Atomic mass dependence of hadron production 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 quark energy loss model. The leading-order computations for hadron multiplicity ratios are presented and compared with the selected HERMES pions production data with the quark hadronization occurring outside the nucleus by means of the hadron formation time. It is found that the obtained energy loss per unit length is 0.440±0.013 GeV/fm for an outgoing quark by the global fit. It is confirmed that the atomic mass number dependence of hadron attenuation is theoretically and experimentally in good agreement with the $A^{2/3}$ power law for quark hadronization occurring outside the nucleus.

Key words: atomic mass dependence, quark energy loss, hadron production, deep inelastic scattering

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1 Introduction

A detailed understanding of the parton propagation and hadronization processes in cold nuclear matter would greatly benefit the study of the jet-quenching and parton energy loss phenomena observed in ultra-relativistic heavy-ion collisions. The semi-inclusive deep inelastic scattering of leptons on nuclei can provide essential information on the parton propagation and hadronization processes in cold nuclear matter. 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 propagates over some distance through the cold nuclear medium, and evolves subsequently into an observed hadron. However, the space-time evolution of the hadronization process in cold nuclear matter is an intrinsically non-perturbative QCD process. At present, reliable QCD calculations of parton hadronization cannot be performed. Therefore, an investigation into this process from the partons produced in the elementary interaction to the observed hadrons on the phenomenological level is of basic importance for the development of theoretical research [1].

Two classes of theoretical phenomenological models were proposed to describe the experimental data from the semi-inclusive deep inelastic scattering of leptons on the nucleus. The experimental data are usually presented in terms of the multiplicity ratio $R^{\mathrm{h}}_{\mathrm{M}}$, which is defined as the ratio of the number of hadrons h produced per deep-inelastic scattering event on a nuclear target with mass number A to that for a deuterium target [2–9]. The first class are the absorption-type models [10–15], which commonly presume that $1-R^{\mathrm{h}}_{\mathrm{M}}\sim A^{1/3}$. Another class of models are the parton energy loss models [16–19], which focus on the parton energy loss that the struck quark experiences in the nuclear environment, and assume that the hadron is formed outside the nucleus without hadron absorption in the nuclear medium. The parton energy loss models predict that $1-R^{\mathrm{h}}_{\mathrm{M}}\sim A^{2/3}$. It is obvious that the different physical mechanism in two classes of phenomenological models directly leads to the different prediction on atomic mass dependence of hadron production in deep inelastic scattering on nuclei. However, recent research indicates that the atomic mass dependence of hadron production is far from as expected by the absorption and parton energy loss models. The authors of Ref. [20,21] find that the mass number dependence of the hadron attenuation $1-R^{\mathrm{h}}_{\mathrm{M}}$ obeys a $A^{2/3}$ law (broken at $A\geqslant 80$) in both energy loss and absorption models. The observed approximate $A^{2/3}$ scaling of experimental data for light nuclei cannot be used as a proof of the energy loss mechanism. In addition, the study on the attenuation of hadron production by using realistic matter distributions [22] shows that the mass number

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dependence for a pure partonic (absorption) mechanism is more complicated than a simple $A^{2/3}(A^{1/3})$ behavior. For this reason, it is hoped that the precise experimental measurement on atomic mass dependence of hadron production would allow us to clearly know the physical mechanism on the hadronization process.

In our preceding article [23], we have calculated the nuclear modifications of hadron production in semi-inclusive deep inelastic scattering in a parton energy loss model. By means of the short hadron formation time, the relevant data with quark hadronization occurring outside the nucleus are picked out from HERMES experimental results [7] on the one-dimensional dependence of the multiplicity ratio $R^{\mathrm{h}}_{\mathrm{M}}$ as a function of the energy fraction z of the virtual photon carried away by the hadron. Our theoretical results show that the nuclear effects on parton distribution functions can be neglected. We find that the theoretical results considering the nuclear modification of fragmentation functions due to quark energy loss are in good agreement with the selected experimental data. The experimental data on the hadron multiplicity ratio do not distinguish between the linear and quadratic dependence of quark energy loss. The obtained energy loss per unit length is 0.38±0.03 GeV/fm for an outgoing quark by the global fit. However, it is worth mentioning that the selected experimental data only involve the multiplicity ratio on helium and neon targets relative to deuterium.

