Cold nuclear matter effects on J/ψ production in d-Au collisions*

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Abstract The medium modifications of J/ψ production in d-Au collisions at $\sqrt{s_{\rm NN}}=200$ GeV are studied in the Glauber model. By means of the c.m. energy loss parameter per collision studied in Drell-Yan process, taking account of the inhomogeneous shadowing effect, we find that the initial-state energy loss effect can be ignored in d-Au collisions at mid-rapidity. Then, the final-state J/ψ absorption effect is also considered and the theoretical results are in good agreement with the recent experimental data given by PHENIX. Finally, the experimental results of J/ψ production in d-Pb collisions are also predicted at RHIC and LHC energies respectively.

Key words inhomogeneous shadowing effect, Glauber Model, J/ψ absorption effect

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1 Introduction

The J/ψ production in cold nuclear matter, which is a leading signal for the creation of hot-dense matter in heavy-ion collisions, is an important topic to be studied. The cold nuclear matter effects include the modification of parton distribution functions, initial-state energy loss, final-state J/ψ absorption, etc. The modification of parton distributions, which have been probed through deep inelastic scattering (DIS) experiment[1], includes shadowing, anti-shadowing and EMC effect. Shadowing is a depletion of partons density in nucleus at small momentum fraction, x, compared with that in a free nucleon. In $\sqrt{s_{\rm NN}}=200$ GeV deuteron-gold (d-Au) collisions at the Relativistic Heavy Ion Collider (RHIC), for positive (deuteron direction) rapidities, gluons are probed that lie well into the shadowing region with momentum fractions in Au, $x_2\approx 3\times10^{-3}$. Since shadowing affects the parton distribution functions before the collision that produce the J/ψ, it is an initial-state effect.

Recently, it is found that shadowing should depend on the spatial position of the interacting parton within the nucleus (inhomogeneous shadowing)[2]. Although DIS experiments are typically insensitive to this position dependence, some spatial inhomogeneity has been observed in νN scattering[3]. Thus the effect should be sensitive to the impact parameter, $\boldsymbol{b}$, at which the collision occurs. Central collisions with low impact parameter should exhibit stronger shadowing effects than collisions in the nuclear periphery[4].

The initial-state energy loss effect in cold nuclear matter, which is another important nuclear effect, is always entangled with the shadowing effect. Thus, a zero energy loss was found in both de-lepton ($l\bar{l}$) and J/ψ production[5]. In 2001, Hirai, Kumano, and Miyama (HKM) proposed two types of nuclear parton distributions without including the proton-nucleus Drell-Yan process[6]. By means of the HKM parameter, the energy loss effect can be disentangled from the shadowing effect and it is found that the rate of energy loss is much larger than that of the former[7, 8]. Recently, there are two kinds of opinion about the energy loss effect in d-Au at RHIC energies. One expects the initial-state energy loss effect should be ignored[9], the other expects it couldn't[10, 11]. In this paper, using the c.m. (center of mass) energy loss

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parameter per collision given by HKM parameter and χ^2 analysis[8], we calculate this effect in the Glauber model[12, 13]. According to the Glauber Model, the projectile nucleon in nucleus B makes many "soft" inelastic collisions with nucleons bound in the nucleus A before making a "hard" collision with the $l\bar{l}$ (or J/ψ) production. During the "soft" collisions the projectile nucleon imparts energy to the struck nucleon and loose energy. In an inelastic collision between nucleus A and B, the probability of having n collisions also depends on the impact parameter $\boldsymbol{b}$, which will make inhomogeneous shadowing more important. In this paper, the inhomogeneous shadowing effect, which can enhance the energy loss effect in Drell-Yan process[4], is also discussed on J/ψ production in d-Au collisions.

Apart from the initial-state shadowing and energy loss effects, the $c\bar{c}$ pair can be dissociated or absorbed in the final state before it can form a J/ψ. The absorption or dissociation can happen on either the nucleus itself, or on light co-moving partons produced when the projectile deuteron enters the nucleus. Since the latter is probably only important in A-A collisions as the number of co-movers created in a p-A or d-A collisions is small, we only consider the nuclear absorbtion effect.

