Observation of a Coherence Length Effect in Exclusive ρ^0 Electroproduction

The HERMES Collaboration

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Exclusive incoherent electroproduction of the $\rho^0(770)$ meson from ^{1}H, ^{2}H, ^{3}He, and ^{14}N targets has been studied by the HERMES experiment at squared four-momentum transfer $Q^2 > 0.4$ GeV^2 and positron energy loss ν from 9 to 20 GeV. The ratio of the ^{14}N to ^{1}H cross sections per nucleon, known as the nuclear transparency, was found to decrease with increasing coherence length of quark-antiquark fluctuations of the virtual photon. The data provide clear evidence of the interaction of the quark-antiquark fluctuations with the nuclear medium.

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The space-time evolution of a virtual quantum state, such as a quark-antiquark ($q\bar{q}$) fluctuation of a photon, can be probed by studying its propagation through a perturbing medium. The unperturbed virtual state can travel a distance l_c, known as the "coherence length," in the laboratory frame during its lifetime. The interactions between the state and the medium can be studied at different values of l_c by varying the kinematics at which the state is produced. In this letter, interactions of a $q\bar{q}$ fluctuation with the nuclear medium are studied by measuring the nuclear dependence of the exclusive ρ^0 electroproduction cross section.

Studies of the hadronic ($q\bar{q}$) structure of high-energy photons started with ground-work by Yang and Mills, Sakurai, Gell-Mann and Zachariasen, and Berman and Drell in the early 1960's [1]. The hadronic structure arises from fluctuations of the (real or virtual) photon to short-lived quark-antiquark states of mass $M_{q\bar{q}}$ and propagation distance $l_c = 2\nu/(Q^2+M_{q\bar{q}}^2)$ [2–4], where $-Q^2$ and ν are the squared mass and laboratory-frame energy of the photon (adopting units where $\hbar = c = 1$). The $q\bar{q}$ fluctuations are assumed to dominate many photon-induced reactions in the laboratory frame [2]. For example in exclusive production of the ρ^0 meson, a $q\bar{q}$ pair is scattered onto the physical ρ^0 mass shell by a diffractive interaction with the target [2–5].

In nuclear targets, photon-induced reactions can be affected by the initial state interactions (ISI) of the $q\bar{q}$ states with the nuclear medium. The ISI are maximized when l_c is large compared to the nuclear radius R_A, and the photon converts to the $q\bar{q}$ pair before entering the nucleus [2–4]. The hadronic ISI vanish in the limit $l_c \ll R_A$ of negligible $q\bar{q}$ interaction path. The dependence of the ISI on l_c can be measured explicitly in exclusive ρ^0 production experiments, where a single mass—namely, the ρ^0 mass—dominates $M_{q\bar{q}}$ and l_c [2–4]. Due largely to limited coverage in l_c, previous experiments have not yet seen the expected l_c dependence [2,6].

In exclusive reactions a specific final state is produced without additional particles, for example $eN \to e\rho^0 N$ (here N is a nucleon). The effect of the nuclear medium on the particles in the initial and final states of such reactions can be characterized by the nuclear transparency T_A. It is defined as the ratio of the measured cross section to that expected in the absence of these initial and final state interactions (ISI and FSI). If the ISI and FSI amplitudes factorize from the exclusive scattering amplitude, then T_A is the probability that no significant ISI or FSI occur. The transparency has been used to study the space-time dynamics of several exclusive reactions [2,6–9]. This paper reports measurements of the nuclear transparency for exclusive incoherent ρ^0 electroproduction on ^{2}H, ^{3}He, and ^{14}N targets at $Q^2 > 0.4$ GeV^2, 9 GeV $< \nu <$ 20 GeV, and 0.6 fm $\lesssim l_c <$ 8 fm. The data provide an explicit demonstration that the interactions of the photon with the nuclear medium depend on the propagation distance l_c of the $q\bar{q}$ pair.