In this paper we extend the proposed quark energy loss model to study the atomic mass dependence of the nuclear attenuation $1-R^{\mathrm{h}}_{\mathrm{M}}$ because whatever the physical mechanism, the atomic mass dependence will be an important ingredient. Although the new HERMES [8] and CLAS [9] data are reported on the multiplicity ratios for three nucleus targets relative to deuterium, in order to explore the atomic mass dependence of the nuclear attenuation, we employ the so-called two-dimensional data from HERMES on the multiplicities for the production of pions on helium, neon, krypton, and xenon targets relative to those for deuterium [7]. Two-dimensional data mean that the multiplicity ratio is presented in a fine binning in one variable and a coarser binning in another variable. The other variables are integrated over within the acceptance of the experiment. The experimental data with quark hadronization occurring outside the nucleus are selected by means of the hadron formation time. It is hoped that new knowledge about the atomic mass dependence of the nuclear attenuation will be aquired.

The remainder of the paper is organized as follows. The brief formalism for the hadron multiplicity in semi-inclusive deep inelastic scattering on the nucleus and nuclear modification of the fragmentation functions owing to quark energy loss are described in Section 2. Then, the numerical computations for $R^{\mathrm{h}}_{\mathrm{M}}$ and the A-dependence of $1-R^{\mathrm{h}}_{\mathrm{M}}$ are presented and compared with experimental data. Finally, a summary is presented.

2 The hadron multiplicity in semi-inclusive deep inelastic scattering on nuclei

At leading order in perturbative QCD, the hadron multiplicity can be obtained from normalizing the semi-inclusive deep inelastic lepton nucleus scattering yield N^{h}_A to the deep inelastic scattering yield N^{DIS}_A,

$$\frac{1}{N^{\mathrm{DIS}}_A}\frac{\mathrm{d}N^{\mathrm{h}}_A}{\mathrm{d}z\mathrm{d}\nu} = \frac{1}{\sigma^{lA}}\int\mathrm{d}x\sum_{\mathrm{f}} e^2_{\mathrm{f}} q^A_{\mathrm{f}}(x,Q^2)\frac{\mathrm{d}\sigma^{lq}}{\mathrm{d}x\mathrm{d}\nu}D^A_{\mathrm{f|h}}(z,Q^2), \tag{1}$$

$$\sigma^{lA} = \int\mathrm{d}x\sum_{\mathrm{f}} e^2_{\mathrm{f}} q^A_{\mathrm{f}}(x,Q^2)\frac{\mathrm{d}\sigma^{lq}}{\mathrm{d}x\mathrm{d}\nu}, \tag{2}$$

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

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

In a similar way to the parton propagation in a nuclear Drell-Yan process [24, 25], the struck quark by the virtual photon can lose its energy owing to multiple scattering from other quarks and gluon radiation while traversing through the nucleus. In our previous article [23], the quark energy loss is written as

$$\Delta E=\alpha\langle L\rangle_A, \tag{4}$$

which is often referred to as the linear quark energy loss. Here, α is the fitted parameter that can be extracted from experimental data. As for quark hadronization occurring outside the nucleus, $\langle L\rangle_A$ is equal to $3/4(1.12A^{1/3})$ fm. By considering the quark energy loss in the nucleus target, the quark energy fragmenting into a hadron shifts from $E_{\mathrm{q}}=\nu$ to $E'_{\mathrm{q}}=\nu-\Delta E$, which results in a rescaling of the energy fraction of the produced hadron:

$$z=\frac{E_{\mathrm{h}}}{\nu}\longrightarrow z'=\frac{E_{\mathrm{h}}}{\nu-\Delta E}, \tag{5}$$

where E_{h} and ΔE are, respectively, the measured hadron energy and the quark energy loss in the nuclear medium. In view of the rescaled energy fraction of the produced hadron, the fragmentation function in the nuclear medium [23]

