PARTICLE PRODUCTION AND PROPAGATION IN NUCLEI*

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(Received November 17, 2003)

We discuss the effects of gluon radiation by the struck quark and the subsequent absorption of the produced hadron in deep inelastic lepton-nucleus scattering. The theoretical picture is compared with HERMES results on multiplicity ratios.

PACS numbers: 25.30.Fj, 25.75.Dw

The fragmentation of light quarks is still not completely understood. The nucleus helps to understand the space time evolution of a parton, since the nucleons play the role of very nearby detectors of the propagating object. Deep inelastic electron nucleus scattering has the advantage that the electron gives a well defined energy ν to the struck quark propagating through cold nuclear matter. The understanding of this process is crucial for the interpretation of ultra-relativistic proton–nucleus and nucleus-nucleus collisions. Due to factorization in deep inelastic scattering the semi-inclusive cross section can be described by the product of a parton distribution function (PDF) with a fragmentation function (FF) *cf.* Fig. 1. In the parton model the probability that a quark with momentum fraction x is present in the target is multiplied with the probability that it hadronizes into a definite hadron which carries a momentum fraction z of the quark. Inclusive electron proton and electron nucleus scattering allows to measure the structure function in both types of targets. Quark hadronization and hadron production can be studied independently in e^+e^- annihilation. Fig. 1 shows a schematic

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.

diagram of semi-inclusive deep inelastic lepton scattering (SIDIS) on a target T, and the definitions of the four momenta of the particles involved in the process. In SIDIS besides the scattered lepton l' the leading hadron h formed from the struck quark is detected with energy $E_h = z\nu$ in the target rest frame. The summation over flavors includes the product of the fragmentation functions and structure functions for each flavor. The experimental data on nuclear effects in hadron production are usually presented in terms of multiplicity ratios as functions of z,ν or recently Q:

$$R_{\rm M}^h(z) = \frac{1}{N_A^\ell}\frac{dN_A^h}{dz} \Big/ \frac{1}{N_D^\ell}\frac{dN_D^h}{dz}. \tag{1}$$

In the above definitions N_A^ℓ is the number of outgoing leptons in DIS processes on a nuclear target of atomic number A, while dN_A^h/dz is the z-distribution of produced hadrons in the same processes; the subscript D refers to the same quantities when the target is a deuteron. In absence of nuclear effects the ratio $R_{\rm M}^h$ would be equal to 1.

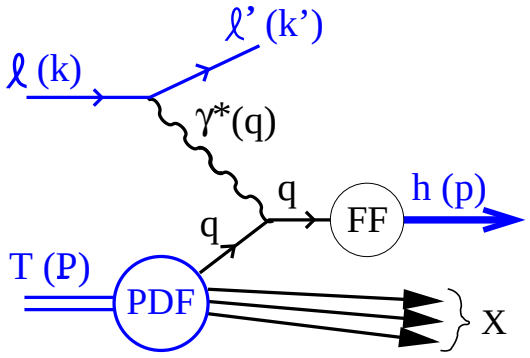


Fig. 1. Semi-inclusive hadron production in deep inelastic scattering on a target T in the pQCD factorization approach. Parton distribution functions (PDF) and fragmentation functions (FF) represent the non-perturbative input.

The HERMES [1] experiment has brought new insight into the question, since it has access to lower energy transfers ν, where the hadronization occurs inside the nucleus,and to a larger range of fractional momenta z which determine the formation length of the hadron. In this paper we give an introductory overview of the different models used in describing hadron production in deep inelastic scattering. These include "QCD inspired" analyses such as the rescaling model [2], energy loss models (with and without higher twist [3–5]), the gluon-bremsstrahlung calculation for leading hadron production [6], and nuclear absorption of the prehadron [2, 7]. For a survey of other approaches we refer to [8]. We also would like to mention the recent

review by the CERN study group on "Hard Probes in Heavy Ion Collisions at the LHC: Jet Physics" [9], which covers the problem of hadronization in a hot medium. This short note will only address the problem of hadronization in deep inelastic scattering.

Parton distribution functions and fragmentation functions both depend on the virtuality Q^2 of the DIS process. This adjustment to the scale Q^2 takes into account all radiated gluons before and after the photon quark interaction in the leading logarithm approximation. In nuclei gluon radiation may be affected by the partial deconfinement of color which follows from overlapping nucleons. The long wavelength spectrum of gluons extends farther into the infrared towards low $Q^2 \propto 1/\lambda^2$ where λ is the confinement scale.

