The dependence of J/ψ-nucleon inelastic cross section on the Feynman variable*

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Abstract: By means of two typical sets of nuclear parton distribution functions, meanwhile taking account of the energy loss of the beam proton and the nuclear absorption of the charmonium states traversing the nuclear matter in the uniform framework of the Glauber model, a leading order phenomenological analysis is given in the color evaporation model of the E866 experimental data on J/ψ production differential cross section ratios $R_{\rm Fe/Be}(x_{\rm F})$. It is shown that the energy loss effect of beam proton on $R_{\rm Fe/Be}(x_{\rm F})$ is more important than the nuclear effects on parton distribution functions in the high Feynman variable $x_{\rm F}$ region. It is found that the J/ψ-nucleon inelastic cross section depends on the Feynman variable $x_{\rm F}$ and increases linearly with $x_{\rm F}$ in the region $x_{\rm F} > 0.2$.

Key words: J/ψ production, nuclear effect, energy loss, nuclear absorption

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1 Introduction

The dissociation of J/ψ due to color-screening [1] in a Quark-Gluon Plasma (QGP) created in high-energy heavy-ion collisions is a reliable signature of deconfinement of the fundamental theory of Quantum Chromodynamics (QCD). The interpretation of J/ψ modification by the medium created in heavy-ion collisions requires an understanding of the different nuclear effects on J/ψ production. Therefore, it is necessary to establish a good baseline by means of the study on J/ψ production in proton-nucleus collisions for clarifying the different nuclear effects on J/ψ suppression.

The nuclear effects on J/ψ production in proton-nucleus collisions include usually not only the nuclear effects on parton distribution functions and initial state energy loss effect, but also the final state nuclear absorption effect of the charm quark pair traversing the nuclear matter. As for the nuclear effects on parton distribution functions, the nuclear parton distribution functions [2, 3] have been obtained by the global analysis method analogous to those of the free proton. Although the nuclear Drell-Yan process is a good tool for studying the initial state energy loss effect, the nuclear Drell-Yan process is only sensitive to the quark energy loss at parton level [4–6]. In J/ψ production in proton-nucleus collisions, the charm quark pair is predominantly due to gluon fusion. However, the gluon energy loss can not yet be constrained by means of the relative experimental data. In our previous article [7], the energy loss of the beam proton in a nuclear environment was determined well at hadron level in the framework of the Glauber model [8] by using the nuclear parton distribution functions from the global analysis and fitting the nuclear Drell-Yan data from the Fermilab E866 experiment [9] for 800 GeV protons incident on a variety of nuclear targets.

In this paper, by means of two typical sets of nuclear parton distribution functions, meanwhile taking account of the energy loss of the beam proton in initial state and the final state nuclear absorption effect of the charmonium states in the uniform framework

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of the Glauber model, a leading order phenomenological analysis in the color evaporation model [10] is performed of the E866 experimental data on J/ψ production differential cross section ratios $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ [11]. The J/ψ suppression is studied quantitatively due to the different nuclear effects in proton-nucleus collisions. It is hoped to have a new knowledge about the final state nuclear absorption effect on J/ψ production in proton-nucleus collisions.

2 Brief formalism for a differential cross section on J/ψ production in proton-nucleus collisions

As for J/ψ production in proton-nucleus collisions, the leading-order contribution results from the gluon fusion (gg) and quark-anti-quark annihilation ($\mathrm{q\bar{q}}$) processes. The differential cross section on J/ψ production is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{F}}} = \rho_{\mathrm{J}/\psi}\int_{2m_{\mathrm{c}}}^{2m_{\mathrm{D}}}\mathrm{d}m\frac{2m}{\sqrt{x_{\mathrm{F}}^2 s+4m^2}}\Bigg[f_{\mathrm{g}}^{\mathrm{p}}(x_1,m^2)f_{\mathrm{g}}^{\mathrm{A}}(x_2,m^2)\sigma_{\mathrm{gg}}(m^2) + \sum_{\mathrm{q=u,d,s}}\Big\{f_{\mathrm{q}}^{\mathrm{p}}(x_1,m^2)f_{\mathrm{\bar{q}}}^{\mathrm{A}}(x_2,m^2)+f_{\mathrm{\bar{q}}}^{\mathrm{p}}(x_1,m^2)f_{\mathrm{q}}^{\mathrm{A}}(x_2,m^2)\Big\}\sigma_{\mathrm{q\bar{q}}}(m^2)\Bigg], \tag{1}$$

where x_1 (x_2) is the momentum fraction of the parton in the beam proton (target nucleon), x_{F} is the Feynman variable, $\sqrt{s}$ 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. σ_{gg} ($\sigma_{\mathrm{q\bar{q}}}$) is the leading-order $\mathrm{c\bar{c}}$ partonic production cross section from the gluon fusion (quark-antiquark annihilation). $\rho_{\mathrm{J}/\psi}$ is the fraction of $\mathrm{c\bar{c}}$ pair which produces the J/ψ state, $f_i^{\mathrm{p}}(x,m^2)$ ($f_i^{\mathrm{A}}(x,m^2)$) is the parton distribution function in the proton (nucleon in the nucleus).

