The Search For The Onset Of Color Transparency

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We briefly review the search for the onset of Color Transparency at intermediate energies. Color Transparency is an unique Quantum Chromo Dynamics phenomena. We also discuss some upcoming experiments and a new proposal that will extended the search to new unexplored phase space.

INTRODUCTION

Color Transparency (CT) refers to the suppression of the interaction between small size color singlet wave packets and hadrons, due to the cancellation of the color fields of Quantum Chromo Dynamics (QCD) [1]. This distinctive property of QCD leads to the vanishing of the final (and initial) state interactions of hadrons with the nuclear medium, in exclusive processes at high momentum transfer. The phenomena of CT is essential for ensuring the well established Bjorken scaling in deep inelastic scattering at high energies. At intermediate energies CT phenomena provide unique probes of the space time evolution of wave packets.

The concept of CT was introduced as an effect of QCD, related to the presence of color degrees of freedom underlying strongly interacting matter [2]. The basic idea is that at sufficiently high momentum transfer, three quarks, each of which would normally interact very strongly with nuclear matter, could form an object of reduced transverse size. In other words at high momentum transfer the scattering process preferentially select amplitudes in the initial and final state hadrons characterized by a small transverse size. This small size object should be 'color neutral' outside of its small radius in order not to radiate gluons. And if this compact size is maintained for distances comparable to the size of the nucleus it would pass through the nuclear medium without further interactions.

One of the observables commonly used in the search for the onset of CT is nuclear transparency, which is defined as the ratio of the cross section per nucleon for an exclusive scattering process on a bound nucleon in the nucleus to the cross section for the same process on a free nucleon. A clear signature for the onset of CT would involve a rise in the nuclear transparency as a function of momentum transfer involved in the process.

Although, CT was first discussed in the context of perturbative QCD, however, later works [3] have indicated that this phenomenon also occurs in a wide variety of models which feature non-perturbative reaction mechanisms. Unambiguous observation of CT is a clear manifestation of hadrons fluctuating to a small size in the nucleus and it contradicts the expectation of traditional Glauber multiple scattering theory, in the domain of its validity. Recently, CT has also been discussed in the context of QCD factorization theorems. These factorization theorems were, over the last few years, derived for various deep inelastic exclusive processes[4–7], and are intrinsically related to accessing the Generalized Parton Distributions (GPD's), introduced by Ji and Radyushkin [8, 9]. The discovery of these GPD's and their connection to certain totally exclusive cross sections has made it possible in principle to rigorously map out the complete nucleon wave functions. The GPD's contain a wealth of information about the transverse momentum and angular momentum carried by the quarks in the proton. Presently, experimental access to such GPD's is amongst the highest priorities in intermediate energy nuclear/particle physics.

For certain exclusive processes such as meson electroproduction, upon absorbing the virtual photon the meson and the baryon move fast in opposite directions. It has been suggested [10] that the outgoing meson maintains a small transverse size which results in a suppression of soft interactions (multiple gluon exchange) between the meson-baryon systems moving fast in opposite directions and thereby leading to factorization. Consequently, factorization is rigorously not possible without the onset of the Color Transparency (CT) phenomenon [10]. The underlying assumption here is that in exclusive"quasielastic" hadron production, the hadron is produced at small interquark distances. However, just the onset of CT is not enough, because higher-twist contributions such as quark transverse momentum contributions can be large at lower Q^2s [11, 12] which could lead to breakdown of factorization. Therefore, the onset of CT in hadron production is a necessary but not sufficient condition for the validity of factorization. It should be noted that it is still uncertain at which four momentum transfer squared (Q^2) value one will reach the factorization regime, and leading-order perturbative QCD is fully applicable. An unambiguous observation of CT would be the first step in determining the onset of the factorization regime. In the last few years, several authors have formally identified connection between GPDs and CT. For example, M. Burkardt and G. Miller [13] have derived the effective size of a hadron in terms of a GPDs. Since CT is a result of the reduced transverse size of the hadron, the discovery of CT would place constraints on the analytic behavior of the GPDs used to derive the effective size of hadrons. This in turn would provide testable predictions for other GPD related observables such as hadron form factors.

DISCOVERY OF CT AT HIGH ENERGIES

At high energies the phenomena of CT arise from the fact that, exclusive processes on a nucleus at high momentum-transfer preferentially select the color singlet small transverse size configuration, which then moves with high momentum through the nucleus. The interactions between the small transverse size configuration and the nucleon is strongly suppressed because the gluon emission amplitudes arising from different quarks cancel. This suppression of the interactions is one of the essential ingredients needed to account for Bjorken scaling in deep-inelastic scattering at small x [14]. Thus the discovery of Bjorken scaling in deep-inelastic scattering can be considered as the first indirect evidence for CT at high energies.

The first direct evidence for CT at high energies came from the A dependence of J/ψ production by real photons in the energy range of $80 - 190$ GeV studied on H, Be, Fe, and Pb targets at Fermilab [15]. These processes select the small transverse size configurations in the initial state which employs the decrease of the transverse separation between q and $\bar{q}$ in the wave function. The measured cross section can be parametrized as $\sigma_A = \sigma_1 A^\alpha$, where σ_1 is a constant independent of A. One expects $\alpha = 4/3$ and the experiment measured $\alpha = 1.4 \pm 0.06 \pm 0.04$ for the coherently produced J/ψ. This result can be interpreted as due to CT at high energies.

CT at high energies was also observed in FNAL experiment E791 [16] which measured the diffractive dissociation of 500 GeV/c pions into dijets when coherently scattering from carbon and platinum targets. The per-nucleon cross section for di-jet production is parametrized as $\sigma = \sigma_0 A^\alpha$, and the values of α obtained from the experiment E791 confirm the predicted [17] strong increase of the cross section with A: $\sigma \propto A^{1.61 \pm 0.08}$ as compared to the predicted $\sigma \propto A^{1.54}$, and the dependence of the cross section on the transverse momentum of each jet with respect to the beam axis (k_t) indicating the preferential selection of the small transverse size configurations in the projectile.