$$D_{\mathrm{f|h}}^{A}(z,Q^2)=D_{\mathrm{f|h}}(z',Q^2), \tag{6}$$

where $D_{\mathrm{f|h}}$ is the standard (vacuum) fragmentation function of a quark of flavour f into a hadron h. Therefore, excluding the influence of nuclear absorption, and considering only the case where hadrons are produced outside the nucleus, the hadron multiplicity can be expressed as

$$\frac{1}{N_A^{\mathrm{DIS}}}\frac{\mathrm{d}N_A^{\mathrm{h}}}{\mathrm{d}z\mathrm{d}\nu}=\frac{1}{\sigma^{lA}}\int\mathrm{d}x\sum_{\mathrm{f}}e_{\mathrm{f}}^2q_{\mathrm{f}}^A(x,Q^2)\frac{\mathrm{d}\sigma^{lq}}{\mathrm{d}x\mathrm{d}\nu}D_{\mathrm{f|h}}(z',Q^2). \tag{7}$$

3 Results and discussion

The HERMES Collaboration at the DESY laboratory performed a series of semi-inclusive deep-inelastic scattering measurements on deuterium, helium, neon, krypton, and xenon targets in order to study hadronization by using a 27.6 GeV positron or electron beam [7]. The hadron multiplicity ratios on the pion two-dimensional distributions were presented.

In the following calculation, we use the two-dimensional data on the multiplicity ratio $R_{\mathrm{M}}^{\mathrm{h}}$ for pions produced on helium, neon, krypton and xenon nuclei, 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 outside the nucleus by means of the hadron formation time $t=z^{0.35}(1-z)\nu/\kappa$ ($\kappa=1$ GeV/fm) [7, 26], which is defined as the time between the moment that the quark is struck by the virtual photon and the moment that the prehadron is formed. If $t>3/4R_A$, hadronization occurs outside the nucleus. Otherwise, hadrons are produced inside the nucleus. Using the criterion, the number of points in selected experimental data is 48 for $R_{\mathrm{M}}^{\pi}(\nu)$ in two z regions of $0.2<z<0.4$ and $0.4<z<0.7$. For the multiplicity ratio R_{M}^{π} as a function of z, there are 57 data points in three ν regions of $6<\nu<12$ GeV, $12<\nu<17$ GeV and $17<\nu<23.5$ GeV.

As for the cases with quark hadronization occuring outside the nucleus, we compute at leading order the hadron multiplicity ratios R_{M}^{π},

$$R_{\mathrm{M}}^{\pi}[\nu(z)] = \int\frac{1}{N_A^{\mathrm{DIS}}}\frac{\mathrm{d}N_A^{\mathrm{h}}(\nu,z)}{\mathrm{d}z\mathrm{d}\nu}\mathrm{d}z(\nu)\bigg/\int\frac{1}{N_{\mathrm{D}}^{\mathrm{DIS}}}\times\frac{\mathrm{d}N_{\mathrm{D}}^{\mathrm{h}}(\nu,z)}{\mathrm{d}z\mathrm{d}\nu}\mathrm{d}z(\nu), \tag{8}$$

for the production of pions by using the CTEQ6L parton density in the proton [27] together with the vacuum fragmentation functions [28], meanwhile taking account of the quark energy loss in cold nuclear matter. In our calculation, the integral range is determined according to the relative experimental kinematic region. Then, the obtained hadron multiplicity ratios R_{M}^{π} are compared with the experimental values for calculating

$$\chi^2=\sum_i^m\left[\frac{R_{\mathrm{M},i}^{\pi,\mathrm{data}}-R_{\mathrm{M},i}^{\pi,\mathrm{theo}}}{\sigma_i^{\mathrm{err}}}\right]^2, \tag{9}$$

where $R_{\mathrm{M},i}^{\pi,\mathrm{data}}$ and $R_{\mathrm{M},i}^{\pi,\mathrm{theo}}$ indicate separately the experimental data and theoretical values of the hadron multiplicity ratio R_{M}^{π}, the experimental error is given by systematic and statistical errors as $(\sigma_i^{\mathrm{err}})^2=(\sigma_i^{\mathrm{syst}})^2+(\sigma_i^{\mathrm{stat}})^2$. Together with the CERN subroutine MINUIT [29], the optimum parameter in quark energy loss expression is obtained by minimizing χ^2. One standard deviation of the optimum parameter in quark energy loss expressions corresponds to an increase of χ^2 by 1 unit from its minimum $\chi^2_{\min}$.