The energy loss of beam proton can induce the decrease of center of mass energy of the nucleon-nucleon collision producing $\mathrm{c\bar{c}}$ when the projectile proton moves through the target nuclei. After the projectile proton has n collisions with nucleons in nuclei, it can be supposed for convenient calculation that the center-of-mass system energy of the nucleon-nucleon collision is

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

where $\Delta\sqrt{s}$ is the center-of-mass system energy loss per collision (see Ref. [7] for more detailed discussion). The probability $P(n)$ of having n collisions in nucleus (A) has been given in the Glauber model [8].

$$P(n)=\frac{\int\mathrm{d}\vec{b}P(n,\vec{b})}{\sum\limits_{n=1}^{A}\int\mathrm{d}\vec{b}P(n,\vec{b})}, \tag{3}$$

where

$$P(n,\vec{b})=\frac{A!}{n!(A-n)!}[T(\vec{b})\sigma_{\mathrm{in}}]^n[1-T(\vec{b})\sigma_{\mathrm{in}}]^{A-n}, \tag{4}$$

σ_{in} ($\sim$ 30 mb) is the non-diffractive cross section for inelastic nucleon-nucleon collision and $T(\vec{b})$ is the thickness function of impact parameter $\vec{b}$. Therefore, the J/ψ production cross section in the nth collision can be rewritten as

$$\frac{\mathrm{d}\sigma^{(n)}}{\mathrm{d}x_{\mathrm{F}}}=\frac{\mathrm{d}\sigma}{\mathrm{d}x'_{\mathrm{F}}}, \tag{5}$$

where the rescaled Feynman variable

$$x'_{\mathrm{F}}=r_{\mathrm{s}}x_{\mathrm{F}}, \tag{6}$$

with the centre-of-mass system energy ratio

$$r_{\mathrm{s}}=\frac{\sqrt{s}}{\sqrt{s'}}. \tag{7}$$

After the partonic hard scattering, the pre-meson charm quark pair travels through the target nucleus. The strong interaction between the pre-meson and the nuclear matter reduces the probability that the pre-meson state forms a J/ψ without being absorbed. In the framework of the Glauber model, the J/ψ survival probability [12] can be calculated as

$$S_{\mathrm{abs}}=\frac{1}{(A-1)\sigma_{\mathrm{abs}}^{\mathrm{J}/\psi}}\int\mathrm{d}\vec{b}(1-\mathrm{e}^{-(A-1)T(\vec{b})\sigma_{\mathrm{abs}}^{\mathrm{J}/\psi}}), \tag{8}$$

where $\sigma_{\mathrm{abs}}^{\mathrm{J}/\psi}$ is the J/ψ-nucleon inelastic cross section. If the factorization between the $\mathrm{c\bar{c}}$ production process and the subsequent possible J/ψ inelastic interaction with nuclear matter is assumed, the J/ψ production cross section in the nth collision is written as

$$\frac{\mathrm{d}\sigma^{(n)}}{\mathrm{d}x_{\mathrm{F}}}=\frac{\mathrm{d}\sigma}{\mathrm{d}x'_{\mathrm{F}}}S_{\mathrm{abs}}. \tag{9}$$

By combining the nuclear effects on parton distribution functions and the initial state energy loss effect with the final state nuclear absorption effect, the differential cross section on J/ψ production in proton-nucleus collisions can be expressed as

$$\left\langle\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{F}}}\right\rangle=\sum_{n=1}^{A}P(n)\frac{\mathrm{d}\sigma^{(n)}}{\mathrm{d}x_{\mathrm{F}}}. \tag{10}$$

The differential cross section ratio of two different nuclear targets bombarded by proton is

$$R_{\mathrm{A1/A2}}(x_{\mathrm{F}})=\left\langle\frac{\mathrm{d}\sigma^{\mathrm{p\text{-}A1}}}{\mathrm{d}x_{\mathrm{F}}}\right\rangle\Bigg/\left\langle\frac{\mathrm{d}\sigma^{\mathrm{p\text{-}A2}}}{\mathrm{d}x_{\mathrm{F}}}\right\rangle. \tag{11}$$

