Hadron formation in electron induced reactions at HERMES energies

T. Falter, W. Cassing, K. Gallmeister and U. Mosel

Institut fuer Theoretische Physik, Universitaet Giessen, D-35392 Giessen, Germany

Abstract. We investigate meson electroproduction off complex nuclei in the kinematic regime of the HERMES experiment using a semi-classical transport model which is based on the Boltzmann-Uehling-Uhlenbeck (BUU) equation. We discuss coherence length and color transparency effects in exclusive $\rho^0$ production as well as hadron formation and attenuation of charged pions, kaons, protons and anti-protons in deep inelastic lepton scattering off nuclei.

High energy meson electroproduction off complex nuclei offers a promising tool to study the physics of hadron formation. The relatively clean nuclear environment of electron induced reactions makes it possible to investigate the timescale of the hadronization process as well as the properties of hadrons immediately after their creation. In addition one can vary the energy and virtuality of the exchanged photon to examine the phenomenon of color transparency (CT).

In previous works [1, 2, 3] we have developed a method to combine the quantum mechanical coherence in the entrance channel of photonuclear reactions with a full coupled channel treatment of the final state interactions (FSI) in the framework of a semi-classical transport model. This allows us to include a much broader class of FSI than usual Glauber theory.

In our approach the lepton-nucleus interaction is split into two parts: 1) In the first step the electron emits a virtual photon which is absorbed on a nucleon of the target nucleus; this interaction produces a bunch of particles that in step 2) are propagated within the transport model. The virtual photon-nucleon interaction itself is simulated by the Monte Carlo generator PYTHIA v6.2 [4] which well reproduces the experimental data on a hydrogen target. Instead of directly interacting with a quark inside the target nucleus the virtual photon might fluctuate into a vector meson ($\rho^0; \omega; \Phi; J^P=1^-$) or perturbatively branch into a $q\bar{q}$ pair before the interaction. While the latter is very unlikely in the kinematic regime of the HERMES experiment as we have shown in Ref. [3] the vector meson fluctuations become important at low $Q^2$ and clearly dominate the exclusive vector meson production measured at HERMES. The coherence length, i.e., the length that the photon travels as such a vector meson fluctuation $V$ can be estimated from the uncertainty principle:

$$l_V = \frac{2\nu}{Q^2 + m_V^2}:$$

Here $\nu$ denotes the energy of the photon, $Q^2$ its virtuality and $m_V$ the mass of the vector meson fluctuation. If $l_V$ becomes larger than the internucleon distance in the nucleus...
the interactions triggered by the vector meson component $V$ get shadowed in nuclear reactions \cite{2,3}.

A direct photon interaction or a non-diffractive interaction of one of the hadronic fluctuations leads to the excitation of one or more hadronic strings which finally fragment into hadrons. The time, that is needed for the fragmentation of the strings and for the hadronization of the fragments, we denote as formation time $\tau_f$ in line with the convention in transport models. For simplicity we assume that the formation time is a constant $\tau_f$ in the rest frame of each hadron and that it does not depend on the particle species. We recall, that due to time dilatation the formation time $t_f$ in the laboratory frame is then proportional to the particle’s energy

$$t_f = \gamma \tau_f = \frac{z_h V}{m_h} \tau_f. \quad (2)$$

Here $m_h$ denotes the hadron’s mass and $z_h$ is the energy fraction of the photon carried by the hadron. The size of $\tau_f$ can be estimated by the time that the constituents of the hadrons need to travel a distance of a typical hadronic radius (0.5–0.8 fm).

The formation time also plays an important role in the investigations of ultra-relativistic heavy ion reactions. For example, the observed quenching of high transverse momentum hadrons in $Au + Au$ reactions relative to $p + p$ collisions is often thought to be due to jet quenching in a quark gluon plasma. However, the attenuation of high $p_T$ hadrons might also be due to hadronic rescattering processes \cite{5} if the hadron formation time $\tau_f$ (in its rest frame) is sufficiently short.

We assume that hadrons, whose constituent quarks and antiquarks are created from the vacuum in the string fragmentation, do not interact with the surrounding nuclear medium within their formation time. For the leading hadrons, i.e. those involving quarks (antiquarks) from the struck nucleon or the hadronic components of the photon, we assume a reduced effective cross section $\sigma_{\text{lead}}$ during the formation time $\tau_f$ and the full hadronic cross section $\sigma_h (h = \pi, K, p, \ldots)$ later on. The hadrons with $z_h$ close to one are predominantly leading hadrons and can interact directly after the photon-nucleon interaction. Particles that emerge from the middle of the string might escape the nucleus due to time dilatation. However, about 2/3 of these intermediate $z_h$ hadrons (mainly pions) are created from the decay of vector mesons that have been created in the string fragmentation. Because of their higher mass $m_h (0.77 – 1.02$ GeV) these vector mesons may form (or hadronize) inside the nucleus (see Eq. (2)) and thus be subject to FSI. The effect of the FSI, finally, will depend dominantly on the nuclear geometry, i.e. the size of the target nucleus.