For all of the selected experimental data on the hadron multiplicity ratios R_{M}^{π} as a function of z and ν, our analysis has in total 105 data points, and 4 nuclei from helium up to xenon. The global fit of all data makes $\alpha=0.440\pm0.013$ with the relative uncertainty $\delta\alpha/\alpha\approx3\%$ and $\chi^2/\mathrm{ndf}=1.02$. It is worthy of note that the value of energy loss per unit length α is a little bit bigger than that in our previous article [23]. However, we think the present value is more realistic because of the precise two-dimensional experimental data on the hadron multiplicity ratios.

To demonstrate intuitively the quark energy loss effect on hadron multiplicity ratio R_{M}^{π}, the experimental data selected for the present analysis are respectively compared with our theoretical predictions on $R_{\mathrm{M}}^{\pi}(\nu)$ in two z domains in Fig. 1 and $R_{\mathrm{M}}^{\pi}(z)$ in three ν domains in Fig. 2 for helium (solid line), neon (dashed line), krypton (dotted line) and xenon (dash dot line) nuclear targets. It is shown that the theoretical results including the nuclear modification of fragmentation functions owing to quark energy loss are in good agreement with the experimental data on the hadron multiplicity ratios.

In order to investigate the atomic mass dependence of hadron production in semi-inclusive deep inelastic lepton-nucleus scattering, the hadron attenuation $1-R_{\mathrm{M}}^{\pi}$ is presumed in terms of a power law:

$$1-R_{\mathrm{M}}^{\pi}=cA^{\kappa}. \tag{10}$$

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

$$\chi^2(c,\kappa)=\sum_i^m\left[\frac{(1-R_{\mathrm{M}}^{\pi})(A_i)-cA_i^{\kappa}}{\sigma_i^{\mathrm{err}}}\right]^2, \tag{11}$$

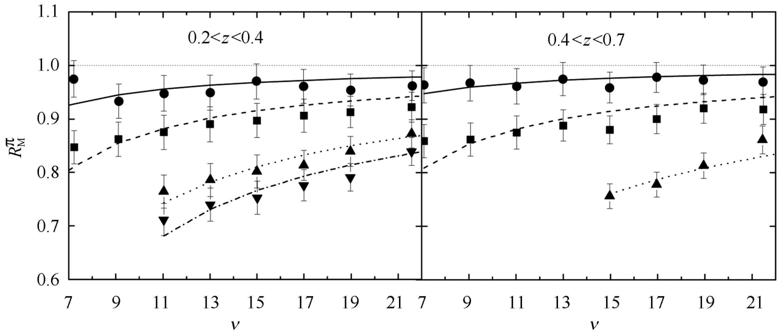

Fig. 1. The calculated multiplicity ratios $R_{\rm M}^{\pi}(\nu)$ in two z regions for pion production on He (solid line), Ne (dashed line), Kr (dotted line) and Xe (dash-dot line) nuclei from the linear quark energy loss. The HERMES data [7] on He (solid circles), Ne (filled boxes), Kr (closed triangles) and Xe (inverted triangles) are shown with the total uncertainty (statistical plus systematic, added quadratically).

