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Measurement of Nuclear Transparencies from Exclusive ρ^0 Meson Production in Muon-Nucleus Scattering at 470 GeV

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Nuclear transparencies measured in exclusive incoherent ρ^0 meson production from deuterium, carbon, calcium, and lead in muon-nucleus scattering are reported. The data were obtained with the E665 spectrometer using the Fermilab Tevatron muon beam with a mean beam energy of 470 GeV. Increases in the nuclear transparencies are observed as the virtuality of the photon increases, as expected from color transparency.

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Exclusive production of vector mesons by virtual photons from complex nuclei was suggested as a way of testing the idea of a "shrinking photon" before the advent of quantum chromodynamics (QCD) [1]. The "size" of the hadronic components of a virtual photon at high 4-momentum transfer squared Q^2 was conjectured to be smaller than the size of a normal hadron, thereby accounting for the point-like behavior and diminished absorption of virtual photons in nuclear interactions.

More recently, vector meson production has been suggested as a way of testing the idea of color transparency [2–5]. According to QCD, exclusive interactions at large momentum transfer select out hadrons with small transverse size which subsequently experience diminished interactions while propagating through a nuclear medium [6]. Therefore one expects the total cross section for a hard, exclusive process that involves nucleons in a nucleus to be proportional to A, the total number of nucleons in the nucleus. The first results on color transparency from a $(p, 2p)$ experiment [7] spurred extensive theoretical activity [8]. A more recent study was performed using the reaction $(e, e'p)$ [9]. It is generally agreed that the observed effects could not be explained by color transparency alone, and measurements at higher energies should clear up the picture significantly. Exclusive production of vector mesons in muon-nucleus scattering at high energies is well-suited for observing color transparency [2–5]. In this case the initial size of the vector meson is controlled by Q^2 [11], the virtuality of the photon. Even at a modest value of $Q^2 = 2$ GeV^2 the transverse separation, varying roughly as $2\hbar c/Q$, is about 0.3 fm, which is much smaller than the size of a normal hadron (≈ 1 fm). Furthermore, in the kinematic region covered by the data reported here (the energy carried by the ρ mesons, ν, is typically 120 GeV) both the coherence length $2\hbar c\nu/(Q^2 + m_{\rm v}^2)$ (the longitudinal distance involved in the production process), and the formation length $\hbar c\nu/m_{\rm v}\delta m_{\rm v}$ (the distance over which the ρ^0 meson grows to its normal size; [4] $m_{\rm v}$ is the mass of vector meson and $\delta m_{\rm v}$ is the typical mass splitting of the vector mesons) are much larger than the size of even the heaviest nucleus. Thus, the resultant ρ^0 mesons should remain small until long after they have left the nucleus. Therefore, one expects the nucleus to be highly transparent to the ρ^0 mesons produced at high Q^2.

In this letter we report results on the transparency measurements from incoherent, exclusive ρ^0 meson production in muon scattering from nuclear targets. Here exclusive production refers to a process in which the ρ^0 meson is the only hadron present in the final state, in addition to the recoiling nucleon, and it carries all the energy of the virtual photon except that elastically transferred to the nucleon (less than 0.2 GeV). The data were obtained at the Fermilab NM beam line with the E665 spectrometer [10]. The mean beam energy was 470 GeV. The momentum resolution of the beam and forward spectrometers are about 0.5% and 1% at 470 GeV/c, respectively. Hadron-electron separation is aided by a fine-grained electromagnetic calorimeter consisting of twenty planes of proportional tubes sandwiched between one-radiation-length lead sheets. Five targets were used for these measurements: liquid hydrogen and deuterium, each one meter long, and solid carbon, calcium and lead. The solid targets, segmented longitudinally into five equal pieces and distributed with equal separation over the length of the liquid targets, are 0.35, 0.16 and 0.028 interaction lengths long, respectively. A remotely controlled target assembly cycled the targets every minute, thus greatly reducing the target-to-target systematic effects associated with long term variations in the running conditions.