The FSI are described by a coupled-channel transport model based on the Boltzmann-Uehling-Uhlenbeck (BUU) equation. For the details of the model we refer the reader to Ref. \cite{6}. The important difference to a purely absorptive treatment of the FSI is that the particles resulting from the $\gamma A$ reaction do not have to be created in the primary $\gamma N$ interaction. In a FSI with a nucleon a hadron might not only be absorbed but also be decelerated in an elastic or inelastic collision. Furthermore, it may in addition produce several low energy particles. In the case of electroproduction of hadrons this finally leads to a redistribution of strength from the high $z_h$ part of the hadron energy spectrum to lower values of the energy fraction $z_h$. 
In Fig. 1 we show the transparency ratio

\[ T_A = \frac{\sigma_{\gamma A!}^{\rho N}}{A \sigma_{\gamma N!}^{\rho N}} \]  

for exclusive \( \rho^0 \) production as a function of the coherence length \( l_{\rho^0} \) in comparison with the HERMES data \[7\]. The solid line displays the result that one gets if one uses our Glauber expression from Ref. \[3\].

The result of the transport model is represented by the open squares. For each data point we have made a separate calculation with the corresponding values of \( \nu \) and \( Q^2 \).

After applying all of the experimental cuts from Ref. \[7\], nearly all of the detected \( \rho^0 \) stem from diffractive \( \rho^0 \) production for which we assume zero formation in the calculations. The \( N \) data seems to support the assumption that the time needed to put the preformed \( \rho^0 \) fluctuation on its mass shell and let the wave function evolve to that of a physical \( \rho^0 \) is small for the considered values of \( Q^2 \). Furthermore, the photon energy is too low to yield a large enough \( \gamma \) factor to make the formation length exceed the internucleon distance and make CT visible. This conclusion is at variance with that reached in Ref. \[8\] where the authors also stress that one might see an onset of CT when investigating the transparency ratio as a function of \( Q^2 \) for fixed coherence length.
FIGURE 2. Calculated multiplicity ratios of $\pi^+$, $\pi^-$, $K^+$, $K^-$, $p$ and $\bar{p}$ for $Kr$ using a fixed leading hadron cross section $\sigma_{lead} = 0.33\sigma_0$ and formation time $\tau_f = 0.5$ fm/c. The experimental data has been taken from Ref. [16].

We now turn to $Kr$ where we expect a stronger effect of the FSI. Unfortunately there is yet no data available to compare with. As can be seen from Fig. 1 the transport calculation for $Kr$ gives a slightly smaller transparency ratio than the Glauber calculation, especially at low values of the coherence length, i.e. small momenta of the produced $\rho^0$. There are two reasons for this: About 10% of the difference arises from the fact that within the transport model the $\rho^0$ is allowed to decay into two pions. The probability that at least one of the pions interacts on its way out of the nucleus is about twice as large as that of the $\rho^0$. The other reason is that in the Glauber calculation only the inelastic part of the $\rho^0N$ cross section enters whereas the transport calculation contains the elastic part as well. Thus all elastic scattering events out of the experimentally imposed $t$-window are neglected in the Glauber description. It is because of this $t$-window that also elastic $\rho^0N$ scattering reduces the transport transparency ratio shown in Fig. 1. Both effects are more enhanced at lower energies and become negligible for the much smaller $N$ nucleus.

In Ref. [9] we investigated the energy $\nu$ and fractional energy $z_h = E_h/\nu$ dependence of the charged hadron multiplicity ratio

$$R_M^h (z; \nu) = \frac{N_h (z; \nu)}{N_e (\nu)} A \frac{N_h (z; \nu)}{N_e (\nu)} D$$

(4)
in DIS off nuclei and compared with the \( N \) and \( Kr \) data from the HERMES collaboration. In Eq. (4) \( N_h(\zeta;\nu) \) represents the number of semi-inclusive hadrons in a given \((\zeta;\nu)\)-bin and \( N_e(\nu) \) the number of inclusive DIS leptons in the same \( \nu \)-bin.

In Ref. [12] the observed \( R^M_M \) spectra were interpreted as being due to a combined effect of a rescaling of the quark fragmentation function in nuclei due to partial deconfinement as well as the absorption of the produced hadrons. Furthermore, calculations based on a pQCD parton model [13, 14] explain the attenuation observed in the multiplicity ratio solely by partonic multiple scattering and induced gluon radiation neglecting any hadronic FSI. It has already been pointed out by the authors of Ref. [12] that a shortcoming of the existing models is the purely absorptive treatment of the FSI. We avoid this problem by using the coupled-channel transport model.

In Ref. [9] we used the high \( \zeta_h \) part of the charged hadron data from Ref. [11] to fix the leading hadron cross section to \( \sigma_{\text{lead}} = 0.33 \sigma_h \) during the formation time. The data for \( N \) and \( Kr \) could then be well described using a formation time \( \tau_f > 0.3 \text{fm/c} \) for all hadrons. This value is compatible with the analysis of antiproton attenuation in \( p + A \) reactions at AGS energies [15].

In Fig. 2 we show the results for the calculated multiplicity ratio of \( \pi^- \), \( \pi^+ \), \( K^- \), \( K^+ \), \( p \) and \( \bar{p} \) for \( Kr \) in comparison with the experimental data [16]. In our calculations we use the kinematic cuts of the HERMES experiment and take the detector geometry into account. We use a constant formation time of 0.5 fm/c and again scale all leading hadron cross sections with the same factor 0.33 during the formation time. Without further fine tuning we get a satisfying description of all the data meaning that the formation times of mesons, baryons and antibaryons are about equal.

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