Hadron formation in semi-inclusive deep inelastic lepton-nucleus scattering*

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Abstract: Hadron production in lepton-nucleus deep inelastic scattering is studied in a model including quark energy loss and nuclear absorption. The leading-order computations for hadron multiplicity ratios are presented and compared with the selected HERMES experimental data with the quark hadronization occurring inside the nucleus by means of the hadron formation time. It is shown that with increase of the energy fraction carried by the hadron, the nuclear suppression on hadron multiplicity ratio from nuclear absorption gets bigger. It is found that when hadronization occurs inside the nucleus, the nuclear absorption is the dominant mechanism causing a reduction of the hadron yield. The atomic mass dependence of hadron attenuation for quark hadronization starting inside the nucleus is confirmed theoretically and experimentally to be proportional to $A^{1/3}$.

Key words: deep inelastic scattering, nuclei, nuclear absorption, hadron production

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1 Introduction

The semi-inclusive deep inelastic scattering of lepton on a nuclear target has been one of the most active frontiers in nuclear physics and particle physics over the past three decades. After the pioneering measurement of hadronization in the nuclear medium at SLAC [1], more precise data were reported by the HERMES [2–6] and CLAS [7] Collaborations. It is desirable that the quantitative information on the quark propagation and hadronization in the nuclear medium can be obtained by means of the observed hadron distributions and multiplicities from various nuclei. Furthermore, the quantitative information can provide enlightenment and references for the study of quark-gluon plasma and its space-time evolution in ultra-relativistic heavy-ion collisions.

In the semi-inclusive deep inelastic scattering on nuclei, a virtual photon from the incident lepton is absorbed by a quark within a nucleus, the highly virtual colored quark traverses over some distance through the cold nuclear medium, and evolves subsequently into an observed hadron. There is a key physical quantity, i.e., the characteristic time of quark propagation, or so-called hadron formation time. The hadron formation time refers in detail to the time between the moment that the quark is struck by the virtual photon and the moment that the prehadron (the predecessor of the final hadron) is formed. If the hadron formation time is short enough, the prehadron is formed inside the target nucleus. In addition to the struck quark energy loss due to multiple interactions with the surrounding nuclear medium and gluon radiation, the prehadron can interact via the relevant hadronic interaction cross section, causing a further reduction of the observed hadron yield. Thereupon, when hadronization takes place inside the nucleus, semi-inclusive deep inelastic lepton-nucleus collisions can provide the important information on the space-time development of the hadronization process in the nuclear medium. It is worth emphasizing that hadronization in the nuclear medium are intrinsically non-perturbative QCD processes. The perturbative calculation cannot be applied to evaluate the underlying interactions in the QCD framework.

Two classes of theoretical phenomenological models, the absorption-type models [8–10] and the parton energy loss models [11–13], were proposed to investigate the experimental data from the semi-inclusive deep inelastic scattering of lepton on the nucleus [14]. However, the two extreme mechanisms do not give the best de-

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scription of the experimental measurements. In addition, whatever the physical mechanism, the atomic mass dependence for the attenuation of hadron production will be an important ingredient. Nonetheless, the recent research [15, 16] indicates that atomic mass dependence of hadron production is far from being expected by the absorption and parton energy loss models. Therefore, it is expected that the atomic mass dependence of hadron production would be allowed to discriminate between the two different mechanisms.

In our preceding article [17], by means of the hadron formation time, the relevant data with quark hadronization occurring outside the nucleus are picked out from HERMES experimental results [5] on the one-dimensional dependence of the multiplicity ratio as a function of the energy fraction z. We have calculated the nuclear modifications of hadron production in semi-inclusive deep inelastic scattering in a parton energy loss model. The energy loss per unit length is obtained for an outgoing quark by the global fit of the selected experimental data. In this paper we employ the so-called two dimensional data from the recent HERMES experiment on the multiplicity ratio for the production of positively and negatively charged pions and kaons [6]. The experimental data with quark hadronization occurring inside the nucleus are selected by means of the hadron formation time. The quark propagation and hadronization are studied in the nuclear medium.

The remainder of the paper is organized as follows. In Section 2, the brief formalism for the hadron multiplicity in semi-inclusive deep inelastic scattering on the nucleus. In Section 3, the numerical computations for the multiplicity ratio are presented and compared with experimental data. Finally, a summary is presented.

