$$

for the E866 experimental data (49 points) by using the EPS09 nuclear parton distributions [16] together with the energy loss parameter of the incident quark ($\beta = 1.21\pm0.09$ GeV/fm) determined from the nuclear Drell-Yan experimental data [26] and the color octet $\mathrm{c\bar{c}}$ energy loss ($\alpha = 2.97$ GeV/fm) determined in our previous work [15]. By minimizing χ^2 with the CERN subroutine MINUIT [28] the value of parameter α is extracted: $\alpha = 2.18\pm0.14$ GeV/fm. One standard deviation of the optimum parameter corresponds to an increase of χ^2 by 1 unit from its minimum χ^2_{min}. The result indicates that the incoming gluons lose more energy than the incident quarks in J/ψ production from p-A collisions, which is in accord with the prediction that gluons lose more energy than quarks because of the stronger coupling to the medium [18–22]. In addition, due to the effects of the modification of the gluon parton distribution functions on the nucleus leading to an additional J/ψ suppression in p-A collisions, the EPS09 uncertainties can be the main source of uncertainty associated with our results.

To identify the energy loss effect of the incoming gluon and incident quark on the J/ψ suppression, the theoretical results are compared with E866 experimental data [4] at $\sqrt{s} = 38.7$ GeV in Figs. 1 and 2, RHIC experimental data [9] at $\sqrt{s} = 200$ GeV in Fig. 3, and LHC experimental data [7, 8] at $\sqrt{s} = 5.0$ TeV in Fig. 4, respectively. The dotted, dashed and solid lines correspond to the results given without initial state energy loss, by considering the incident quark energy loss effect, and the energy loss of the incident quark together with incoming gluon energy loss.

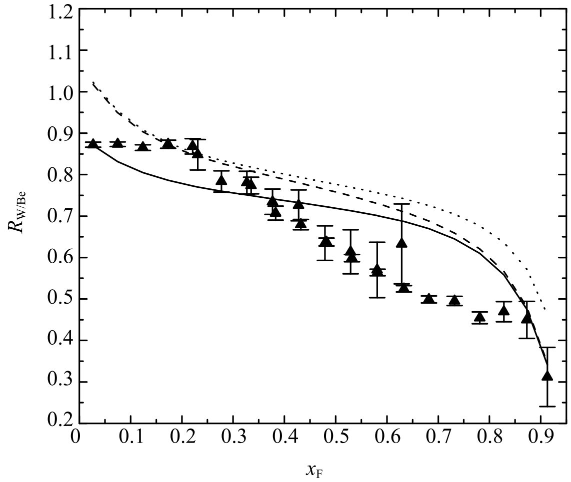

Fig. 1. The calculated J/ψ production cross section ratios $R_{\mathrm{W/Be}}(x_{\mathrm{F}})$ without the initial state energy loss (dotted line), with the incident quark energy loss effect (dashed line), and with the energy loss of incoming quark and gluon (solid line). The solid triangles are the E866 experimental data [4].

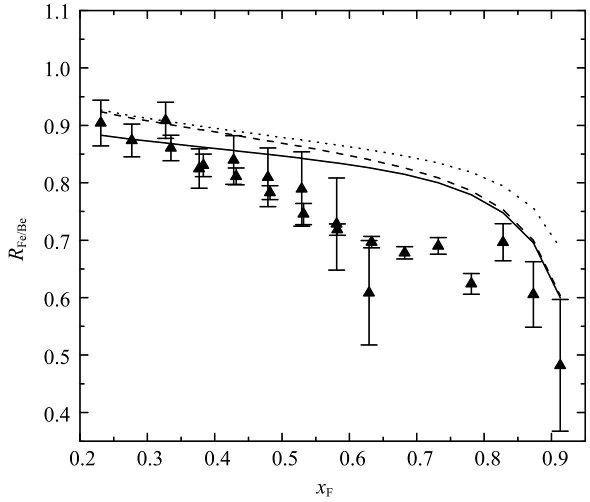

Fig. 2. The calculated J/ψ production cross section ratios $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ without the initial state energy loss (dotted line), with the incident quark energy loss effect (dashed line), and with the energy loss of incoming quark and gluon (solid line). The solid triangles are the E866 experimental data [4].

As can be seen in Figs. 1 and 2, the nuclear suppression due to the incident quark energy loss is negligible in the region $x_\mathrm{F} < 0.3$, increases gradually for $x_\mathrm{F} < 0.8$, and becomes steeper for $x_\mathrm{F} > 0.8$. The suppression from the energy loss effect of the incoming gluon, on the other hand, is much steeper in the region $x_\mathrm{F} < 0.3$, reduces gradually for $x_\mathrm{F} < 0.8$, and becomes negligible for $x_\mathrm{F} > 0.8$. It is clear that the incident gluon energy loss plays an important role in the suppression of the J/ψ production cross section ratios $R_{\mathrm{W(Fe)/Be}}(x_\mathrm{F})$ in the small x_F region (especially for $x_\mathrm{F} < 0.3$), and the energy loss effect of incoming quarks is obvious in the large x_F region (especially for $x_\mathrm{F} > 0.8$). We can see that the experimental data on J/ψ production at E866 energy ($\sqrt{s} = 38.7$ GeV) can give a good test for the identity of the incident parton which loses its energy in the nuclear medium.

