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Initial-State Nuclear Effects in High Energy p-A Drell-Yan Process*

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Abstract Nuclear shadowing and energy loss effects are two important initial-state nuclear effects in hadron-nucleus collisions. In this paper, by means of the nuclear parton distributions extracted only from lepton deep-inelastic scattering experimental data, the energy loss effect in Drell-Yan dimuon production process is studied in the color string model. By a χ^2 analysis of the experimental data given by FNAL E772 and E866, we found the rate of quark energy loss per unit path length: $-\mathrm{d}E/\mathrm{d}z = 2.06\mathrm{GeV/fm}$, which is almost the same as the result expected by the model $-\mathrm{d}E/\mathrm{d}z \approx 2\mathrm{GeV/fm}$. The calculated results are compared with the E772 and E866 data. It is shown that the theoretical results considered the energy loss effect are in good agreement with the experimental data.

Key words color string model, energy loss, Drell-Yan

1 Introduction

Measurements of the nuclear structure functions in deep inelastic scattering (DIS) indicate clearly that the parton distributions of bound nucleons are different from those of free nucleons[1]. At low parton momentum fractions, $x < 0.05$, the ratio of the nuclear parton density relative to the nucleon is less than unity (the shadowing region). In the intermediate x regime, $x \sim 0.15$, this ratio is larger than unity (antishadowing) while at higher x it drops below unity once more (the EMC region). The effect also depends on the scale of the interaction, the square of the momentum transfer, M^2. As the collisions energy increases, the values of x probed in the collision are decreased, making shadowing more important. Since shadowing affects the parton distribution functions before the collision that produces the dimuon in the p-A Drell-Yan process[2], it is an initial state nuclear effect.

The initial state energy loss effect in nuclear matter, which can be measured best by high energy nuclear Drell-Yan process, is another initial state nuclear effect apart from the nuclear shadowing effect. Since they are similar in many respects, it is very important to disentangle between the effects of shadowing and energy loss.

In 1999, Eskola, Kolhinen, and Salgado (EKS)[3] suggested a set of nuclear parton distributions which were studied within the framework of the DGLAP(Dokshitzer-Gribov-Lipatov-Altarelli-Parisi) evolution. The E772 Drell-Yan data, which are subject to corrections for energy loss, were included in EKS shadowing parameter. Thus the EKS “shadowing” already includes corrections for energy loss. In 2001, Hirai, Kumano, and Miyama(HKM)[4] proposed

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nuclear parton distributions, which were obtained by a χ^2 global analysis of experimental data on nuclear structure functions without including the proton-nucleus Drell-Yan process. In our present analysis we use the HKM nuclear shadowing parametrization.

Having studied the energy loss effect in the Glauber model[5, 6], which describes this phenomena as the hadron projectile suffering multiple collisions and repeating energy loss in the nucleus, we will employ the color string model[7]. According to the model, the hadron is retarded by the color string with tension k after an inelastic collision. Due to the constant retarding action of the string, the leading projectile quark will lose energy. In addition, the leading quark, which propagates through the nucleus, may also radiate gluon and consequently lose energy. In this paper, by means of the HKM nuclear parton distributions, the energy loss effect in the Drell-Yan process is analyzed within the color string model. By a χ^2 analysis of the experimental data given by Fermi National Accelerator Laboratory (FNAL) E772[8] and E866[9], the rate of quark energy loss per unit path length is given. Finally, the calculated results are compared with the experimental data.

