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Q^2 DEPENDENCE OF NUCLEAR TRANSPARENCY FOR INCOHERENT ρ^0 ELECTROPRODUCTION

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Measurements of exclusive incoherent electroproduction of $\rho^0(770)$ meson from ^{2}H, ^{12}C, and ^{63}Cu targets up to $Q^2 = 4$ GeV^2 are proposed using the CLAS detector at Jefferson Lab. The objective of these measurements is to determine the Q^2 dependence of the nuclear transparency ratio for the two nuclear targets: ^{12}C and ^{63}Cu at fixed coherence length of quark-antiquark fluctuations of the virtual photon. A sizeable rise of the nuclear transparency is predicted and can be measured in this experiment. A relatively large increase of the nuclear transparency can be considered as a signature of the onset of color transparency.

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1. Introduction

One of the major goals of Jefferson Lab (JLab) is to explore and study the interface between the nucleonic picture of the strong interaction and the partonic one. Although the standard nuclear models are successful in reproducing the overall picture of hadrons interacting at large distances, and QCD is convincing in the description of the quarks interacting weakly at short distances (perturbative QCD), the physics connecting the two regimes is almost non existent. When probing distances comparable to those separating the quarks, classical nuclear physics should break down at some point, yet the nucleonic picture still describes many features of the strong interaction. The alternative is to look for the onset of experimentally accessible phenomena which are naturaly predicted by QCD. Color transparency (CT) could be a potential candidate. Its basic concepts imply that in exclusive hard processes at large momentum transfer (Q), the hadron has more chance to escape intact from a nuclear target if its wave-function fluctuates into a configuration which contains only valence quarks with small transverse separation. This small size object should lead to a vanishing absorption when it propagates through the nucleus. By studying the onset of color transparency, one could improve our understanding of the dynamics of bound states in QCD and therefore help to build a detailed picture of photon and electron interactions with nuclei at intermediate energies.

E02-110 experiment [1] will measure the Q^2 dependence of the nuclear transparency ratio in incoherent diffractive ρ^0 electroproduction on carbon and copper, for fixed coherence lengths. Two energies of the electron beam at 6 and 4 GeV are proposed to be used. The Q^2 range is up to 4 GeV^2. Measurable effects of about 40% are predicted for the covered Q^2 region. The proposed experiment seeks to measure the nuclear transparency of the ρ^0 meson with 8% to 15% uncertainties, dominated by systematics in the low Q^2 region and by statistics at high Q^2.

2. *Physical motivations*

The color-transparency phenomenon illustrates the power of exclusive reactions to isolate simple elementary quark configurations. For a hard exclusive reaction, such as vector meson electroproduction on the nucleon, the scattering amplitude at large momentum transfer is suppressed by powers of Q^2 if the hadron (vector meson in this case) contains more than the minimal number of constituents. This is derived from the QCD-based quark-counting rules. It is more likely that the hadron containing valence quarks only, participates in the scattering. Moreover, each quark, connected to another one by a hard gluon exchange carrying momentum of order Q, should be found within a distance of order $1/Q$. Therefore, at large Q^2 one selects a very special quark configuration where all connected quarks are close together, forming a small-size color-neutral configuration called *point-like configuration* (PLC). During a formation time $\tau_{\mathrm{f}} = 2\nu/(M_{v'}^2 - M_v^2)$, where ν is the energy of the virtual photon and M_v is the mass of the vector meson in its ground state and $M_{v'}$ its first orbital excitation mass, the *mini hadron* evolves to a normal hadron. Such an object is unable to emit or absorb soft gluons. Therefore, its strong interaction with the other nucleons becomes significantly reduced, and then the nuclear medium becomes more transparent. Consequently, the signature of CT is an increase in the nuclear transparency T_{A} with increasing hardness of the reaction. 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 interaction (ISI and FSI). It can be measured by taking the ratio of nuclear per-nucleon (σ_{A}/A) to free nucleon (σ_{N}) cross sections

$$T_{\mathrm{A}} = \frac{\sigma_{\mathrm{A}}}{A\sigma_{\mathrm{N}}} \,. \tag{1}$$