Recently, the new experimental results are presented about the modification of J/ψ production in d-Au collisions relative to that in p-p collisions at $\sqrt{s_{\rm NN}} = 200$ GeV[14]. In this paper, taking account of the cold nuclear effects mentioned above, we calculate the nuclear modification factor, $R_{\rm dAu}$, versus y and the $R_{\rm dAu}$(b) ratios for the same rapidity values versus the number of binary NN collisions, $N_{\rm coll}$(b). Finally, we also predict the results of J/ψ production in d-Pb collisions at RHIC and LHC (Large Hadron Collider) energies respectively.

2 Method

According to the color evaporation model (CEM), charmonium production is treated identically as $c\bar{c}$ production below the $D\bar{D}$ threshold, neglecting color and spin. If the inhomogeneous shadowing effect is considered, the leading order (LO) rapidity distributions of J/ψ's produced in d-Au collisions at the impact parameter $\boldsymbol{b}$ is[9]

$$\frac{{\rm d}\sigma}{{\rm d}y{\rm d}^2\boldsymbol{b}{\rm d}^2\boldsymbol{b}_{\rm B}} = 2F_{{\rm J}/\psi}K_{\rm th}\int {\rm d}z_{\rm A}{\rm d}z_{\rm B}\int_{2m_{\rm c}}^{2m_{\rm D}} M{\rm d}M \times \Big\{F_{\rm g}^{\rm d}(x_1,M^2,\boldsymbol{b}_{\rm B},z_{\rm B})F_{\rm g}^{\rm Au} \times (x_2,M^2,\boldsymbol{b}+\boldsymbol{b}_{\rm B},z_{\rm A})\sigma_{\rm gg}(M^2)/s_{\rm NN} + \sum_{\rm q=u,d,s}\big[F_{\rm q}^{\rm d}(x_1,M^2,\boldsymbol{b}_{\rm B},z_{\rm B})F_{\bar{\rm q}}^{\rm Au}(x_2,M^2,\boldsymbol{b}+\boldsymbol{b}_{\rm B},z_{\rm A}) + F_{\bar{\rm q}}^{\rm d}(x_1,M^2,\boldsymbol{b}_{\rm B},z_{\rm B})F_{\rm q}^{\rm Au}(x_2,M^2,\boldsymbol{b}+\boldsymbol{b}_{\rm B},z_{\rm A})\big] \times \sigma_{{\rm q}\bar{\rm q}(M^2)}/s_{\rm NN}\Big\}, \tag{1}$$

where x_1 and x_2 are the fractions of the nucleon momentum carried by the projectile and target partons respectively, $M^2 = x_1x_2s_{\rm NN}$ and $x_{1,2} = (M/\sqrt{s_{\rm NN}})\exp(\pm y)$. $F_{{\rm J}/\psi}$, which is fixed at next-to-leading-order (NLO)[15], is the fraction of $c\bar{c}$ pairs below the $D\bar{D}$ threshold that become J/ψ's, and the K factor, $K_{\rm th}$, scales the LO cross section to the NLO value. Both the fraction $F_{{\rm J}/\psi}$ and the factor $K_{\rm th}$ are independent of rapidity and drop out of the ratios. The LO partonic cross sections for gluon fusion and $q\bar{q}$ annihilation are given by Ref. [16].

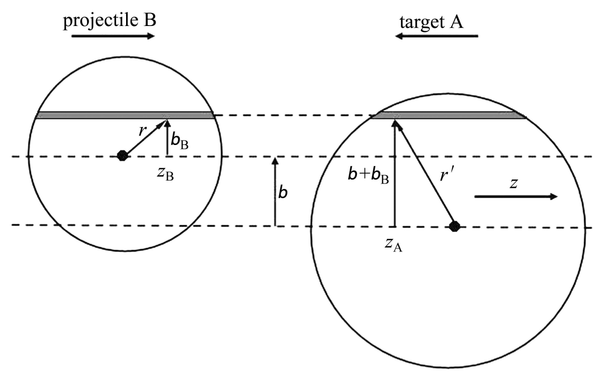

Fig. 1. Transverse view schematic representation of the Glauber Model.