The data were obtained during the 1995-1997 running periods of the HERMES experiment using ^{1}H, ^{2}H, ^{3}He, and ^{14}N internal gas targets in the 27.5 GeV HERA positron storage ring at DESY. The scattered e^+ and the $\pi^+\pi^-$ pair from the ρ^0 decay ($\approx 100\%$ branching ratio) were detected in the HERMES forward spectrometer [10].

The ρ^0 production sample was extracted from events with exactly three tracks: a scattered positron and two oppositely-charged hadrons. The relevant 4-momenta are: k (k') of the incident (scattered) positron, $q \equiv k - k'$ of the virtual photon, P of the struck nucleon, P_{h^+} and P_{h^-} of the detected hadrons, $v \equiv P_{h^+} + P_{h^-}$ of the ρ^0 candidate, and $P_Y \equiv P + q - v$ of the undetected final state Y. The relevant Lorentz invariants are: $Q^2 = -q^2 > 0$; $\nu = q \cdot P/M$ (here M is the proton mass); an exclusivity measure $\Delta E = (P_Y^2 - M^2)/2M$; the invariant mass $M_{\pi\pi} = \sqrt{v^2}$ assuming the detected hadrons are pions; the squared 4-momentum transfer $t = (q - v)^2$ to the target; the maximum value t_0 of t for fixed ν, Q^2, P_Y^2, and $M_{\pi\pi}$; and the above-threshold momentum transfer $t' = t - t_0 < 0$.

For nuclear targets, the diffractive interaction with the target can occur incoherently from individual nucleons or coherently from the nucleus as a whole. The incoherent exclusive ρ^0 production signal was extracted in the kinematic region $t'_l < -t' < 0.4$ GeV^2, -2 GeV $< \Delta E <$ 0.6 GeV, 0.6 GeV $< M_{\pi\pi} <$ 1 GeV, and 9 GeV $< \nu <$ 20 GeV. The lower $-t'$ limit, t'_l, is chosen separately for each target and l_c bin to maximize statistics while keeping small the contribution from coherent scattering; t'_l is 0.03 to 0.06 GeV^2 for ^{2}H, 0.03 to 0.14 GeV^2 for ^{3}He, and 0.05 to 0.09 GeV^2 for ^{14}N.

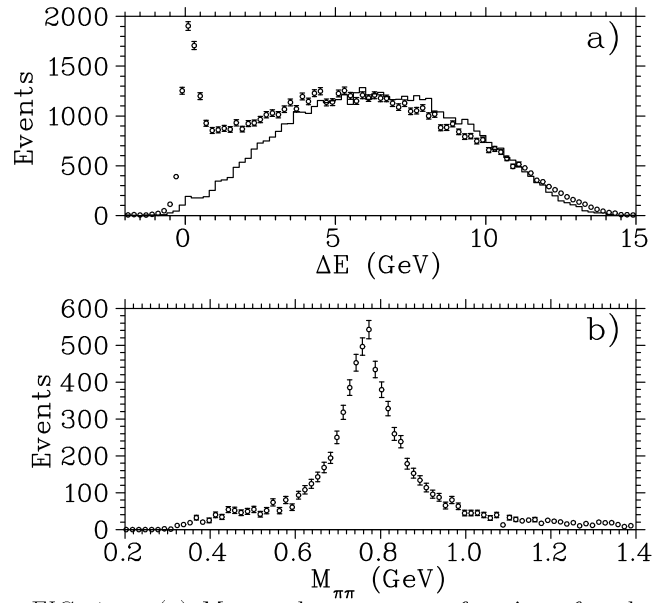

FIG. 1. (a) Measured events as a function of exclusivity variable ΔE for the ^{1}H, ^{2}H, ^{3}He, and ^{14}N data passing the experimental cuts; the distribution is shown for 0.1 GeV^2 $< -t' <$ 0.4 GeV^2 (open circles) and for 0.7 GeV^2 $< -t' <$ 5 GeV^2 (histogram, scaled to the same total counts at $\Delta E >$ 3 GeV). (b) Invariant mass distribution for the exclusive events at 0.1 GeV^2 $< -t' <$ 0.4 GeV^2.

