Overview of Color Transparency Measurements

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Abstract. One of the most challenging topics in Quantum Chromo-Dynamics (QCD) for decades is the study of nucleon structure in terms of the fundamental QCD picture of quarks and gluons. Performing this study over a range of energies helps understand the dynamics of strong interaction, and gives a reasonable description of the transition from colored confined partons to the ordinary colorless hadrons. One of the best tools to study this transition is to search for the onset of Color Transparency (CT), one of the predicted phenomena of QCD. Color transparency refers to the suppression of final (and/or initial) state interactions caused by the cancellation of color fields in a special configuration of quarks and gluons with small transverse separation. I will give an overview of the CT measurements that were carried through the production of different hadrons at various energies, and highlight the future experiments planned for the 12 GeV upgrade at Jefferson Lab.

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INTRODUCTION

According to QCD, point like color-neutral objects, such as those produced in exclusive processes at sufficiently high momentum transfer, have small transverse size. Hence, they are expected to travel through nuclear medium experiencing reduced attenuation [1]. This phenomenon is known as color transparency, a novel property of QCD, that helps us understand the transition from the hadronic degrees of freedom to the fundamental quark-gluon degrees of freedom of QCD. CT refers to the suppression of the final (and/or initial) state interactions of hadrons with the nuclear medium. This suppression is caused by the cancellation of color fields produced by a system of closely separated quarks and gluons, commonly known as small size configuration (SSC) with a transverse size $r_\perp \sim 1/Q$ [2, 3].

To experimentally search for CT, we measure the nuclear transparency T_A defined as the ratio of the cross section per nucleon on a bound nucleon to that on a free nucleon. The signature of CT is the monotonic rise in T_A with energy or four-momentum transfer squared (Q^2). The CT idea came originally from QED, from the decay of cosmic ray pion in an emulsion. It was found that the (e^+, e^-) pair produced near the interaction point, acts as an electric dipole with small radius and vanishing electromagnetic interaction cross section proportional to the square of its size [4]. In QCD, in analogy to QED, a color-neutral object made of a quark and an anti-quark ($q\bar{q}$) or three quarks (qqq) acts as a color dipole with vanishing interaction cross section [5].

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In the last decades, several studies were dedicated to search for the CT signal in meson and baryon productions. While the CT searches on meson production were all promising, the results for baryon production, mainly proton knockout, were indecisive. Accordingly, it seems easier to bring the $q\bar{q}$ of a meson close together to form a SSC, than the qqq of a baryon [6], which makes meson production more appropriate to study CT at low energy. Establishing CT on meson production is crucial for understanding the dynamics of hard reactions, where it is possible to separate the perturbative and non-perturbative parts of the interaction, known as the factorization theorem. Thus, it is important to observe the onset of CT to prove the validity of this theorem [7].

BARYON PRODUCTION

- **Proton Scattering $\mathbf{A(p,2p)}$ Experiments.** The first attempt to measure CT was carried out at the Brookhaven National Lab (BNL) using quasi-elastic proton scattering $A(p,2p)$ reaction off nuclei [8]. The nuclear transparency was defined as the ratio of the quasi-elastic cross section in a nuclear target to the free elastic pp cross section. The measured results showed a rise in T_A with the effective beam momentum up to $9.5\,GeV$, which is consistent with CT expectations. However, it was surprisingly followed by a drop at higher momenta. As a cross-check, a series of similar experiments were performed afterwards at BNL [9, 10], and all confirmed the same behavior [11]. One proposed explanation described this behavior as an interference between the short and long distance amplitudes in the free pp cross section, where the nuclear medium acts as a filter for the long distance amplitudes [12, 13]. A second explanation associated the unexpected decrease with the crossing of the open charm threshold [14].

- **Electron Scattering $\mathbf{A(e,e'p)}$ Experiments.** Due to the simplicity of the elementary electron-proton interaction mechanism compared to the proton-proton one, the quasi-free $A(e,e'p)$ reaction was used in the next series of experiments conducted at MIT-Bates [15], SLAC [16, 17] and JLab [18, 19] to look for CT effects. Even with the wide coverage of Q^2 up to $8.1\,GeV^2$, none of these experiments succeeded to produce evidence for CT. Furthermore, all these data sets were consistent with the conventional Glauber-type model of Pandharipande and Pieper [20].