The nuclear parton densities for gold, $F_{\rm j}^{\rm Au}(x, M^2,\boldsymbol{b}_{\rm Au},z_{\rm A})$, are the product of the nucleon density in the nucleus, $\rho_{\rm Au}(r')$, and a shadowing ratio, $S_{\rm P,\rho}^{\rm j}(A,x,M^2,\boldsymbol{b}_{\rm Au})$, where $\boldsymbol{b}_{\rm Au}(=\boldsymbol{b}+\boldsymbol{b}_{\rm B})$ and $z_{\rm A}$ are the transverse and longitudinal location of the parton in position space (shown in Fig. 1). The shadowing effect of deuteron is ignored. Thus,

$$F_{\rm i}^{\rm d}(x,M^2,\boldsymbol{b}_{\rm B},z_{\rm B}) = \rho_{\rm d}(r)f_{\rm i}^{\rm N}(x,M^2), \tag{2}$$

$$F_{\rm j}^{\rm Au}(x,M^2,\boldsymbol{b}_{\rm Au},z_{\rm A}) = \rho_{\rm Au}(r')S_{\rm P,\rho}^{\rm j}(A,x,M^2,\boldsymbol{b}_{\rm Au})f_{\rm j}^{\rm N}(x,M^2), \tag{3}$$

where $r = \sqrt{\boldsymbol{b}_{\rm B}^2+z_{\rm B}^2}$ and $r' = \sqrt{\boldsymbol{b}_{\rm Au}^2+z_{\rm A}^2}$. The deuteron density distribution $\rho_{\rm d}(r) = |\psi(r)|^2$ and the wave function

$$\psi(r) = \frac{u(r)}{r}\Phi_{\rm S} + \frac{w(r)}{r}\Phi_{\rm D}, \tag{4}$$

which contains S- and D-wave components. The Húlthen form[17] is used for the radial functions $u(r)$ and $w(r)$. The nucleon densities of gold (lead) are parameterized by a Fermi distribution[18]:

$$\rho_{\rm Au}(r') = \rho_0/\{1+\exp[(r'-R_{\rm Au})/a]\}. \tag{5}$$

For ^{197}Au, $R_{\rm Au}=6.516$ fm, $a=0.535$ fm and ρ_0 is determined by $\int\rho_{\rm Au}(r')\mathrm{d}^2\boldsymbol{b}_{\rm Au}\mathrm{d}z_{\rm A}=A$.

In Eq. (3), the ratio for the spatial dependence of shadowing is[4, 9]

$$S^{\rm j}_{\rm P,\rho}(A,x,M^2,\boldsymbol{b}_{\rm Au}) = 1+N_\rho(S^{\rm j}_{\rm P}(A,x,M^2)-1)\times \frac{\int \mathrm{d}z\rho_{\rm Au}(\boldsymbol{b}_{\rm Au},z)}{\int \mathrm{d}z\rho_{\rm Au}(0,z)}\ , \tag{6}$$

where N_ρ is chosen so that

$$\int\mathrm{d}^2\boldsymbol{b}_{\rm Au}\mathrm{d}z_{\rm A}\rho_{\rm Au}(r')S^{\rm j}_{\rm P,\rho}(A,x,M^2,\boldsymbol{b}_{\rm Au})=S^{\rm j}_{\rm P}(A,x,M^2).$$

By means of the HKM nuclear parton distribution functions, we have $S^{\rm j}_{\rm P,\rho}(A,x,M^2) = f^{\rm j}_{\rm A}(x,M^2)/f^{\rm j}_{\rm p}(x,M^2)$.

The initial-state energy loss effect, which is also an important nuclear effect, is always considered in the Glauber Model. In d-Au collisions, according to the Glauber model, the nucleon in deuteron may make many "soft" inelastic collisions with nucleons in Au before producing the final $\mathrm{c\bar{c}}$ pairs. Since the deuteron is an extended system and can not be treated as a point particle, the probability of one nucleon from nucleus B(d) having n collisions with nucleus A(Au) at $\boldsymbol{b}$ should be expressed as[19]

$$P(n,\boldsymbol{b},\boldsymbol{b}_{\rm B})=[T_{\rm B}(b_{\rm B})\sigma_{\rm in}]\frac{A!}{n!(A-n)!}[T_{\rm A}(|\boldsymbol{b}+\boldsymbol{b}_{\rm B}|)\sigma_{\rm in}]^n\times [1-T_{\rm A}(|\boldsymbol{b}+\boldsymbol{b}_{\rm B}|)\sigma_{\rm in}]^{A-n}/\sigma^{\rm AB}_{\rm in}, \tag{7}$$