2 Method

In the Drell-Yan process, the leading-order contribution comes from the annihilation of the quark and antiquark into a lepton pair, $\mathrm{q\bar{q}} \to \gamma^* \to \mathrm{l^+l^-}$. The partonic cross section for Drell-Yan dimuon production is

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}M} = \frac{8\pi\alpha^2}{9M} e_{\mathrm{f}}^2 \delta(\hat{s} - M^2), \tag{1}$$

where α is the fine structure constant, e_{f} is the fractional quark charge of flavor f and $\hat{s} = x_1 x_2 s$ is the energy of the center of mass (CM) of a $\mathrm{q\bar{q}}$ collision. Then the differential cross section of the hadronic Drell-Yan process can be obtained from the above-mentioned cross section of the partonic process with the quark distributions in both the beam and target particles. In order to obtain the x_1 dependence differential cross section, the variable M should be integrated.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_1} = K\frac{8\pi\alpha^2}{9x_1 s}\sum_{\mathrm{f}}\int\frac{\mathrm{d}M}{M} e_{\mathrm{f}}^2 \big[q_{\mathrm{f}}^{\mathrm{p}}(x_1, M^2)\bar{q}_{\mathrm{f}}^{\mathrm{A}}(x_2, M^2) + \bar{q}_{\mathrm{f}}^{\mathrm{p}}(x_1, M^2) q_{\mathrm{f}}^{\mathrm{A}}(x_2, M^2)\big], \tag{2}$$

where K is the high-order Quantum Chromodynamics (QCD) correction, the sum runs over the light flavor f=u, d, s and $q(\bar{q})_{\mathrm{f}}^{\mathrm{p(A)}}(x)$ represents the quark (anti-quark) distribution in the proton(nucleus), and the integral range of M is determined according to the E772 and E866 experimental kinematic region.

Now let us take into account the initial state energy loss effect. According to the color string model, there are two cases for the dimuon production in the Drell-Yan process. As shown at the bottom in Fig. 1, the first is that the dimuon pair may be produced in the first inelastic interaction without energy loss effect. The second, which is illustrated at the top in Fig. 1, is that the beam hadron may experience its first soft inelastic interaction at the point z_1. Then the leading projectile quark in the debris of the beam hadron, being retarded by the color string with tension k, reach the point z where the dimuon pair is produced. On the one hand, due to the constant retarding action of the string, the leading projectile quark loses energy with a constant rate per unit length. On the other hand, gluon radiation originating in the first inelastic interaction[10] and gluon radiation by multiple interactions of the quark in the medium[11] can also induce energy loss. So the energy E of the projectile hadron in the second case will decrease by $\Delta E = -\mathrm{d}E/\mathrm{d}z \Delta z$ with $\Delta z = z - z_1$. Thus the lepton pair production cross section in the Drell-Yan process can be written as[7]

$$\begin{aligned}\left\langle\frac{\mathrm{d}\sigma}{\mathrm{d}x_1}\right\rangle = {} & \frac{1}{A}\int\mathrm{d}^2\boldsymbol{b}\int_{-\infty}^{\infty}\mathrm{d}z\rho(\boldsymbol{b}, z)\times \\ & \exp\left[-\sigma_{\mathrm{in}}\int_{-\infty}^{z}\mathrm{d}z_1\rho(\boldsymbol{b}, z_1)\right]\times \\ & \left\{\frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}x_1}[1-\delta(\boldsymbol{b}, z)]/2 + \frac{\mathrm{d}\sigma_{\mathrm{pn}}}{\mathrm{d}x_1}[1+\delta(\boldsymbol{b}, z)]/2\right\} + \\ & \frac{1}{A}\int\mathrm{d}^2\boldsymbol{b}\int_{-\infty}^{\infty}\mathrm{d}z\rho(\boldsymbol{b}, z)\int_{-\infty}^{z}\mathrm{d}z_1\sigma_{\mathrm{in}}\rho(\boldsymbol{b}, z_1)\times \\ & \exp\left[-\sigma_{\mathrm{in}}\int_{-\infty}^{z_1}\mathrm{d}z_2\rho(\boldsymbol{b}, z_2)\right]\times \\ & \left\{\frac{\mathrm{d}\sigma'_{\mathrm{pp}}}{\mathrm{d}x_1}[1-\delta(\boldsymbol{b}, z)]/2 + \frac{\mathrm{d}\sigma'_{\mathrm{pn}}}{\mathrm{d}x_1}[1+\delta(\boldsymbol{b}, z)]/2\right\},\end{aligned} \tag{3}$$

where the first term corresponds to the first case for the dimuon pair production, and the exponential factor in the second term, which corresponds to the second case, requires that there isn't inelastic interaction of the beam hadron prior to the point z_1.

