Color Transparency and Correlation Effects in Quasielastic Electron-Nucleus Scattering at High Momentum Transfer

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The effects of nucleon-nucleon correlations and color transparency on the final-state interaction of the struck nucleon in electron-nucleus scattering at high-momentum transfer are discussed. The results of realistic microscopic calculations show that both the mechanisms lead to an enhancement of the nuclear transparency, and that the correlation effects are larger up to momenta $Q^2 \sim 4$ (GeV/c)^2.

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The possible occurrence of the effect generally referred to as color transparency (CT) was predicted by Brodsky [1] and Mueller [2] in the early 1980s. The mechanism leading to CT can be qualitatively understood by considering the expansion of hadronic wave functions in a complete set of Fock states having a specific number of quarks. Since the amplitudes for exclusive processes involve a factor $1/Q^2$ for each constituent, the valence state having the lowest number of quarks is expected to be dominant in scattering processes involving large momentum transfer Q^2. The transparency effect follows from the fact that such a state, being smaller in size, interacts weakly with nuclear matter. In the standard CT scenario a hadron traveling through the nuclear medium after absorbing a large momentum is initially "small," its typical transverse size being $\sim 1/Q$, and evolves back to its standard configuration within a distance from the interaction point which increases with increasing Q^2. Explicit models to describe the evolution of the hadronic cross section associated with the occurrence of CT, inspired by the parton model and perturbative quantum chromodynamics (PQCD), have been proposed in Ref. [3].

An experiment to measure the effect of CT in proton-nucleus scattering has been recently carried out at Brookhaven [4]. Its results seem to agree fairly well with the theoretical predictions based on the PQCD model of Ref. [3] up to incident proton momenta $p_{\text{inc}} \sim 10$ GeV/c, while showing a completely different behavior at larger momenta.

Experimental evidence for the occurrence of CT can perhaps best be obtained from (e,e') and $(e,e'p)$ electron scattering experiments at high-momentum transfer, by studying the A and Q^2 dependence of the nuclear absorption of the struck proton. In fact, CT is expected to lead to a modification of the final-state interaction (FSI) of the struck nucleon with respect to that calculated from the elementary nucleon-nucleon (NN) scattering amplitudes.

In this paper we discuss a semiclassical treatment of FSI in electron-nucleus scattering which can be readily extended to include the effect of CT. The present approach, which can be regarded as a generalization of the widely employed Glauber theory [5], allows for a consistent treatment of the correlation effects arising from the fact that the struck nucleon was bound in the nuclear target in the initial state. We first give a short outline of the theory and then discuss the results of numerical calculations of the inclusive (e,e') cross section of nuclear matter at momentum transfer $Q \sim 2$ GeV/c and of the total nuclear transparency evaluated for the $(e,e'p)$ reaction in quasifree kinematics at $Q^2 = 2$ to 10 (GeV/c)^2 on ^{12}C, ^{56}Fe, and ^{208}Pb.

Let $\mathbf{p}$ be the momentum of the struck nucleon, with the $\hat{\mathbf{z}}$ axis defined along $\mathbf{p}$. In the quasifree kinematics, for large momentum transfer $\mathbf{q}$, $\mathbf{p} \sim \mathbf{q}$. Let $\mathbf{r}' = \mathbf{b} + \hat{\mathbf{p}} z'$ be the position of the nucleon when it is struck, with $\mathbf{b}$ being the impact parameter. According to Glauber multiple scattering theory [5], the state of the struck nucleon traveling through the nuclear medium is described by the wave function

$$\Psi_p(\mathbf{r}) = e^{i\mathbf{p}\cdot\mathbf{r}} \varphi_p(\mathbf{r}) , \tag{1}$$

$$\varphi_p(\mathbf{r}) = \varphi_p(\mathbf{b} + \hat{\mathbf{p}} z) = \exp\left(\frac{i}{\hbar v} \int_{z'}^{z} dz'' \, V(\mathbf{b} + \hat{\mathbf{p}} z'') \right) , \tag{2}$$

where v is the velocity of the nucleon. The imaginary part of the scattering potential $V(\mathbf{r}'' = \mathbf{b} + \hat{\mathbf{p}} z'')$ gives the decay of $\Psi_p(\mathbf{r})$. In the standard Glauber approximation (GA) it is approximated by

$$\mathcal{I} V(\mathbf{r}'') = \tfrac{1}{2} \hbar v \sigma \rho(\mathbf{r}'') + \frac{\hbar v}{2\pi p} \rho(\mathbf{r}'') [\mathcal{I} f_p(0)] = -W(\mathbf{r}'') , \tag{3}$$

where $\rho(\mathbf{r}'')$ is the target density at $\mathbf{r}''$, σ is the total NN cross section, and $f_p(0)$ is the forward scattering amplitude. The total nuclear transparency is then obtained as

$$T=\frac{1}{Z}\int d^2b\,dz'\rho_p(\mathbf{r}')\exp\left[\frac{2}{\hbar v}\int_{z'}^{\infty}dz''W(\mathbf{b}+\hat{\mathbf{p}}z'')\right], \tag{4}$$

where $\rho_p(\mathbf{r}')$ is the proton density.