A number of experiments have searched for an increase in the nuclear transparency. Unfortunately, only few of them were able to claim confirmation of CT. The first experiment to investigate CT was performed by Carroll et al. [2] at Brookhaven National Laboratory. Quasielastic (p,2p) scattering from each of several nuclei was compared to pp elastic scattering in hydrogen at incident proton momenta of 6, 10, and 12 GeV/c. Its results do not support a monotonic increase in transparency with Q^2 as predicted by CT: the transparency increases for Q^2 from 3 to 8 GeV^2, but then decreases for higher Q^2, up to 11 GeV^2. This subsequent decrease was explained as a consequence of soft processes that interfere with pertubative QCD in free pp scattering but are suppressed in the nuclear medium [4]. Due to the simplicity of the elementary electron-proton interaction compared to proton-proton one, the quasi-free A(e,e′p) reaction was suggested as an alternative [3 − 6]. Unfortunately, both the SLAC [7] and JLab [8,9] experiments failed to produce evidence of CT even for the Q^2 values as large as 8 GeV^2. The clearest signal of CT was observed in the E791 experiment [10] at Fermilab. The A-dependence of the diffractive dissociation into di-jets of 500 GeV/c pions scattering coherently from carbon and platinum targets was measured. It was found that the cross-section can be parametrized as $\sigma = \sigma_0 A^\alpha$, with $\alpha = 1.6$. This result is quite consistent with theoretical calculations [11 − 13] including CT effects and is obviously inconsistent with a cross-section proportional to $A^{2/3}$ which is typical of inclusive π-nucleus interactions. Another Fermilab experiment, E665 [14], reported interesting indications of CT using a 470 (GeV/c) muon beam. Exclusive diffractive ρ-meson production from nuclear targets was used to determine the nuclear transparency. The increase of the nuclear transparency with Q^2 was only suggestive of CT because the statistical precision of the data was not sufficient. Recent measurements perfomed by the HERMES collaboration using exclusive ρ^0electroproduction off nitrogen add further evidence for the existence of CT [15].

CT effects at moderate energies are more problematic than they are at high energies. One should deal in this case with other mechanisms that contain no explicit QCD dynamics and which may mock the CT signal. The experimental studies of CT were mainly focused on the quasi-elastic electron scattering (e,e′p) process. In these measurements, inelastic corrections could mock [16] the CT signal. The existence of such processes was confirmed by the measurements of the total cross sections of neutron [17] and neutral K-meson [18] interactions with nuclei. Due to these inelastic corrections, the cross-section is smaller, i.e. the nuclear medium is more transparent than is expected by the Glauber approximation. This effect increases with the ejectile energy. Thus, it will also increase with Q^2 because the energy $\nu = Q^2/2m_{\mathrm{N}}$ and Q^2 are correlated in the quasi-elastic peak. The first-order inelastic corrections has been estimated in Ref. [16]. It was found that the growth of nuclear transparency with Q^2 in quasi-elastic electron scattering off nuclei could imitate the onset of CT up to $Q^2 \sim 20$ GeV^2.