In Figs. 3 and 4, the theoretical results for J/ψ production cross section ratios $R_{\mathrm{Au(Pb)/p}}$ as a function of y are compared with RHIC [9] and LHC [7,8] experimental data, respectively. From Fig. 3 we can see that the dotted line and the dashed line appear to overlap, which indicates that the energy loss effect due to the incoming quark plays no role in the J/ψ production at RHIC energy. In contrast, the nuclear suppression due to the incident gluon energy loss is obvious, especially in the range $y < -1.5$, reduces gradually with the increase of y, and becomes negligible for $y > 2.0$. From Fig. 4, the incident quark energy loss effect has little impact on the J/ψ production cross section ratio $R_{\mathrm{Pb/p}}(y)$ at LHC energy, and the energy loss due to the incoming gluon plays an important role in the nuclear suppression, especially in the range $y < -3.5$, reduces gradually with the increase of y, and becomes negligible for $y > -1.5$. In the present work, it is found that the energy loss of the incoming gluon plays an important role in the suppression of J/ψ production in a wide energy range from $\sqrt{s} = 38.7$ GeV to $\sqrt{s} = 5.0$ TeV, and the influence of incident quark energy loss can be ignored for high energies, such as RHIC energy and LHC energy.

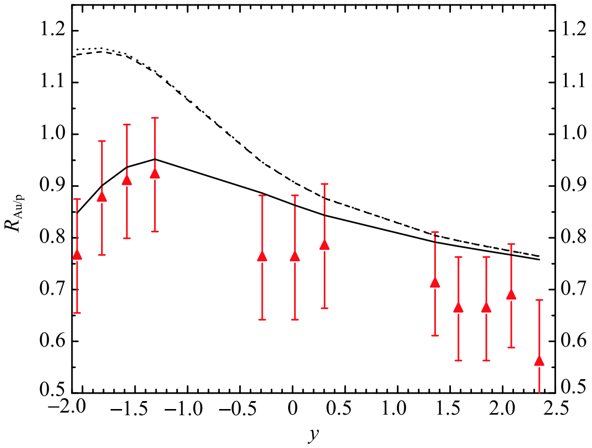

Fig. 3. The calculated J/ψ production cross section ratios $R_{\mathrm{Au/p}}(y)$ without the initial state energy loss (dotted line), with the incident quark energy loss effect (dashed line), and with the energy loss of incoming quark and gluon (solid line). The solid triangles are the RHIC experimental data [9].

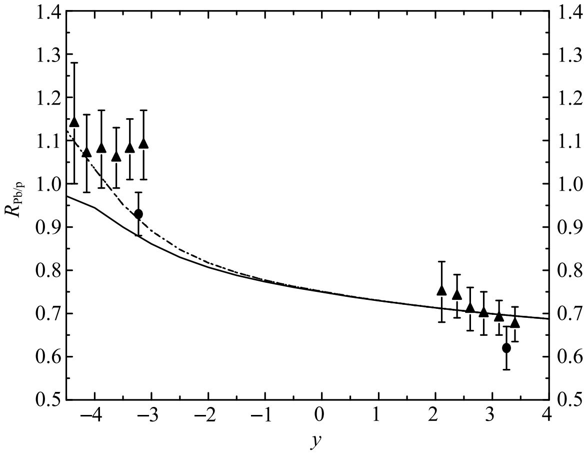

Fig. 4. The calculated J/ψ production cross section ratios $R_{\mathrm{Pb/p}}(y)$ without the initial state energy loss (dotted line), with the incident quark energy loss effect (dashed line), and with the energy loss of incoming quark and gluon (solid line). The solid triangles and filled circles correspond to the experimental data from the ALICE Collaboration [7] and LHCb Collaboration [8] at the LHC, respectively.

4 Summary

Following our previous work [14, 15], we have studied the energy loss effect of incoming gluons from J/ψ production in p-A (or d-A) collisions. By means of the EPS09 nuclear parton distributions [16] together with the energy loss of the incident quark ($\mathrm{d}E/\mathrm{d}L = 1.21 \pm 0.09$ GeV/fm determined in our work [26]) and color octet $c\bar{c}$ ($\mathrm{d}E/\mathrm{d}L = 2.97 \pm 0.74$ GeV/fm determined in our study [15]), we have given a phenomenological analysis at leading order for the J/ψ production cross section ratios $R_{\mathrm{W(Fe)/Be}}(x_\mathrm{F})$ for the E866 experimental data (49 points) and extracted the gluon mean energy loss per unit path length $\mathrm{d}E/\mathrm{d}L = 2.18 \pm 0.14$ GeV/fm by minimizing χ^2 with the CERN subroutine MINUIT [28]. This result indicates that the incoming gluons lose more energy than the incident quarks, which supports the prediction that gluons lose more energy than quarks because of the stronger coupling to the medium [18–22]. In addition, the EPS09 uncertainties can be the main source of uncertainty associated with our results, owing to the effects of the modification of the gluon parton distribution functions on the nucleus leading to an additional J/ψ suppression in p-A collisions. To identify the energy loss effect of the incoming gluon and quark on the J/ψ suppression, the theoretical results were compared with E866 [4], RHIC [9], and LHC [7, 8] experimental data. We find that the nuclear suppression due to the incident gluon (quark) energy loss reduces (increases) with the increase of the kinematic variable x_{F} (or y). The energy loss of the incoming gluon plays an important role in the suppression of J/ψ production in a wide energy range from $\sqrt{s}=38.7$ GeV to $\sqrt{s}=5.0$ TeV, and the influence of incident quark energy loss can be ignored for high energy, such as at RHIC energy and LHC energy.

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