Color transparency at energies available at the CERN COMPASS experiment

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Pionic quasielastic knockout of protons from nuclei at 200 GeV show very large effects of color transparency as $-t$ increases from 0 to several GeV^2. Similar effects are expected for quasielastic photoproduction of vector mesons.

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I. INTRODUCTION

In the very special situation of high-momentum-transfer coherent processes the strong interactions between hadrons and nuclei could be extinguished, causing shadowing to disappear and the nucleus to become quantum-mechanically transparent. This phenomenon is known as color transparency [1–4]. In more technical language, color transparency is the vanishing of initial and final-state interactions, predicted by QCD to occur in high-momentum-transfer quasielastic nuclear reactions. In these reactions, the scattering amplitudes consist of a sum of terms involving different intermediate states and the same final state. Thus one adds different contributions to obtain the scattering amplitude. Under such conditions the effects of gluons emitted by small color-singlet systems tend to cancel [5] and can nearly vanish. Thus color transparency is also known as color coherence.

The important dynamical question is whether or not small color-singlet systems, often referred to as point-like configurations (PLC's), are produced as intermediate states in high momentum transfer reactions. Perturbative QCD predicts that a PLC is formed in many two-body hadronic processes at very large momentum transfer [1,6]. However, PLC's can also be formed under nonperturbative dynamics [7,8]. Therefore measurements of color transparency are important for clarifying the dynamics of bound states in QCD.

Observing color transparency requires that a PLC is formed and that the energies are high enough so that the PLC does not expand completely to the size of a physical hadron while traversing the target [9–11]. The frozen approximation must be valid.

A direct observation of high-energy color transparency in the A dependence of diffractive di-jet production by pions was reported in Ref. [12]. The results were in accord with the prediction of Ref. [13]. See also Ref. [14]. Evidence for color transparency (small hadronic cross sections) was observed in other types of processes, also occurring at high energy: in the A dependence of J/ψ photoproduction [15], in the Q^2 dependence of the t slope of diffractive ρ^0 production in deep inelastic muon scattering (where Q^2 is the invariant mass of the virtual photon and t denotes the negative square of the momentum transfer from the virtual photon to the target proton), and in the energy and flavor dependences of vector meson production in ep scattering at Hadron-Elektron-Ring-Anlage [16]. For all of these processes the energy is high enough so that the produced small-size configuration does not expand significantly as it makes its way out of the nucleus.

For hard, high-energy processes in which a small dipole is produced (pion diffraction into two jets) or the initial state is highly localized (exclusive production of mesons for large values of Q^2), one can prove factorization theorems that allow the scattering amplitude to be represented as the product of the generalized parton densities of the target, hard interaction block, and wave functions of the projectile and the final system in the frame where they have high momenta [13,17–19]. The proofs require the color transparency property of perturbative QCD, understood in the sense of the suppression $\propto d^2$ of multiple interactions of a color electric dipole moment. Note that the definition of color transparency does not simply correspond to the nuclear amplitude being A times the nucleonic amplitude because both the gluon G_A and quark sea S_A densities may depend upon the nuclear environment. Instead, color transparency corresponds to the dominance of the leading twist term in the relevant scattering amplitude [13].

At the energies available at JLAB and BNL expansion effects do occur. Experimental studies of high momentum transfer processes in $(e, e'p)$ and (p,pp) reactions have so far failed to produce convincing evidence of color transparency [20–23]. First data on the reaction $A(p, 2p)$ at large scattering angles were obtained at BNL. They were followed by the dedicated experiment [21]. The final results of Ref. [21] can be summarized as follows. An eikonal approximation calculation agrees with data for $p_p = 5.9$ GeV/c, and the transparency increases significantly for momenta up to about $p_p = 9$ GeV/c. Thus it seems that momenta of the incoming proton ∼10 GeV are sufficient to significantly suppress expansion effects. Therefore one can use proton projectiles with energies above ∼10 GeV to study other aspects of the strong interaction dynamics. But the observed drop in transparency for values of p_p ranging from 11.5 to 14.2 GeV/c represents a problem for all current models, including those found in Refs. [24–28] because of its broad range in energy. This suggests that the leading-power quark-exchange mechanism for elastic scattering dominates only at very large energies. It is natural to expect that it is easier to observe color transparency for the interaction/production of mesons than for baryons because only two quarks have to come close together. A high-resolution pion production experiment reported evidence for the onset of color transparency [29] at JLAB in the process $eA \to e\pi^+ A^*$. The experimental results agree well with the predictions of Refs. [30,31], which found small, but significant effects of color transparency. For another approach for describing pion production involving color transparency see [32].