These experiments have unambiguously established the presence of small size $q\bar{q}$ Fock components in light mesons and show that at transverse separations, d ≤ 0.3 fm, perturbative QCD reasonably describes small "$q\bar{q}$ - dipole" - nucleon interactions for $10^{-4} < x < 10^{-2}$. Thus, Color transparency is well established for the small dipole interaction with nuclei for $x \sim 10^{-2}$. However, these high energy experiments do not provide any information about the appropriate energy regime for the onset of CT.

SEARCH FOR THE ONSET OF CT AT INTERMEDIATE ENERGIES

At intermediate energies, in addition to the preferential selection of the small size configuration, the expansion or contraction of the interacting small size configuration is also very important. The maximal longitudinal distance for which coherence effects are still present (coherence lengths) is determined by the minimal characteristic internal excitation energies of the hadron. At intermediate energies these longitudinal distance scales are not large enough for the small size configuration to escape without interaction and this leads to strong suppression of the color transparency effect [18, 19]. In this energy regime, the interplay between the selection of the small transverse size and its subsequent expansion determines the energy scale for the onset of CT. Estimates [18, 19] show that for the case of the knock out of a nucleon, the coherence is completely lost at distances $l_c \sim 0.4 \div 0.6$ fm $\cdot$ p_h, where p_h is the momentum of the final hadron measured in GeV/c. Hence even if a nucleon is produced in a small size configuration it has to have momentum significantly larger than $p_N[GeV/c] > r_{NN}/0.5 \sim 4\ GeV$ for a significant change of the transparency (here $r_{NN} \sim 2\ fm$ is the typical mean free path of a nucleon in the nucleus). This corresponds to $Q^2 > 8$ (GeV/c)^2.

One of the popular models for the time development of the small size configuration is the quantum diffusion model [18];

$$\sigma^{PLC}(Z) = (\sigma_{hard} + \frac{Z}{l_c}[\sigma - \sigma_{hard}])\theta(l_c - Z) + \sigma\theta\,(Z - l_c) \quad (1)$$

where the coherence lengths l_c is given by,

$$l_c = \frac{2p_h}{\Delta M_h^2}, \quad (2)$$

where $\Delta M_h^2 = m_{inter}^2 - m_h^2$ is the typical energy non-conservation in the intermediate state, and based on the additive quark model wave function $\Delta M_h^2 \sim 0.7\ GeV^2$.

Early experiments

The first attempt to measure the onset of CT at intermediate energies used large angle $A(p, 2p)$ reaction [20] at the Brookhaven National Lab (BNL). In this experiment large angle pp and quasielastic $(p, 2p)$ scattering were simultaneously measured in hydrogen and several nuclear targets, at incident proton momenta of 6 - 12 GeV/c. The nuclear transparency was extracted from the ratio of quasielastic cross section from a nuclear target to the free pp elastic cross section. The transparency was found to increase as predicted by CT, between 6 - 9.5 GeV/c but decreased between 9.5 and 12 GeV/c. A dedicated followup experiment EVA [21] extended these measurements to 14.4 GeV/c. The final results from both experiments [22] are shown in Fig 1. In addition to the energy dependence of the transparency the angular dependence ($80 < \theta_{c.m.} < 90$) of the transparency was also measured.

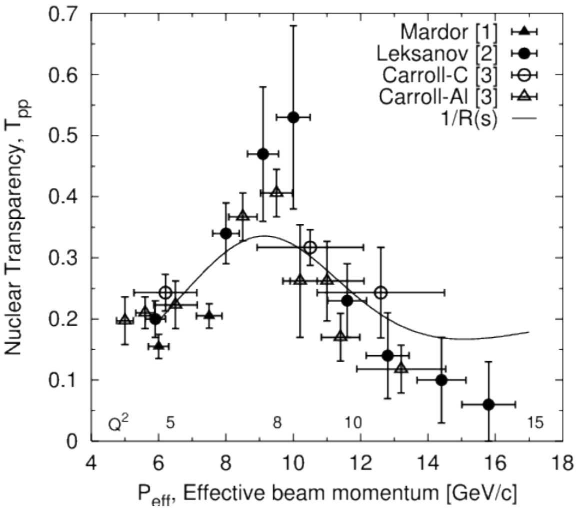

FIG. 1: The nuclear transparency values for ^{12}C and ^{27}Al (scaled by $(\frac{27}{12})^{1/3}$) versus the effective beam momentum. The curved line is the inverse of $R(s)$ as defined in the text [22].

The initial rise in transparency between p_p= 6 - 9.5 GeV/c is consistent with the selection of a point like configuration and its subsequent expansion over distances comparable to the nuclear radius. However, At the non-monotonous energy dependence of the transparency, is a problem for all current models with just CT. Two possible explanations have been suggested for the observed energy dependence above p_p= 9 GeV/c. One explained that the energy dependence arises from an interference between a hard amplitude, which dominates the high energy *pp* elastic scattering cross section, and a soft amplitude arising from higher order radiative process, also known as Landshoff mechanism [23, 24]. The *pp* elastic scattering cross section near $90^\circ_{c.m.}$ degrees varies with c.m. energy (s) as;

$$\frac{d\sigma}{dt_{pp}}(\theta = 90^\circ_{c.m.}) = R(s)s^{-10} \tag{3}$$

In the Landshoff mechanism picture, the long-ranged portion of the amplitude is attenuated by the nuclear matter, and the interference disappears for the nuclear cross section and hence the energy dependence of the transparency should be the inverse of $R(s)$, as shown. The second explanation [25] suggests that the energy dependence of the *pp* elastic scattering cross section scaled by s^{-10} corresponds to a resonance or threshold for a new scale of physics, such as charmed quark resonance or other exotic QCD multi-quark states.