Exclusive incoherent electroproduction of vector mesons off nuclei has also been suggested [19] as a sensitive way to detect CT. In these processes, a fluctuation of the virtual photon gives rise to a quark-antiquark ($q\overline{q}$) pair that travels through the nuclear medium evolving from the initial state, with Q^2 dependent size (the transverse size of the hadronic fluctuation is $r_\perp \sim 1/Q$), to develop the vector meson detected in the final state. Therefore, increasing the photon virtuality Q^2, one can squeeze the size of the produced ($q\overline{q}$) wave packet. The hadronic structure of high-energy photons was realized back in the 1960's (for review see Ref. [20]). In the laboratory frame, the photon fluctuation can propagate over a distance l_{c} known as the *coherence length*. The coherence length can be estimated relying on the uncertainty principle and Lorentz time dilatation as $l_{\mathrm{c}} = 2\nu/(Q^2 + M^2_{q\overline{q}})$, where ν is the energy of the photon in the laboratory frame, $-Q^2$ is its squared mass and $M_{q\overline{q}}$ is the mass of the ($q\overline{q}$) pair. In the case of exclusive ρ^0 electroproduction, the mass of $q\overline{q}$ is dominated by the ρ^0 mass. The produced small-size colorless hadronic system will then propagate through the nuclear medium with reduced attenuation because its cross section is proportional to its size ($\sigma(r) \propto r^2$). The effect of the nuclear medium on the particles in the initial and final states can be characterized by the nuclear transparency. Our ultimate goal is searching for a rise of $T_{\rm A}$ with Q^2 as a signal for the onset of CT. However, one has to be careful about all other effects that can imitate this signal. Indeed, the HERMES experiment [21] has shown that $T_{\rm A}$ increases when $l_{\rm c}$ varies from long to short compared to the size of the nucleus. This is due to the fact that the nuclear medium seen by the $(q\bar{q})$ fluctuation becomes shorter. Thus the $(q\bar{q})$ interacts less. This situation occurs when Q^2 increases at fixed ν. This so called *coherence-length effect* (CL) must be under control to avoid mixing it with the CT effect.

We propose to measure the nuclear transparency for exclusive incoherent ρ^0 electroproduction on ^{2}H, ^{12}C and ^{63}Cu targets up to $Q^2 = 4$ GeV^2 and for fixed $l_{\rm c}$ values: $l_{\rm c} = 0.4$ fm and $l_{\rm c} = 0.5$ fm. Binning the data in a way which keeps $l_{\rm c}$ constant represents a simple prescription to eliminate the CL effect from the Q^2 dependence of the nuclear transparency. Moreover, because the chosen values of $l_{\rm c}$ are shorter than the mean free path of the vector meson in the nuclear medium, it is obvious that there is no nuclear shadowing in the initial state. By isolating the CL effect, the Glauber model predicts no variation of $T_{\rm A}$ with Q^2. Following a recent work by Kopeliovich and collaborators [22], an important increase of the nuclear transparency with Q^2 is predicted as a signal for the onset of CT. The suggested reaction was exclusive incoherent ρ^0 electroproduction on nuclei for fixed $l_{\rm c}$ values. The authors have developed a quantum mechanical approach based on the light cone QCD Green function formalism. This formalism naturally incorporates the interference between the CL effect (ISI) and CT effect (FSI). Due to quark-hadron duality, it becomes equivalent to the full multichannel problem in the hadronic presentation. These calculations have succeeded in describing the coherence-length dependence of the nuclear transparency reported by the HERMES collaboration [21] and are also in good agreement with the FNAL E665 measurements [14].

3. The experiment

The schematic of the reaction is given in Fig. 1. The incident electron scatters off the target nucleus and exchanges a virtual photon. The photon interacts with one of the nucleons inside the nucleus and eventually produces a ρ^0 meson. The ρ^0 decays into two pions. We propose to perform these measurements at Hall B with electron beams of 6 GeV and 4 GeV at maximum luminosity of ($2 \times 10^{34}\,{\rm cm}^{-2}{\rm s}^{-1}$) per nucleon. Three targets will be used: deuterium, carbon and copper. The scattered electron will be detected to determine Q^2. The coincident detection of the two pions will allow the identification of ρ^0 particles using their reconstructed invariant mass. We will also measure ρ^0 photoproduction to complete our measurements with a point at $Q^2 = 0$. For this purpose, a tagged photon beam of 1.7 to 2.2 GeV at maximum flux ($0.8 \times 10^7 \gamma$/s) will be used on the same set of targets. Since the coherence-length effect can imitate the color-transparency effect, we will study the

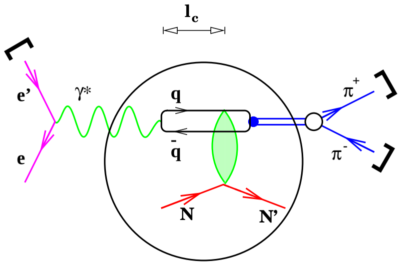


Fig. 1. Exclusive leptoproduction of the ρ^0 meson.