In the present note we observe that studying the quasielastic knockout of a proton from a nucleus by the high-energy pions available at COMPASS offers a unique opportunity to observe the pionic PLC and even to study its cross section as a function of $-t$. Our analysis applies also to another reaction that can be studied by COMPASS—quasielastic production of vector mesons in muon—nucleus interactions. The theory is presented in Sec. II, and the results in Sec. II. Kinematic considerations, which show that the proton emission angle is large enough for proton detection, are presented in Sec. IV.

II. THEORY FOR THE NUCLEAR $\pi, \pi p$ REACTION AT HIGH MOMENTUM TRANSFER

It is worthwhile to discuss color transparency for quasielastic scattering of pions from an initially bound proton. The basic postulate is that at large center-of-mass angles, where $-t > -t_0 \sim 1\ \text{GeV}^2$ the reaction proceeds by components PLC of the pion wave function in which the quarks are closely separated. At high energies, where the space-time evolution of small-sized PLC wave packets is slow, one can introduce a notion of the cross section of scattering of a small dipole configuration (say $q\bar{q}$) of transverse size d on the nucleon [13,33], which in the leading log approximation is given by [17]

$$\sigma(d, x_N) = \frac{\pi^2}{3}\alpha_s\left(Q^2_{\text{eff}}\right)d^2\left[xG_N\left(x, Q^2_{\text{eff}}\right) + 2/3xS_N\left(x, Q^2_{\text{eff}}\right)\right], \tag{1}$$

where $Q^2_{\text{eff}} = \lambda/d^2$, $\lambda = 4 \div 10$, $x = Q^2_{\text{eff}}/s$, with s the invariant energy of the dipole-nucleon system and S is the sea quark distribution for quarks making up the dipole. The matching description of σ_L in momentum and coordinate space leads to $\lambda \sim 9$. However, sensitivity to the value of λ for small d is small. At the same time, use of a smaller value of $\lambda \sim 4$ allows us to make a smooth extrapolation to $\sigma(d, x_N)$ for large dipole sizes. The difference between Eq. (1) and the simplest two gluon exchange model [34] is significant for large values of x for which x is very small. An alternative earlier estimate is based on perturbative QCD and which assumes a smooth matching with the soft regime yields [35]

$$\sigma(d, x_N) \approx \sigma_{\text{PLC}} \equiv \sigma_{\text{tot}}(p)\frac{n^2\langle k_t^2\rangle}{Q^2_{\text{eff}}}, \quad d^2 \sim \frac{1}{Q^2_{\text{eff}}}, \tag{2}$$

as the cross section for the initially produced PLC, of momentum p, with $n = 2$ for the pion, $n = 3$ for the proton, and $\langle k_t^2\rangle^{1/2} \simeq 0.35\ \text{GeV}$.

The advantage of COMPASS is that if PLC's are involved in a large-$|-t|$, high-energy process, such configurations move through the nucleus without changing their size. Thus there is an opportunity to test the approximations Eqs. (1) and (2). For a cm scattering angle θ_c the invariant momentum transfer t is given by

$$-t = 4p_c^2\sin^2(\theta_c/2) = Q^2_{\text{eff}}. \tag{3}$$

At COMPASS $p_c^2 \approx 100\ \text{GeV}^2$ so $-t$ changes from 0 to $10\ \text{GeV}^2$ as θ_c changes from 0 to about 0.35. It is also important to observe that $-t$ plays the role of Q^2_{eff} that appears in Eqs. (1) and (2). The kinetic energy of the outgoing proton varies from 0 to about 5 GeV over that same range. The momentum of the proton must be at least 1 GeV/c for our considerations to be relevant, so we focus on $-t$ greater than about $1\ \text{GeV}^2$.