The kinematic variables describing exclusive vector meson production are: $Q^2 = -(k - k')^2$, $\nu = p \cdot q/M$, $x_{\rm bj} = Q^2/2M\nu$, $t = (q - r)^2$, $t' = t - t_{\rm min}$, and $z = E_\rho/\nu$, where k, k', q, r and p are the four momenta of the incoming muon, the outgoing muon, the virtual photon, the vector meson and the target proton, respectively, $-Q^2$ is the invariant mass squared of the virtual photon, ν is the energy loss of the muon in the laboratory, t is the four-momentum transfer squared between the vector meson and the nucleon, z is the fraction of the energy lost by the muon that is carried by the vector meson, $| t_{\rm min} |$ is the minimum $| t |$ allowed by the kinematics ($t_{\rm min}$ corresponds to the limit of zero angle between $\mathbf{q}$ and $\mathbf{r}$ in the lab system for fixed values of ν, Q^2 and mass of the vector meson), E_ρ is the energy of the ρ^0 meson and M is the mass of the proton.

Events accepted by the present analysis were required to have exactly two oppositely charged hadrons in addition to the scattered muon (the recoil nucleon was not detected). The energies of the hadrons were required to be greater than 10 GeV to ensure that the particles were in well-understood regions of acceptance of the forward spectrometer. The electromagnetic calorimeter information served to eliminate events in which electrons from photon conversion are mistakenly identified as hadrons. Events from ϕ meson production were rejected by removing all events with $m_{KK} \leq$1.05 GeV/c^2, where m_{KK} is the invariant mass reconstructed assuming that the observed particles are kaons. Inelastic (events for which the ρ^0 meson was accompanied by other undetected particles) and combinatorial (events for which the invariant mass of a pair of uncorrelated oppositely charged hadrons was close to the ρ mass) contamination was suppressed by a cut on z : -1.5 $\leq (z-1)/\delta z \leq 3$ where δz is the uncertainty in z as calculated from the measurement errors. To further reduce contributions from events in which additional particles were produced, but not reconstructed, the number of unused hits in the vertex drift chambers, which accept all particles with an energy greater than 1 GeV, was limited to a value consistent with the normal level of spurious hits. Events originating from non-target interactions were removed statistically assuming that they came from carbon-like material. The following additional cuts were imposed on the final data sample: $Q^2 \geq 0.1$ GeV^2, $\nu \geq 20$ GeV, $\delta\nu/\nu \leq 0.25$, $m_{\pi\pi} \leq 1.5$ GeV/c^2 and $| t' | \leq 0.8$ GeV^2. Fig. 1 shows the distribution of $(z-1)/\delta z$ for all the events passing the selection criteria described above except the cut on $(z-1)/\delta z$ itself.