2 The theoretical framework

At leading order (LO) in perturbative QCD, the hadron multiplicity can be obtained from normalizing the semi-inclusive deep inelastic lepton nucleus scattering yield $N_A^{\rm h}$ to the deep inelastic scattering yield $N_A^{\rm DIS}$,

$$\frac{1}{N_A^{\rm DIS}}\frac{{\rm d}N_A^{\rm h}}{{\rm d}z{\rm d}\nu}=\frac{1}{\sigma^{lA}}\int{\rm d}x\sum_{\rm f}e_{\rm f}^2q_{\rm f}^A(x,Q^2)\frac{{\rm d}\sigma^{lq}}{{\rm d}x{\rm d}\nu}D_{\rm f|h}^A(z,Q^2), \tag{1}$$

$$\sigma^{lA}=\int{\rm d}x\sum_{\rm f}e_{\rm f}^2q_{\rm f}^A(x,Q^2)\frac{{\rm d}\sigma^{lq}}{{\rm d}x{\rm d}\nu}, \tag{2}$$

$$\frac{{\rm d}\sigma^{lq}}{{\rm d}x{\rm d}\nu}=Mx\frac{4\pi\alpha_{\rm s}^2}{Q^4}[1+(1-y)^2]. \tag{3}$$

In the above equation, ν is the virtual photon energy, $e_{\rm f}$ is the charge of the quark with flavor f, $q_{\rm f}^A(x,Q^2)$ is the nuclear quark distribution function with Bjorken variable x and photon virtuality Q^2, ${\rm d}\sigma^{lq}/{\rm d}x{\rm d}\nu$ is the differential cross section for lepton-quark scattering at leading order, $D_{\rm f|h}^A(z,Q^2)$ is the nuclear modified fragmentation function of a quark of flavor f into a hadron h, and $\alpha_{\rm s}$ and y are the fine structure constant and the fraction of the incident lepton energy transferred to the target, respectively.

After a quark within a nucleus interacts with a virtual photon from the incident lepton, the struck quark can lose its energy owing to multiple scattering and gluon radiation while propagating through the nucleus. The quark energy fragmenting into a hadron shifts from $E_{\rm q}=\nu$ to $E'_{\rm q}=\nu-\Delta E$, which results in a rescaling of the energy fraction of the produced hadron:

$$z=\frac{E_{\rm h}}{\nu}\longrightarrow z'=\frac{E_{\rm h}}{\nu-\Delta E}, \tag{4}$$

where $E_{\rm h}$ and ΔE are, respectively, the measured hadron energy and the quark energy loss in the nuclear medium. Thus, the fragmentation function in the nuclear medium is assumed to be [17]

$$D_{\rm f|h}^A(z,Q^2)=D_{\rm f|h}(z',Q^2), \tag{5}$$

where $D_{\rm f|h}$ is the standard (vacuum) fragmentation function of a quark of flavor f into a hadron h.

In order to further consider the hadronization in the nuclear medium, it is assumed that the quark struck by the virtual photon at a longitudinal position y fragments into a prehadronic state at the point y' and soon after the final hadron is created. The prehadronic state and the final hadron propagate through nuclear matter and interact with the surrounding nucleons in the target nucleus, causing a further reduction of the observed hadron yield. In the case of treating the prehadron and the hadron as a single object created at y', Bialas and Chmaj [18] provided the probability $P_{\rm h}(y',y)$ that the virtual colored quark fragments into a hadron at a distance $y'-y$,

$$P_{\rm h}(y',y)=1-{\rm e}^{-(y'-y)/t}, \tag{6}$$

where t is the hadron formation time. The survival probability $S_A(b,y)^{A-1}$ of this hadron can be obtained from

$$S_A(b,y)=1-\sigma_{\rm h}\int_y^\infty{\rm d}y'P_{\rm h}(y',y)\rho_A(b,y'), \tag{7}$$

where $\sigma_{\rm h}$ is the hadron-nucleon inelastic cross section, and $\rho_A(b,y')$ is the nuclear density profile normalized to unity as a function of impact parameter b and longitudinal coordinate y'. Furthermore, the nuclear absorption factor $N_A(z,\nu)$, which is defined as the probability that neither the prehadron nor hadron have interacted with a nucleon, is given as,

$$N_A(z,\nu)=\int{\rm d}^2b\int_{-\infty}^\infty{\rm d}y\rho_A(b,y)S_A(b,y)^{A-1}. \tag{8}$$