The distribution of the selected events in ΔE is shown for all targets in Figure 1a. Exclusive $eN \to eh^+h^-N$ events, where the undetected final state consists of a nucleon recoiling without excitation, occur at $\Delta E = 0$. *Non-exclusive* events that involve the production of additional, undetected particles appear at larger ΔE. The events with $\Delta E \gtrsim 3$ GeV are predominantly due to deep inelastic scattering (DIS). The ΔE dependence of DIS events is measured at $0.7 < -t' < 5$ GeV^2 where the diffractive exclusive signal is negligible (see histogram in Figure 1a). The DIS background below the exclusive peak is subtracted for each target and kinematic bin separately, assuming the shape of the background is independent of t' and normalizing to the number of events measured at $t'_l < -t' < 0.4$ GeV^2 and $\Delta E > 3$ GeV. The difference at $\Delta E \sim 2$ GeV between the two distributions shown in Figure 1a is due mainly to the radiative tail of the exclusive peak and to ρ^0 production events where the diffractive interaction excites the nucleon. Except for small kinematic shifts, these processes do not affect the propagation of the virtual photon or outgoing ρ^0 through the nuclear medium.

The exclusive $M_{\pi\pi}$ distribution, shown in Figure 1b, is dominated by resonant production of the $\rho^0(770)$, with small interfering contributions from exclusive production of non-resonant $\pi^+\pi^-$ pairs and of the $\omega(782)$ resonance (in its 2% decay branch to $\pi^+\pi^-$ [11]). Background from the two-kaon decay of exclusively-produced $\phi(1020)$ mesons, which would appear at $M_{\pi\pi} < 0.5$ GeV, is eliminated by requiring that the two-kaon invariant mass be greater than 1.04 GeV.

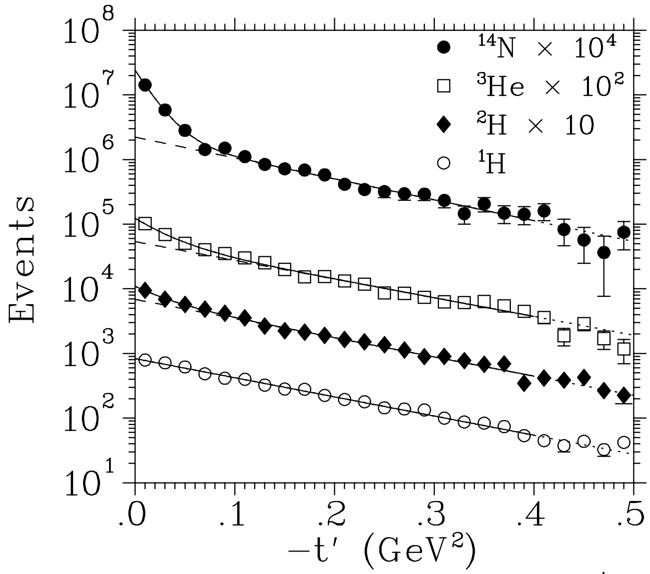

FIG. 2. Distribution of momentum transfer t' for exclusive ρ^0-production from ^{1}H, ^{2}H, ^{3}He, and ^{14}N targets. The solid curves are fit to $a_N(b_N e^{b_N t'} + f_A b_A e^{b_A t'})$, the dotted lines are extrapolations beyond the fit interval $-t' < 0.4$ GeV^2, and the dashed lines are the inferred incoherent contributions.

The exclusive $-t'$ distributions for the ^{1}H, ^{2}H, ^{3}He, and ^{14}N nuclei are shown in Figure 2. The data exhibit the rapid falloff expected for a diffractive process. To isolate incoherent scattering, the data are fit to a shape giving the sum of incoherent and coherent contributions, $b_N e^{b_N t'} + f_A b_A e^{b_A t'}$ (solid curves). Here f_A is the ratio of coherent to incoherent total counts and