where $\sigma_{\rm in}$($\sim$ 42 mb at RHIC energies) is the cross section in an inelastic nucleon-nucleon collision, and $T_{\rm B}(b_{\rm B})\sigma_{\rm in}$, as shown in Fig. 1, is the probability of finding a nucleon in the flux tube of nucleus B at location $b_{\rm B}$. The factor $\dfrac{A!}{n!(A-n)!}$ represents the number for finding n collisions out of A possible nucleon-nucleon encounters, the factor $[T_{\rm A}(|\boldsymbol{b}+\boldsymbol{b}_{\rm B}|)\sigma_{\rm in}]^n$ gives the probability of having exactly n collisions and the last factor gives the probability of having A-n misses. The thickness function

$$T_{\rm B}(b_{\rm B})=\int\rho_{\rm d}(r)\mathrm{d}z_{\rm B},\quad T_{\rm A}(|\boldsymbol{b}+\boldsymbol{b}_{\rm B}|)=\int\rho_{\rm Au}(r')\mathrm{d}z_{\rm A},$$

and Eq. (7) is normalized according to

$$\sum_{n=1}^{\rm A}P(n,\boldsymbol{b},\boldsymbol{b}_{\rm B})=1.$$

After the nucleon in deuteron has n collisions with nucleons in Au, the c.m. system energy of the nucleon-nucleon collision producing a $\mathrm{c\bar{c}}$ will be $\sqrt{s'_{\rm NN}}=\sqrt{s_{\rm NN}}-(n-1)\dfrac{\mathrm{d}\sqrt{s_{\rm NN}}}{\mathrm{d}n}$, where $\dfrac{\mathrm{d}\sqrt{s_{\rm NN}}}{\mathrm{d}n}$ is the average c.m. energy loss per collision. Therefore, the cross section of having n collisions for J/ψ production in d-Au collisions at $\boldsymbol{b}$ can be written as

$$\begin{aligned}\frac{\mathrm{d}\sigma^{(n)}}{\mathrm{d}y\mathrm{d}^2\boldsymbol{b}\mathrm{d}^2\boldsymbol{b}_{\rm B}}={}&2F_{{\rm J}/\psi}K_{\rm th}\int\mathrm{d}z_{\rm A}\mathrm{d}z_{\rm B}\int_{2m_{\rm c}}^{2m_{\rm D}}M\mathrm{d}M\times\\ &\Big\{F^{\rm d}_{\rm g}(x'_1,M^2,\boldsymbol{b}_{\rm B},z_{\rm B})\times\\ &F^{\rm Au}_{\rm g}(x'_2,M^2,\boldsymbol{b}+\boldsymbol{b}_{\rm B},z_{\rm A})\sigma_{\rm gg}(M^2)/s'_{\rm NN}+\\ &\sum_{\rm q=u,d,s}[F^{\rm d}_{\rm q}(x'_1,M^2,\boldsymbol{b}_{\rm B},z_{\rm B})F^{\rm Au}_{\rm \bar{q}}(x'_2,M^2,\boldsymbol{b}+\boldsymbol{b}_{\rm B},z_{\rm A})+\\ &F^{\rm d}_{\rm \bar{q}}(x'_1,M^2,\boldsymbol{b}_{\rm B},z_{\rm B})\times\\ &F^{\rm Au}_{\rm q}(x'_2,M^2,\boldsymbol{b}+\boldsymbol{b}_{\rm B},z_{\rm A})]\sigma_{\rm q\bar{q}(M^2)}/s'_{\rm NN}\Big\},\end{aligned} \tag{8}$$

where the rescaled quantities are defined as $x'_{1,2}=r_{\rm s}x_{1,2}$ with the ratio $r_{\rm s}=\dfrac{\sqrt{s_{\rm NN}}}{\sqrt{s'_{\rm NN}}}$.

