Q^2 Dependence of Nuclear Transparency for Exclusive ρ^0 Production

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Exclusive coherent and incoherent electroproduction of the ρ^0 meson from ^{1}H and ^{14}N targets has been studied at the HERMES experiment as a function of coherence length (l_c), corresponding to the lifetime of hadronic fluctuations of the virtual photon, and squared four-momentum of the virtual photon ($-Q^2$). The ratio of ^{14}N to ^{1}H cross sections per nucleon, called nuclear transparency, was found to increase (decrease) with increasing l_c for coherent (incoherent) ρ^0 electroproduction. For fixed l_c, a rise of nuclear transparency with Q^2 is observed for both coherent and incoherent ρ^0 production, which is in agreement with theoretical calculations of color transparency.

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One of the fundamental predictions of QCD is the existence of a phenomenon called color transparency (CT), whose characteristic feature is that, at sufficiently high squared four-momentum transfer ($-Q^2$) to a hadron, the initial state and final state interactions of that hadron traversing a nuclear medium vanish [1–7]. The idea is that the dominant amplitudes for exclusive reactions at high Q^2 involve hadrons of reduced transverse size, and that these small color-singlet objects or small size configurations (SSC) have reduced interactions with hadrons in the surrounding nuclear medium. Moreover, it is assumed that these SSC remain small long enough to traverse the nucleus.

Several experiments in search of CT [8–11] have been carried out over the last 20 years. Although none of these experiments is in conflict with CT, only a few have shown evidence for it. The first evidence for CT came from quasifree charge exchange scattering data of 40 GeV/c negative pions on carbon [12] as suggested in Ref. [13]. Further evidence for CT comes from Fermilab experiment E791 on the A dependence of coherent diffractive dissociation of 500 GeV/c pions into di-jets [14]. This result shows a platinum to carbon cross section about 10 times larger than expected if soft processes would dominate, which is qualitatively consistent with theoretical calculations of CT effects [15,16]. Also experiment E665 on exclusive incoherent ρ^0 muoproduction from nuclei [17] gives an indication of CT. However, that signal is of indecisive statistical significance. In this Letter we report new evidence of CT in exclusive coherent and incoherent ρ^0 electroproduction using a novel analysis technique.

When searching for CT, a commonly used observable is the nuclear transparency $T = \sigma_A/(A\sigma_p)$, which is the ratio of the nuclear cross section per nucleon to that on the proton. For diffractive incoherent reactions on a nuclear target, where the nucleus is excited or breaks up, CT predicts that as Q^2 becomes large, T approaches unity, independent of A. For coherent reactions, where the interaction leaves the whole nucleus intact in its ground state, the same observable is used in spite of the fact that it can no longer be associated directly with the probability of escape of the hadron from the nucleus.

In order to study CT for exclusive electroproduction of ρ^0 mesons, one has to select a sample of ρ^0 mesons produced by photons with large Q^2. In these processes, the hadronic structure of a high energy virtual photon [18] in the form of a $q\bar{q}$ pair has a transverse size $r_\perp \sim 1/Q$ [3]. The $q\bar{q}$ fluctuation of the virtual photon can propagate over a distance l_c known as the coherence length. It is given [4,18] by $l_c = \frac{2\nu}{Q^2+M_{q\bar{q}}^2}$, where ν is the virtual photon energy and $M_{q\bar{q}}$ is the invariant mass of the $q\bar{q}$ pair. This SSC can propagate through the nuclear medium with little interaction. After the $q\bar{q}$ pair is put on-shell, it will evolve to a normal-size ρ^0 meson over a distance l_f called the formation length. It is a governing scale for the CT effect and is given [3] by $l_f = \frac{2\nu}{m_{V'}^2-m_V^2}$, where m_V is the mass of the ρ^0 meson in the ground state and $m_{V'}$ the mass of its first radial excitation.