$e^{b_N t'}$ ($e^{b_A t'}$) represents the product of the ρ^0 and struck nucleon (nucleus) elastic form factors, squared [12]. The incoherent slope parameter b_N for each nucleus (measured to an accuracy of about 0.5 GeV^{-2}) is consistent with the hydrogen value $b_N = (6.82 \pm 0.15)$ GeV^{-2}. The coherent slope parameters $b_{^2\mathrm{H}} = (33.3 \pm 9.8)$ GeV^{-2}, $b_{^3\mathrm{He}} = (32.5 \pm 5.7)$ GeV^{-2}, and $b_{^{14}\mathrm{N}} = (57.2 \pm 3.3)$ GeV^{-2} are consistent with the values predicted by the relationship $b_A \approx R_A^2/3$ [12] and the measured electromagnetic RMS radii $R_{^2\mathrm{H}} = 2.1$ fm, $R_{^3\mathrm{He}} = 1.9$ fm, and $R_{^{14}\mathrm{N}} = 2.5$ fm [13].

In the absence of ISI and FSI, the cross section σ_A for incoherent ρ^0 production from a nucleus with A nucleons would be $A\sigma_H$ (assuming the expected isospin symmetry $\sigma_n = \sigma_H$ [2], where n and H refer to the neutron and ^{1}H). The nuclear transparency is therefore $T_A \equiv \sigma_A/(A\sigma_H) = N_A L_H/(A N_H L_A)$, where the second equality follows from the A-independence of the experimental acceptance. Here $N_{A,H}$ is the number of incoherent events in the range $t'_l < -t' < 0.4$ GeV^2; N_A is corrected for the coherent contribution using the t' fit for each l_c bin (t'_l is chosen so that the correction factor is less than 1.05 with an uncertainty of less than 4%). The integral $L_{A,H}$ of the effective luminosity is determined from the number of inclusive DIS positrons and the published nuclear DIS structure functions [14], with a correction for the efficiency ($\gtrsim 0.8$) for tracking the h^+h^- pair.

The dominant systematic uncertainties are from possible differences in the spectrometer performance for the nuclear and ^{1}H data (estimated by studying the time dependence of $N_{A,H}/L_{A,H}$ and other normalized yields) and from the treatment of the non-exclusive background (estimated by studying the dependence of T_A on ΔE). The systematic uncertainty in the overall normalization of $T_{^2\mathrm{H}}$, $T_{^3\mathrm{He}}$, or $T_{^{14}\mathrm{N}}$ is 2.7%, 5.5%, or 5.9% respectively. The additional point-to-point systematic uncertainty includes the fit uncertainty in the coherent contribution. The T_A results are unchanged at the 3% level (and the systematic uncertainties are essentially unchanged) if the non-exclusive background is not subtracted.

The nuclear transparencies for ^{2}H (filled diamond), ^{3}He (open square), and ^{14}N (filled circle) are shown as functions of the coherence length l_c in Figure 3. Within uncertainties the ^{2}H and ^{3}He transparencies are independent of l_c: $T_{^2\mathrm{H}} = 0.970 \pm 0.024$ (statistical) ± 0.040 (systematic) and $T_{^3\mathrm{He}} = 0.862 \pm 0.042 \pm 0.061$. The consistency of the deuterium transparency with unity suggests that $\sigma_n \approx \sigma_H$ and that the ISI and FSI are small in ^{2}H. The average ^{3}He transparency is 1.9 standard deviations below unity.

The nitrogen transparency exhibits the decrease expected from the onset of hadronic ISI as l_c increases. The decrease from 0.681 ± 0.060 at $l_c < 2$ fm to 0.401 ± 0.054 at $l_c > 3.6$ fm (errors exclude normalization uncertainty) has a 3.5 standard deviation statistical significance. In the absence of ISI variations, the transparency would exhibit a small ($< 3\%$) *increase* with l_c due to the known [2] energy dependence of the $\rho^0 N$ cross section.