With combining the influence of nuclear absorption of the final hadron and quark energy loss on the hadron production occurring inside the nucleus, the hadron multiplicity can be presented as

$$\frac{1}{N_A^{\rm DIS}}\frac{{\rm d}N_A^{\rm h}}{{\rm d}z{\rm d}\nu} = \frac{1}{\sigma^{lA}}\int{\rm d}x\sum_{\rm f}e_{\rm f}^2q_{\rm f}^A(x,Q^2)\frac{{\rm d}\sigma^{lq}}{{\rm d}x{\rm d}\nu} \times D_{\rm f|h}(z',Q^2)N_A(z,\nu). \quad (9)$$

3 Results and discussion

The HERMES Collaboration recently reported the two-dimensional data on the multiplicity ratios for positively and negatively charged pions and kaons produced on neon, krypton, and xenon targets relative to deuterium, in three z slices as a function of ν, and in three ν slices as a function of z. We pick out the experimental data with quark hadronization occurring inside the nucleus by means of the hadron formation time $t=z^{0.35}(1-z)\nu/\kappa$ (κ=1 GeV/fm) [19]. More specifically, if t is less than L_A ($L_A = 3/4R_A$ fm), hadronization occurs inside the nucleus. Otherwise, hadrons are produced outside the target nucleus. As for the cases with quark hadronization occurring inside the nucleus, we compute at leading order the hadron multiplicity ratios $R_A^{\rm h}$,

$$R_A^{\rm h}[z]=\int\frac{1}{N_A^{\rm DIS}}\frac{{\rm d}N_A^{\rm h}(\nu,z)}{{\rm d}z{\rm d}\nu}{\rm d}\nu \Bigg/ \int\frac{1}{N_{\rm D}^{\rm DIS}}\frac{{\rm d}N_{\rm D}^{\rm h}(\nu,z)}{{\rm d}z{\rm d}\nu}{\rm d}\nu. \quad (10)$$

In the calculation, the nuclear effects on deuterium target are ignored. The CTEQ6L parton density in the proton [20] is used together with the vacuum fragmentation functions [21].

Concerning the energy loss of the struck quark while propagating through the nucleus, the linear quark energy loss parameterization [22, 23] was employed, which is written as

$$\Delta E=\alpha L_A, \quad (11)$$

where α is the parameter that can be extracted from experimental data, and L_A is the path length a quark takes in the target nucleus. As for the nuclear density profile, the Woods-Saxon distribution was used,

$$\rho(r)=\rho_0/(1+\exp(r-r_A)/a), \quad (12)$$

where a=0.545, and $r_A=1.12A^{1/3}$ fm [24].

In order to determine the parameter α in quark energy loss expression and the cross-section $\sigma_{\rm h}$ in nuclear absorption factor, the calculated hadron multiplicity ratios $R_A^{\rm h}$ are compared with the selected experimental values by using the CERN subroutine MINUIT [25] and minimizing χ^2,

$$\chi^2=\sum_i^m\left[\frac{R_{A,i}^{\rm h,data}-R_{A,i}^{\rm h,theo}}{\sigma_i^{\rm err}}\right]^2, \quad (13)$$

where $R_{A,i}^{\rm h,data}$ and $R_{A,i}^{\rm h,theo}$ indicate separately the experimental data and theoretical values of the hadron multiplicity ratio $R_A^{\rm h}$, the experimental error is given by systematic and statistical errors as $(\sigma_i^{\rm err})^2=(\sigma_i^{\rm syst})^2+(\sigma_i^{\rm stat})^2$. The uncertainties of the optimum α and $\sigma_{\rm h}$ are obtained with an increase of χ^2 by 4.61 unit from the minimum $\chi^2_{\rm min}$, which corresponds, in the case of normally distributed fit parameters, to the 90% covered region of the total probability distribution.

