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Abstract

J/ψ suppression in p-A collisions from energy loss effect in cold nuclear matter is investigated. By means of the EPPS21 nPDFs, the value of the transport coefficient in cold nuclear matter is extracted ($\hat{q} = 0.024 \pm 0.002$ GeV^2/fm) from E866 experimental data ($\sqrt{s} = 40$ GeV, \$0.20

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Full Text

Preamble

J/ Suppression in p-A Collisions from Energy Loss Effect in Cold Nuclear Matter

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Abstract

J/ suppression in p-A collisions from energy loss effects in cold nuclear matter is investigated using the EPPS21 nuclear parton distribution functions (nPDFs). The transport coefficient in cold nuclear matter is extracted ($\hat{q} = 0.024 \pm 0.002$ GeV^2/fm) from E866 experimental data ($\sqrt{s} = 40$ GeV, $0.20 < x_F < 0.65$), RHIC data ($\sqrt{s} = 200$ GeV, $-2.05 < y < 2.35$), and LHC data ($\sqrt{s} = 5.0$ TeV, $-4.36 < y < 3.40$). The obtained results demonstrate that fully coherent energy loss (FCEL) of the produced $c\bar{c}$ pair plays a more important role in J/ suppression for E866 data, incident parton energy loss following the Landau-Pomeranchuk-Migdal (LPM) regime has a certain impact especially for RHIC data, and corrections from nPDFs become most important for LHC data. This may be induced by the fact that EPPS21 nPDFs use more data from LHC (LHCb) and D-meson production experiments to constrain the correction parameters, possibly overestimating the influence of nPDFs nuclear effects.

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Keywords: energy loss, parton distribution, J/ production
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Introduction

With improved precision and variety in RHIC and LHC measurements, the theory of nuclear effects (such as parton energy loss) in quark-gluon plasma (QGP) and jet quenching phenomenology in heavy-ion collisions—proposed as a potential signal of QGP—has been thoroughly explored over the past decade [1,2]. To quantify the properties of QGP, detailed studies of parton dynamics in cold nuclear matter and various nuclear effects expected in p-A collisions are required. J/ suppression in p-A collisions provides an ideal tool for investigating parton dynamics and nuclear effects in cold nuclear matter.

Generally speaking, several nuclear effects induce J/ suppression in p-A collisions: (i) incident parton energy loss caused by gluon radiation due to multiple scattering of fast partons passing through the nucleus [3,4]; (ii) corrections to parton distribution functions from effects such as nuclear shadowing, anti-shadowing, EMC effect, and Fermi motion effect in different regions of parton momentum fraction [5-8]; (iii) energy loss of the produced $c\bar{c}$ pair traveling through the nucleus [9,10]; and (iv) the so-called nuclear absorption effect caused by strong interactions between the pre-meson charm quark pair and nuclear matter [11]. Hard processes in h-A collisions are sensitive to different timescales of gluon radiation. Hence, incident parton energy loss mainly follows the LPM regime [12,13] in view of $t_f < L_A$ ($t_f \propto 1/q_T^2$ [14] and L_A denoting the path length in the nuclear target), while the energy loss of the $c\bar{c}$ pair in the final state may follow the factorization regime—usually referred to as fully coherent energy loss—because $t_f \gg L_A$ [15].