The phenomena determining nuclear transparency form an intricate mixture of coherence and formation length effects. They have a different appearance for coherent and incoherent ρ^0 production. For incoherent production, the probability for the $q\bar{q}$ pair to interact with the nuclear medium increases with l_c until l_c exceeds the nuclear size [19,20]. For values of the l_c smaller than the nucleus, this coherence length effect [20] can mimic the Q^2 dependence of the nuclear transparency predicted by CT. For coherent ρ^0 production, in contrast, the nuclear form factor suppresses the apparent nuclear transparency. Small l_c corresponds to a large longitudinal momentum transfer ($q_c \sim 1/l_c$), where the form factor is small. Hence, T decreases with Q^2 in coherent production. This behavior cannot mimic CT, but also in this case, the coherence length effects can significantly modify the Q^2 dependence, thus obscuring the clean observation of a CT effect. In order to disentangle the effects of coherence length from those of CT, it is important to study the variation of T with Q^2, while keeping l_c fixed [21]. In this way, a change of T with Q^2 can be associated with the onset of CT.

A rigorous quantum mechanical description of the SSC evolution, based on the light-cone Green function formalism [21], naturally incorporates the effects of both coherence length and CT. In this formalism it is shown that the signature of CT is a positive slope of the Q^2 dependence of nuclear transparency at fixed coherence length for both coherent and incoherent ρ^0 production. We have sought this signature.

The data were obtained during the 1996–1997 running periods of the HERMES experiment in the 27.5 GeV HERA positron storage ring at DESY. Stored beam currents ranged from 5 to 40 mA. Integrated luminosities of 108 and 50 pb^{-1} were collected on ^{1}H and ^{14}N internal gas targets, respectively. The corresponding average target thicknesses were 10^{14} and 10^{15} nucleons/cm^2. The thicknesses were additionally varied by factors of 0.5 to 10, depending on how much the HERMES internal target was allowed to limit the HERA beam lifetime. The scattered e^+ and the $\pi^+\pi^-$ pair from the ρ^0 decay were detected in the HERMES spectrometer [22].

The ρ^0 production sample was extracted from events with exactly three tracks: a scattered positron and two oppositely charged hadrons, as described in detail in Ref. [20]. Events with π^0 mesons were excluded by disregarding events with an untracked cluster in the calorimeter. Evaluated for each event were the Bjorken scaling variable $x = Q^2/2m_p\nu$, with m_p the mass of the proton, the squared four-momentum transfer to the target $t' = t - t_0$, with t_0 its minimum value, and the photon-nucleon invariant mass squared $W^2 = m_p^2 + 2m_p\nu - Q^2$. The kinematic coverage in ν, x, and W is $5 < \nu < 24$ GeV, $0.01 < x < 0.35$, and $3 < W < 6.5$ GeV, with mean values of 13.3 GeV, 0.07, and 4.9 GeV, respectively.

The exclusive ρ^0 production signal was extracted in the kinematic region $-2 < \Delta E < 0.6$ GeV and $0.6 < M_{\pi\pi} < 1$ GeV, where $\Delta E = \nu - E_\rho + \frac{t}{2m_p}$ is the exclusivity variable [20,23] with E_ρ the energy of the produced ρ^0 meson, and $M_{\pi\pi}$ the invariant mass of the detected hadron pair, assuming that they were pions. In the analysis of nuclear transparency for coherent production, the exclusive ρ^0 mesons have been selected with $|t'| < 0.045$ GeV^2 for nitrogen and $|t'| < 0.4$ GeV^2 for hydrogen, while in the analysis for incoherent production the t' restriction was $0.09 < |t'| < 0.4$ GeV^2 for both data samples. The resolution of ΔE is about 0.25 GeV [23], and the t' resolution is about 0.008 GeV^2. It has been shown [20] that the incoherent t' slope parameter b_p for various nuclei is consistent with the hydrogen value $b_p = (7.08 \pm 0.3)$ GeV^{-2}, and that the observed Q^2 dependence of b_p agrees well with other existing data [24]. The coherent slope parameter on nitrogen, $b^{14}\mathrm{N} = (57.2 \pm 3.3)$ GeV^{-2}, is in agreement with the values predicted by the relationship $b_A \approx R_A^2/3$ [25], where R_A is the nuclear radius.

The background under the exclusive ρ^0 peak has been described earlier [20]. It is mainly caused by hadrons from semi-inclusive deep inelastic scattering (DIS). Part of this background is removed by excluding the region $|t'| > 0.4$ GeV^2, where the background dominates the ρ^0 yield. The remaining background ($6\% \pm 3\%$) is estimated from the number of events measured at $|t'| < 0.4$ GeV^2 and $\Delta E > 3$ GeV, and subtracted [20]. The double-diffractive contribution to the incoherent ρ^0 production cross section is found to be ($4\% \pm 2\%$) [23], for which the data were corrected. For coherent ρ^0 production the contamination due to double-diffractive dissociation is found to be less than 1%.