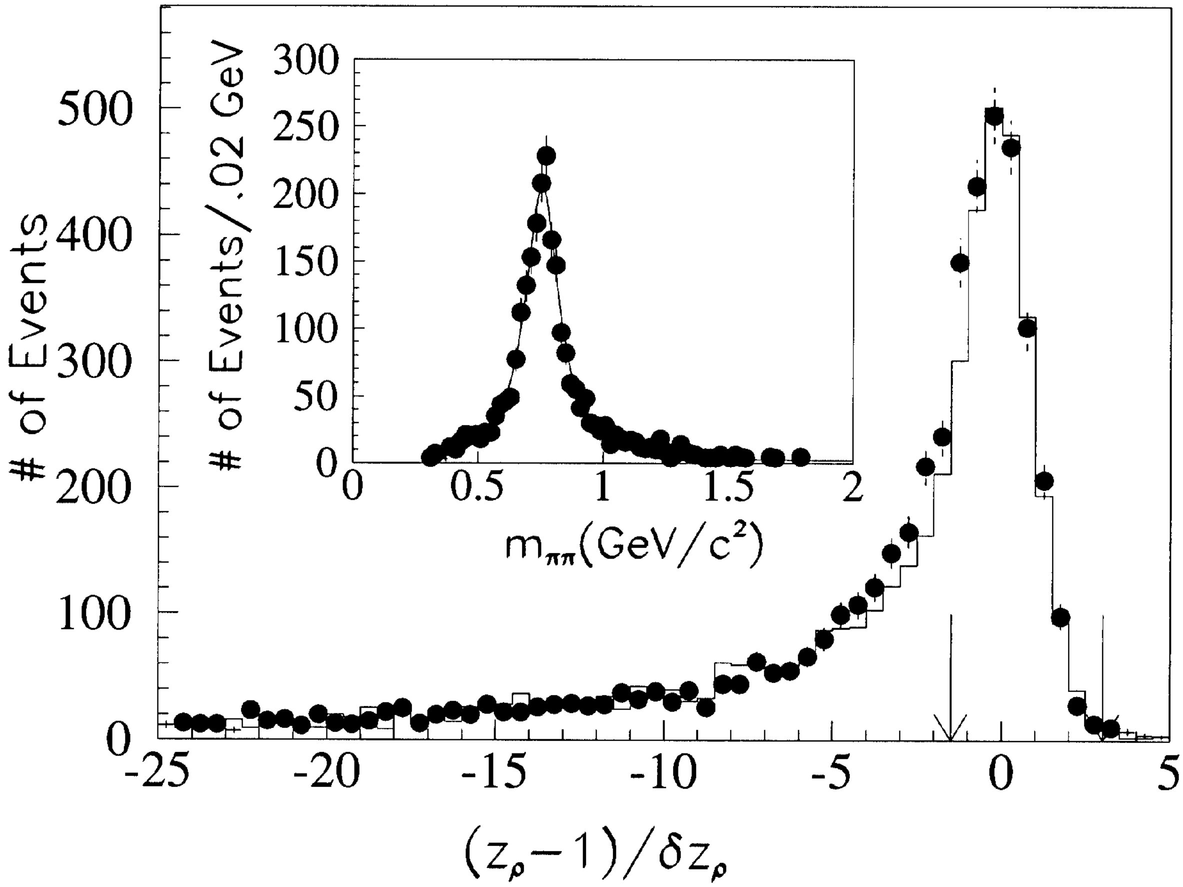

FIG. 1. The $(z-1)/\delta z$ distribution for incoherent ρ^0 candidates from the data (points) and the simulated sample (histogram). The Monte Carlo sample includes contributions from exclusive ρ^0 and inclusive background events only. The region accepted is indicated by arrows. Shown in the inset is the invariant-mass distribution for the ρ^0 candidates.

The invariant mass $m_{\pi\pi}$, obtained assuming that the observed hadrons are pions is shown in the inset to Fig. 1. The curve is a fit to a p-wave Breit-Wigner form multiplied by a mass skewing factor $(m_\rho/m_{\pi\pi})^n$ [12,13]. The results are $m_\rho = 0.780 \pm 0.004$ GeV/c^2, $\Gamma_\rho = 0.188 \pm 0.010$ GeV/c^2 and $n = 3.18 \pm 0.18$.

Exclusive production of vector mesons from a nuclear target can be coherent, corresponding to production from the nucleus as a whole, or incoherent, corresponding to production from individual nucleons in the nucleus. Since the rate of fall-off of the t' distribution for a diffractive scattering process measures the physical size of the scatterer, one expects to see t' fall steeply initially (coherent), followed by a region with a more shallow slope (incoherent). The observed t' distributions for hydrogen and calcium are shown in Fig. 2. Two distinct processes are clearly identifiable. The line for hydrogen is a fit to $N_n * e^{-b_n|t'|}$ using only the points between 0.08 and 0.50 GeV^2 ($b_n = 6.29 \pm 0.37$ GeV^{-2}). The lines for calcium are fits to $N_A * e^{-b_A|t'|}$ using only points between 0.00 and 0.02 GeV^2 ($b_A = 100 \pm 6$ GeV^{-2}) and $N_n * e^{-b_n|t'|}$ using only points between 0.08 and 0.50 GeV^2 ($b_n = 6.20 \pm 0.53$ GeV^{-2}).