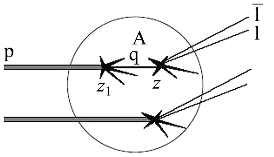

Fig. 1. The space-time pattern for Drell-Yan dimuon pair production off a nucleus. The lower example illustrates a case where the dimuon pair is produced in the first inelastic interaction without energy loss effect, and the upper one illustrates a case when the beam hadron experiences a soft inelastic interaction prior to the hard interaction in which the $l\bar{l}$ is produced.

In Eq. (3), $\rho(\boldsymbol{b}, z)$ is the nucleon density in the nucleus, depending on the impact parameter $\boldsymbol{b}$ and the longitudinal coordinate z, and $\sigma_{\rm in}(\sim 30{\rm mb})$ is the nucleon-nucleon inelastic cross section. $\delta(\boldsymbol{b}, z)$ is the relative difference of the neutron and proton densities so that $\delta(b,z)=(\rho_{\rm n}-\rho_{\rm p})/\rho=1-2\rho_{\rm p}/\rho$. If ρ and $\rho_{\rm p}$ are taken the same form given in Ref. [12], $\delta(b,z)$ will be equal to $1-2Z/A$. Thus the lepton pair production cross section in the Drell-Yan process can be rewritten as

$$\begin{aligned}\left\langle\frac{{\rm d}\sigma}{{\rm d}x_1}\right\rangle = & \frac{1}{A}\int {\rm d}^2\boldsymbol{b}\int_{-\infty}^{\infty}{\rm d}z\rho(\boldsymbol{b},z)\times \\ & \exp\left[-\sigma_{\rm in}\int_{-\infty}^{z}{\rm d}z_1\rho(\boldsymbol{b},z_1)\right]\frac{{\rm d}\sigma}{{\rm d}x_1}+ \\ & \frac{1}{A}\int {\rm d}^2\boldsymbol{b}\int_{-\infty}^{\infty}{\rm d}z\rho(\boldsymbol{b},z)\int_{-\infty}^{z}{\rm d}z_1\sigma_{\rm in}\rho(\boldsymbol{b},z_1)\times \\ & \exp\left[-\sigma_{\rm in}\int_{-\infty}^{z_1}{\rm d}z_2\rho(\boldsymbol{b},z_2)\right]\frac{{\rm d}\sigma'}{{\rm d}x_1}, \end{aligned}\tag{4}$$

where $\frac{{\rm d}\sigma}{{\rm d}x_1}$ in the first term is given by Eq. (2) and $\frac{{\rm d}\sigma'}{{\rm d}x_1}$ in the second term should be rewritten as

$$\begin{aligned}\frac{{\rm d}\sigma'}{{\rm d}x_1} = & K\frac{8\pi\alpha^2}{9x_1's}\sum_{\rm f}\int\frac{{\rm d}M}{M}e_{\rm f}^2\left[q_{\rm f}^{\rm p}(x_1',M^2)\bar{q}_{\rm f}^{\rm A}(x_2,M^2)+\right. \\ & \left.\bar{q}_{\rm f}^{\rm p}(x_1',M^2)q_{\rm f}^{\rm A}(x_2,M^2)\right], \end{aligned}\tag{5}$$

with the re-scaled quantity $x_1' = x_1+\Delta x_1 = x_1 + (-{\rm d}E/{\rm d}z)\Delta z/E$.