At JLAB energies the PLC expands while it moves through the nucleus. This complication is avoided at COMPASS. The pionic PLC easily transverses the nucleus without expanding. The proton may or may not be initially produced as a PLC. If it is produced as a PLC it will expand as it moves through the nucleus. In the advent of expansion σ_{PLC} of Eq. (2) is replaced by an effective cross section σ_{eff}, which takes the changing size of the wave packet into account. The effective interaction contains two parts, one for a propagation distance l less than a length l_h describing the interaction of the expanding PLC, another for larger values of $l > l_h$ describing the final-state interaction of the physical particle. We use the expression [35]

$$\sigma_{\text{eff}}(p, l) = \sigma_{\text{tot}}(p)\left[\left(\frac{n^2\langle k_t^2\rangle}{Q^2} + \frac{l}{l_h}\left(1 - \frac{n^2\langle k_t^2\rangle}{Q^2}\right)\right) \times \theta(l_h - l) + \theta(l - l_h)\right], \tag{4}$$

where $l = |\mathbf{p}\cdot\mathbf{l}/p|$, where $\mathbf{p}$ is the momentum and $\mathbf{l}$ is the displacement from the point where the hard scattering occurs. The quantity $l_h = 2p/\Delta M^2$, with $\Delta M^2 = 0.7\ \text{GeV}^2$ for pions. The prediction that the interaction of the PLC will be approximately proportional to the propagation distance l for $l < l_h$ is called the quantum diffusion model. The length l_h controls the physics. The conventional approach of Glauber theory is achieved as l_h approaches 0. For pions of momentum 200 GeV/c l_h is much larger than the diameter of any stable nuclear target. For protons, the value of ΔM^2 could be higher than that for pions, and the momentum is typically 2–3 GeV/c, depending on the value of $-t$. Here we take ΔM^2 to be the same for pions and protons. The large effects of color transparency that we will observe are mainly due to pionic PLC's, so the value of ΔM^2 for protons is not very important.

The transparency T_A is defined here as the ratio of the observed nuclear $\pi, \pi p$ cross section to A (the nucleon number) times the cross section on a free nucleon $\frac{d\sigma}{dt}$, with perfect transparency occurring for $T_A \to 1$:

$$T_A(\mathbf{p}_0, \mathbf{p}_1, \mathbf{p}_2) \equiv \frac{\frac{d\sigma_A}{dt}}{A\frac{d\sigma}{dt}}. \tag{5}$$

The nuclear transparency T_A is given by

$$T_A(\mathbf{p}_0, \mathbf{p}_1, \mathbf{p}_2) \approx \int d^3r\rho_A(r)\mathcal{P}_0(\mathbf{p}_0, \mathbf{r})\mathcal{P}_1(\mathbf{p}_1, \mathbf{r})\mathcal{P}_2(\mathbf{p}_2, \mathbf{r}). \tag{6}$$

The survival probability $\mathcal{P}_i(\mathbf{p}_i, \mathbf{r})$ for a hadron of momentum $\mathbf{p}_i$ is given by

$$\mathcal{P}_i(\mathbf{p}_i, \mathbf{r}) = \exp\left[-\int_{\text{path}} dl\ \sigma_{\text{eff}}(\mathbf{p}_i, l)\right]\rho_A(r). \qquad (7)$$

The direction of the path denoted by l is defined by the vector $\mathbf{p}_i$. Thus in Eq. (7) one integrates from the point $\mathbf{r}$ to infinity in the direction of $\mathbf{p}_i$.

In the absence of the effects of color transparency, one expects that Glauber theory will provide a reasonable description of the data. In this case l_c is set to 0 for both pions and protons. We take the nuclear density to

$$\rho_A(r) = \frac{\rho_0}{1 + e^{\frac{r-R}{a}}}, \qquad (8)$$

with $R = 1.1A^{1/3}$ fm, and $a = 0.54$ fm, with ρ_0 chosen to normalize the density to the nucleon number A.

III. RESULTS

Figure 1 shows the transparency of Eq. (6) for ^{208}Pb with the effects of color transparency and in the Glauber calculation ($l_h = 0$). There is a gigantic effect predicted by our formula in Eq. (4). For pions the effective cross section is given by Eq. (2) and varying $-t$ has a big effect on the survival probabilities. The proton is strongly influenced by the final-state interactions.