Various nuclear modifications have been proposed to explain J/ suppression in p-A collisions [9,16-19]. Nevertheless, disentangling the respective contributions from initial-state parton energy loss, nPDF nuclear effects, final-state $c\bar{c}$ energy loss, and nuclear absorption has always been challenging. Owing to poor comprehension of the underlying mechanisms driving in-medium corrections to nucleon substructure, nuclear parton distribution functions are generally constrained by fitting experimental data from p-A collisions, such as nuclear Drell-Yan data from E866 [20] and E772 [21], J/ production data from LHC and LHCb experiments [22,23], and so on. This may lead these nPDF sets to overestimate corrections regarding nuclear effects on parton distribution functions in J/ production. Additionally, both incident parton LPM energy loss and produced $c\bar{c}$ FCEL effects may induce observed J/ suppression in p-A collisions. Energy loss effects in cold nuclear matter represent another important nuclear effect. Thus, in this article, using E866 [24,25], RHIC [26], and LHC experimental data [22,23], we investigate J/ suppression induced by FCEL effects of the produced $c\bar{c}$ pair and incident parton LPM energy loss effects while simultaneously considering nPDF nuclear effects. Our results may quantitatively describe the influence on J/ suppression from nuclear effects on parton distribution functions in the nucleus, FCEL effects of the produced $c\bar{c}$ in the final state, and incident quark (gluon) energy loss effects according to the LPM regime.

Formalism for Nuclear Modification of J/ Production Induced by Fully Coherent Energy Loss Effect

According to the color evaporation model (CEM) [27], the differential cross section of J/ production in p-A collisions can be expressed as:

$$\frac{d\sigma}{dx_F} = \rho_{J/\psi} \left\{ \sum_{q=u,d,s} \left[f_p^q(x_1, m^2) f_A^{\bar{q}}(x_2, m^2) + f_p^{\bar{q}}(x_1, m^2) f_A^q(x_2, m^2) \right] \sigma_{q\bar{q}}(m^2) + f_p^g(x_1, m^2) f_A^g(x_2, m^2) \sigma_{gg}(m^2) \right\}$$

where $\rho_{J/\psi}$ represents the probability of a $c\bar{c}$ pair producing the J/ particle, f_p^i and f_A^i are the parton distribution functions in the proton and nucleus with momentum fractions x_1 and x_2, respectively. σ_{gg} and $\sigma_{q\bar{q}}$ denote the LO $c\bar{c}$ partonic production cross sections from gluon fusion and quark-antiquark annihilation, respectively. Additional parameters include charm-quark mass $m_c = 1.3$ GeV, D meson mass $m_D = 1.87$ GeV, $m^2 = \hat{s}x_{1x}2$ ($\hat{s}$ is the center-of-mass energy of the hadronic collision), and $x_F = x_1 - x_2$. The rapidity y is given by $\sinh y = -\frac{E_T}{m_T} x_F$, with $x_{1,2} = \frac{\sqrt{x_F^2(1-m^2/s)^2+4m^2/s} \pm x_F(1-m^2/s)}{2}$. Here y is the rapidity and E (E_p) is the energy of the produced $c\bar{c}$ pair (projectile proton) in the rest frame of the target nucleus, with $E = E_p e^y$ and $m_T = \sqrt{p_T^2 + m^2}$.

In J/ formation, it is generally believed that the $c\bar{c}$ pair is first produced from the interaction between a projectile and target parton, followed by non-perturbative formation of the colorless asymptotic state. Thus, in J/ production from p-A collisions, both the incident quark (gluon) and the produced $c\bar{c}$ experience energy loss in cold nuclear matter while traveling through the nucleus. As discussed in Section 1, the energy loss of the incident quark (gluon) in cold nuclear matter follows the LPM regime [12,13] due to the gluon formation time $t_f < L_A$. The probability distribution associated with LPM energy loss has been proposed by Baier, Dokshitzer, Mueller, Peigné, and Schiff (BDMPS) [28,29] and can be expressed as [30,31]:

$$D(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega_i} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right) \exp\left[- \int d\omega \frac{dI(\omega)}{d\omega} \right]$$

Based on independent gluon emission, $D(\epsilon)$ is the normalized sum of emission probabilities for an arbitrary number n of gluons carrying total energy ϵ, and $dI(\omega)/d\omega$ is the medium-induced gluon spectrum. In the LPM regime, the parton average energy loss $\langle \epsilon \rangle_{\text{LPM}}$ is independent of parton energy:

$$\langle\epsilon\rangle_{\mathrm{LPM}} \propto C_R \cdot \hat{q} L_A^2$$

with C_R representing the Casimir of the propagating particle ($C_R = 4/3$ for a quark and $C_R = 3$ for a gluon) and $\hat{q}$ the transport coefficient. Consequently, the effect of LPM fractional energy loss may vanish in the high-energy limit due to its independence from parton energy.