Table 1. The values of parameters α, $\sigma_{\rm h}$ and χ^2/ndf for positively and negatively charged pions and kaons extracted from the selected data on $R_A^{\rm h}$ for hadron produced on krypton and xenon nuclei, as a function of z in $4<\nu<11$ GeV and $11<\nu<14$ GeV.

identified hadron	α/(GeV/fm)	$\sigma_{\rm h}$/mb	χ^2/ndf
π^+	0.09±0.01	29.8±0.1	0.34
π^-	0.06±0.01	30.0±0.2	0.24
k^+	0.06±0.02	18.7±0.2	0.22
k^-	0.14±0.04	21.8±1.1	0.47

Table 1 summarizes χ^2 per number of degrees of freedom (χ^2/ndf), the determined parameters α and $\sigma_{\rm h}$ by calculating the hadron multiplicity ratios $R_A^{\rm h}$ for positively and negatively charged pions and kaons production on krypton nucleus relative to the deuteron as a function of z in $4<\nu<11$ GeV and on xenon nucleus in $4<\nu<11$ GeV as well as $11<\nu<14$ GeV from the selected HERMES experiment data [6]. It is shown that the theoretical results considering the nuclear absorption and the nuclear modification of fragmentation functions owing to quark energy loss give an excellent description of the experimental data with the values of χ^2/ndf being far smaller than 1. From Table 1, it can be seen that the quark energy loss required to describe the measurements for hadronization occurring inside the nucleus cannot be properly determined for negatively charged pions and kaons production because the relative uncertainty $\delta\alpha/\alpha$ is very large. In detail, $\delta\alpha/\alpha$ are approximately 17%, 33% and 28% for negatively charged pions and positively and negatively charged kaons production, respectively. However, $\delta\alpha/\alpha\approx 11\%$ for positively charged pions production, the energy loss per unit length is pinned down as $\alpha=0.09$ GeV/fm. Of particular concern is that the value of α is much smaller than the one from our paper [17]. The reason for this result is worthy of us further investigating.

It is believed that the colored quark created at the virtual photon-quark interaction point can lose its energy by experiencing multiple interactions with the surrounding nuclear medium and induced gluon radiation. Therefore, the energy loss per unit length is put to α=0.09 GeV/fm. The values of $\sigma_{\rm h}$ and χ^2/ndf extracted from the selected data on $R_A^{\rm h}$ are listed in Table 2 by means of the χ^2 analysis. It can be seen that the agreement between the theoretical calculations and selected data is still good. The fit of the selected data in the pre-