Quasielastic Electron Scattering on Nuclei

Compared to hadronic probes the weaker electromagnetic probe samples the complete nuclear volume, the fundamental electron-proton scattering cross section is smoothly varying and is accurately known over a wide kinematic range and detailed knowledge of the nucleon energy and momentum distribution inside a variety of nuclei have been measured extensively in low energy experiments.

In quasielastic $(e, e'p)$ scattering from nuclei the electron scatters from a single proton which is moving due to its Fermi momentum [26]. In the plane wave impulse approximation (PWIA) the proton is ejected without final state interactions with the residual A-1 nucleons. The measured A(e, e'p) cross section would be reduced compared to the PWIA prediction in the presence of final state interactions, where the proton can scatter both elastically and inelastically from the surrounding nucleons as it exits the nucleus. The deviations from the simple PWIA expectation is used as a measure of the nuclear transparency. In the limit of complete color transparency, the final state interactions would vanish and the nuclear transparency would approach unity. Nuclear transparency can be written as

$$T(Q^2) = \frac{\int_V d^3p_m dE_m Y_{exp}(E_m, \vec{p}_m)}{\int_V d^3p_m dE_m Y_{PWIA}(E_m, \vec{p}_m)}, \tag{4}$$

where the integral is over the phase space V defined by the cuts on missing energy E_m (typically < 80 MeV) and missing momentum $|\vec{p}_m|$ (typically < 300 MeV/c), $Y_{exp}(E_m, \vec{p}_m)$ and $Y_{PWIA}(E_m, \vec{p}_m)$ are the corresponding experimental and PWIA yields. The E_m cut prevents inelastic contributions above pion production threshold. In the conventional nuclear physics picture one expects the nuclear transparency to show the same energy dependence as the energy dependence of the $N - N$ cross section. Other effects such as short-range correlations and the density dependence of the $N-N$ cross section will affect the absolute magnitude of the nuclear transparency but have little influence on the energy (Q^2) dependence of the transparency. Thus the onset of CT would manifest as a rise in the nuclear transparency as a function of increasing Q^2. However, even a conclusive experimental observation of a rise in nuclear transparency with increasing Q^2, may not necessarily be an unambiguous observation of CT [27], because such a rise can also be caused by the diffractive production of inelastic intermediate states by the knocked-out proton while it propagates through the medium.

The $(e, e'p)$ reaction is expected to be simpler to understand than the (p, pp) reaction and is not effected by either of the two explanations proposed to account for the observed energy dependence of nuclear transparency in (p, pp) reactions discussed earlier. The first electron scattering experiment to look for the onset of CT was the NE-18 A(e,e'p) experiment at SLAC [28]. This experiment yielded distributions in missing energy and momentum completely consistent with conventional nuclear physics and the extracted transparencies exclude sizable CT effects up to $Q^2 = 6.8$ $(GeV/c)^2$ in contrast to the results from the A(p,2p) experiments [20]. Later experiments with greatly improved statistics and systematic uncertainties compared to the NE-18 experiment [28], and with increased Q^2 range was carried out at JLab [29, 30].

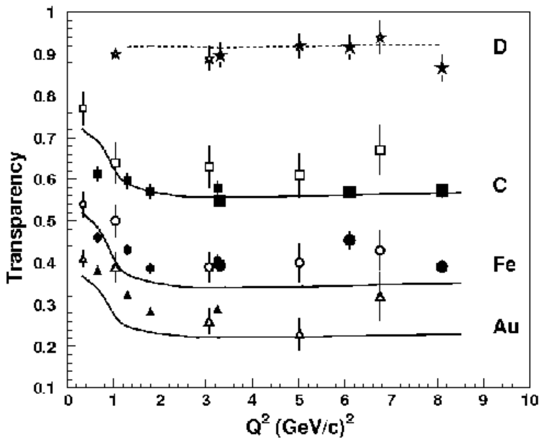

FIG. 2: A compilation of transparency for $(e, e'p)$ quasielastic scattering from D (stars), C (squares), Fe (circles), and Au (triangles) taken from Ref. [30]. Data from the two JLab experiments [29, 30] are shown as solid points. The previous SLAC data [28] are shown by large open symbols, and the previous Bates data [31] are shown by small open symbols, at the lowest Q^2 on C, Ni, and Ta targets, respectively. The errors shown for the JLab measurement (solid points) include statistical and the point-to-point systematic (2.3%) uncertainties, but do not include model dependent systematic uncertainties on the simulations or normalization-type errors. The net systematic errors, adding point-to-point, normalization-type and model-dependent errors in quadrature, are estimated to be (3.8%), (4.6%), and (6.2%) corresponding to D, C, and Fe, respectively. The error bars for the other data sets include their net systematic and statistical errors. The solid curves shown from $0.2 < Q^2 < 8.5$ $(GeV/c)^2$ are Glauber calculations from Ref. [32]. In the case of D, the dashed curve is a Glauber calculation from Ref. [33].

A compilation of the measured transparency $T(Q^2)$ values (defined as ratio of measured to PWIA cross sections) from all electron scattering experiments are presented in Fig. 2. The results show no Q^2 dependence in the nuclear transparency data above $Q^2 > 2$ $(GeV/c)^2$. The energy dependence below $Q^2 = 2$ $(GeV/c)^2$ is consistent with the energy dependence of the p-nucleon cross section. Above $Q^2 = 2$ $(GeV/c)^2$, excellent constant-value fits were obtained for the various transparency results. In Fig. 2 the measured transparency is compared with the results from correlated Glauber calculations, including rescattering through third order [32] (solid curves for $0.2 < Q^2 < 8.5$ $(GeV/c)^2$). In the case of deuterium the dashed curve shows a generalized Eikonal approximation calculation [34] which coincides with Glauber calculations for small missing momenta [33]. Although these calculations can describe the Q^2 dependence of the nuclear transparencies, the absolute magnitude of the transparencies are underpredicted for the heavier nuclei. This behavior persists even after the model-dependent systematic uncertainties are accounted for. The independence of the transparencies versus Q^2 may also result from a canceling of effects in the hard electron-proton scattering and CT.