In the final state of J/ production from p-A collisions, when the produced $c\bar{c}$ pair travels through the nucleus, the FCEL effect arising from interference of gluon emission amplitudes is expected because $t_f \gg L_A$. Unlike incident quark (gluon) energy loss, FCEL is associated with particle energy E, and the induced spectrum $\omega dI_R/d\omega$ derived in [15,32-34] can be expressed as:

$$\omega \frac{dI_R}{d\omega} = \frac{\alpha_s C_R}{\pi}(C_a + C_R - C_b)\left\{\ln\left(1+\frac{\omega^2}{\omega_c^2}\right) - \ln\left(1+\frac{\omega^2}{\omega_d^2}\right)\right\}$$

where C_a and C_b are the Casimir color charges of incoming partons from the proton and target nucleus, respectively. The quenching weight associated with fully coherent energy loss is defined as a function of medium-induced energy loss ϵ and particle energy E:

$$P(\epsilon, E) = \exp\left\{-\int \frac{d\omega}{\omega}\omega\frac{dI_R}{d\omega}\right\}\delta(\epsilon - \epsilon_{\mathrm{rad}})$$

It can be derived that the average energy loss $\langle\epsilon\rangle_{\mathrm{FCEL}}$ scales linearly with particle energy E in the rest frame of the medium [15]:

$$\langle\epsilon\rangle_{\mathrm{FCEL}} \propto (C_a + C_R - C_b) \cdot \hat{q} L_A \cdot E$$

Thus, being linearly dependent on particle energy E, fully coherent energy loss exceeds LPM energy loss in cold nuclear matter unless the particle energy becomes very small. Consequently, the FCEL effect of the produced $c\bar{c}$ may play a more important role in J/ suppression in h-A collisions than the LPM energy loss effect of the incident parton.

In J/ production from p-A collisions, both incident quark (gluon) energy loss ($\epsilon_{q(g)}$) according to the LPM regime and fully coherent energy loss of the produced $c\bar{c}$ ($\epsilon_{c\bar{c}}$) in the final state can induce rescaling of the parton momentum fraction: $x_F \to x'_F = x_F + \Delta x_F$, $x_{1q(g)} \to x'_{1q(g)} = x_{1q(g)} + \Delta x_{1q(g)}$, with $\Delta x_F = \epsilon_{c\bar{c}}/E_p$ and $\Delta x_{1q(g)} = \epsilon_{q(g)}/E_p$. Based on this momentum fraction rescaling, the differential cross section of J/ production $d\sigma/dx_F$ in p-A collisions (shown in Equation (1)) can be modified by energy loss effects in cold nuclear matter.

Results and Discussion

To investigate J/ suppression from p-A collisions due to energy loss effects in cold nuclear matter, we perform calculations of cross-sectional ratios modified by: (i) EPPS21 nPDFs [5] (abbreviated as "EPPS21"), (ii) the $c\bar{c}$ FCEL effect together with EPPS21 nPDFs (abbreviated as "$\Delta E_{\mathrm{FCEL}} + \mathrm{EPPS21}$"), and (iii) the $c\bar{c}$ FCEL effect together with incident quark (gluon) energy loss effects and EPPS21 nPDFs (abbreviated as "$\Delta E_{\mathrm{FCEL}} + \Delta E_{\mathrm{LPM}} + \mathrm{EPPS21}$").

