Color Transparency and Quark Propagation

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Abstract: Experiments with unpolarized nuclear targets at HERMES can be used to obtain data on exclusive ρ^0 electroproduction and semi-inclusive hadron production. The $A(e,e'\rho^0)$ data have the potential of providing evidence for the color transparency hypothesis. The semi-inclusive data can provide detailed information on the effect of the nuclear medium on quark propagation. Estimates are presented of the data quality that can be obtained for a range of nuclear targets.

1 Introduction

During its first year of operation the HERMES experiment has demonstrated its capability for measuring nucleon spin-structure functions in deep-inelastic scattering. The same apparatus can also be used for measurements on unpolarized $A > 3$ nuclear gas targets, in which the nuclear medium acts as a probe of non-perturbative QCD effects. In particular, the effect of the nuclear medium on hadron production in deep-inelastic scattering can be studied. The prospects for two such experiments at HERMES are discussed in this paper.

In semi-inclusive deep-inelastic scattering the struck quark will propagate over a certain distance (and time) before interactions with other quarks (and gluons) lead to the production of the detected hadron. When the quark propagation process is embedded in the nuclear medium, the number of hadrons produced will depend on the interaction of the propagating quark with neighboring nucleons. Experiments at SLAC [1] and CERN [2] have yielded first evidence for a modification of the quark-propagation process in the nuclear medium. Semi-inclusive measurements at HERMES on various nuclear targets will enable a systematic study of quark-propagation, thus providing the first quantitative data on the formation time $\tau_{\rm form}$.

Exclusive ρ^0 electroproduction on nuclei is expected to be a sensitive means of searching for color transparency, the proposed reduction of initial and final state interaction effects in nuclei due to the formation of a hadron of small initial transverse size. Data from the recent Fermilab deep-inelastic muon scattering experiment E665 contain a hint of color transparency in the reaction $A(\mu,\mu'\rho^0)$ [3]. Compared to E665, $A(e,e'\rho^0)$ measurements at HERMES have the advantage of higher statistical precision and considerably better missing energy resolution ($\sim 0.5\,$GeV instead of 5 GeV), which should allow improved exclusion of contamination from other reaction channels. Moreover, at HERMES the data can also be used to determine $\tau_{\rm exp}$, the time it takes for an exclusively produced ρ^0 meson to expand from an initial color-transparent point-like configuration to its usual size. The expansion time is closely related to the hadron formation time $\tau_{\rm form}$, and is probably similar in magnitude. The proper times $\tau_{\rm form}$ and $\tau_{\rm exp}$ are fundamental properties determined by hadron internal dynamics, and should not vary with kinematics or target.

2 Color Transparency in $A(e, e'\rho^0)$

The nuclear transparency T_A is defined as the ratio of the measured exclusive cross section to the cross section in the absence of initial and final state interactions (ISI and FSI). It can be measured by taking the ratio of nuclear per-nucleon to free nucleon cross sections:

$$T_A = \frac{\sigma_A}{A\sigma_N}. \tag{1}$$

Elastic and inelastic ISI and FSI can move flux out of the experimental acceptance or from exclusive to non-exclusive channels, resulting in $T_A \leq 1$. In 1982 Mueller and Brodsky [4] proposed the color-transparency effect: the ISI and FSI should be suppressed at high Q^2 and ν because the exclusive reaction selects or produces hadrons in a spatially small, non-interacting state (the point-like configuration or PLC). Three experiments have searched for the resulting increase in the nuclear transparency, using the reactions $A(p, 2p)$ [5], $A(e, e'p)$ [6], and $A(\mu, \mu'\rho^0)$ [3]. None has yielded a consistent, unambiguous confirmation of the phenomenon.

There are three necessary conditions for color transparency: (i) the exclusive reaction mechanism must select or produce hadrons of reduced transverse size (the point-like configuration); (ii) the small hadrons must experience reduced initial and final-state interactions (color screening); and (iii) the hadrons must remain small long enough to produce a detectable enhancement of nuclear transparency. Color screening is fairly well-justified experimentally and theoretically for all three reactions [4]. Dominance of the point-like configuration in the reaction mechanism at moderate Q^2 values is on much stronger theoretical ground for the reaction $A(e, e'\rho^0)$ than for the reactions $A(p, 2p)$ and $A(e, e'p)$. Qualitatively this can be understood from the mechanism that is assumed to dominate the exclusive, incoherent $A(e, e'\rho^0)$ reaction, i.e. a ρ^0 meson is produced as a fluctuation of a short-wavelength virtual photon into a small-sized quark-antiquark pair.

Count rates for exclusive, incoherent ρ^0 production were estimated on the basis of the preliminary analysis of the 1995 HERMES data for ρ^0 production on ^{3}He. The A-dependence observed in the Fermilab E665 $A(\mu, \mu'\rho^0)$ [3] experiment were used to extrapolate the rates to different nuclei. Figure 1 shows the expected precision for nuclear transparency measurements, assuming that σ_N is determined from the ^{1}H and ^{2}H data only (we expect $T_{^2\rm H} \approx 1$). A month of data taking for each target is assumed, where one month is assumed to contain 30 fills of 6.7 hours each, with an average current of 20 mA. For the target thickness the maximum number of nucleons per cm^2 commensurate with a HERA positron life time of 45 hours is taken. Expected improvements in the extraction of $A(e, e'\rho^0)$ events should lead to significantly better statistical accuracy than shown in the figure.