MESON PRODUCTION

- **Pion production.** The strongest evidence of CT signal came from the high energy E791 experiment [21] at Fermi National Accelerator Lab (FNAL). The experiment measured the A-dependence of the diffractive dissociation into di-jets of $500\,GeV$ negative pions scattering coherently from carbon and platinum targets. The per-nucleus cross section was parameterized as $\sigma = \sigma_0 A^{\alpha}$, and gave a result of $\alpha \sim 1.6$, which is consistent with theoretical predictions including CT, and very different from the typical $\alpha = 2/3$ parameterizing the inclusive π-nucleus interaction cross section.

The first investigation of CT signal at medium energy was performed via pion photoproduction from ^4He in Hall A at JLab [22]. The experiment studied the process

$\gamma n \rightarrow \pi^- p$ at $\theta^{\pi}_{cm} = 70^\circ$ and 90°. The nuclear transparency was calculated as the ratio of the pion photoproduction cross section from ^4He to ^2H. The results showed a deviation from the traditional nuclear calculations at higher energies. But due to a poor statistical precision, the authors concluded that a further measurement is needed to confirm this observation.

The most recent experiment to look for pion-CT was carried out in Hall C at JLab [23]. The experiment measured the electroproduction of π^+ from several nuclear targets over a wide Q^2 range from 1.1 to $4.7\,GeV^2$. The results of A and Q^2 dependence in nuclear transparency showed a positive slope, which is qualitatively consistent with theoretical predictions including CT effects [24, 25]. However, a well established positively charged pion-CT signal is expected with an extended measurements to higher Q^2 values up to $10\,GeV^2$ after the 12 GeV JLab upgrade [26].

- **ρ^0 production.** Exclusive ρ^0 electro(lepto)-production was used in several experiments to look for CT effects due to the simplicity of its production mechanism. In this process, the virtual photon originating from the scattering of the incident lepton over the target nucleus fluctuates into a $q\bar{q}$ pair of small transverse size proportional to $1/Q$. The $q\bar{q}$ pair propagates in a medium evolving from the initial to a final state, where the SSC is formed and subsequently materializes into a vector meson. Thus, increasing the photon virtuality, Q^2, ensures the production of a SSC by squeezing the size of the $q\bar{q}$ wave packet. However, the CT is sensitive to two production time scales that can affect its signature. The first characteristic time is related to the propagation length of a $q\bar{q}$, known as the coherence length l_c. When l_c varies from small to large compared to the free mean path of a produced meson on the nuclear medium, it causes an increase of T_A with Q^2, that could mimic the CT signal [27]. This effect, known as the Coherence Length (CL), arises when the initial state interaction is dominated by the hadronic interaction of $q\bar{q}$ with the medium. To control this effect, one has to study T_A as function of Q^2 at fixed l_c or targets the small l_c region (less than $\sim 1\,fm$) where no Q^2 dependence on l_c is expected. The second time scale is related to the expansion time, known as the formation time, of the SSC to a regular meson (or generally hadron) that has to be larger than the nuclear radius to suppress the final state interactions.

The first experiment that used a diffractive ρ^0 leptoproduction off nuclei to investigate CT was carried out at FNAL by the E665 collaboration [28] using a $470\,GeV$ muon beam. Due to the lack of good statistical precision, the slight increase seen on the nuclear transparency as function of Q^2 were only suggestive for a CT signal.

The second experiement was performed at DESY by the HERMES collaboration [32] which studied exclusive coherent and incoherent ρ^0 production off ^2H and ^{14}N targets using a $27.5\,GeV$ positron beam. To avoid mixing the CL effect with CT, the Q^2 dependence in T_A was studied for fixed l_c bins. A simultaneous linear fit over all l_c bins gave a common Q^2-dependence slope that was treated as a positve signal of CT, which was consistent with theoretical predictions of Kopeliovich et al. [33].