Before the $\mathrm{c\bar{c}}$ pair can escape the target, it may interact with nucleons and be dissociated or absorbed. The effect of nuclear absorption alone on the J/ψ production in d-Au collisions may be expressed as[20]

$$\frac{\mathrm{d}\sigma_{\rm dAu}}{\mathrm{d}y} = \frac{\mathrm{d}\sigma_{\rm pp}}{\mathrm{d}y}\int\mathrm{d}^2\boldsymbol{b}_{\rm Au}\mathrm{d}z_{\rm A}\cdot\rho_{\rm Au}(\boldsymbol{b}_{\rm Au},z_{\rm A})\times \exp\left\{-\int_{z_{\rm A}}^{\infty}\mathrm{d}z'_{\rm A}\rho_{\rm Au}(\boldsymbol{b}_{\rm Au},z'_{\rm A})\sigma_{\rm abs}\right\}, \tag{9}$$

where $z_{\rm A}$ is the longitudinal production point of the $\mathrm{c\bar{c}}$ pair and $z'_{\rm A}$ is the point at which the state is absorbed. If the nucleon absorption cross section, $\sigma_{\rm abs}$, is considered as a constant, independent of the production mechanism, Eq. (9) can be conveniently written as[20]

$$\frac{\mathrm{d}\sigma_{\rm dAu}}{\mathrm{d}y}=\frac{\mathrm{d}\sigma_{\rm pp}}{\mathrm{d}y}A^{\alpha}\ , \tag{10}$$

where $\alpha=-9\sigma_{\rm abs}/(16\pi r_0^2)$ with $r_0=1.2$ fm.

Combining the ingredients mentioned above, the cross section for J/ψ production in d-Au collisions at $\boldsymbol{b}$ can be given by

$$\frac{\mathrm{d}\sigma_{\rm dAu}}{\mathrm{d}y\mathrm{d}^2\boldsymbol{b}}=\sum_{n=1}^{A}\int\mathrm{d}^2\boldsymbol{b}_{\rm B}P(n,\boldsymbol{b},\boldsymbol{b}_{\rm B})\frac{\mathrm{d}\sigma^{(n)}}{\mathrm{d}y\mathrm{d}^2\boldsymbol{b}\mathrm{d}^2\boldsymbol{b}_{\rm B}}A^{\alpha}, \tag{11}$$

and the average cross section is

$$\left\langle\frac{\mathrm{d}\sigma_{\rm dAu}}{\mathrm{d}y}\right\rangle=\int\mathrm{d}^2\boldsymbol{b}\frac{\mathrm{d}\sigma_{\rm dAu}}{\mathrm{d}y\mathrm{d}^2\boldsymbol{b}}\ . \tag{12}$$

3 Results and discussion

By means of Eq. (6), the ratios $S^{\rm j}_{\rm P,\rho}$ versus $b_{\rm Au}/R_{\rm Au}$ for gluon (solid curve), valence (dashed curve) and sea (dotted curve) quark of u are shown in Fig. 2. The similar homogeneous shadowing values are taken and $M=2m_{\rm c}$. It is shown that all of them have a strong b dependence when $b_{\rm Au}/R_{\rm Au}<1$.

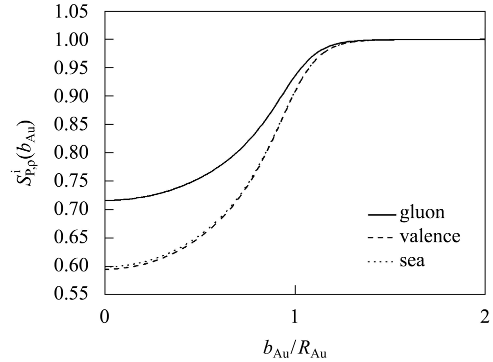

Fig. 2. The inhomogeneous shadowing ratios $S^{\mathrm{j}}_{\mathrm{P},\rho}$ versus $b_{\mathrm{Au}}/R_{\mathrm{Au}}$ for gluon (solid), valence quark of u (dashed) and sea quark of u (dotted).

In order to compare with the experimental data from PHENIX[14], we introduce the nuclear modification factor

$$R_{\mathrm{dAu}}=\frac{1}{\langle N_{\mathrm{coll}}\rangle}\frac{\langle \mathrm{d}\sigma_{\mathrm{dAu}}/\mathrm{d}y\rangle}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}y}, \tag{13}$$