In the present analysis, events with $|t'| > 0.1$ GeV^2 were selected for the incoherent sample (the same cut is applied for all targets). Contributions from coherent events were estimated by integrating the fitted coherent exponential functions from 0.1 GeV^2 to infinity. The level of coherent background (subtracted from the signal) was less than 1% for all but the deuterium target for which the contamination was about 8%.

The main source of background comes from events in which a ρ^0, or a pair of oppositely charged hadrons with $m_{\pi\pi}$ consistent with the ρ^0 mass, are produced through fragmentation with a sum of z values close to 1 and no other detected particles. A Lund-based Monte-Carlo [14] program was used to generate a sample of deep-inelastic events. These events were subjected to the same analysis procedure as that used for the data. The surviving events were then normalized to the data by demanding that the number of total events integrated over $(z-1)/\delta z$ (from minus infinity to -3) from the Monte-Carlo sample be equal to that of the data. The estimated background events were then subtracted from the data.

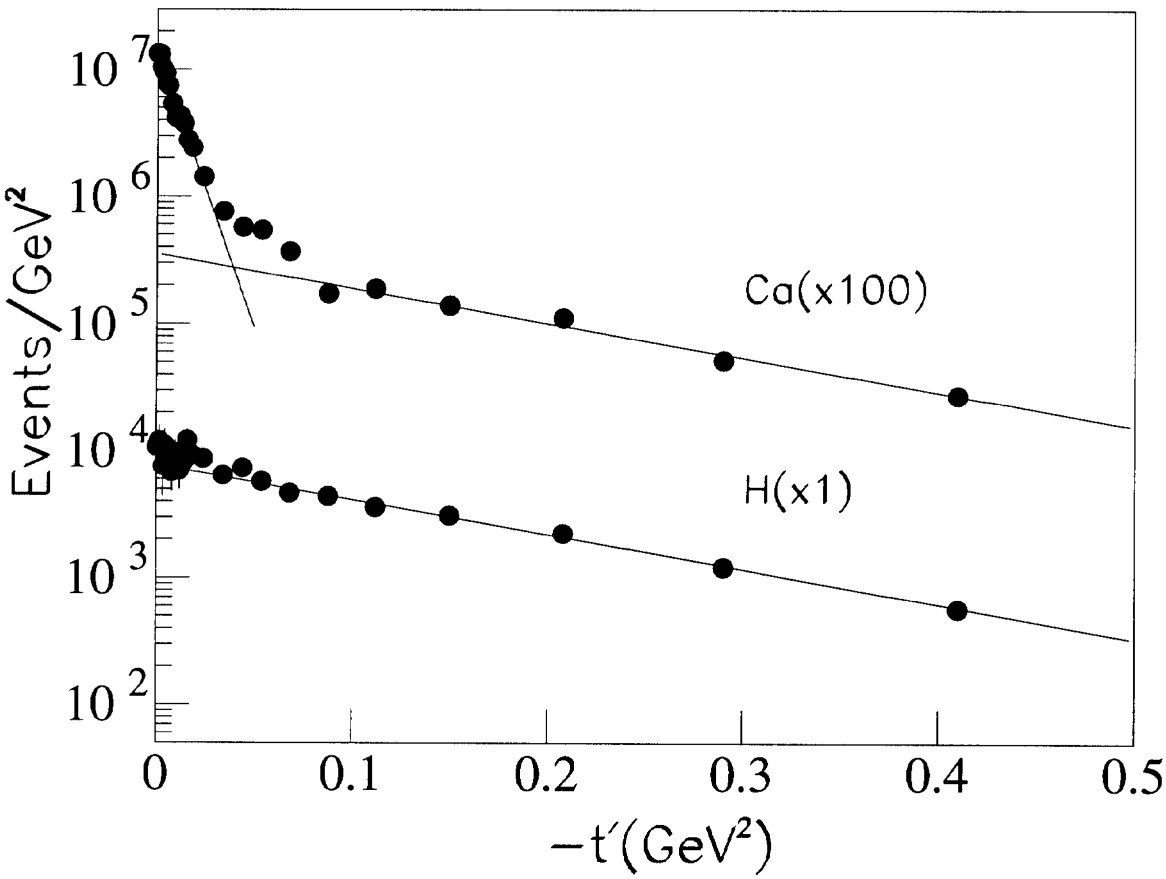

FIG. 2. The t' distributions (uncorrected) for hydrogen (lower curve) and calcium (upper curve).