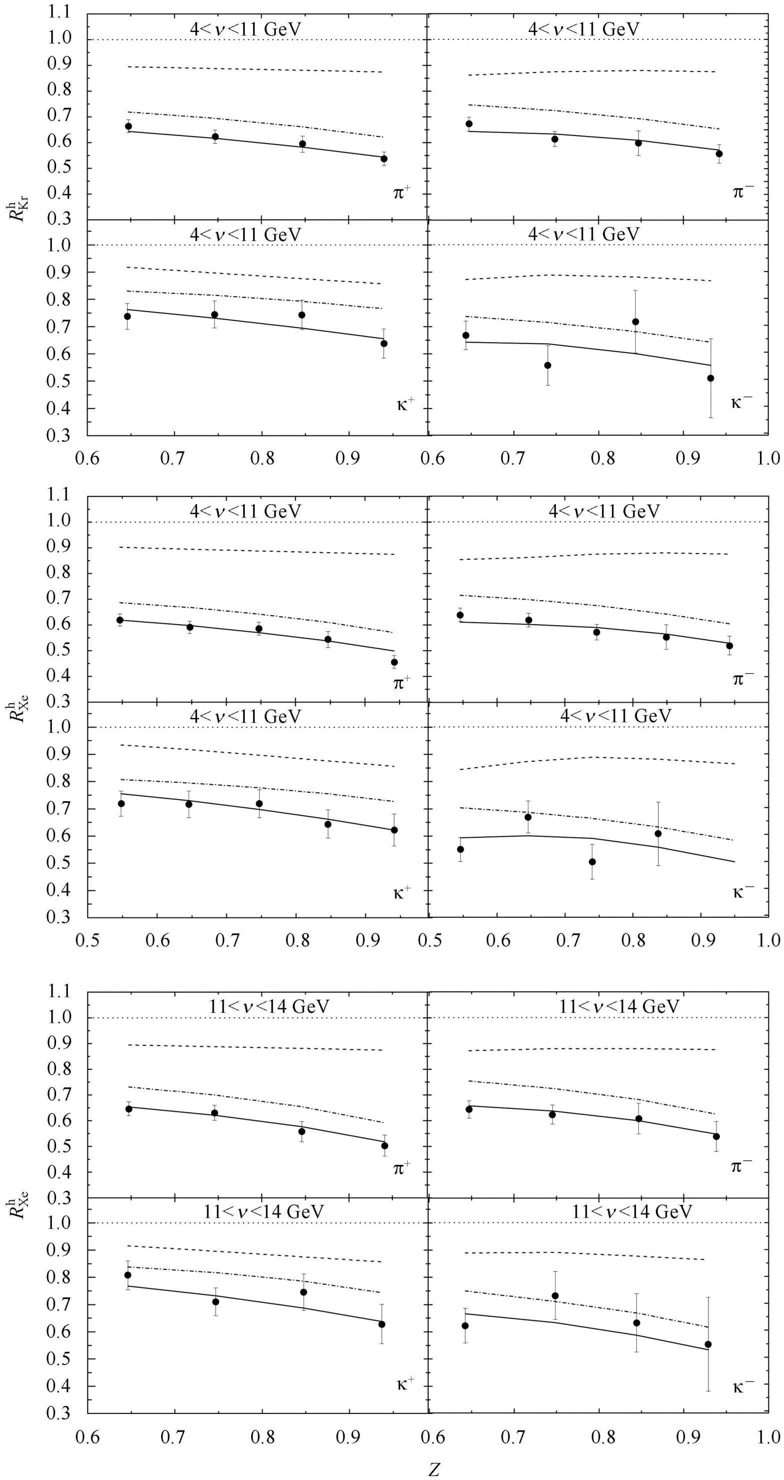

Fig. 1. The calculated multiplicity ratios R_A^h for positively and negatively charged pions and kaons production on Kr and Xe nuclei with the combination of nuclear absorption and quark energy loss (solid line), only considering quark energy loss (dashed line), and only nuclear absorption (dash dot line). The relative optimal parameters σ_h are taken from Table 2 with $\alpha = 0.09$ GeV/fm. The HERMES data [6] on Kr and Xe nuclei are shown with the total uncertainty (statistical plus systematic, added quadratically).

Table 2. The values of $\sigma_{\rm h}$ and χ^2/ndf extracted from the selected data on $R_A^{\rm h}$ with $\alpha = 0.09$ GeV/fm.

identified hadron	$\sigma_{\rm h}$/mb	χ^2/ndf
π^+	29.9±0.2	0.31
π^-	26.3±0.2	0.30
k^+	15.5±0.1	0.23
k^-	28.7±0.8	0.44

sent analysis leads to the cross sections of 29.9±0.2 mb, 26.3±0.2 mb, 15.5±0.1 mb and 28.7±0.8 mb for positively and negatively charged pions and kaons.

In order to explore respectively the influence of nuclear absorption and quark energy loss on the hadron multiplicity ratios $R_A^{\rm h}$, the theoretical multiplicity ratios are compared with the selected HERMES experimental data for positively and negatively charged pions and kaons production in Fig. 1. The dashed, dash dot, and solid lines are the results on $R_A^{\rm h}$ by considering the quark energy loss, nuclear absorption and nuclear absorption plus quark energy loss, respectively. It is apparent that the computed results with the combination of nuclear absorption and quark energy loss are in good agreement with the experimental data. In theory, when the value of z increases to 1, the nuclear suppression on $R_A^{\rm h}$ from quark energy loss effect is diminished gradually. However, the ignoration of nuclear effects on the deuterium target gives this feature on the quark energy loss effect in Fig.1. The nuclear absorption effect adds further to the nuclear suppression on $R_A^{\rm h}$. Taking the example of the hadron multiplicity ratios $R_A^{\rm h}(z)$ in the region of $0.65\leqslant z\leqslant 0.94$ in $4<\nu<11$ GeV for positively charged pions production on krypton, the influence of quark energy loss changes from 11% to 14% while the impact of nuclear absorption increases from 28% to 38% with the increase of z. Therefore, it can be concluded that the nuclear absorption becomes the dominant effect for the selected experimental data with quark hadronization occurring inside the nucleus.