In addition to the Q^2 dependence of the nuclear transparencies, the nuclear mass number A dependence of the nuclear transparency was also studied by parametrization of the transparency to the form $T = cA^{\alpha(Q^2)}$. Within uncertainties, the constant c is found to be consistent with unity as expected and the constant α to exhibit no Q^2 dependence up to $Q^2 = 8.1$ $(GeV/c)^2$ with a nearly constant value of $\alpha = -0.24$ for $Q^2 > 2.0$ $(GeV/c)^2$. This is also consistent with conventional nuclear physics calculations using Glauber approximation.

The existing worlds data rule out any onset of CT effects larger than 7% over the Q^2 range of 2.0 - 8.1 $(GeV/c)^2$, with a confidence level of at least 90%. The $(e, e'p)$ data seem to suggest that a Q^2 of 8 $(GeV/c)^2$ is not large enough to overcome the expansion of the small transverse size objects selected in the hard $e-p$ scattering process.

Meson Production Experiments

It is expected that it is more probable to reach the CT regime at lower energies for the interaction/production of mesons than for baryons since only two quarks have to come close together and a quark-antiquark pair is more likely to form a small size object [35]. Further, it is important to note that the unambiguous observation of the onset of CT is a critical precondition for the validity of the factorization theorem for meson production [36]. This is because in the regime where CT applies, the outgoing meson retains a small transverse size (inter-quark distance) while soft interactions like multiple gluon exchange between the meson produced from the hard interaction and the baryon are highly suppressed. QCD factorization is thus rigorously not possible without the onset of CT [37].

As described earlier, the J/ψ coherent and quasielastic photoproduction experiments did find a weak absorption of J/ψ indicating presence of CT. Support for CT was also observed in the coherent diffractive dissociation of 500 GeV/c negative pions into di-jets. There was also hints for CT in several ρ-meson production experiments [38, 39]. However all of these high energy experiments did not have good enough resolution in the missing mass to suppress hadron production at the nucleus vertex, making interpretation of these experiments somewhat ambiguous. Moreover, these high energy experiments do not tell us anything about the onset of CT.

Experiments at Jefferson Lab

A high resolution experiment of pion production recently reported evidence for the onset of CT [40] in the process $eA \to e\pi^+A^*$. New results for the ρ-meson production at JLab have also confirm the early onset of CT in mesons [41]. The pion electroproduction and rho experiments together conclusively demonstrate the onset of CT in the few GeV energy range. These experiments are discussed below.

Pion Production Experiments

(i) Pion photoproduction

At low momentum transfers a photon can be described as a superposition of vector meson states, while at high momentum transfers it can fluctuate to a point like configuration. This partonic description of the photon has been experimentally demonstrated at high energy via the $1/t$ suppression of the vector meson states at high momentum transfer data from the H1 experiment at HERA [42], however the transition between the two regimes is unknown. A point like photon would have a significantly larger photon transparency, defined as the ratio of the photonuclear cross section to the photo-nucleon cross section normalized to the number of nucleons in the nucleus. The onset of CT would lead to an even larger increase in the photon transparency as calculated in Ref. [43]. Therefore, photonuclear reactions are a natural, yet typically unexplored, fit in the search for CT.

The onset of CT was first explored in a pion photoproduction experiment at JLab. In this experiment nuclear transparency of the $\gamma n \to \pi^- p$ process was measured as a ratio of pion photoproduction cross section from ^{4}He to ^{2}H [44]. The ^{4}He nucleus has several advantages as a choice for the studying the onset of CT. Exact nuclear ground state wavefunction are available for ^{4}He [45], these along with the elementary hadron-nucleon cross-sections can be used to carry out precise calculations of the nuclear transparency [46]. Therefore, precise measurement of nuclear transparency from ^{4}He nuclei constitute a benchmark test of traditional nuclear calculations. In addition, light nuclei such as ^{4}He are predicted to be better for the onset of CT phenomenon because of their relatively small nuclear sizes, which are smaller than the expansion length scales of the small size object [18].

The photopion results on ^{4}He appears to deviate from the traditional nuclear physics calculations at the higher energies. The slopes of the measured transparency obtained from the three points which are above the resonance region (above $E_\gamma = 2.25$ GeV) are in good agreement, within experimental uncertainties, with the slopes predicted by the calculations including CT [18] and they seem to deviate from the slopes predicted by the Glauber calculations [46] without CT at the $1\sigma(2\sigma)$ level for $\theta^\pi_{CM} = 70°(90°)$. These data suggest the onset of behavior predicted for CT, but future experiments with significantly improved statistical and systematic precision are essential to confirm such conclusions.

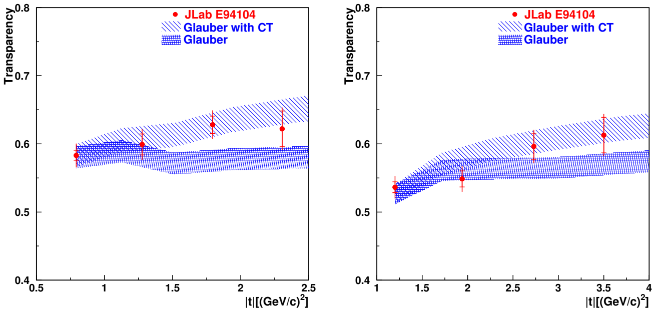

FIG. 3: The nuclear transparency of $^4He(\gamma, p\pi)$ at $\theta^\pi_{cm} = 70°$ (left) and $\theta^\pi_{cm} = 90°$ (right), as a function of momentum transfer square $|t|$ [44]. The inner error bars shown are statistical uncertainties only, while the outer error bars are statistical and point-to-point systematic uncertainties (2.7%) added in quadrature. In addition there is a 4% normalization/scale systematic uncertainty which leads to a total systematic uncertainty of 4.8%.