For incoherent ρ^0 production the nuclear transparency has been evaluated as $T_{\rm inc} = \sigma_{\rm inc}^A/(A\sigma_p) = N_{\rm inc}^A \mathcal{L}_p/(AN_p\mathcal{L}_A)$ [20], where p refers to ^{1}H, A refers to ^{14}N, $N_{\rm inc}^A$ is the number of incoherent events, N_p is the number of events on ^{1}H, and $\mathcal{L}_{A,p}$ is the effective luminosity of the nitrogen or hydrogen samples, corrected for detector and reconstruction inefficiencies. In addition, a "Pauli blocking" correction has been applied, which accounts for the absence of incoherent ρ^0 production on nitrogen at momentum transfers $|t'|$ smaller than the nuclear Fermi momentum [26].

For coherent ρ^0 production the quantity $T_c = \sigma_c^A/(A\sigma_p)$ is evaluated. Some additional correction factors have been applied to σ_c^A to extract T_c because different t' requirements have been applied to the nitrogen and the hydrogen data. These include the ratio of the different acceptance correction factors caused by the different t' regions selected, which has been obtained from Monte Carlo simulations of exclusive ρ^0 production in a 4π geometry and in the HERMES acceptance [23]; the radiative correction factors [27], which were calculated separately for nitrogen and hydrogen for each l_c bin; and the contamination of incoherent background in the coherent sample. No Q^2 dependence has been observed for the ratios of any of the correction factors.

The nuclear transparencies for coherent and incoherent ρ^0 production are presented in Fig. 1. The data for incoherent ρ^0 production supersede the previously published data [20], as the present analysis includes Pauli blocking corrections and the same requirement on t' over the entire coherence length region. The data decrease with increasing l_c, as expected from the effects of initial state interactions.

The nuclear transparency for coherent ρ^0 production increases with coherence length as expected from the effects of the nuclear form factor [21]. Good agreement is found between the measured nuclear transparencies, integrated over the available Q^2 region, and calculations including both the coherence length and CT effects [21] evaluated for each l_c bin at their mean experimental l_c and Q^2 values, given by the curves in Fig. 1. The effect of the nuclear form factor on T_c is included in the calculations. However, when extracting the Q^2 dependence of T_c for separate l_c bins, the Q^2 slope is unaffected if l_c is fixed [21].

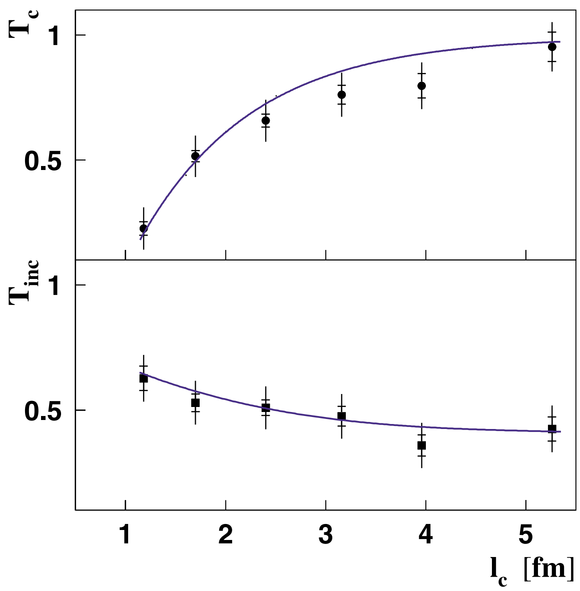

FIG. 1 (color online). Nuclear transparency as a function of coherence length for coherent (top panel) and incoherent (bottom panel) ρ^0 production on nitrogen, compared to predictions with CT effects included (curves) [21]. The inner error bars include only statistical uncertainties, while the outer error bars present the statistical and systematic uncertainties added in quadrature.