In order to investigate theoretically the atomic mass dependence of hadron production in semi-inclusive deep inelastic lepton-nucleus scattering for quark hadronization occurring inside the nucleus, the hadron attenuation $1-R_A^{\rm h}$ is presumed in terms of a power law:

$$1-R_A^{\rm h}=cA^{1/3(2/3)}. \tag{14}$$

In general, the coefficient c depends on the kinematic variable $z(\nu)$ and the atomic mass number A. The optimal parameter c in the power law can be determined by chi-square minimization, i.e., the χ^2 merit function

$$\chi^2(c)=\sum_i^m\left[\frac{(1-R_A^{\rm h})(A_i)-cA_i^{1/3(2/3)}}{\sigma_i^{\rm err}}\right]^2, \tag{15}$$

is minimized with respect to the coefficient c. Here $\sigma_i^{\rm err}$ is the uncertainty of the theoretical value $R_A^{\rm h}$ due to the cross section $\sigma_{\rm h}$. We evaluate the uncertainty of $R_A^{\rm h}[z,\sigma_{\rm h}]$ with respect to the optimized cross-section $\sigma_{\rm h}$ by using Hessian method and assuming linear error propagation:

$$\delta R_A^{\rm h}[z,\sigma_{\rm h}]=\Delta\chi^2\frac{\partial R_A^{\rm h}[z,\sigma_{\rm h}]}{\partial\sigma_{\rm h}}\left[\frac{\partial^2 R_A^{\rm h}[z,\sigma_{\rm h}]}{\partial^2\sigma_{\rm h}}\right]^{-1/2}. \tag{16}$$

In our estimation, $\Delta\chi^2 = 1$ with the confidence level P=0.6826.

We compute the hadron multiplicity ratio $R_A^{\rm h}$ for positively and negatively charged pions and kaons production on krypton, stannum, xenon and tungsten nuclei relative to deuterium target in our model of the quark energy loss plus nuclear absorption. In order to compare with the relative experimental data, the regions of kinematics variable ν and z are limited to being the same as those from the selected data on krypton and xenon nuclei with quark hadronization occurring inside the nucleus. In our calculation, the energy loss per unit length α=0.09 GeV/fm, the cross sections $\sigma_{\rm h}$ for positively and negatively charged pions and kaons are separately taken from Table 2. The obtained best-fit coefficient c with its uncertainty and χ^2/ndf for the fit $1-R_A^{\rm h}=cA^{1/3}$ ($cA^{2/3}$) indicate that the atomic mass dependence of hadron production for quark hadronization starting inside the nucleus is in good agreement with $1-R_A^{\rm h}\sim A^{1/3}$.

The theoretical results from our model are compared with the selected HERMES experimental data for various hadron production in Fig. 2 and Fig. 3. In the two figures the selected HERMES data on $R_A^{\rm h}$ for ^{84}Kr and ^{131}Xe [6] are presented as $1-R_A^{\rm h}$ for the various selected z-bins as empty triangles. The solid circles show the corresponding results of our model for four species hadron production on krypton, stannum, xenon and tungsten nuclei relative to deuterium target. In addition the solid (dashed) lines are the best fits to $1-R_A^{\rm h}=cA^{1/3}$ ($cA^{2/3}$) of the theory results. It is worth mentioning that the experimental points are shifted slightly to the right to avoid overlap with our model values. It is found from Fig. 2 and Fig. 3 that our model is in support of the power law $1-R_A^{\rm h}\sim A^{1/3}$. From what has been discussed above, when hadronization occurs inside the nucleus, the nuclear absorption is the dominant mechanism which causes a reduction of the hadron yield. Therefore, we can confirm the theoretical prediction from the nuclear absorption model on the power law: $1-R_A^{\rm h}\sim A^{1/3}$. Overall, the comparison between the experimental and theoretical results shows they are in reasonable agreement. The fact demonstrates that the experimental data is consistent with the $A^{1/3}$ power law for quark hadronization occurring inside the nucleus.