Q^2 dependence of T_A at fixed l_c values. Because of CLAS limited acceptence in the forward direction, one has to use 4 GeV electron beam to access Q^2 values below 0.75 GeV^2.

A new event generator of ρ^0 electroproduction from both protons and nuclear targets has been implemented. The three independent kinematical variables: W, Q^2 and the momentum transfer, t, are generated according to their experimental distributions. W and Q^2 are generated according to the flux of virtual photons $\Gamma(W, Q^2)$ exchanged between the incident electron and the target

$$\Gamma(Q^2, W) = \frac{\alpha}{8\pi^2} \times \frac{W}{ME^2} \times \frac{W^2 - M^2}{MQ^2} \times \frac{1}{1-\epsilon}\,, \tag{2}$$

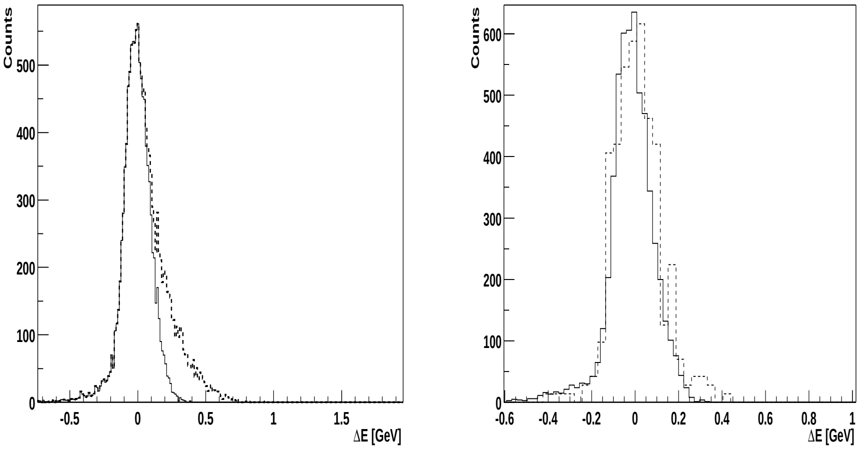
where M is the mass of the target. E and E' are, respectively, the energies of incident and scattered electrons, $\nu = E - E'$ is the energy of the virtual photon, and the variable $\epsilon = [1 + 2(Q^2 + \nu^2)/(4EE' - Q^2)]^{-1}$ is its polarization. The momentum transfer t is generated according to the experimental differential cross section $\mathrm{d}\sigma/\mathrm{d}t$ reported in Ref. [23] and fitted by the exponential form

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t'} = A \exp(-b(W, Q^2)\, t'), \tag{3}$$

where $t' = |t - t_{\mathrm{min}}|$, and t_{min} are the minimal values of t. The values of the slope $b(W, Q^2)$ measured for different W and Q^2 bins have been considered. Fermi momentum of nucleons inside the nucleus has been taken into account. The momentum of the struck nucleon is generated inside the corresponding Fermi momentum sphere of radius P_{F}. Experimental values of P_{F} [24] have been used. The generator considers also the decay of ρ^0 into a pair of pions $\pi^+\pi^-$. Pion angles are generated assuming s-channel helicity conservation. Using the generator's output as input to the fast simulation code of the CLAS detector, FASTMC [25] and taking the CLAS torus magnetic field at half its maximum value, we have been able to study the acceptance and efficiency of CLAS to detect the three particles: the scattered electron and the ρ^0 decay pions $\pi^+\pi^-$. Before studying the acceptance, kinematical cuts have been applied to well identify the reaction of interest. We use $W > 2$ GeV cut to avoid the resonance region, $z = E_\rho/\nu > 0.8$, to select the elastic process, and $|\Delta E| < 0.2$ GeV cut to reduce the contamination from non-exclusive events, where