The most recent experiment that used a diffractive incoherent ρ^0 electroproduction off carbon and iron targets was conducted in Hall B at JLab [34] using a 5 GeV electron beam. The data were collected simultanously on deuterium and nuclear targets to reduce the systematic uncertainties on the nuclear transparency extracted from heavy nuclei relative to deuterium. The nuclear transparency ratio of ^{12}C and ^{56}Fe nuclei were

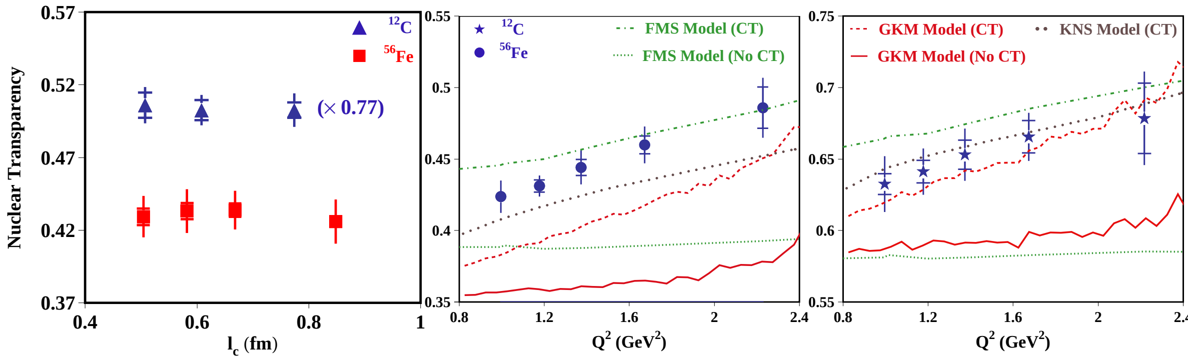

FIGURE 1. Left: Nuclear transparency as function of l_c. The carbon data were scaled by a factor of 0.77 to match the scale of iron data. Right: Nuclear transparency as function of Q^2. The theoretical curves are the predictions of the FMS (red) [29] and GKM (green) [30] models with (dashed-dotted and dashed curves, respectively) and without (dotted and solid curves, respectively) CT effects. The brown dotted curve is the KNS CT prediction [31]. All models except KNS include the pion absorption effect when the ρ^0 decays inside the nucleus. In both plots, 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. The normalization uncertainties, which are independent of l_c and Q^2, are not shown in both plots.

studied as function of l_c and Q^2, as shown in Fig. 1. The measurement of T_A as function of l_c, depicted in Fig. 1 (left), doesn't manifest any l_c dependence as expected since the l_c range is much smaller than the ^{12}C and ^{56}Fe nuclear radii of 2.7 and 4.6 fm, respectively. However, the Q^2 dependence, illustrated in Fig. 1 (right), shows a significant increase of T_A with Q^2 consistent with the theoretical predictions including CT effects of Frankfurt-Miller-Strikman (FMS) [29], Gallmeister-Kaskulov-Mosel (GKM) [30] and Kopeliovich-Nemchik-Schmidt (KNS) [31]. Despite the difference in the nuclear transparency magnitude between the three models, they all agree with the measured Q^2-dependence slope given by a linear fit of the form; $T_A = aQ^2 + b$, to the CT results. The observed rise of T_A with Q^2 corresponds to a $(12.5 \pm 4.1)\%$ and $(11 \pm 2.3)\%$ decrease in the absorption of the ρ^0 in ^{12}C and ^{56}Fe, respectively, and supports the idea of the creation of small size configurations, their relatively slow expansion and their reduced interaction with the nuclear medium. A proposed extension of these measurements [35] has been approved for the JLab 12 GeV upgrade by including an additional heavy nuclei and going to much higher Q^2 values up to $5.5\,GeV^2$. This will allow a more careful study to disentangle the CT and CL effects and all other effects related to the SSC formation and its subsequent expansion and interaction with the nuclear medium.

SUMMARY

Color transparency is one of the interesting finding in nuclear physics, that proves the creation of small size configurations and their subsequent slow expansion and suppressed interaction with the nuclear medium. While a CT signal was never seen on baryon production, the search on meson production was successful, first at high energy with negatively charged pions, followed recently with a clear onset of CT at low energy with exclusive π^+ and ρ^0 electroproduction. Therefore, the early CT onset seen on ρ^0 results compared to π^+ proves that the diffractive meson production is the optimal mechanism to verify CT. A clear onset of a CT signal in exclusive meson production is important to prove the onset of factorization that will play a major role in the physics program looking for mesons production in hard exclusive reactions at JLab 12 GeV.

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