Therefore in DGLAP evolution in nuclear structure and fragmentation functions the starting scale is smaller and they evolve over a larger interval in momentum compared with the corresponding functions in the nucleon at the same scale Q. The solution of the DGLAP equation gives $q_{\rm f}^A(x,Q) = q_{\rm f}(x,\xi_A(Q)Q)$ and $D_{\rm f}^{h|A}(z,Q) = D_{\rm f}^h(z,\xi_A(Q)Q)$, where the scale factor $\xi_A(Q)$ is related to the deconfinement scale λ_A which is proportional to the overlap of nucleons inside the given nucleus. Typical values of the scale factor are $\xi_A = 1.2$ for Kr or Xe. The multiplicity ratio is calculated by using the rescaled parton distribution functions and the rescaled fragmentation functions. Because of the ν dependence of the fragmentation process in DIS on nuclei the assumption of factorization is certainly open to criticism. Most models do not derive the fragmentation process from scratch and only manipulate the factorized formula

$$\frac{1}{N_A^\ell}\frac{dN_A^h}{dz} = \frac{1}{\sigma^{\gamma^* A}} \int\limits_{\text{exp. cuts}} dx\, d\nu \sum_{\rm f} e_{\rm f}^2\, q_{\rm f}^{(A,Z)}(x,\xi_A\, Q)\, \frac{d\sigma^{\gamma^* q}}{dx\, d\nu}\, D_{\rm f}^h(z,\xi_A\, Q). \quad (2)$$

In the formula above $e_{\rm f}$ is the electric charge of a quark of flavor f, $d\sigma^{\gamma^* q}/dx\, d\nu$ is the differential cross-section for a $\gamma^* q$ scattering computed in pQCD at leading order. Due to Lorentz dilatation, at large values of ν the hadrons are expected to form mainly outside the nucleus, so that the effect of reinteractions of the hadron with the nucleus are minimal. Gluon radiation is also induced by scatterings of the struck quark with the nucleons in the nucleus. Various ideas have been proposed to calculate this process. Medium induced gluon radiation [3] leads to an energy loss per unit length

$$\frac{dE}{dL} = -\frac{3}{2}\alpha_{\rm s}\langle p_{\rm t}^2\rangle_L = -\frac{3}{2}\alpha_{\rm s}\langle p_{\rm t}^2\rangle_0 \frac{L}{\lambda} \quad (3)$$

which is proportional to the acquired $\langle p_{\rm t}^2\rangle_L$ along the path length L. Because of the random walk in transverse space the total transverse momentum

can be calculated from each individual momentum transfer times the number of collisions, which is related to the mean free path λ. Numerically in cold matter the energy loss proposed by various authors varies between 0.19 GeV/fm$< dE/dL <$ 0.5 GeV/fm for $L = 5$ fm *cf.* Ref. [9]. In specific models there is either a $1/Q^2$ dependence, *i.e.* a higher twist dependence, or a logarithmic dependence on Q^2 for the energy loss. If there would be only energy loss (which we do not believe) and no absorption in the HERMES regime, then typical numbers on the upper edge of this band are needed to reproduce the experimental data on $R_{\rm M}$. Once a prehadron has been produced, it can be absorbed in the nucleus, *i.e.* make an inelastic collision and change its z fraction. In the gluon bremsstrahlung model [6] the time scale for prehadron formation is related to the gluon coherence time which is determined by the light cone energy difference between the gluon quark system and the quark:

$$t_{\rm coh} = \frac{2\nu z(1-z)}{k_{\rm t}^2}\,. \tag{4}$$

Therefore the prehadron formation time is short for large z and small z. It increases with z because of Lorentz time dilatation and it is small for large z, since the hadron has to be formed instantaneously, otherwise the energy loss downstream is too large. In Ref. [6] the gluon radiation model is constructed based on this formation time. It has the nice feature that it is mainly perturbative and therefore is well suited to the large Q^2 physics of deep inelastic scattering. In practice, however, the problem lies in combining a probability for quark gluon formation which is integrated over the characteristic resolution of the gluons with the overlap matrix element between the quark gluon state and the hadron. Here further development is needed.

Let me finally come to report about the status of the work by Accardi, Muccifora and myself [2]. In order to treat the multiplicity ratios in the low-ν region adequately, we consider the formation of the prehadron and its subsequent interaction in the nuclear medium. As the hadron formation length $l_{\rm f}$ decreases by decreasing ν, the effect of nuclear interaction becomes more relevant in the kinematic region of HERMES relative to EMC , and the effect is amplified in a heavy target as the formation length $l_{\rm f}$ is of the same size as the nuclear radius. Our theoretical model follows closely the Lund model for the fragmentation process [10]. The space-time development of the fragmentation process begins when the quark q is ejected from a nucleon. The quark propagates and the color string between the quark and the remnant breaks into smaller pieces. Hadrons are ordered according to their rank i. Note that the first-rank hadron is always created at the end after the original quark has traversed a distance L.