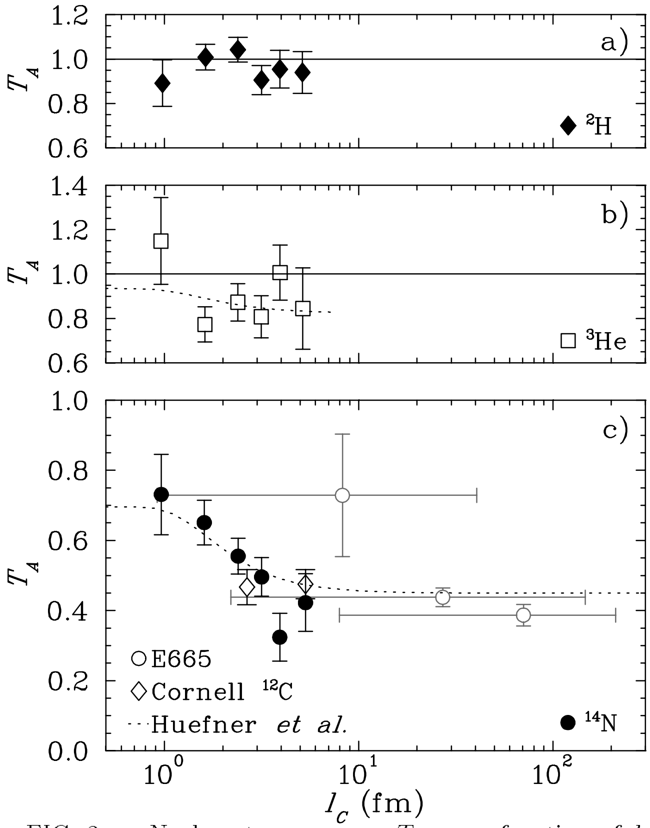

FIG. 3. Nuclear transparency T_A as a function of l_c for a) ^{2}H (filled diamond), b) ^{3}He (open square), and c) ^{14}N (filled circle) targets. The error bars include statistical and point-to-point systematic uncertainties added in quadrature. The systematic uncertainty in the overall normalization of T_A is not shown. Panel (c) includes comparisons with previous expriments with photon (open diamonds) [6] and muon (open circle) [8] beams. Due to the acceptance for $20 < \nu \lesssim 370$ GeV, the three Q^2 bins measured by [8] correspond to broad ranges in l_c (horizontal error bars). The dashed curves are the Glauber calculation of Hüfner *et al.* for ^{3}He and ^{14}N [3].

Figure 3c also shows the transparency to incoherent ρ^0 production measured at Cornell with 4 and 8 GeV photons [6] and by the E665 collaboration at FNAL with 470 GeV muons [8]. These results are consistent with the present data but give no indication of a variation with l_c. The E665 $T_{^{14}\mathrm{N}}$ values are inferred from the published A-dependence [8]. The E665 value for $T_{^{14}\mathrm{N}}$ at $l_c \sim 8$ fm was measured at $\nu \gtrsim 100$ GeV and $Q^2 > 3$ GeV^2 [8], and may therefore be influenced by color transparency. Color transparency implies that at high Q^2 and ν the $q\bar{q}$ pair (and the subsequent ρ^0) is produced and propagates in a non-interacting configuration of reduced transverse size, resulting in $T_A \to 1$ [2,5,15,16]. For this reason data collected by the NMC collaboration with a muon beam at 40 GeV $< \nu <$ 180 GeV and $Q^2 > 2$ GeV^2 [9] are not included in Figure 3c.

The $T_{^{14}\mathrm{N}}$ and $T_{^{3}\mathrm{He}}$ data are consistent with a recent prediction (dashed curves in Figure 3) of the coherence length effect [3], although the statistics for $T_{^{3}\mathrm{He}}$ are not sufficient to demonstrate the l_c variation. The prediction uses Glauber multiple-scattering theory [17], where the total ρ^0 production amplitude is the sum of the amplitudes from each nucleon, modified by elastic and inelastic rescattering of the outgoing ρ^0 on the other nucleons. In this model, the $q\bar{q}$ fluctuation from which the ρ^0 originates is found to interact with the nuclear medium like a ρ^0 [3]. The strength of the ρ^0 and $q\bar{q}$ interactions govern the transparency at small l_c and its l_c dependence, respectively. The consistency of the model with the data therefore suggests that when l_c is large, the $q\bar{q}$ ISI are approximately as strong as the ρ^0 FSI. For the ν values of the present measurement, color transparency is expected to produce little deviation from the Glauber prediction [3,16].