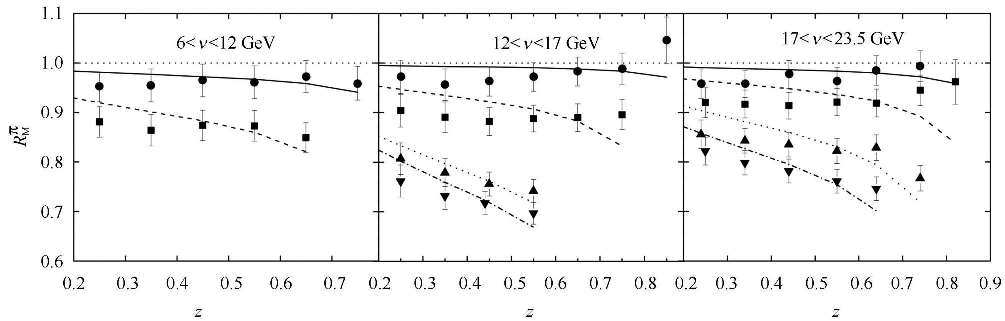

Fig. 2. The calculated multiplicity ratios $R_{\rm M}^{\pi}(z)$ in three ν regions for pions production on He (solid line), Ne (dashed line), Kr (dotted line) and Xe (dash-dot line) nuclei from the linear quark energy loss. The other comments are the same as those in Fig. 1.

is minimized with respect to c and κ. Here $\sigma_i^{\rm err}$ is the uncertainty of the theoretical or the experimental points, respectively. For the case of the theoretical computations, we evaluate the uncertainty of $R_{\rm M}^{\pi}[\nu(z),\alpha]$ with respect to the optimized parameter α by using the Hessian method and assuming linear error propagation:

$$\delta R_{\rm M}^{\pi}[\nu(z),\alpha]=\Delta\chi^2\frac{\partial R_{\rm M}^{\pi}[\nu(z),\alpha]}{\partial\alpha}\left[\frac{\partial^2 R_{\rm M}^{\pi}[\nu(z),\alpha]}{\partial^2\alpha}\right]^{-1/2}. \quad (12)$$

In our estimation, the $\Delta\chi^2$ value is obtained by the following procedure. The confidence level P could be chosen as the one-σ-error range of the normal distribution. For one parameter, $P=0.6826$ is obtained with $\Delta\chi^2=1$.

The best-fit coefficient c and exponent κ with their uncertainties for the fit $1-R_{\rm M}^{\pi}=cA^{\kappa}$ are summarized in Table 1 at fixed ν bins in the region $0.2<z<0.4$ and at fixed z bins in two regions of $12<\nu<17$ GeV and $17<\nu<23.5$ GeV both from the experimental data [7] and our model calculation on the hadron attenuation $1-R_{\rm M}^{\pi}$ for pion production on helium, neon, krypton and xenon nuclei. As can be seen from the Table 1, the relative uncertainties of coefficient c, $\delta c/c$, are very large for the selected experimental data and our model calculation. The large relative uncertainties $\delta c/c$ manifest that the coefficient c is not determined well. In addition, the values of exponent κ obtained from our model are overall larger than those from the experimental data while the values of coefficient c given by our model prediction

Table 1. The coefficient c and exponent κ with their uncertainties for the fit $1-R_{\rm M}^{\pi}=cA^{\kappa}$ for pion production at fixed ν and z bins, both for the selected experimental data and our model calculation. The nuclei included in the fits are helium, neon, krypton and xenon nuclei.

ν	experiment		theory	
	$c[10^{-2}]$	κ	$c[10^{-2}]$	κ
	$0.2<z<0.4$			
11.04	4.26±3.93	0.39±0.20	1.49±0.91	0.60±0.13
13.01	3.87±4.01	0.39±0.22	1.23±0.75	0.61±0.13
15.00	2.98±3.59	0.43±0.25	1.06±0.64	0.61±0.13
16.99	3.16±3.73	0.40±0.25	0.93±0.55	0.61±0.13
18.98	3.16±3.76	0.38±0.25	0.84±0.49	0.61±0.13
21.57	3.01±3.91	0.34±0.27	0.76±0.43	0.61±0.12
z	$12<\nu<17$ GeV			
0.25	2.74±3.59	0.44±0.27	1.00±0.47	0.63±0.10
0.35	3.54±3.60	0.41±0.22	1.25±0.59	0.62±0.10
0.55	3.21±2.93	0.46±0.19	1.81±0.84	0.61±0.10
	$17<\nu<23.5$ GeV			
0.34	2.93±3.55	0.39±0.26	0.97±0.70	0.60±0.15
0.44	2.32±3.14	0.45±0.28	1.17±0.84	0.60±0.15
0.55	2.27±3.27	0.48±0.30	1.41±1.03	0.59±0.16
0.64	1.63±3.10	0.55±0.37	1.77±1.27	0.59±0.15

are in general smaller than those from the experimental data. The fact indicates that the exponent κ and coefficient c are strongly correlated.