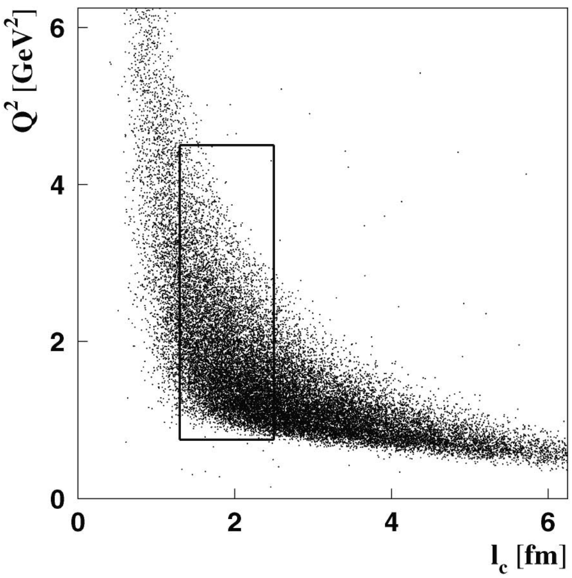

FIG. 2. Distribution of Q^2 versus coherence length for exclusive ρ^0 production on hydrogen and nitrogen. The region surrounded by the rectangle represents the subset that was used for the two-dimensional analysis of the nuclear transparency.

The systematic uncertainties are separated into Q^2- and l_c-dependent and kinematics-independent contributions. The ratio of the integrated luminosities represents the largest source of kinematics-independent uncertainties. An additional contribution comes from double-diffractive dissociation. The total estimated systematic uncertainty from all normalization factors is 11%. The kinematics-dependent systematic uncertainties have been studied as a function of l_c and Q^2 on a bin-by-bin basis. The main contributions come from DIS background subtraction, acceptance corrections, the efficiency of the ΔE exclusivity cut, the corrections due to "Pauli blocking," and the application of radiative corrections. None of the kinematics-dependent systematic uncertainties cancel in the coherent nuclear transparency because of the different t' cuts that are applied, and they increase at small and at large coherence length values. At small l_c, and correspondingly large Q^2, the uncertainties in the coherent to incoherent separation via the t' slope parameters b_p and b^{14}N, and the background subtraction dominate. At large l_c, the uncertainty in the acceptance correction factor becomes large. Thus, the contribution of the kinematics-dependent systematic uncertainty varies between 8% and 14%. This results in a combined systematic uncertainty of 14% to 18% for the nuclear transparency measurements presented in Fig. 1.

A two-dimensional analysis of the nuclear transparency as a function of coherence length and Q^2 has been performed, which represents a new approach in the search for CT. It is constrained by the phase space boundaries displayed in Fig. 2. Since the combination of statistical significance and Q^2 coverage is largest near $l_c \simeq 2.0$ fm, the region $1.3 < l_c < 2.5$ fm has been chosen for this two-dimensional analysis. To deconvolute the CT and coherence length effects, coherence length bins of 0.1 fm were used. These finite bins introduce an additional systematic uncertainty in the Q^2 slope of 0.008 and

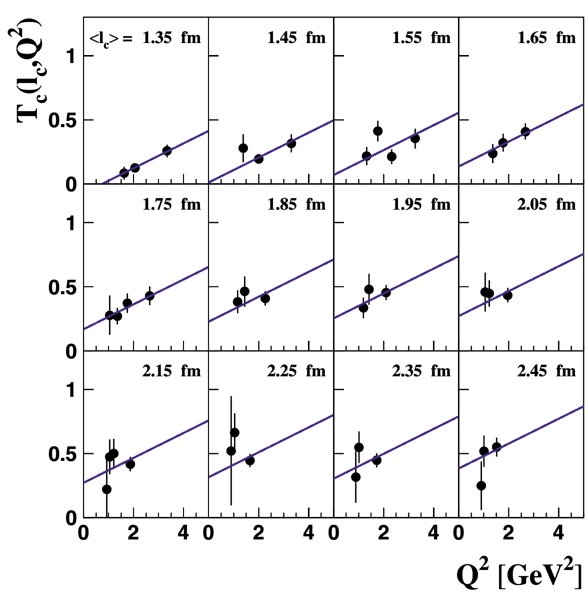

FIG. 3 (color online). Nuclear transparency as a function of Q^2 in specific coherence length bins (as indicated in each panel) for coherent ρ^0 production on nitrogen. The straight line is the result of the common fit of the Q^2 dependence. The error bars include only statistical uncertainties.