(ii) Pion electroproduction

The first extensive study of the pion electroproduction on a number of nuclear targets (^{1}H, ^{2}H, ^{12}C, ^{27}Al, ^{63}Cu and ^{197}Au) was carried out at JLab in 2004. This experiment (piCT) made it possible for the first time to determine simultaneously the A and Q^2 dependence of the pion differential cross section for Q^2=1-5 (GeV/c)^2 [40, 47]. The fraction of pions which can escape from the nucleus is the pion nuclear transparency. In the quasi-free picture, the ratio of the longitudinal to transverse cross section from a bound proton inside the nucleus is expected to be the same as that from a free proton, this also provides the means to test the appropriateness of the quasi-free approximation. Assuming the dominance of the quasi-free process, one can extract the nuclear transparency of the pions, by taking the ratio of the acceptance corrected cross sections from the nuclear target to those from the proton and/or deuteron.

The piCT experiment verified the dominance of the quasi-free process by comparing the ratios of the longitudinal to transverse cross sections from nuclear targets with those obtained from a nucleon target. Within experimental uncertainties, the σ_L/σ_T ratios were found to be independent of A [47]. This can be viewed as a confirmation of the quasi-free reaction mechanism. Additionally, the restriction of $-t \leq 0.5$ (GeV/c)^2 minimized contributions from rescattering or multi-nucleon effects.

The pion nuclear transparency was calculated as the ratio of pion electroproduction cross sections from the nuclear target to those from the proton [40], but in order to reduce the uncertainty due the unknown elementary pion electroproduction off a neutron and uncertainties in the Fermi smearing corrections, the pion nuclear transparency was later redefined [47] as the ratio of pion electroproduction cross sections from the nuclear target to those from the deuteron. The deuterium nuclear transparency was found to be independent of P_π (or Q^2) with 81% probability, hence, both methods yielded almost identical nuclear transparencies. The extracted transparency as a function of the pion momentum P_π for all targets is shown in Fig. 4.

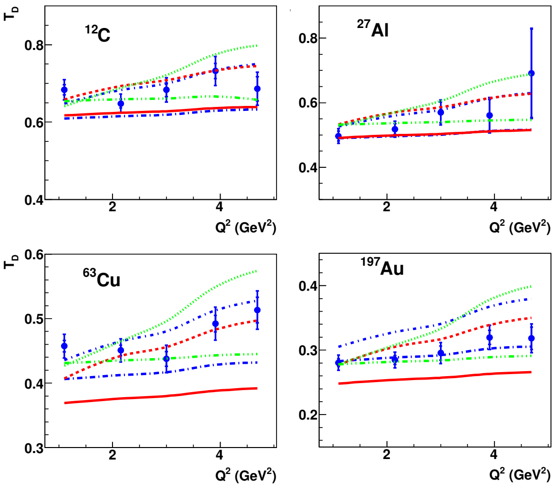

FIG. 4: Nuclear transparency vs P_π for ^{12}C, ^{27}Al, ^{63}Cu, and ^{197}Au. The inner error bars are the statistical uncertainties and the outer error bars are the statistical and point-to-point systematic uncertainties added in quadrature. The solid circles (blue) are the high ϵ (virtual photon polarization) points, while the solid squares (red) are the low ϵ points. The dark (blue) bands are the model uncertainties. The dashed and solid lines (red) are Glauber calculations from Larson, *et al.* [48], with and without CT, respectively. Similarly, the dot-short dash and dot-long dash lines (blue) are Glauber calculations with and without CT from Cosyn, *et al.* [49]. The dotted and dot-dot-dashed lines (green) are microscopic+BUU transport calculations from Kaskulov *et al.* [50], with and without CT, respectively.

The measured pion nuclear transparencies are compared to three different calculations. Although, all three calculations use an effective interaction based on the quantum diffusion model [18] to incorporate the CT effect, the underlying conventional nuclear physics is calculated very differently. The calculations of Larson, *et al.* [48], use a semi-classical formula based on the eikonal approximation, Cosyn *et al.* use a relativistic multiple-scattering Glauber approximation (RMSGA) integrated over the kinematic range of the experiment and compare it to a relativistic plane wave impulse approximation (RPWIA) to calculate the nuclear transparency. Finally, Kaskulov, *et al.* [50] use a model built around a microscopic description [52] of the elementary ^{1}H$(e, e'\pi^+)$n process, which is divided into a soft hadronic part and a hard partonic or a deep inelastic scattering production part. For the reaction on nuclei, the elementary interaction is kept the same and nuclear effects such as Fermi motion, Pauli blocking and nuclear shadowing, are incorporated. Finally, all produced pre-hadrons and hadrons are propagated through the nuclear medium according to the Boltzmann-Uehling-Uhlenbeck (BUU) transport equation. The nuclear transparency is calculated as the ratio of the differential cross section calculated in this model, with and without final state interactions. The production time and the formation time are taken from a Monte Carlo calculation based on the Lund fragmentation model [64] as described in Ref. [65]. Only the DIS part of the cross section is affected by the pre-hadronic interaction and thus in this model only the DIS events are responsible for the CT effect. In the conventional nuclear physics picture the pion nuclear transparency is expected to be nearly constants over the pion momentum range of the experiment, because the hadron-nucleon cross sections are nearly independent of momentum over this range of momenta. Instead, the observed pion nuclear transparency results (as compared both to hydrogen and deuterium cross sections) show a steady rise versus pion momentum for the nuclear ($A > 2$) targets, causing a deviation from calculations which do not include CT. And measured rise in nuclear transparency versus P_π are consistent with the rise in transparency in all three calculations that include CT, even though the underlying cause for the rise in nuclear transparency is different for the different model calculations.