In consideration of the strong correlation between the exponent κ and coefficient c, we further assume the hadron attenuation $1-R_{\rm M}^{\pi}$ in terms of the power law:

$$1-R_{\rm M}^{\pi}=cA^{2/3}. \tag{13}$$

Here the coefficient c is a free parameter. The best-fit parameter c can be pinned down by chi-square minimization. Table 2 summarizes the coefficient c and χ^2/ndf by the fit $1-R_{\rm M}^{\pi}=cA^{2/3}$ for pion production at fixed ν and z values from the selected experimental data and our model calculation. It is shown that the values of coefficient c increase (decrease) with increasing values of $z(\nu)$. Regarding the numerical results from our model, the atomic mass number dependence of hadron attenuation is shown to agree well with the $A^{2/3}$ power law. In addition, the computed results from the selected experimental data with the quark hadronization occurring outside the nucleus, are overall consistent with the theoretical prediction on $1-R_{\rm M}^{\pi}\sim A^{2/3}$ from the parton energy loss model. Therefore, we can conclude apparently that with marked difference from the relative research results [20–22], our model and the selected experimental data from HERMES conditionally support the power law $1-R_{\rm M}^{\pi}\sim A^{2/3}$.

Table 2. The coefficient c and χ^2/ndf by the fit $1-R_{\rm M}^{\pi}=cA^{2/3}$ for pion production at fixed ν and z bins, both for the selected experimental data and our model calculation. The nuclei included in the fits are helium, neon, krypton and xenon nuclei.

ν	experiment		theory	
	$c[10^{-2}]$	χ^2/ndf	$c[10^{-2}]$	χ^2/ndf
		$0.2<z<0.4$		
11.04	1.19±0.20	1.83	1.12±0.25	0.20
13.01	1.08±0.21	1.37	0.94±0.21	0.20
15.00	1.01±0.21	1.07	0.82±0.19	0.20
16.99	0.93±0.19	1.06	0.72±0.16	0.20
18.98	0.84±0.18	1.11	0.65±0.15	0.20
21.57	0.66±0.18	1.11	0.59±0.13	0.21
z		$12<\nu<17$ GeV		
0.25	0.97±0.21	0.85	0.83±0.11	0.34
0.35	1.10±0.18	1.37	1.00±0.14	0.38
0.55	1.25±0.16	1.61	1.39±0.19	0.43
		$17<\nu<23.5$ GeV		
0.34	0.81±0.17	1.03	0.72±0.14	0.17
0.44	0.87±0.17	0.86	0.85±0.17	0.18
0.55	0.94±0.18	0.49	1.01±0.20	0.18
0.64	0.96±0.20	0.50	1.25±0.23	0.19

4 Summary

Hadron production in lepton-nucleus deep inelastic scattering is intrinsically a non-perturbative QCD process without the reliable QCD calculations. In the proposed quark energy loss model, the experimental data with the quark hadronization occurring outside 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 it with the selected HERMES experimental results for pions produced on helium, neon, krypton and xenon nuclei. Our results show that the theoretical expectations with the fragmentation functions modified due to quark energy loss are in good agreement with the experimental data. We obtain the outgoing quark energy loss per unit path length α=0.440±0.013 GeV/fm from the global fit of all selected data. As for quark hadronization occurring outside the nucleus, it is demonstrated quantitatively that the mass number dependence of the hadron attenuation $1-R_{\rm M}^{\rm h}$ agrees well with the $A^{2/3}$ power law from both the selected experimental data and our model calculation. Our study manifests that the process of hadronization in cold nuclear matter is most probably a combination of the parton energy loss and hadronic absorption.

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