If color transparency is observed, the nuclear transparency $T_A(Q^2, \nu)$ at high Q^2 will exhibit a dependence on ν. At low ν the ISI and FSI correspond to those of the ρ^0-meson, while at high ν, T_A probes the much weaker interaction of the point-like configuration. The midpoint in the variation in T_A occurs at lab frame expansion time $t_{\rm exp} = \gamma\tau_{\rm exp} \approx R_A$. For typical

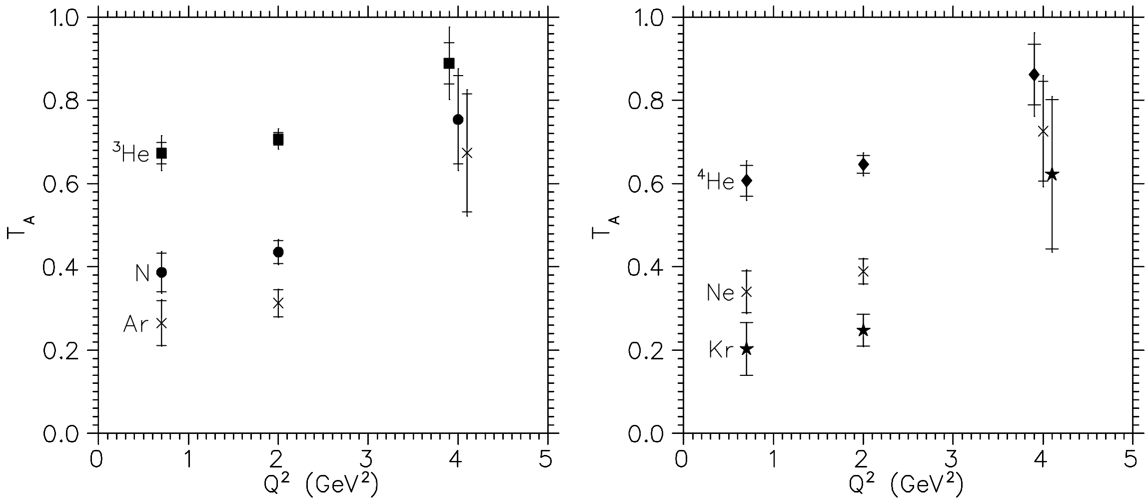

Figure 1: *Nuclear transparency T_A for the candidate $A > 3$ targets, with errors expected after 30 fills. The inner error bars show the errors expected in the limit of very large statistics on ^1H (applicable in the case of future ^1H data from a laser-driven source).*

PLC expansion models, this is approximately where $dT_A/d\nu$ is largest and sensitivity to $\tau_{\rm exp}$ is maximal:

$$\tau_{\rm exp} \approx \frac{R_A}{\gamma} \approx \frac{R_A M_\rho}{\nu}. \tag{2}$$

Therefore, HERMES not only has the potential of observing evidence for color transparency, but also first measurements of the expansion time τ_{exp} can be obtained.

3 Quark Propagation

The process of hadron formation in deep inelastic scattering cannot be calculated from first principles as it occurs at energy-momentum scales where pQCD is not applicable. Consequently phenomenological models have been developed to describe the process. In these models a formation time $\tau_{\rm form}$ is introduced representing the time between the primary hard interaction and the actual formation of the observed hadron. By embedding the hadron-formation process in the nuclear medium, one obtains an experimental tool to modify the formation process and thus obtain information on $\tau_{\rm form}$. In this section the prospects for such measurements at HERMES are discussed.

Experimental studies of quark-propagation inside the nuclear medium involve (among other observables) measurements of the "attenuation" ratio R_A of hadrons produced in semi-inclusive deep inelastic scattering off nuclear target A and the same yield measured on deuterium (D):

$$R_{\rm A}(z) = (\frac{1}{\sigma_A}\frac{d\sigma_A}{dz})/(\frac{1}{\sigma_D}\frac{d\sigma_D}{dz}), \tag{3}$$

where $d\sigma/dz$ is the cross section for the production of a hadron with fraction z of the energy transfer, and σ_A is the cross section for production of all hadrons. Note that R_A is the semi-inclusive analogue of the nuclear transparency in exclusive reactions such as $A(e, e'\rho^0)$. Due to reinteractions of the propagating quarks with the surrounding medium the quantity $R_{\rm A}(z)$