The nuclear mass number A dependence of the nuclear transparency gives further insight on the proper interpretation of the data in terms of an onset of CT. The entire nuclear transparency data set was examined using a single parameter fit to $T = A^{\alpha(Q^2)-1}$, where A is the nuclear mass number and $\alpha(Q^2)$ is the free parameter. Even though this single-parameter fit is simplistic and neglects local A-dependent shell or density effects, it does not affect the final conclusion that the A-dependence changes with Q^2. Thus, even though the exact value of α may come with a variety of nuclear physics uncertainties, a significant empirical Q^2 dependence is observed from the data. In Fig. 5, we compare α as function of Q^2, extracted from the single parameter form $T = A^{\alpha(Q^2)-1}$, along with the calculations including CT effects of Larson, *et al.* [48] and Cosyn, *et al.* [49].

The results of the pion electroproduction experiment demonstrate that both the energy and A dependence of the nuclear transparency show a significant deviation

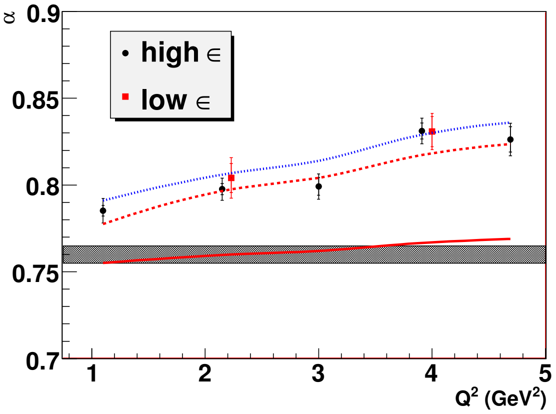

FIG. 5: The parameter $\alpha(Q^2)$, as extracted from a fit of the nuclear transparency to the form $T = A^{(\alpha-1)}$ (solid black circles). The inner error bars indicate the statistical uncertainties, and the outer error bars are the quadrature sum of statistical, systematic and modeling uncertainties. The hatched band is the value of $\alpha(Q^2)$ extracted from pion-nucleus scattering data [51]. The solid, dashed and dotted lines are α obtained from fitting the A-dependence of the theoretical calculations: the Glauber and Glauber+CT calculations of Ref. [48], and the Glauber + CT (including short-range correlation effects) calculations of Ref. [49], respectively. The red circles show the α values extracted at the low virtual photon polarization (ϵ) kinematics.

from the expectations of conventional nuclear physics and are consistent with calculations that include CT. The results can be seen as a clear indication of the onset of CT for pions.

Rho Elecroproduction

Electroproduction of vector mesons from nuclei is another excellent tool to investigate the formation and propagation of quark-antiquark ($q\bar{q}$) pairs under well-controlled kinematical conditions. These $q\bar{q}$ states of mass $M_{q\bar{q}}$ can propagate over a distance l_c known as the coherence length and given by $l_c = 2\nu/(Q^2 + M^2_{q\bar{q}})$, where $-Q^2$ and ν are the squared mass and energy of the photon in the lab frame (for reviews and references see e.g [53, 54]). The HERMES collaboration at DESY [55] used exclusive incoherent electroproduction off ^{1}H and ^{14}N to study the interaction of the $q\bar{q}$ fluctuation with the nuclear medium by measuring the nuclear transparencies of ^{14}N relative to ^{1}H as a function of the coherence length l_c. They found a coherence length dependence of the nuclear transparency of ^{14}N that is consistent with the onset of hadronic initial state interactions where the $q\bar{q}$ pair interacts with the nuclear medium like a ρ^0 meson. When the coherence length l_c is smaller than the mean free path of the ρ^0 meson in the nuclear medium, it is expected that the initial state interaction of the $q\bar{q}$ is predominantly electromagnetic and thus the nuclear transparency is independent of l_c. The probability of the $q\bar{q}$ pair to interact with the nuclear medium increases with l_c until l_c exceeds the nuclear size [56]. The HERMES measurements have important implications for the study of color transparency using ρ^0 meson electroproduction, where the CT signal would be the increase of the nuclear transparency with Q^2, which controls the initial size of the ρ^0 meson. These results demonstrate that the increase of the nuclear transparency when l_c decreases (Q^2 increases) can mimic the CT effects. Therefore, to unambiguously identify the CT signal, one should keep l_c fixed while measuring the Q^2 dependence of the nuclear transparency, or perform the measurements in the regions where no l_c dependence is expected.

When CT effects are present, a photon of high virtuality Q^2 is expected to produce a $q\bar{q}$ pair with small $\sim 1/Q^2$ transverse separation, which will have reduced interaction in the nuclear medium. The dynamical evolution of this small size colorless $q\bar{q}$ pair to a normal size ρ^0 is controlled by the time or length scale called formation time t_f or formation length $l_f = c\ t_f$ given by $l_f = 2\nu/({m_{v'}}^2 - {m_v}^2)$, where m_v is the mass of the ρ^0 in the ground state and $m_{v'}$ is the mass of its first radial excitation.