In order to compare with the experimental data from the E772[8] and E866[9] collaboration, we introduce the nuclear Drell-Yan ratios:

$$R_{A_1/A_2}(x_1)=\frac{\left\langle\dfrac{{\rm d}\sigma^{{\rm p}\text{-}A_1}}{{\rm d}x_1}\right\rangle}{\left\langle\dfrac{{\rm d}\sigma^{{\rm p}\text{-}A_2}}{{\rm d}x_1}\right\rangle}.\tag{6}$$

In our theoretical analysis, χ^2 is calculated with the Drell-Yan differential cross section ratios R_{A_1/A_2} as

$$\chi^2=\sum_j\frac{\left(R_{A_1/A_2,j}^{\rm data}-R_{A_1/A_2,j}^{\rm theo}\right)^2}{\left(R_{A_1/A_2,j}^{\rm err}\right)^2},\tag{7}$$

where $R_{A_1/A_2,j}^{\rm data}(R_{A_1/A_2,j}^{\rm theo})$ indicates the experimental data (theoretical values) for the ratio R_{A_1/A_2}, and $R_{A_1/A_2,j}^{\rm err}$ denotes the systematic errors in the experiment.

3 Results and discussion

By employing the HKM for nuclear parton distribution functions together with Martin, Roberts, Stirling, and Thorne(MRST)[13] parton distribution functions in a proton, we have adjusted $-{\rm d}E/{\rm d}z$ (free parameter) to fit the entire set of ratios C/D, Ca/D, Fe/D, W/D, Fe/Be and W/Be from E772[8] and E866[9] with Eq. (7). With $\chi^2_{\rm min}/$ (degree of freedom)=1.19, we find the rate of energy loss:

$$-\frac{{\rm d}E}{{\rm d}z}=2.06{\rm GeV/fm}.$$

According to the model, the energy-loss rate $-{\rm d}E/{\rm d}z$, related to the string tension ($k\approx 1{\rm GeV/fm}$)[7] and to gluon radiation[10, 11], has different origins and should be added. The rate of energy loss is expected to be $-{\rm d}E/{\rm d}z \approx 2{\rm GeV/fm}$, which is in good agreement with our result. Furthermore, our result is also almost the same as the value given in Ref. [14] ($-{\rm d}E/{\rm d}z = 2.18\pm0.31{\rm GeV/fm}$) when they try to make mixture of the energy loss and shadowing effects.

The calculated results are shown in Figs. 2 — 4. Fig. 2 shows the ratios of the cross section per nucleon for p-Fe to p-D and the experimental data are from E772[8]. The solid and dashed curves correspond to the results without and with energy loss. Theoretically, being taken account of the energy loss effect, the sea quark in the projectile proton will decrease for $x_1' > x_1$, so the cross section decreases. Fig. 3 and Fig. 4 show the cross section per nucleon for p-Fe to p-Be and p-W to p-Be, respectively. The figure comments for Fig. 3 and Fig. 4 are the same as in Fig. 2 and the experimental data are from E866[9]. From comparison with the experimental data, it is found that our theoretical results considered energy loss effect are in good agreement with the experimental data.

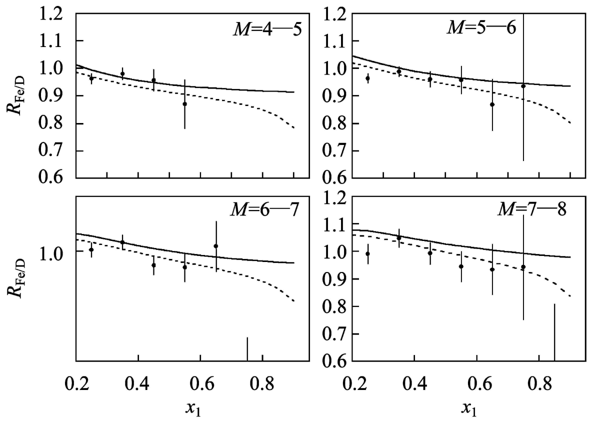

Fig. 2. The nuclear Drell-Yan cross section ratios R_{A_1/A_2} on Fe to D for various M intervals. The solid and dashed curves correspond to the results without and with energy loss, respectively. The experimental data are taken from E772[8].