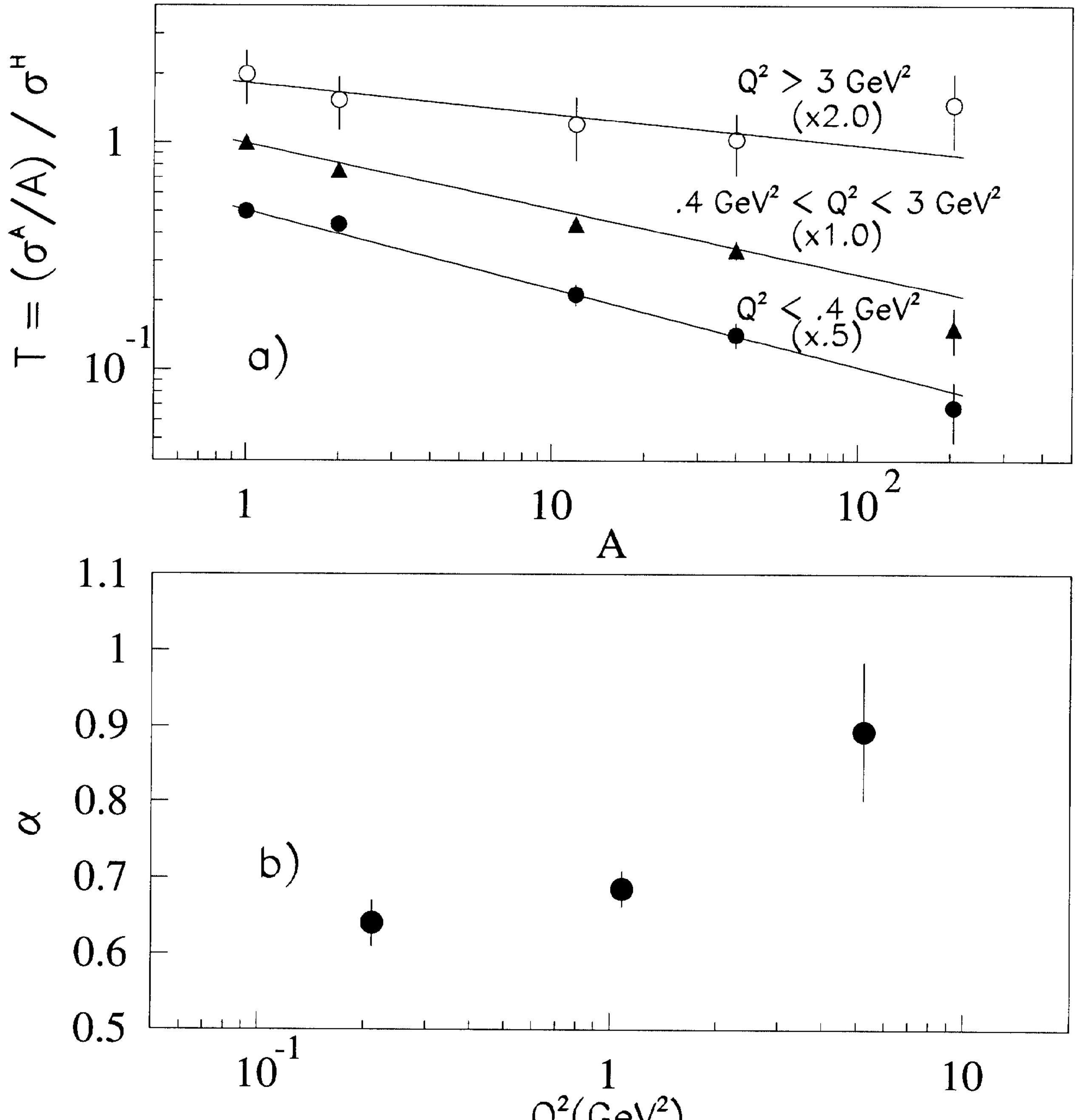

FIG. 3. a) The transparency T, defined in the text, as a function of A for three Q^2 regions. Note that the points have been multiplied by 2, 1 and 0.5 respectively for the three Q^2 points. b) α as a function of Q^2. The errors are statistical only.

The nuclear transparency T, defined as $\sigma^{\rm A}/{\rm A}\sigma^{\rm H}$, for incoherent ρ^0 production off deuterium, carbon, calcium and lead versus A for three different Q^2 regions are shown in Fig 3a. The curves are fits to the form $NA^{\alpha-1}$. In Fig. 3b we show α as a function of Q^2. The α values are 0.640±0.030, 0.685±0.024, and 0.893±0.092, corresponding to Q^2 values of 0.212, 1.08 and 5.24 GeV^2 respectively. The corresponding average x_{bj} and ν values are $< x_{bj} >$ = 0.0016, 0.0069, 0.0330; $< \nu >$ = 144, 115, 122 GeV respectively. The probability of α being constant is 2.7%. In contrast, the α values characterizing nuclear shadowing measured from inclusive μA scattering by EMC [15] are significantly larger and vary between 0.94 and 0.98 over the Q^2 region between 0.3 and 10 GeV^2. The limit $\alpha = 1$ implies that all the nucleons in the nucleus participate in the production equally, i.e., the nucleus is completely transparent. At low Q^2, the value of α we measure is about 2/3, a value characteristic of soft nuclear interactions. The observed rise in T as a function of Q^2 agrees well with the expectations for color transparency. On the other hand, if we assume that the intermediate $q\bar{q}$ state and the produced ρ^0 meson are of normal size, the Glauber [16] multiple scattering mechanism predicts a Q^2-independent transparency.