3 Results and discussion

The Fermilab Experiment 866 (E866) [11] reported the differential cross section ratios $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ on J/ψ production of 800 GeV proton induced iron and beryllium target. The covered kinematical range was $0.2 < x_{\mathrm{F}} < 0.95$. The experimental data were provided in intermediate x_{F} ($0.2 < x_{\mathrm{F}} < 0.65$) and large x_{F} ($0.3 < x_{\mathrm{F}} < 0.95$), respectively. In order to clarify the conventional nuclear effects on J/ψ production in proton-nucleus collisions, the differential cross section ratio $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ at leading order is calculated in the color evaporation model and compared with the E866 experimental data. In the calculation, we use HKM [2] and EPS [3] nuclear parton distribution functions together with CTEQ6L parton density in the proton [13]. The center-of-mass system energy loss per collision $\Delta\sqrt{s}$ is from our fitting the nuclear Drell-Yan experimental data in the Glauber model [7]. The J/ψ-nucleon inelastic cross section $\sigma_{\mathrm{abs}}^{\mathrm{J}/\psi}$ is determined in the J/ψ survival probability formula.

In order to investigate the nuclear effects on parton distribution functions, by means of HKM and EPS nuclear parton distribution functions, the differential cross section ratios $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ are calculated and compared with the E866 experimental data [4] in Fig. 1. The solid and dotted lines are the theoretical results on $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ from EPS and HKM parameterizations, respectively. It can be seen that in the region $0.2 < x_{\mathrm{F}} < 0.95$, the nuclear suppression from the nuclear effects on parton distribution functions is approximately 1% to 5% and 4% to 12% for HKM and EPS parameterizations, respectively. The difference of the calculated $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ between the two typical sets of nuclear parton distribution functions results from that HKM nuclear parton distributions were determined only by means of the existing experimental data on nuclear structure functions without including the proton-nucleus Drell-Yan process, however, the EPS parameterizations employed additionally the proton-nucleus Drell-Yan experimental data without considering the energy loss effect in this process. Therefore, the EPS parameterizations could overestimate the nuclear effects on the parton distribution functions.

In Fig. 2 we show the comparison of the experimental data with the calculated $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ by using the HKM and EPS nuclear parton distributions together with the energy loss of the beam proton. It is found that the nuclear suppression on $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ from the energy loss effect increases gradually in the region $0.2 \leqslant x_{\mathrm{F}} \leqslant 0.8$ and becomes much steeper in the region $x_{\mathrm{F}} > 0.8$. As for the HKM and EPS nuclear parton distributions, the total suppression from the nuclear effects on the parton distribution functions and energy loss effect is approximately 3% to 31% and 7% to 38% in the range $0.2 \leqslant x_{\mathrm{F}} \leqslant 0.95$, respectively. It is apparent that the energy loss effect on $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ becomes larger with the increase of x_{F}, especially in the high x_{F} region. Therefore, the energy loss effect, resulting in the suppression on $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$,

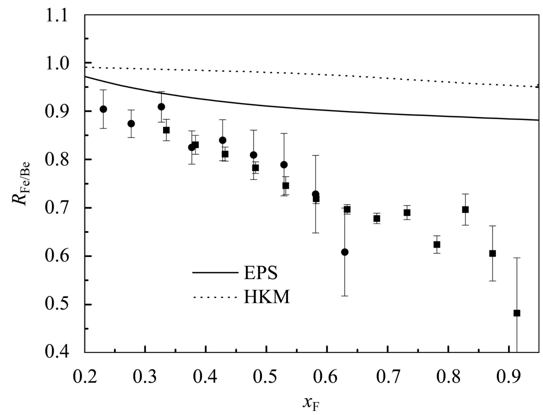

Fig. 1. The J/ψ production cross section ratio $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$. The solid circles (filled boxes) are the E866 experimental data [11] in the region $0.2 < x_{\mathrm{F}} < 0.65$ ($0.3 < x_{\mathrm{F}} < 0.95$). With considering only the nuclear effects on the parton distribution functions, the solid and dotted lines correspond to the theoretical results from the EPS and HKM parameterizations, respectively.