Based on the calculation schemes for the $c\bar{c}$ FCEL effect and incident quark (gluon) LPM energy loss effect discussed in Section II, we perform a leading-order phenomenological analysis of J/ production cross-section ratios. Using the CERN subroutine MINUIT [35], the transport coefficient in cold nuclear matter is extracted ($\hat{q} = 0.024 \pm 0.002$ GeV^2/fm), and the resulting χ^2/ndf values from E866 data [24,25], RHIC data [26], and LHC data [22,23] are shown in Table 1 . Notably, the extracted value $\hat{q} = 0.024 \pm 0.002$ GeV^2/fm is smaller than that estimated from various phenomenological studies in Ref. [34] ($\hat{q} = 0.07 \pm 0.02$ GeV^2/fm) and consistent with the value obtained in Ref. [36] ($\hat{q} = 0.024 \pm 0.008$ GeV^2/fm). This discrepancy may arise because calculations of J/ suppression in Ref. [34] do not consider incident quark (gluon) energy loss effects.

From Table 1, the χ^2/ndf values obtained by fitting calculations (modified by EPPS21 nPDFs [5], $c\bar{c}$ FCEL effect with EPPS21 nPDFs, and $c\bar{c}$ FCEL effect with incident parton energy loss and EPPS21 nPDFs) to E866 data at 40 GeV and $0.20 < x_F < 0.65$ are 21.50, 0.47, and 0.43, respectively. This indicates that the $c\bar{c}$ FCEL effect in the final state plays an important role in J/ suppression for the E866 experiment at $\sqrt{s} = 40$ GeV and $0.20 < x_F < 0.65$. The corresponding χ^2/ndf values from RHIC data are 2.13, 2.03, and 1.40, indicating that corrections from EPPS21 nPDFs nuclear effects play an important role in J/ suppression at $\sqrt{s} = 200$ GeV and $-2.05 < y < 2.35$, LPM energy loss of the incident parton also has some influence, and the $c\bar{c}$ FCEL effect has little influence.

Additionally, the corresponding χ^2/ndf values from LHC data are 1.49, 1.97, and 1.83, indicating that corrections from EPPS21 nPDFs are in good agreement with LHC data at $\sqrt{s} = 5.0$ TeV and $-4.36 < y < 3.40$, while energy loss from the produced $c\bar{c}$ and incident quark (gluon) have little influence on J/ production. It is worth mentioning that, compared to other nPDF sets, EPPS21 includes more data from proton-lead collisions at LHC and LHCb experiments at 5 TeV and 8 TeV, leading to significantly better-constrained gluon distributions at small and intermediate momentum fraction x. Therefore, calculations using only EPPS21 nPDFs agree well with LHC data and provide better fits to RHIC data where nuclear effects on gluon distributions are more obvious. Nevertheless, corrections from EPPS21 nPDFs may overestimate nPDFs nuclear effects for RHIC and LHC data, which can reduce the influence of energy loss effects from the produced $c\bar{c}$ and incident parton.

To directly display the quantitative role of corrections from nuclear effects on parton distribution functions, the $c\bar{c}$ FCEL effect in the final state, and incident quark (gluon) LPM energy loss effects, Figures 1-3 show cross-sectional ratios calculated with EPPS21 nPDFs [5] (dotted lines), EPPS16 nPDFs [37] (dash-dotted lines), $c\bar{c}$ FCEL effect with EPPS21 (dashed lines), and $c\bar{c}$ FCEL effect with incident parton LPM energy loss and EPPS21 (solid lines).

[Figure 1: see original paper] shows that for the E866 experiment ($\sqrt{s} = 40$ GeV, $0.20 < x_F < 0.65$) [24,25], the $c\bar{c}$ FCEL effect on J/ suppression is significant and becomes more apparent with increasing x_F and target mass. Corrections from nuclear effects on parton distribution functions are relatively obvious, and incident quark (gluon) LPM energy loss also has a certain impact on J/ suppression. Additionally, results obtained using only EPPS16 nPDFs show a more significant role in J/ production depletion than those using only EPPS21 nPDFs. This occurs because EPPS16 includes more E866 data to constrain nPDFs correction parameters, which may lead to overestimation of nuclear effects on parton distribution functions in J/ production. Using EPPS21 nPDFs, J/ production cross-section ratios modified by $c\bar{c}$ FCEL effects together with incident parton LPM energy loss show the best agreement with E866 experimental data ($\sqrt{s} = 40$ GeV, $0.20 < x_F < 0.65$).