$$L = \frac{\nu}{\kappa} \tag{5}$$

where κ is the string tension. This length can be very large but this does not mean that long strings exist in the nucleus, because the string breaks and prehadrons are formed. In the original paper [2] we choose a prehadron cross section equal to the hadron cross section and adjusted the string tension to fit the data. We think it is more realistic that the prehadron coming from gluon radiation of the struck quark is smaller than the final hadron. In a new paper in preparation good results are obtained with $\sigma(prehadron) \approx 1/3\sigma(hadron)$ and keeping the string tension $\kappa = 1$ GeV/fm. There are two relevant lengths for the fragmentation process, the position l_* at which the prehadron is formed and the distance $l_h \leq L$ at which the hadron is formed. In the Lund model these two lengths are related: [10]:

$$l_h = l_* + zL \ . \tag{6}$$

At fixed z they both increase linearly with the virtual photon energy ν. However, as functions of z they behave rather differently, especially at $z \to 1$, where $l_* \to 0$ and $l_h \to L$. We have calculated the prehadronic formation length $\langle l_{\rm F} \rangle$ in the Lund model which behaves as $\langle l_{\rm F} \rangle \to \frac{1}{\kappa}(1-z)\nu$ as $z \to 1$, in agreement with the formation length suggested by the gluon bremsstrahlung model [6]. We introduce a nuclear absorption factor $\mathcal{N}_A(z,\nu)$ which is calculated in the Bialas–Chmaj (BC) model [7]. It represents the probability that neither the prehadron nor the hadron has interacted with a nucleon. The multiplicity ratio then reads as follows:

$$\frac{1}{N_A^\ell}\frac{dN_A^h}{dz} = \frac{1}{\sigma^{\gamma^* A}} \int\limits_{\text{exp. cuts}} dx\, d\nu \sum_{\rm f} e_{\rm f}^2\, q_{\rm f}(x, \xi_A\, Q)\, \frac{d\sigma^{\gamma^* q}}{dx\, d\nu}\, D_{\rm f}^h(z, \xi_A\, Q)\, \mathcal{N}_A(z,\nu)\,. \tag{7}$$

We compare our theoretical predictions with the HERMES data.

The rescaling plus absorption model gives the respective multiplicity ratios shown in Ref. [1]. In Fig. 2 one sees that the general agreement is rather satisfactory, only the K^- spectra are not accurately predicted. The very exact HERMES data demand a consideration of the details of fragmentation. The K^- mesons contain $\bar{u}s$ quarks which are not valence quarks of the proton, therefore they can only be created as second rank hadrons. We are currently considering differences in kaon, pion, proton and antiproton spectra which are due to different fragmentation processes.

In summary, the rescaling plus nuclear absorption model [2] can describe the HERMES data on the nuclear modification of hadron production in DIS processes quite well. A more reasonable choice of parameters with the vacuum string tension and a smaller prehadronic cross section does not change this property. The A-dependence in the absorption model is simple. If there is total absorption, then the number of produced hadrons is proportional to

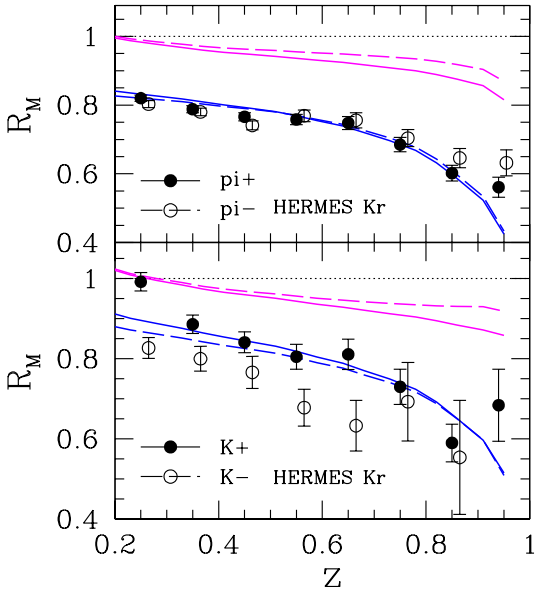


Fig. 2. z-distributions for charge- and flavor-separated hadrons at HERMES on Krypton target. The upper pair of curves includes rescaling without absorption, and the lower pair rescaling plus Bialas–Chmaj absorption with an effective string tension 0.4 GeV/fm.

$A^{2/3}$ for large nuclei since only hadrons from the away surface of the nucleus can contribute to the cross section. The nuclei analysed so far experimentally are not so heavy, then the A-dependence becomes z- and ν-dependent. To assess the usefulness of this variable, quantitative analyses in different models are needed. If one studies the Q^2 dependence of the multiplicity ratios one sees a weak rise of $R_{\rm M}$ at small Q^2 followed by an extended plateau. This points to gluon radiation before the prehadron is formed. Probably in most cases of the HERMES experiment the prehadron is produced rather quickly and the gluon is radiated only along a short path, but the radiation has to be analysed in order to derive the needed prehadron cross section from color transparency. Finally in high energy nucleus–nucleus collisions many more challenges lie ahead. The hope is that one can use the knowledge from deep inelastic scattering in nuclei to deduce carefully the properties of the new matter which the particles have traversed.

I am very grateful to A. Accardi, V. Muccifora and B. Kopeliovich for discussions. I thank all organizers, especially A. Bialas for the very stimulating meeting in Cracow. This work is partially funded by the exchange program between the universities of Cracow and Heidelberg.

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