where $\langle N_{\mathrm{coll}}\rangle$ is the average number of binary NN collisions. In our calculation, the HKM shadowing parameters[6] are used and the theoretical results are shown in Fig. 3. The solid and dashed curves correspond to the results of the inhomogeneous shadowing effect without and with energy loss, respectively. The value of $\mathrm{d}\sqrt{s_{\mathrm{NN}}}/\mathrm{d}n$, which has been studied detailedly in Drell-Yan process[8], is taken as 0.2 GeV. It is shown that the influence of initial-state energy loss effect is small at mid-rapidity in d-Au collisions at RHIC energies. First of all, the energy loss effect is obvious only at large momentum fraction, x, but $x_{1(2)}$ is small when the rapidity $|y|<3$ in $\sqrt{s_{\mathrm{NN}}}=200$ GeV d-Au collisions. Second, the value of $\mathrm{d}\sqrt{s_{\mathrm{NN}}}/\mathrm{d}n$ (~ 0.2 GeV) is small in contrast with $\sqrt{s_{\mathrm{NN}}}(=200$ GeV) at RHIC. In Refs. [10, 11], which expects that the energy loss effect should not be ignored, the rest frame of the nucleus is employed. Since different J/ψ production theories are adopted in the target rest frame and c.m. system, the influence of energy loss effect on J/ψ production cross section in d-Au collisions are also different. The dotted curve is the result of initial-state shadowing and energy loss effects together with final-state absorption effect and the results agree with the experimental data.

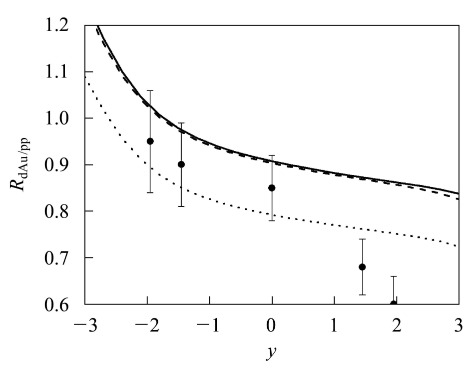

Fig. 3. The minimum bias R_{dAu} versus rapidity. The solid and dashed curves correspond to the inhomogeneous shadowing results without and with energy loss, respectively. The dotted curve is obtained from combining the inhomogeneous shadowing and energy loss effects with the J/ψ absorption effect.

Figure 4 shows the $R_{\mathrm{dAu}}(b)$ ratios for the same rapidity values as a function of the number of binary NN collisions

$$N_{\mathrm{coll}}(b)=\sigma_{\mathrm{in}}\int \mathrm{d}^2\boldsymbol{b}_{\mathrm{B}}T_{\mathrm{B}}(b_{\mathrm{B}})T_{\mathrm{A}}(|\boldsymbol{b}+\boldsymbol{b}_{\mathrm{B}}|), \tag{14}$$

and the ratio $R_{\mathrm{dAu}}(b)$ is defined as

$$R_{\mathrm{dAu}}(b)=\frac{1}{N_{\mathrm{coll}}(b)}\frac{\int \mathrm{d}y\frac{\mathrm{d}\sigma_{\mathrm{dAu}}}{\mathrm{d}y\mathrm{d}^2\boldsymbol{b}}}{\int \mathrm{d}y\frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}y}}. \tag{15}$$

The integral rapidity ranges are $-2.2<y<-1.2$ for

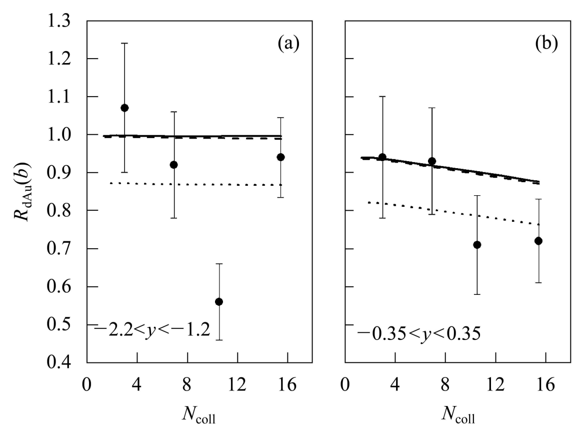

Fig. 4. The $R_{\mathrm{dAu}}(b)$ ratios versus N_{coll} with the same figure captions as in Fig. 3.

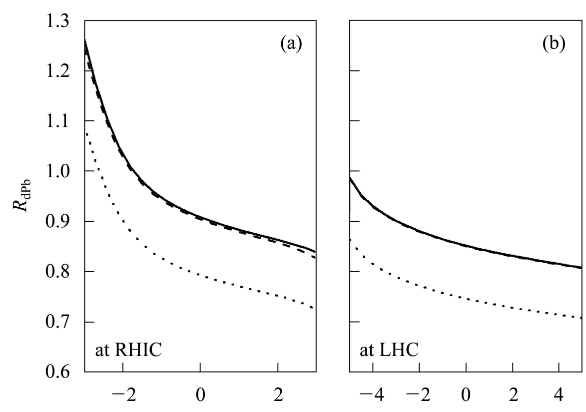

Fig. 5. The minimum bias R_{dPb} versus rapidity at RHIC(a) and LHC(b) energies with the same figure captions as in Fig. 3.