In Ref. [6] the Glauber approach has been generalized to the case of a nucleon initially bound in the target ground state, as it is appropriate for (e,e'), and $(e,e'p)$ experiments. Because of the strongly repulsive core of the NN interaction and to the Pauli statistical correlations the two-body density $\rho_2(\mathbf{r}'',\mathbf{r}')$ is not uniformly distributed at $\mathbf{r}''\sim\mathbf{r}'$. Nucleons in nuclear ground states are essentially surrounded by a hole produced by nuclear correlations. As a consequence, the nuclear density $\rho(\mathbf{r}'')$ entering the definition of W has to be replaced by the product $G(\mathbf{r}'',\mathbf{r}')\rho(\mathbf{r}'')$, where the function $G(\mathbf{r}'',\mathbf{r}')$ is related to the pair correlation function $g(\mathbf{r}'',\mathbf{r}')$ [7], defined as the ratio between the two-body density function $\rho_2(\mathbf{r}'',\mathbf{r}')$ and its uncorrelated estimate $\rho(\mathbf{r}'')\rho(\mathbf{r}')$. The calculation of $G(\mathbf{r}'',\mathbf{r}')$ is discussed in Ref. [6] for the case of uniform nuclear matter in which both G and g are functions of the interparticle distance $|\mathbf{r}''-\mathbf{r}'|$. In this case one obtains

$$G(z''-z')=\frac{1}{z''-z'}\int_{z'}^{z''}dz'''\int\frac{d^3k}{(2\pi)^3}\frac{\mathcal{I}f_p(k)}{\mathcal{I}f_p(0)}\times\int d^3r\,e^{i\mathbf{k}\cdot[\mathbf{r}-\hat{\mathbf{p}}(z'''-z')]}g(r)\,. \tag{5}$$

It may be easily verified that if $g(r)=1$, i.e, if there are no correlations, then $G(z''-z')=1$. Moreover, if $\mathcal{I}f_p(k)$ is taken to be independent of the momentum transfer $\mathbf{k}$, i.e., if the NN scattering potential has a very small range, then $G(z''-z')=g(z''-z')$.

The function $G(z''-z')$ has a very weak dependence on the density of the uniform medium, as illustrated in Fig. 1. The largest difference between $\sigma G(z)$ calculated at equilibrium density of nuclear matter (thin solid line of Fig. 1) and that evaluated at half equilibrium density (dotted line of Fig. 1) occurs at $z=0$ and is $\sim 5\%$. Therefore, it may be reasonable to approximate the $G(z''-z')$ in nuclei by $G(z''-z')$ calculated for nuclear matter. One then obtains the correlated Glauber approximation (CGA) for T:

$$T=\frac{1}{Z}\int d^2b\,dz'\rho(\mathbf{r}')\times\exp\left[-\int_{z'}^{\infty}dz''\sigma G(z''-z')\rho(\mathbf{r}'')\right]. \tag{6}$$

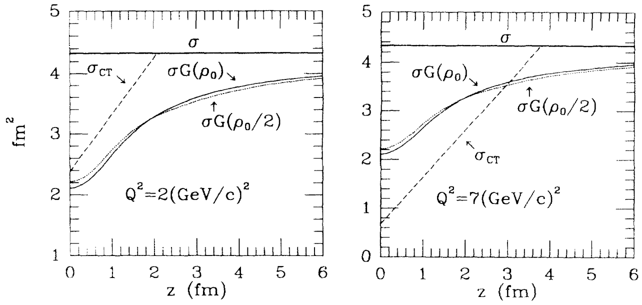

FIG. 1. The $\sigma_{\rm CT}(z)$ is compared with $\sigma G(z,\rho_0/2)$ and $\sigma G(z,\rho_0)$ in nuclear matter.

The modification due to CT can be easily included in either GA or CGA, by replacing the constant cross section σ by $\sigma_{\rm CT}(z''-z')$. We have used the PQCD model of Ref. [3] in which

$$\sigma_{\rm CT}(z)=\sigma\left\{\left[\frac{z}{L}+\frac{\langle 9k_T^2\rangle}{Q^2}\left(1-\frac{z}{L}\right)\right]\theta(L-z)+\theta(z-L)\right\}, \tag{7}$$

where $\langle k_T^2\rangle^{1/2}\sim 0.35$ GeV/c and $L=2p/\Delta m^2$, with $\Delta m^2=0.7$ GeV^2.