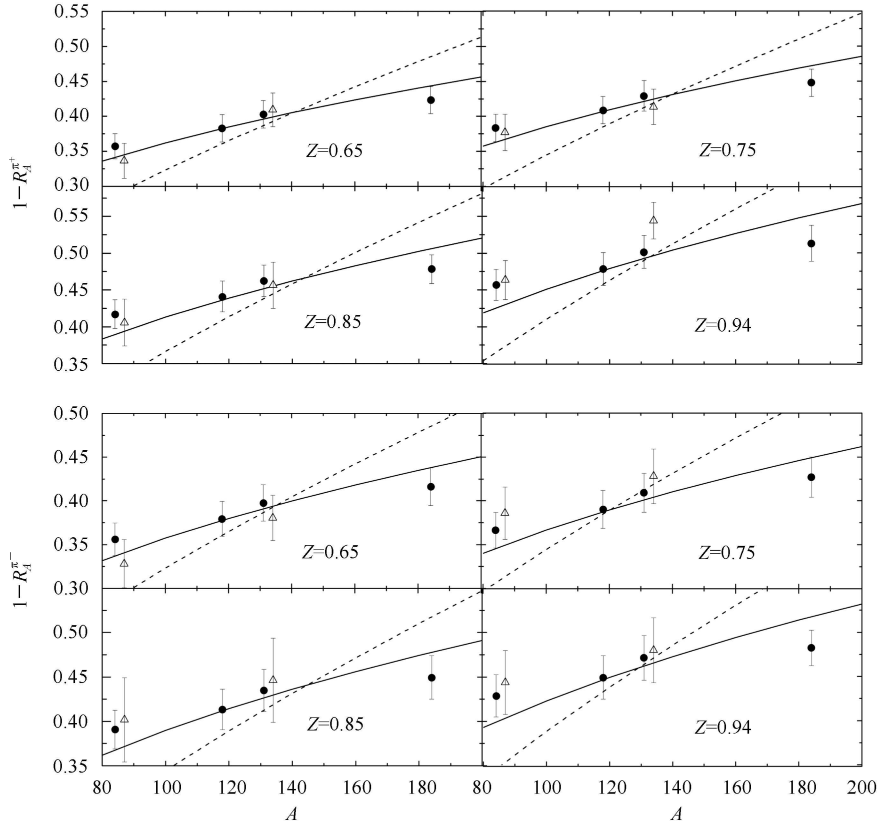

Fig. 2. The selected HERMES data on $R_A^{\rm h}$(h=π^+, π^-) for ^{84}Kr and ^{131}Xe [6] are presented as $1-R_A^{\rm h}$ for various z values as empty triangles, respectively. Our model results for $1-R_A^{\rm h}$ including values for A=84, 118, 131, 184 (Kr, Sn, Xe, W) are shown by solid circles. Note that the experimental points (empty triangle) are shifted slightly to the right to avoid overlap with our model values. The solid lines (dashed lines) are the calculated results to $1-R_A^{\rm h}=cA^{1/3}$ ($cA^{2/3}$).

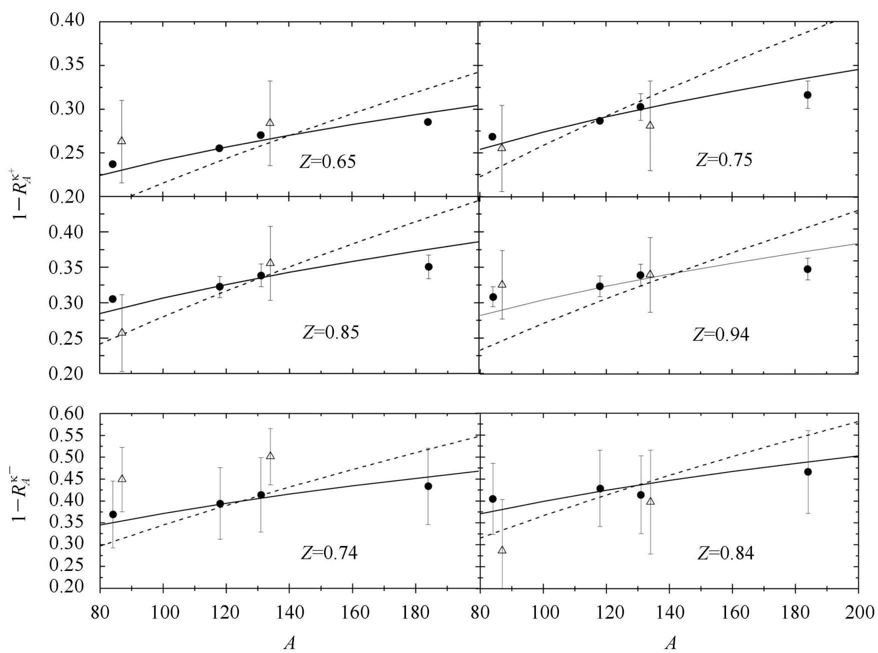

Fig. 3. The selected HERMES data on $R_A^{\rm h}$ (h=k$^+$, k$^-$) for ^{84}Kr and ^{131}Xe [6]. The other comments are the same as those in Fig. 2.