(a) and $-0.35 < y < 0.35$ for (b). The figure captions are the same as Fig. 3 and the data come from Ref. [14]. It is shown that the energy loss effect is small in both Fig. 4(a) and Fig. 4(b).

For predicting the new experimental results, the theoretical results of the factor R_{dPb} for deuteron-lead(d-Pb) collisions at RHIC (200 GeV) and LHC (6.2 TeV) energies are shown in Fig. 5. The figure captions are the same as Fig. 3. Since the value of $\mathrm{d}\sqrt{s_{\text{NN}}}/\mathrm{d}n$ (~ 0.2 GeV) is too small to be considered in contrast with $\sqrt{s_{\text{NN}}}$ ($= 6.2$ TeV), there is no energy loss effect at LHC energies (shown in Fig. 5(b)).

In summary, the initial-state energy loss effect, which is verified to be small at mid-rapidity in d-Au collisions at RHIC energies, is studied in the Glauber model. Taking account of final-state absorption, the theoretical results are in good agreement with the recent experimental data given by PHENIX. Though the initial-state energy loss effect can be ignored at mid-rapidity in d-Au collisions at RHIC energies, the initial-state multi-scattering is expected to display a strong suppression in the large transverse momentum jet production. We will study the J/ψ jet production recently.

References

1 Aubert J J et al. Nucl. Phys. B, 1987, **293**: 740; Arneodo M. Phys. Rep., 1994, **240**: 301

2 Emel'yanov V, Khodinov A, Klein S R, Vogt R. Phys. Rev. C, 2000, **61**: 044904

3 Kitagaki T et al. Phys. Lett. B, 1988, **214**: 281

4 WANG H M, SUN X J, ZHANG B A. Phys. Scr., 2007, **75**: 651—655

5 Vasiliev M A et al. Phys. Rev. Lett., 1999, **83**: 2304—2307; Nagle J L, Bennett M J. Phys. Lett. B, 1999, **465**: 21—26

6 Hirai M, Kumano S, Miyama M. Phys. Rev. D, 2001, **64**: 034003; Hirai M, Kumano S, Nagai T H. Phys. Rev. C, 2004, **70**: 044905

7 Johnson M B et al. Phys. Rev. C, 2002, **65**: 025203

8 DUAN Chun-Gui et al. Eur. Phys. J. C, 2003, **29**: 557—561; WANG H M, SUN X J, HOU Z Y. HEP & NP, 2007,**31**(11): 1040—1044 (in Chinese)

9 Vogt R. Phys. Rev. C, 2005, **71**: 054902

10 Kopeliovich B Z et al. Nucl. Phys. A, 2004, **740**: 211—245

11 Vitev I et al. Acta Phys. Hung. A, 2006, **27**: 275—279

12 Glauber R J. In Lectures in Theoretical Physics. New York: Interscience, 1959, Vol.1: 1—315

13 YANG Jian-Jun, LI Guang-Lie. Eur. Phys., 1998, **J.C5**: 719—722

14 Adare A et al. nucl-ex/0711.3917 v1

15 Gavai R V, Kharzeev D, Schuler G, Sridhar K, Vogt R. Int. J. Mod. Phys. A, 1995, **10**: 3043

16 Barger V, Keung W Y, Philips R N. Z. Phys. C, 1980, **6**: 169; Phys. Lett. B, 1980, **91**: 253

17 Kharzeev D, Levin E M, Nardi M. Nuclear Physics A, 2004, **730**: 448—459; Húlthen L, Sagawara M, in Handbüch der Physik, 1957, 39

18 de Vries H, de Jager C W, de Vries C. Atomic Data and Nuclear Data Tables, 1987, **36**: 495—536

19 Wong C Y. Introduction to High-Energy Heavy-Ion Collisions. Singapore: World Scientific Publishing, 1994. 249

20 Vogt R. Phys. Rev. C, 2000, **61**: 035203