The CLAS collaboration at JLab measured the nuclear transparency for incoherent exclusive ρ^0 electroproduction off carbon and iron relative to deuterium [41] using a 5 GeV electron beam. Both the deuterium target and the solid target (carbon, iron) were exposed to the beam simultaneously to reduce systematic uncertainties in the nuclear ratio and allow high precision measurements. The ρ^0 mesons were identified through the reconstructed invariant mass of the two detected pions with 0.6 $< M_{\pi^+\pi^-} <$ 1 GeV. A set of kinematic conditions were imposed to identify exclusive diffractive and incoherent ρ^0 events, and the t distributions for exclusive events were fit with an exponential form Ae^{-bt}. The slope parameters b for ^{2}H (3.59 ± 0.5), C (3.67 ± 0.8) and Fe (3.72 ± 0.6) were reasonably consistent with the hydrogen measurements [57] of 2.63 ± 0.44 taken with 5.75 GeV beam energy. The transparencies for C and Fe are shown as a function of l_c in Fig. 6. As expected, they do not exhibit any l_c dependence because l_c is much shorter than the C and Fe nuclear radii of 2.7 and 4.6 fm respectively. Consequently, the coherence length effect cannot mimic the CT signal in this experiment. Figure 6 shows the increase of the transparency with Q^2 for both C and Fe, indicating the onset of CT phenomenon. The rise in transparency with Q^2 corresponds to an $(11 \pm 2.3)\%$ and $(12.5 \pm 4.1)\%$ decrease in the absorption of the ρ^0 in Fe and C respectively. The Q^2 dependence of the transparency was fitted by a linear form $T_A = a\ Q^2 + b$.

The extracted slopes "a" for C and Fe are in good agreement with both Kopeliovich-Nemchik-Schmidt (KNS) [58] and Gallmeister-Kaskulov-Mosel

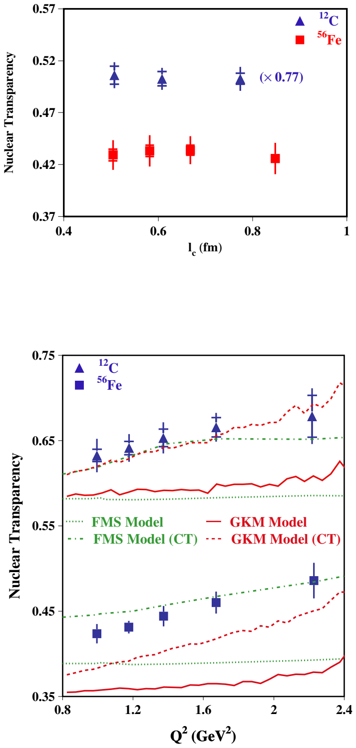

FIG. 6: (Top panel) Nuclear transparency as a function of l_c. The carbon data has been scaled by a factor 0.77 to fit in the same figure with the iron data [41]. (Bottom panel) Nuclear transparency as a function of Q^2. The curves are predictions of the FMS [60] (red) and GKM [59] (green) models with (dashed-dotted and dashed curves), respectively) and without (dotted and solid curves, respectively) CT. Both models include the pion absorption effect when the ρ^0 meson decays inside the nucleus. The inner error bars are the statistical uncertainties and the outer ones are the statistical and the point-to-point systematic uncertainties added in quadrature.

(GKM) [59] predictions, but somewhat larger than the Frankfurt-Miller-Strikman (FMS) [60] calculations. While the KNS and GKM models yield an approximately linear Q^2 dependence, the FMS calculation yields a more complicated Q^2 dependence as shown in Fig. 6 (bottom). The measured slope for carbon corresponds to a drop in the absorption of the ρ^0 from 37% at $Q^2 = 1$ (GeV/c)^2 to 32% at $Q^2 = 2.2$ (GeV/c)^2, in reasonable agreement with the calculations. The measured slopes both in CLAS and HERMES are fairly well described by the KNS model. The FMS model is quite successful in reproducing both the slopes and the magnitudes of the nuclear transparencies, while taking into account both CT effect and the ρ^0 decaying inside the nucleus and the subsequent pion absorption effect. The same model is successful in reproducing the JLab pion electroproduction data discussed above.

The onset of CT in ρ^0 electroproduction seems to occur at lower Q^2 than in the pion measurements. This early onset suggests that diffractive meson production might be the optimal way to create small size $q\bar{q}$ pair. The Q^2 dependence of the transparency ratio is mainly sensitive to the reduced interaction of the $q\bar{q}$ pair as it evolves into a full-sized hadron, and thus depends strongly on the formation time during which the small size configuration's color fields expand to form a ρ^0 meson. The formation time used by the FMS and GKM models is between 1.1 and 2.4 fm for ρ^0 mesons produced with momenta from 2 to 4.3 GeV while the KNS model uses an expansion length roughly a factor of two smaller. The agreement between the observed Q^2 dependence and these models suggests that these assumed expansion distances are reasonable. Having established these features, detailed studies of the theoretical models will allow the first quantitative evaluation of the structure and evolution properties of the small size configurations. Such studies will be further enhanced by future measurements [62], which will include additional nuclei and extend to higher Q^2 values.

FUTURE EXPERIMENTS

There are already approved plans for extending CT studies of the $A(e, e'p)$, $A(e, e'\pi)$ reactions to much higher energies at the upgraded JLab. This will finally allow us to reach kinematics where l_c is larger than the interaction length for a nucleon/pion in the nuclear media. The extension of the $A(e, e'p)$ experiment will double the Q^2 range covered from the current $Q^2 = 8.0$ $(GeV/c)^2$ to $Q^2 = 16.0$ $(GeV/c)^2$. At these higher Q^2 values CT predictions diverge appreciably from the predictions of conventional calculations. As mentioned earlier the BNL $A(p, 2p)$ data seem to establish a definite increase in nuclear transparency for nucleon momenta between about 6 and 10 GeV/c. For $A(e, e'p)$ measurements comparable momenta of the ejected nucleon correspond to about 10 $< Q^2 <$ 17 (GeV/c)^2, exactly the range of the proposed extension. Hence, this would unambiguously answer the question whether one has entered the CT region for nucleons, and help establish the threshold for the onset of CT phenomena in three-quark hadrons.