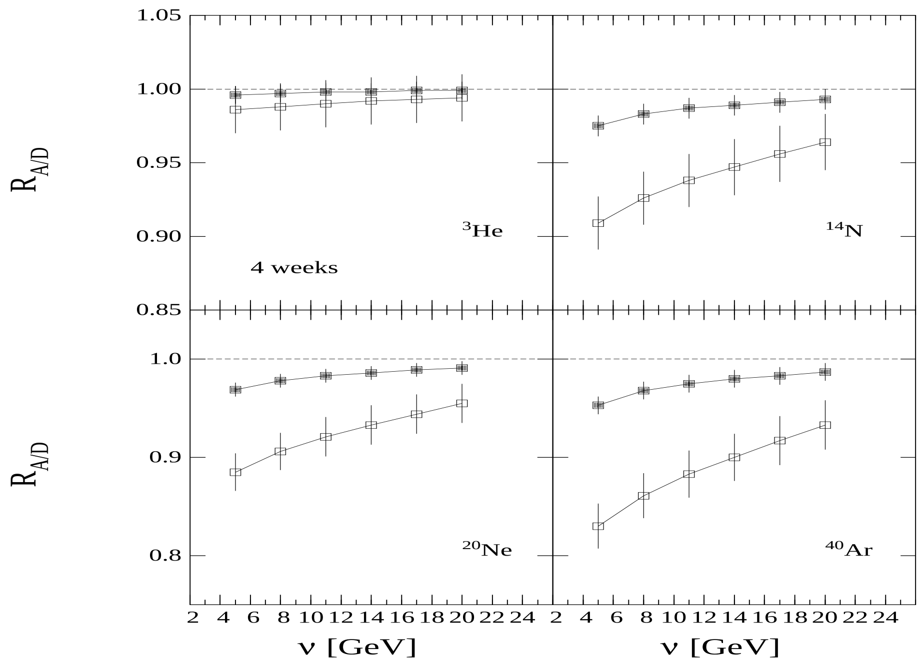

Figure 2: *Attenuation ratios for four different target nuclei. The solid (open) squares represent the results for detection of leading pions (protons). The error bars correspond to 30 fills at 20 mA average current with target thicknesses correponding to a 45 hr electron-beam lifetime.*

will be less than unity. The probability of such reinteractions is determined by the product of the quark-nucleon cross section σ_{qN} and the pathlength l_{form} traversed. Hence, a systematic study of $R_{\text{A}}(z)$ for various nuclei should provide quantitative information on σ_{qN} and l_{form}, or—equivalently—the time τ_{form}.

In the literature quite a few models have been proposed to describe quark propagation in the medium. Good overviews can be found in refs. [7], [8], and [9]. For our present purposes we will only consider the formulation proposed by Low and Gottfried [10]:

$$t_{\text{form}} = \gamma \tau_{\text{form}} \approx \left(\frac{E_h}{M_h}\right) \tau_{\text{form}} = \frac{z\nu}{M_h} \tau_{\text{form}}, \tag{4}$$

where γ is the Lorentz factor, and E_h and M_h represent the energy and mass of the detected hadron. In order to ensure that the detected hadron is a fragmentation product of the struck quark a *leading* hadron must be selected, *i.e.* $z = E_h/\nu > 0.5$. Using this expression for t_{form} (and assuming $\sigma_{qN} = 0$) the experimental prospects for measurements of $R_{\text{A}}(z)$ have been investigated.

Monte-Carlo simulations were performed with a modified version of the PEPSI code for selected nuclear targets. The acceptance of HERMES was only crudely implemented, omitting all details incorporated in a full Monte Carlo. On the basis of these simulations we have evaluated attenuation ratios for all gaseous nuclear targets mentioned in section 2. Selected results are displayed in figure 2 for leading pions and protons. The error bars displayed are based on the equivalent of 30 fills of running time at 20 mA beam average current and the maximum target thicknesses allowed by electron beam lifetime considerations. Hence, the simulated data correspond to the same running conditions as were used in section 2. The uncertainties also include a contribution from the ^{2}H data, *i.e.* it is assumed that the equivalent of 30 fills of unpolarized ^{2}H data at $n = 1.0 \times 10^{15}$ atoms/cm^2 is available.

In doing the simulations the following cuts were imposed: (i) $z \geq 0.5$; (ii) $Q^2 \geq 1.0\,(\mathrm{GeV/c})^2$; and $W \geq 2$ GeV. These cuts ensured the selection of semi-inclusive deep inelastic scattering events with a leading hadron that can be associated with the current quark.

As expected from the chosen expression of t_{form} the results show a strong dependence on the hadron type. In particular the protons are very sensitive to the medium effects. We conclude that data of the quality displayed in figure 2 will be a sensitive tool in selecting the appropriate model for quark-propagation processes.

4 Conclusion

The quality of the data that can be obtained at HERMES under standard beam conditions for measurements of transparency factors for exclusive incoherent ρ^0 production and semi-inclusive production of leading pions and protons has been evaluated. It has been shown that the equivalent of one month of data taking will yield data that could provide evidence of color transparency. At the same time the ν-distributions of semi-inclusively produced hadrons will provide information on the influence of the nuclear medium on quark propagation. Such data can be used to determine the hadron expansion and formation times.

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