Since the procedure for background subtraction depends on the Monte-Carlo input, uncertainties in the hadron z distributions could, in principle, affect the deduced transparencies. The effects of these uncertainties on α measurements were studied by varying the absolute levels of inclusive contributions. A 10% change in background contamination resulted in a change of less than 3% in α.

Effects due to secondary interactions in the target were estimated by subdividing the targets into up-stream and down-stream halves and performing the analysis separately. Effects due to remaining photon conversion events mimicking exclusive ρ^0 events were estimated by varying the kinematic cuts and comparing the resultant transparencies. Errors on normalization were estimated with different procedures of counting incident muons in the experiment. No statistically significant effects were found from any of these studies.

In summary, we have measured the nuclear transparencies in incoherent, exclusive ρ^0

production off deuterium, carbon, calcium and lead. Increases in the transparencies with Q^2 are observed, in agreement with the predictions of color transparency.

We would like to point out that the following two issues need to be explicitly addressed in a quantitative interpretation of these results. The first issue is the definition of transparency. Clearly, transparencies presented here do not exclude final-state elastic interactions. Events in which the produced ρ^0 mesons undergo elastic interactions are included in the transparency analysis provided that the energy losses introduced from these interactions are small. The effect on the Q^2-dependence from this inclusion is expected to be small. The second issue is the fact that the recoiling nucleons are not detected in this measurement. This means that the measured transparencies as defined here represent an average over sub-processes corresponding to different recoil systems.

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