The extension of the $A(e, e'\pi)$ experiment will also double the Q^2 range covered from the current $Q^2 = 5.0$ $(GeV/c)^2$ to $Q^2 = 10.0$ $(GeV/c)^2$. A Q^2 dependence of the pion transparency in nuclei may also be introduced by conventional nuclear physics effects at the lower Q^2s. Thus one must simultaneously examine both the Q^2 and the A dependence of the meson transparency. Several independent calculations [3, 61] predict the CT effect to be largest around Q^2 of 10 (GeV/c)^2, which is in agreement with the observation of full CT in the Fermilab experiment mentioned above. Using the data collected at 6 GeV as a baseline, the new data could help confirm and establish the CT phenomena in mesons on a firm footing.

The JLab 12 GeV $A(e, e'\rho^0)$ experiment [62] will extend the maximum Q^2 reach from 2.2 to 5.5 $(\mathrm{GeV/c})^2$, which will allow for significant increase in the momentum and energy transfer involved in the reaction. Therefore, one expects to produce smaller configurations that live longer: the optimum parameters for CT studies. Several nuclei including deuterium, carbon, iron and tin will be studied. Measurements with different nuclei sizes are important for quantitative understanding of the small size configuration's formation time and its interaction in the nuclear medium. The dependence of the nuclear transparency on the coherence length will be measured for l_c range up to 2.5 fm. The measurements will be performed for fixed coherence length.

In addition to these experiments that are expected to collect data over the next year, a new experimental program is being proposed using the high energy photon beam and the GlueX apparatus in Hall D at JLab [68]. A unique feature of photonuclear reaction is that the entire energy of the photon is transferred in the reaction, regardless of the momentum transfer. At Hall D photon energies this ensures freezing of the expansion times even for moderate momentum transfers, thus sampling a completely different (and complementary) phase-space as compared to past and future $(e, e\ p)$ studies. The photon probe allows the interaction vertexes to be uniformly distributed all over the nuclear volume. But, without CT, the requirement to detect the emergent final state particles restricts the interaction vertex to the rim of the nucleus, from which these particles can escape without considerable re-interaction. For the kinematical phase-space allowed by the Hall D beam and GlueX spectrometer, Ref [43] predicts large CT effects that can be observed in both the ratio of the measured cross-section to Glauber calculations and in the A-dependence of the measured cross-section at large momentum transfers. The simultaneous measurement of a few reaction channels and the ability to create ratios and super ratios of transparencies will allow us to study these processes with small systematical and statistical uncertainties and to strongly constrain the theoretical interpretation. These measurements will probe a completely different region of the "freezing-vs-squeezing" phase space and are therefore complementary to the approved 12 GeV experiment to study CT in pion and ρ-electroproduction as well as in quasielastic proton knockout. The dramatic difference in the "freezing-vs-squeezing" phase space covered by photonuclear and electronuclear experiment is shown in Fig. 7.

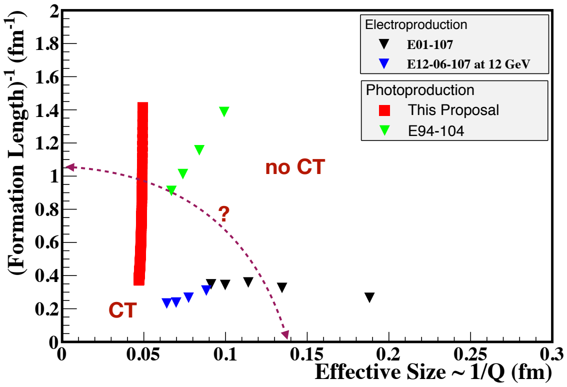

FIG. 7: The phase space in inverse formation length ("freezing") and effective size ("squeezing") covered by photonuclear and electronuclear reactions. The blue points represent the kinematic settings of the approved 12 GeV $(e, e^{'}\pi)$ experiment, while the black points represent the published $(e, e^{'}\pi)$ results [40]. The red band represent the kinematic settings for a new photonuclear experimental program being proposed in Hall D using the GlueX apparatus [68]. The green points represent the published photopion results [44].

CONCLUSIONS

Color Transparency is a key property of QCD. It offers a unique probe of "color", a defining feature of QCD, yet totally invisible in the observed structure of ordinary nuclear matter. CT is well established at very high energies, where the small size configuration is highly relativistic and its lifetime in the nucleus rest frame is dilated, causing it to stay small while traversing the nucleus. At low and intermediate energies, the situation is more challenging because the small size configuration starts expanding inside the nucleus. However, studying CT at low and intermediate energies provides valuable information on the small size configuration formation, expansion dynamics and most importantly, its interactions with the nuclear medium as a function of its color field. Furthermore, the onset of CT is a necessary condition for factorization, which is an important requirement for accessing GPDs in deep exclusive meson production. Important experimental efforts have been dedicated to the search for CT both at high and low/medium energies. No evidence for CT in the baryon sector was observed while complementary measurements in the meson sector can definitely be considered as a strong evidence for the CT phenomenon. One should point out the latest pion and rho meson measurements from Jefferson lab. Establishing the onset of CT phenomenon is just the beginning. The next step, which is about to get underway at the newly upgraded

Jefferson Lab, is to understand quantitatively the small size configuration formation time and its interaction in the nuclear environment. This will be achieved by extending the Q^2 range, which will allow for a significant increase in the momentum and energy transfer involved in the reaction. The measurements on several nuclei with different sizes will also allow studying the space-time properties of these small size configurations during their evolution to full size hadrons. Moreover, a new experiment being proposed using the GlueX apparatus and the photon beam in Hall D will allow us to explore new regimes that as yet remain unexplored.

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