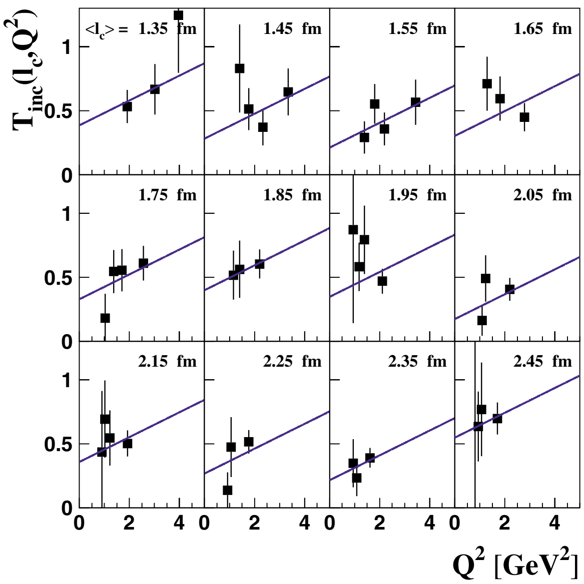

FIG. 4 (color online). As for Fig. 3, except here for incoherent production.

0.004 GeV^{-2} for coherent and incoherent ρ^0 production, respectively. In order to extract the Q^2 dependence, each l_c bin was independently split into 3 or 4 Q^2 bins.

The nuclear transparency was extracted in each (l_c, Q^2) bin, and is shown in Figs. 3 and 4 for $12 l_c$ bins each for coherent and incoherent ρ^0 production. The low statistics in each (l_c, Q^2) bin makes it difficult to fit the slope of the Q^2 dependence for each coherence length bin separately. Instead, the data have been fitted with a common Q^2 slope (P_1), which has been extracted assuming $T_{c(\mathrm{inc})} = \sigma_{c(\mathrm{inc})^{14}\mathrm{N}}(l_c, Q^2)/A\sigma_p = P_0 + P_1 Q^2$, letting P_0 vary independently in each l_c bin and keeping P_1 as common free parameter. The results are displayed as the lines in Figs. 3 and 4. In both cases the reduced-χ^2 values are close to unity. The common slope parameter of the Q^2 dependence, P_1, represents the signature of the CT effect averaged over the coherence length range. This procedure was performed separately for the coherent and incoherent data. The Q^2 slope was found to vary by at most 17% (20%) for the coherent (incoherent) data when shifting the l_c window used in the fit from 1.0–2.2 fm to 1.4–2.6 fm. This variation is treated as an additional systematic uncertainty. The results of these fits are compared to theoretical calculations [21] in Table I. If the results are combined, the common value and the total uncertainty for the slope of the Q^2 dependence of exclusive ρ^0 production is (0.074 ± 0.023) GeV^{-2}. This is in agreement with the combined theoretical prediction of about 0.058 GeV^{-2}.

In summary, the transparency of the ^{14}N nucleus to exclusive coherent and incoherent ρ^0 electroproduction was measured by the HERMES collaboration as a function of both Q^2 and the coherence length of $q\bar{q}$ fluctuations of the virtual photon. Positive slopes of the Q^2 dependence of the nuclear transparency have been observed on nitrogen for $l_c = 1.3$–2.5 fm and $Q^2 = 0.9$–4 GeV^2 for exclusive coherent and incoherent ρ^0 production. Those values are in agreement with theoretical calculations [21], wherein a positive slope of the Q^2 dependence of the nuclear transparency is a signature of color transparency. This result not only adds further evidence for the existence of the color transparency phenomenon, but it also elucidates the complex interplay of various effects on the production of exclusive ρ^0 mesons at modestly high energies.

TABLE I. Fitted slope parameters of the Q^2 dependence of the nuclear transparency on nitrogen with statistical and systematic uncertainties given separately. The results are compared to theoretical predictions [21].

Data sample	Measured Q^2 slope (GeV^{-2})	Prediction (GeV^{-2})
Coherent	$0.070 \pm 0.021 \pm 0.017$	0.060
Incoherent	$0.089 \pm 0.046 \pm 0.020$	0.048

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