This effect of the proton final-state interactions is illustrated in Fig. 2. This figure displays the ratio of T_A of Eq. (6) to the same quantity computed by setting the pion σ_{eff} to zero. The large ratio seen indicates a large range of values of $-t$ for which the nucleus is nearly completely transparent to pions.

The previous results are driven by Eq. (4). However, there is no independent information about this quantity as it enters pion-nucleon elastic scattering. Hence we explore the sensitivity of the transparency as a function of A to the variation of the the strength of the interaction of the pion with the nucleon. This is shown in Fig. 3. If σ_{eff} is

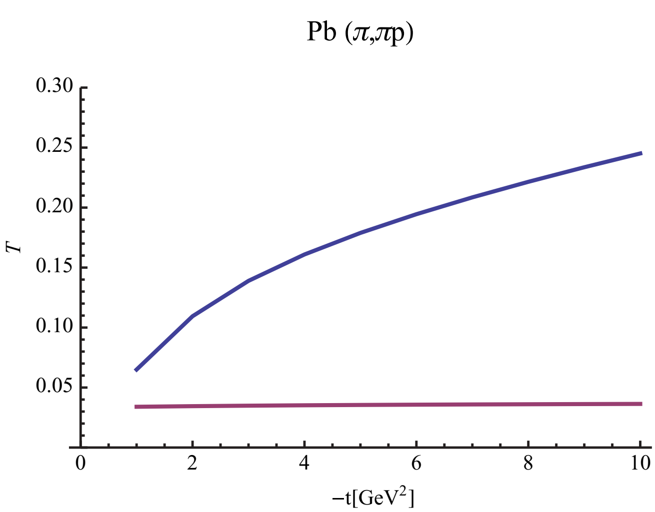

FIG. 1. (Color online) The transparency for the $\pi, \pi p$ reaction on ^{208}Pb. The blue curve includes the effects of color transparency. The lower purple curve represents the effects of the Glauber calculation.

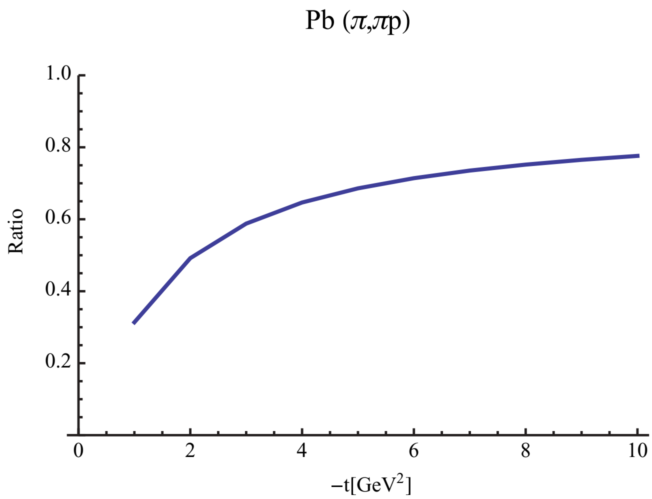

FIG. 2. (Color online) Ratio of transparency full to plane wave pion for the $\pi, \pi p$ reaction on ^{208}Pb. The curve includes the effects of color transparency.

reduced from the full value of 25 to 15 mb, one can observe a strong change of the transparency. Hence one will be able to observe even a relatively modest squeezing of the pion wave function well before the full color transparency is reached.

Our results are also applicable to the process of large $-t$ photoproduction of vector mesons from nuclei, like $\gamma + A \to \rho^0 + N + (A-1)^*$. Indeed, for small $-t$ it was established a long time ago that the vector dominance model describes well the ρ-meson photoproduction with $\sigma_{\rho N} = \sigma_{\pi N}$. Squeezing in this case should be similar or even stronger than in the pion case due to a singular behavior of the photon wave function at small transverse separations. Note here that recent studies have suggested that in the regime when the momentum transfer is larger than the hardness scale of the reaction, the elastic cross section should be energy independent in a wide energy range [**?**]. Inspecting the recent data on the $\gamma + p \to \rho^0 + p$ reaction [37] we notice that the data are consistent with cross section being energy independent starting with $-t \geqslant 0.7 \div 0.8$ GeV^2.