Moreover, special emphasis is that our conclusion on the power law is apparently different from the ones from Refs. [15] and [16]. The authors of Ref. [15] find that contrary to common expectations for absorption models, the mass number dependence of the hadron attenuation $1-R_A^{\mathrm{h}}$ is proportional to $A^{2/3}$ in leading order. In addition, the study on the attenuation of hadron production by using realistic matter distributions [16] shows that the mass number dependence for a pure partonic (absorption) mechanism is more complicated than a simple $A^{2/3}(A^{1/3})$ behavior.

4 Summary

Hadron production in lepton-nucleus deep inelastic scattering is studied in our model including quark energy loss and nuclear absorption. In the proposed model, the experimental data with the quarks hadronization occurring inside the nucleus are selected by means of the hadron formation time. We perform a leading order phenomenological analysis on the hadron multiplicity ratio, and compare with the HERMES experimental results for hadron produced on krypton and xenon nuclei. It is found that the nuclear suppression on hadron multiplicity ratio from nuclear absorption gets bigger as the kinematics variable z rises. When hadronization occurs inside the nucleus, the nuclear absorption is the dominant mechanism causing a reduction of the hadron yield. The atomic mass dependence of hadron production for quark hadronization starting inside the nucleus is theoretically and experimentally in good agreement with $1-R_A^{\mathrm{h}}\sim A^{1/3}$.

What we should note is that the value of α is much smaller than that from our previous article. The reason for this result is worthy of our further studying. Also, we suggest that future semi-inclusive deep-inelastic scattering measurements should increase the amount of target nucleus, and collect data up to heavy nuclei like Sn and Pb. The precise experimental result will help unravel the space-time dynamics of the hadronization process.

References

1 Osborne L et al. Phys. Rev. Lett., 1978, **40**: 1624
2 Airapetian A et al. Eur. Phys. J. C, 2001, **20**: 479
3 Airapetian A et al. Phys. Lett. B, 2003, **577**: 37
4 Airapetian A et al. Phys. Rev. Lett., 2006, **96**: 162301
5 Airapetian A et al. Nucl. Phys. B, 2007, **780**: 1
6 Airapetian A et al. Eur. Phys. J. A, 2011, **47**: 113
7 Daniel A et al. Phys. Lett. B, 2011, **706**: 26
8 Bialas A, Gyulassy M. Nucl. Phys. B, 1987, **291**: 793
9 Akopov N, Grigoryan L, Akopov Z. Eur. Phys. J. C, 2005, **44**: 219
10 Falter T, Cassing W, Gallmeister K, Mosel U. Phys. Rev. C, 2004, **70**: 054609
11 WANG E, WANG X N. Phys. Rev. Lett., 2002, **89**: 162301
12 Arleo F. Eur. Phys. J. C, 2003, **30**: 213
13 DENG Wei-Tian, WANG Xin-Nian. Phys. Rev. C, 2010, **81**: 024902
14 Accardi A et al. Riv. Nuovo Cim., 2010, **32**: 439
15 Accardi A et al. Nucl. Phys. A, 2005, **761**: 67
16 Blok H P, Lapiks L. Phys. Rev. C, 2006, **73**: 038201
17 SONG Li-Hua, DUAN Chun-Gui. Phys. Rev. C, 2010, **81**: 035207
18 Bialas A, Chmaj T. Phys. Lett. B, 1983, **133**: 241
19 Accardi A. Eur. Phys. J. C, 2007, **49**: 347
20 Pumplin J et al. J. High Energy Phys., 2002, **07**: 012
21 Hirai M, Kumano S, Nagai T H, Sudoh K. Phys. Rev. D, 2007, **75**: 094009
22 DUAN C G et al. Phys. Rev. C, 2009, **79**: 048201
23 SONG Li-Hua, DUAN Chun-Gui, LIU Na. Phys. Lett. B, 2012, **708**: 68
24 Capella A, Krzywicki A. Phys. Rev. D, 1977, **18**: 3357
25 James F. CERN Program Library Long Writeup D506