$$\Delta E = \nu - E_\rho + t/2M_{\mathrm{p}} \tag{4}$$

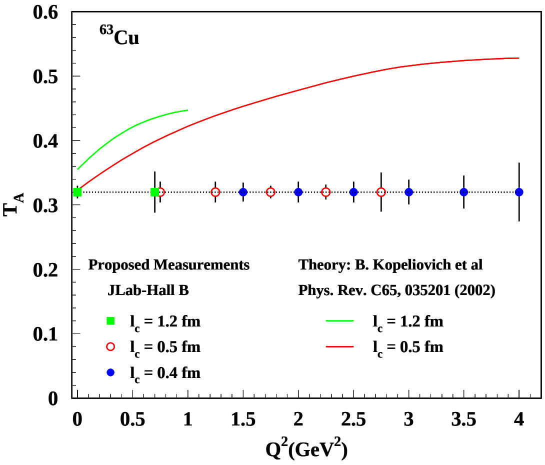
is the energy missing from the $\pi^+\pi^-$ pair due to the creation of any additional final state particles (excitations of the recoil nucleus don't affect ΔE within the resolution). The cut on ΔE is closely related to the cut $z \simeq 1$ but has the advantage that it includes the correction for the kinetic energy $-t/2M_\mathrm{p}$ of the recoil nucleon and that the inelastic threshold $\Delta E = m_\pi + m_\pi^2/2M_\mathrm{p}$ is independent of ν. One could expect that the z and ΔE cuts would be equivalent, but as you can see from Fig. 2a, the solid curve corresponding to ΔE from 4 GeV CLAS carbon



(a) **(b)**

Fig. 2. (a): Dashed curve corresponds to ΔE from 4 GeV electron beam on carbon in our kinematic region (t' and W cuts). The solid curve is after $z > 0.8$ cut. (b): Solid curve corresponds to ΔE from 4 GeV electron beam on carbon in our kinematic region (t', W and z cuts). The dashed curve corresponds to ΔE from GSIM with a pure exclusive diffractive ρ^0 electroproduction generator. Note that the GSIM curve was scaled by a factor 14 to match the amplitude of the data.

Fig. 3. Theoretical predictions [19] and expected statistical accuracy.



data with $z > 0.8$ cut is much cleaner than the one (dashed curve) without it. In Fig. 2b, the solid curve corresponds to the 4 GeV carbon data with Z cut and the dashed one is obtained from the GSIM CLAS Monte Carlo with a pure exclusive ρ^0 electroproduction generator as input. The agreement between the data and the simulation is a good indication of our ability to identify the exclusive channel. The cut $-t' < 0.5$ GeV^2 has also been used to select the diffractive process. To exclude coherent production, we use $-t' > 0.1$ GeV^2 cut. The projected measurements at the proposed values of $l_{\rm c}$ are presented in Fig. 3. Curves are the expectations of Ref. [22]. They show a CT effect on the value of $T_{\rm A}$ at $Q^2 \sim 4$ GeV^2 of 65% for copper, meanwhile Glauber calculations predict no Q^2 dependence of the nuclear transparency. We must recall that data with all possible values of $l_{\rm c}$, Q^2 and t' will be taken at the same time and will certainly be used. A common fit to all available data at fixed l_c with the slope of Q^2 as a free parameter will be performed. One can use $T_{\rm A} = a + b\,l_c + c\,Q^2$ form with a, b and c as free parameters. This fitting procedure will allow the determination of the Q^2 dependence (parameter c) with greater precision. Using only $l_{\rm c}$ values of 0.4, 0.5 and 1.2 fm, we can obtain $4\,\sigma$ precision on the Q^2 slope parameter c for carbon and $5\,\sigma$ for copper. The measurements at $Q^2 = 0$ will put stronger constraint on the value of the parameter a.