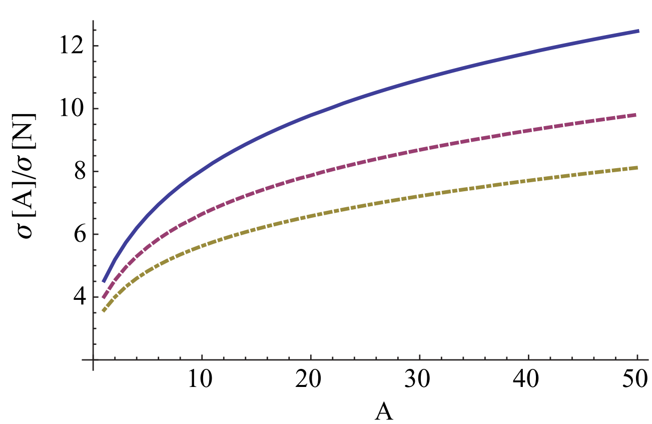

FIG. 3. (Color online) Ratios of nuclear $\sigma(A)$ to $\sigma(N)$ for three different values of the effective cross section: 25 mb (dot-dashed), 20 mb (dashed), and 15 mb (solid).

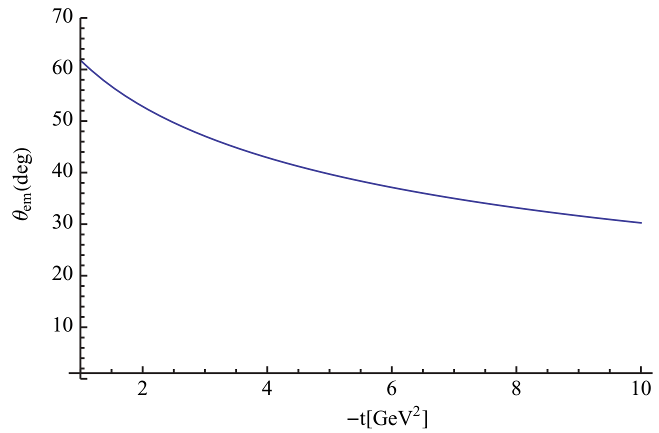

FIG. 4. (Color online) Proton emission angle θ_{em} as a function of $-t$. Exact kinematics are used for a proton initially at rest.

IV. KINEMATIC CONSIDERATIONS

Let us analyze the pattern of the emission of the protons that determines requirements on the recoil detector. The specific feature of high-energy kinematics is that the "minus" component of the momentum of the struck proton is conserved as the "minus" components of the initial and final pion are very small—the difference is of the order $-t/s$. Hence the four-momentum of the final proton satisfies the condition

$$\alpha = \left(\sqrt{m_N^2 + \vec{p}^2} - p_3\right)/m_N, \quad p_t = q_t + k_t, \tag{9}$$

where $-t = q_t^2$, the light cone fraction α is typically within the range $|\alpha - 1| \leqslant 0.2$, and k_t is the transverse momentum of the struck nucleon in the initial state (typically $\leqslant 0.2$ GeV/c)

$$p_3 = m_N/2(\alpha^{-1} - \alpha) + \frac{p_t^2}{2\alpha m_N}. \tag{10}$$

The first term in the right-hand side is small as compared to the second term, which is of the order $-t/2m_N$. Hence the emission angle (relative to the beam direction) is approximately given by

$$\theta_{em} = \tan^{-1}(p_3/p_t) \approx \tan^{-1}(p_t/2\alpha m_N). \tag{11}$$

One can see from Eq. (11) that Fermi motion leads to a modest smearing of the emission angle in the t range we discuss. Also the angle θ_{em} remains large in the whole range we discuss, which simplifies detection of such protons. This is shown in Fig. 4.

V. SUMMARY

We conclude that a measurement of the transparency in the pion quasielastic scattering off nuclei in the COMPASS kinematics may allow us to observe a novel color transparency phenomenon. Parallel studies using quasireal photon production in $\mu + p$ scattering that will be feasible with COMPASS also look promising.

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