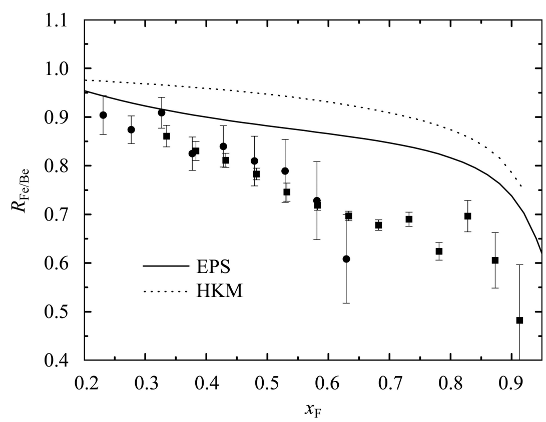

Fig. 2. The ratio $R_{\mathrm{Fe/Be}}(x_{\mathrm{F}})$ by combining the nuclear effects on the parton distributions with the energy loss effect of the beam proton. The comments are the same as Fig. 1.

is more important than the nuclear effects on parton distributions in high x_F region. It is shown that the theoretical results on $R_{Fe/Be}(x_F)$ deviate also from the E866 experimental data. The remain deviation from the experimental data needs to be contributed by the final state nuclear absorption effect.

Based on the nuclear effects on the parton distribution functions and the energy loss of the beam proton, we add further the nuclear absorption effect in the final state. It is found that if the J/ψ-nucleon inelastic cross section $\sigma_{abs}^{J/\psi}$ is fixed as an absolute constant, our theoretical results on $R_{Fe/Be}(x_F)$ are not in agreement with the experimental data. The Fermilab Experiment 866 presented also the results in terms of α from $R_{Fe/Be}(x_F)$, where α is obtained by assuming the cross section dependence on nuclear mass, A, to be of the form $\sigma_A = \sigma_N \times A^{\alpha}$, where σ_N is the cross section on a nucleon. By using the experimental data on α versus x_F, the J/ψ-nucleon inelastic cross section $\sigma_{abs}^{J/\psi}$ is obtained as a function of x_F. Our theoretical results are shown in Fig. 3. The solid circles and empty boxes correspond to the values of $\sigma_{abs}^{J/\psi}$ based on two typical sets of nuclear parton distribution functions. It can be seen that the value of $\sigma_{abs}^{J/\psi}$ becomes larger with the increase of x_F in the region $x_F > 0.2$ if the two values are excluded with deviation from the tendency in the range $x_F > 0.7$. Therefore, It can be concluded that the J/ψ-nucleon inelastic cross section $\sigma_{abs}^{J/\psi}$ depends on the Feynman variable x_F and increases linearly with x_F in the region $x_F > 0.2$.

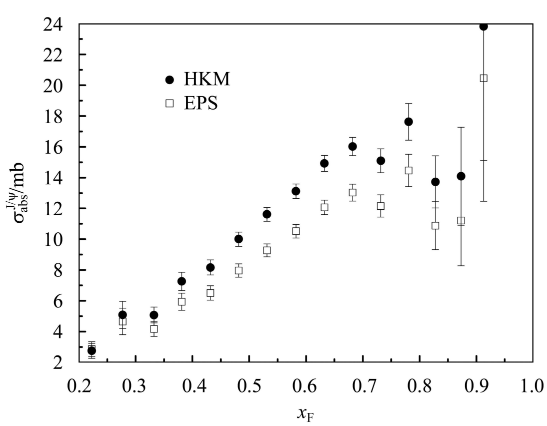

Fig. 3. The J/ψ-nucleon inelastic cross section $\sigma_{abs}^{J/\psi}$ as a function of x_F by means of HKM (solid circles) and EPS (empty boxes) nuclear parton distribution functions, repectively.

4 Summary and concluding remarks

In summary, the robust interpretation of J/ψ production in heavy ion collisions requires a deep and quantitative understanding of the basic mechanisms responsible for the suppression of J/ψ production due to the nuclear effects. The good baseline is hoped to be establish by means of the study on J/ψ production in proton-nucleus collisions to clarify the conventional nuclear suppression mechanism. A leading order phenomenological analysis is performed in the color evaporation model of the E866 experimental data on J/ψ production differential cross section ratios $R_{Fe/Be}(x_F)$. By using two typical sets of nuclear parton distribution functions, meanwhile taking account of the energy loss of the beam proton and the nuclear absorption effect in the uniform framework of the Glauber model, the J/ψ suppression is investigated quantitatively due to the different nuclear effects in proton-nucleus collisions. It is found that the energy loss effect of beam proton on $R_{Fe/Be}(x_F)$ is more important than the nuclear effects on the parton distribution functions in the high Feynman variable x_F region. The J/ψ-nucleon inelastic cross section depends on the Feynman variable x_F and increases linearly with x_F in the region $x_F > 0.2$.

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