4. Systematic uncertainties

In this section, various sources of systematic uncertainties will be discussed. These sources include the absorption of the decay pions inside the nucleus, the background subtraction and the radiative corrections.

4.1. Pion absorption

To consider the absorption of ρ^0 decay pions inside the nucleus, we have used the intranuclear cascade model ISABEL [26]. ISABEL uses experimental nucleon-nucleon and π-nucleon cross sections and angular distributions and can simulate N-A and π-A interactions. First, using the decay length of produced ρ^0 particles, we have determined the proportion of events where the ρ^0 decays inside the nucleus. Then, for these events, each of the decay pions is sent as projectile on the nucleus where it generates an intranuclear cascade. The proportion of absorbed ρ^0 decreases with Q^2 because higher Q^2 corresponds to more energetic decay pions to which the nucleus is more transparent. For example, at low Q^2, 10% of the decay pions against only 2% at high Q^2 are absorbed on carbon. Table 1 summarizes the results of these calculations for both carbon and copper. Lower limits in this table correspond to high Q^2 and upper limits to low Q^2. Errors are estimated assuming a 30% error on the result of ISABEL due to the precision of the cross sections. The same

TABLE 1. Nuclear absorption effect and the corresponding errors.

Target	ρ^0 decay inside	$\pi^+\pi^-$absorbed	Error
Carbon	10 - 30%	2 - 10%	1 - 3%
Copper	20 - 50%	4 - 16%	2 - 5%

code was used to study the influence of the nuclear medium on the reconstructed $\pi^+\pi^-$ invariant mass. It was found that the effect of the pion energy and angular straggling in the nuclear medium does not affect the shape of the reconstructed ρ^0 mass.

4.2. Background contributions

Analysis of the existing CLAS electroproduction data off the carbon with a 4.45 GeV electron beam showed that incoherent diffractive ρ^0 electroproduction process can be reliably identified. The invariant mass of the detected $\pi^+\pi^-$ presented in Fig. 4 shows the typical ρ^0 mass distribution. Due to the fact that the ρ^0 meson is a quite large resonance, the main issue one has to deal with is the background subtraction. Many processes can contribute to this background. The main channels that can produce a $\pi^+\pi^-$ pair in the final state and could contribute to the background are:

- $\gamma^* \mathrm{p} \to \mathrm{p}\omega$ $(\pi^+\pi^-\pi^0: \ 88.8\%, \ \ \pi^+\pi^-: \ 2.2\%)$,
- $\gamma^* \mathrm{p} \to \mathrm{p}\phi$ $(\mathrm{K}^+\mathrm{K}^-: \ 49.1\%, \ \rho\pi + \pi^+\pi^-\pi^0: \ 15.5\%)$,
- $\gamma^* \mathrm{p} \to \mathrm{p}f_2(1270)$ $(\pi^+\pi^-: \ 84.7\%, \ \pi^+\pi^-2\pi^0: \ 7.1\%, \ 2\pi^+2\pi^-: \ 2.8\%)$,
- $\gamma^* \mathrm{p} \to \mathrm{p}\Delta^{++}\pi^0, \to \mathrm{p}\pi^+\pi^-$,
- $\gamma^* \mathrm{p} \to \mathrm{p}\Delta^0\pi^+ \to \mathrm{p}\pi^-\pi^+$.