For RHIC experimental data ($\sqrt{s} = 200$ GeV, $-2.05 < y < 2.35$) [26], [Figure 2: see original paper] shows that in the region $-1.5 < y < 1.5$, the $c\bar{c}$ FCEL effect on J/ suppression is more obvious, while in the region $y < -0.5$, incident parton LPM energy loss plays a more important role. This indicates that both $c\bar{c}$ FCEL and incident parton LPM energy loss effects should be considered concurrently when investigating the quantitative role of nuclear corrections on J/ suppression in cold nuclear matter. This is evident from theoretical results combining $c\bar{c}$ FCEL effects, incident parton LPM energy loss, and EPPS21 nPDFs showing better consistency with RHIC data. Additionally, in regions $y < -0.4$ or $y > 0$, results modified only by EPPS21 nPDFs show more significant J/ production depletion than those modified only by EPPS16 nPDFs. This reflects that EPPS21 provides better-constrained gluon distributions at small y than EPPS16 due to including more LHC and LHCb experimental data, though it may overestimate nPDFs nuclear effects at larger y regions from including D-meson production data to constrain EPPS21 correction parameters.

For LHC experimental data ($\sqrt{s} = 5.0$ TeV, $-4.36 < y < 3.40$) [22,23], [Figure 3: see original paper] displays that nuclear modification on J/ production from parton distribution function effects is most important, and theoretical results using only EPPS21 nPDFs provide the best agreement with LHC data. Nuclear modification from $c\bar{c}$ FCEL effects or incident parton LPM energy loss has little influence on J/ production. [Figure 3: see original paper] also shows that results modified only by EPPS21 nPDFs give more significant J/ production depletion than those modified only by EPPS16 nPDFs in larger y regions. This may indicate that EPPS21 overestimates nuclear modification on J/ production at LHC induced by parton distribution function effects, by including more LHC, LHCb, and D-meson production data to constrain correction parameters.

Summary

Using E866 [24,25], RHIC [26], and LHC experimental data [22,23], we investigate J/ suppression induced by $c\bar{c}$ FCEL effects and incident parton LPM energy loss effects in p-A collisions while simultaneously considering nPDF nuclear effects. A leading-order phenomenological analysis of J/ production cross-section ratios is performed using the CERN subroutine MINUIT [35], and the transport coefficient in cold nuclear matter is extracted ($\hat{q} = 0.024 \pm 0.002$ GeV^2/fm) from E866 data ($\sqrt{s} = 40$ GeV, $0.20 < x_F < 0.65$), RHIC data ($\sqrt{s} = 200$ GeV, $-2.05 < y < 2.35$), and LHC data ($\sqrt{s} = 5.0$ TeV, $-4.36 < y < 3.40$).

For E866 data ($\sqrt{s} = 40$ GeV, $0.20 < x_F < 0.65$), the $c\bar{c}$ FCEL effect in the final state plays an important role in J/ suppression, and using EPPS21 nPDFs, J/ production cross-section ratios modified by $c\bar{c}$ FCEL effects together with incident parton LPM energy loss show the best agreement with E866 experimental data ($\chi^2/\text{ndf} = 0.43$). For RHIC data ($\sqrt{s} = 200$ GeV, $-2.05 < y < 2.35$) and LHC data ($\sqrt{s} = 5.0$ TeV, $-4.36 < y < 3.40$), energy loss from the produced $c\bar{c}$ and incident parton still plays a certain role in J/ suppression, while corrections from nPDFs become more important. This may be induced by EPPS21 using more LHC (LHCb) and D-meson production data to constrain correction parameters, potentially overestimating nPDFs nuclear effects on J/ production at large center-of-mass energies. It is sensible that future operation of better-constrained nPDFs from more precise measurements at LHC or RHIC can significantly facilitate understanding and calculating energy loss effects in cold nuclear matter.

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