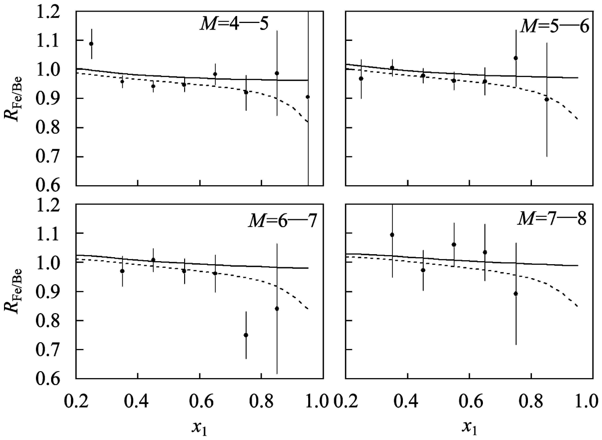

Fig. 3. The nuclear Drell-Yan cross section ratios R_{A_1/A_2} on Fe to Be for various M intervals. The comments are the same as in Fig. 2 and the experimental data are from E866[9].

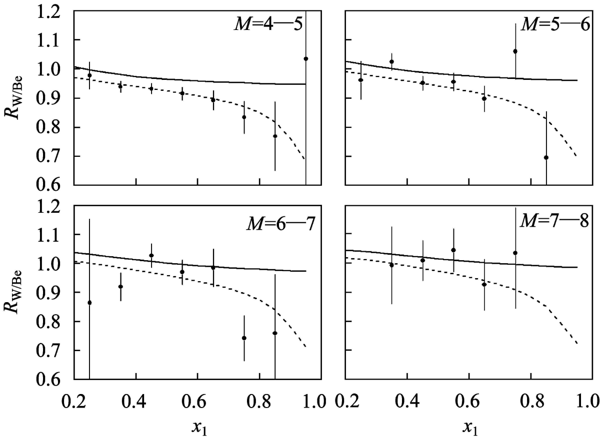

Fig. 4. The nuclear Drell-Yan cross section ratios R_{A_1/A_2} on W to Be for various M intervals. The comments are the same as in Fig. 2 and the experimental data are from E866[9].

In summary, by a χ^2 analysis of the experimental data given by FNAL E772 and E866, the rate of quark energy loss per unit path length is given and the result agrees with the result expected by the color string model. Comparing with the experimental data, it is shown that the theoretical results with energy loss are in good agreement with the experimental data. Although the abundant data of the electron and the muon deep inelastic scattering off nuclei are currently available, the valence quark distributions in the small x region and anti-quark distributions are still difficult to be extracted, and only the valence quark distributions in large x region can relatively be well determined. In order to calculate the cross section of nuclear reactions in high energy accurately and find the signal of quark-gluon plasma in high energy heavy-ion collisions, one must have accurate nuclear parton distributions. In addition, as energy loss effect in the Drell-Yan process being studied in the color string model, it is found that the shadowing effect should also depend on the impact parameter $\boldsymbol{b}$ (inhomogeneous shadowing effect)[15]. Having studied the inhomogeneous shadowing effect in the Glauber model[16], we will study this effect in the color string model in the future.

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高能p-A碰撞Drell-Yan过程中的初态核效应*

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摘要 核遮蔽和能量损失效应是p-A碰撞中两种重要的初态核效应. 本文利用从轻子–原子核深度非弹性散射实验数据中抽取的束缚核子的部分子分布函数, 在色弦模型中研究了Drell-Yan双轻子对产生过程中的能量损失效应. 通过对FNAL E772和E866实验数据的χ^2分析, 得到夸克在冷核中的能量损失率为$-\mathrm{d}E/\mathrm{d}z=2.06\mathrm{GeV/fm}$. 这和该模型理论预言的结果($-\mathrm{d}E/\mathrm{d}z\sim 2\mathrm{GeV/fm}$)一致. 通过将理论计算结果与实验数据进行比较, 发现考虑到能量损失后能很好的解释实验现象.

关键词 色弦模型 能量损失 Drell-Yan过程

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