A non detected π^0 in the 3π decay of ω is one of the sources of contamination to the ρ^0 peak. We expect the corresponding $M_{\pi^+\pi^-}$ spectrum to be centered about 0.45 GeV with a width of 0.075 GeV (using Dalitz plot for $\omega \to 3\pi$). This means that a majority of these events is outside the relevant ρ^0 invariant mass window. We estimated the residual contamination to be about 2%. The contribution of the $\pi^+\pi^-$ pairs of the $\omega(782)$ resonance to the ρ signal is expected to be small due to its 2% decay branch to $\pi^+\pi^-$. Considering the higher mass of the resonance f_2, we expect that most of them will be eliminated by cutting on ΔE, but due to its large width a residual contribution could mix with the high-mass tail of the ρ^0. A

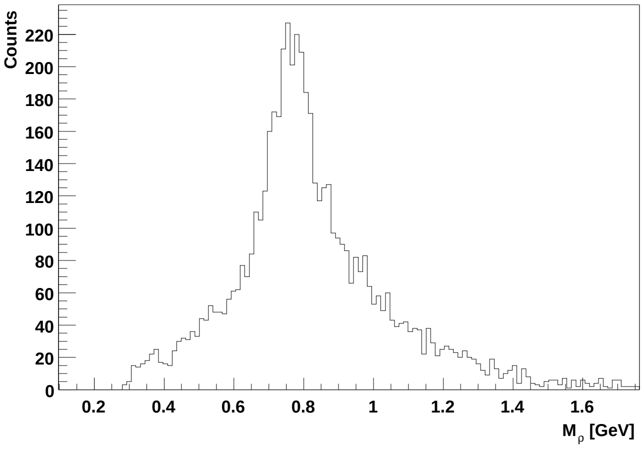


Fig. 4. Reconstructed invariant mass of the ρ^0 decay pions using CLAS data of 4 GeV *electron beam on carbon.*

recent Hall B collaboration analysis [32] showed that f_2 becomes more important at high $|t'|$, and cutting on $|t'| < 0.5$ GeV will reduce this contribution to less than 1%. For the other sources of background, the CLAS collaboration has already published data on ρ^0 photoproduction off the proton [33]. This paper shows that the systematic uncertainties related to the background subtraction are about 5% in our t' region. Despite this, one could expected that in the case of nuclear targets, the quoted systematic error can be higher. We believe that this error on the nuclear ratio could be kept at the 5% level, as shown by HERMES analysis.

4.3. *Radiative corrections*

The radiative corrections to the ρ^0 production cross section are estimated using the code DIFFRAD [34] written for exclusive vector meson production. In addition to the radiation of real photons, this code includes "virtual" corrections like vacuum polarization and vertex corrections. The mean values of the kinematical variables Q^2, W^2 and t, calculated using our MONTE CARLO model for the considered (l_c, Q^2) bins, are used as input to the numerical version of the code. The correction to the cross section is found to vary from 5 to 15%. The correction to the nuclear transparency, which is the ratio of the cross section on a nuclear target to the one measured on a nucleon, is 1−5%. Considering the cross section model dependence of the correction, we expect the corresponding systematic error to be less than 2%.

5. *Conclusions*

The main goal of E02-110 experiment is to look for the onset of CT in the incoherent diffractive ρ^0 electro and photoproduction on deuterium, carbon and copper over a large Q^2 range from 0 to 4 GeV^2. A large effect is predicted by theoritical calculations. This experiment is scheduled to run at Jefferson Laboratory by the end of the year 2003.

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OVISNOST NUKLEARNE PROZIRNOSTI O Q^2 ZA NEKOHERENTNU ELEKTROTVORBU ρ^0

Predlažemo mjerenja ekskluzivne elektrotvorbe $\rho^0(770)$ mezona u metama ^{2}H, ^{12}C i ^{63}Cu, za $Q^2 = 4$ GeV^2, pomoću detektora CLAS u Jeffersonovom Labu. Cilj mjerenja je određivanje nuklearne prozirnosti u ovisnosti o Q^2 za dvije nuklearne mete, ^{12}C i ^{63}Cu, pri određenoj koherentnoj duljini fluktuacija kvark-antikvark virtualnog fotona. Predviđa se znatno povećanje nuklearne prozirnosti koje se može mjeriti u predloženom eksperimentu. Znatan porast nuklearne prozirnosti bi se smatrao znakom za pojavu prozirnosti boje.