The data support the hypothesis [2,18] that absorption of the photon's $q\bar{q}$ component contributes to the shadowing observed in real and virtual photon nuclear cross sections. Shadowing denotes that the cross sections grow more slowly than linearly in A. It is observed for inclusive DIS at small Bjorken $x = Q^2/2M\nu$ and for elastic and inclusive real photon scattering at high energies.

In summary, the transparency of the ^{2}H, ^{3}He, and ^{14}N nuclei to exclusive incoherent ρ^0 electroproduction was measured by the HERMES experiment as a function of the coherence length of $q\bar{q}$ fluctuations of the virtual photon. The measured transparencies agree well with previous data and with a prediction using the standard treatment of high-energy initial and final state interactions. The transparency of the nitrogen nucleus exhibits a significant decrease with l_c, which is attributed to initial state interactions of the $q\bar{q}$ fluctuation from which the ρ^0 originates.

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[1] C.N. Yang and R.L. Mills, Phys. Rev. **96**, 191 (1954); J.J. Sakurai, Ann. Phys. **11**, 1 (1960); M. Gell-Mann and F. Zachariasen, Phys. Rev. **124**, 953 (1961); S.M. Berman and S.D. Drell, Phys. Rev. **133**, 791B (1964).
[2] T.H. Bauer *et al.*, Rev. Mod. Phys. **50**, 261 (1978), and references therein.
[3] J. Hüfner *et al.*, Phys. Lett. B **383**, 362 (1996); B.Z. Kopeliovich and J. Nemchik, private communication.
[4] K. Gottfried and D.R. Yennie, Phys. Rev. **182**, 1595 (1969).
[5] S.J. Brodsky *et al.*, Phys. Rev. D **50**, 3134 (1994).
[6] G.N. McClellan *et al.*, Phys. Rev. Lett. **23**, 554 (1969).
[7] A.S. Carroll *et al.*, Phys. Rev. Lett. **61**, 1698 (1988); T.G. O'Neill *et al.*, Phys. Lett. B **351**, 87 (1995).
[8] M.R. Adams *et al.*, Phys. Rev. Lett. **74**, 1525 (1995).
[9] M. Arneodo *et al.*, Nucl. Phys. B **429**, 503 (1994).
[10] K. Ackerstaff *et al.*, Phys. Lett. B **404**, 383 (1997); K. Ackerstaff *et al.*, DESY 98-057 (1998), hep-ex 9806008 (1998), Nucl. Instr. and Meth. **A** (in press).
[11] Particle Data Group, Europ. Phys. Journ. C **3**, 1 (1998).
[12] B. Povh and J. Hüfner, Phys. Rev. Lett. **58**, 1612 (1987).
[13] H. de Vries *et al.*, At. Data Nucl. Data Tables **36**, 495 (1987).
[14] P. Amaudruz *et al.*, Nucl. Phys. B **441**, 3 (1995).
[15] S.J. Brodsky and A.H. Mueller, Phys. Lett. B **206**, 685 (1988); L.L. Frankfurt *et al.*, Ann. Rev. Nucl. Part. Sci. **45**, 501 (1994); B.Z. Kopeliovich *et al.*, Phys. Lett. B **324**, 469 (1994); P. Jain *et al.*, Phys. Rep. **271**, 67 (1996); O. Benhar *et al.*, Journ. Exp. Theor. Phys. **84**, 421 (1997).
[16] J. Huefner and B.Z. Kopeliovich, Phys. Lett. B **403**, 128 (1997).
[17] R.J. Glauber, in: Lectures in Theor. Phys., Vol. 1, eds. W.E. Brittin and L.G. Duham (Intersciences, New York, 1959).
[18] B. Badelek and J. Kwiciński, Rev. Mod. Phys. **68**, 445 (1996), and references therein; G. Piller and W. Weise, Phys. Rev. C **42**, R1834 (1990).