It should be noted that the ground-state correlations and CT both lead to a suppression of the absorptive part of V at small $z''-z'$, and therefore have to be regarded as competing mechanisms whose relative importance has to be carefully investigated. This feature is illustrated in Fig. 1 where the z dependence of $\sigma G(z)$ and $\sigma_{\rm CT}(z)$ are compared for two different values of Q^2 and proton momentum $|\mathbf{p}|^2=Q^2+\omega^2$ with $\omega=Q^2/2m$. It turns out that the hole at small z produced by NN correlations is much larger than the one associated with CT at $Q^2=2$ (GeV/c)^2, whereas the situation starts to reverse at $Q^2=7$ (GeV/c)^2.

The theoretical procedure described above has been recently applied to study FSI effects in inclusive electron-nucleus scattering at momentum transfer $Q\sim 2$ GeV/c [6]. The (e,e') cross section has been calculated for infinite nuclear matter, using the spectral function of Ref. [8] and including the contributions of both elastic and inelastic electron-nucleon scattering processes. In Fig. 2 the theoretical results are compared with the empirical nuclear matter cross section obtained from the extrapolation of the existing data to infinite A [9]. The three theoretical curves correspond to different treatments of the absorptive part of the potential felt by the struck nucleon traveling through the nucleon medium. The dash-dotted line represents the results of the standard GA, whereas the solid and the dashed curves have been obtained using CGA, with and without inclusion of CT, respectively. NN correlations and CT both produce an appreciable lowering of the FSI. CT significantly affects the cross section in the low-energy loss wing [$\omega<800$ MeV, corresponding to $Q^2\sim 2.7$ (GeV/c)^2], bringing the theoretical predictions in good agreement with the data.

An experiment designed to study the Q^2 and A dependence of the quasielastic $(e,e'p)$ scattering, in a kinematical region extending up to $Q^2=7$ (GeV/c)^2, has been re-

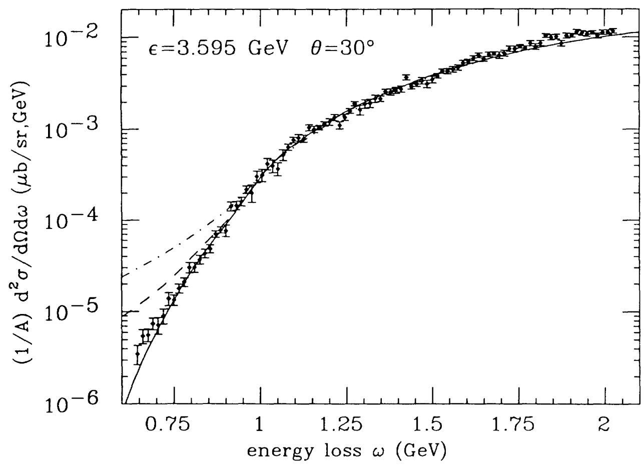

FIG. 2. Inclusive cross section for electron scattering by nuclear matter at incident energy 3.595 GeV and scattering angle $\vartheta=30°$. Dash-dotted line: GA; dashed line: CGA; solid line: CGA with $\sigma_{CT}(z)$.

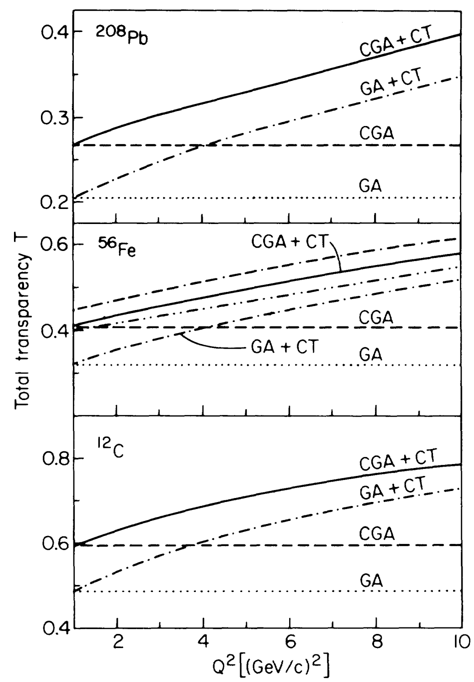

FIG. 3. Total transparencies [Eq. (6)] of ^{208}Pb, ^{56}Fe, and ^{12}C evaluated as a function of Q^2. Dotted line: GA; dashed line: CGA; dash-dotted line: GA with $\sigma_{CT}(z)$ (GA+CT); solid line: CGA with $\sigma_{CT}(z)$ (CG+CT). The dash-double-dotted and dot-double-dashed lines show the sensitivity of the CGA+CT results to $G(r)$ and σ.

cently proposed [10]. Since in the region of the quasielastic peak the reaction mechanism appears to be well under control and the effect of the nucleon being off-shell is rather small, it is hoped that such data could provide clear-cut evidence of the occurrence of CT.

The results for T of ^{12}C, ^{56}Fe, and ^{208}Pb, calculated for the kinematical conditions proposed in Ref. [10], are summarized in Fig. 3. The calculations have been performed using nuclear density distributions obtained by fitting the elastic electron-nucleus scattering data. The dotted and the dashed lines show the behavior of the total transparency estimated with the GA and CGA, respectively, and a constant $\sigma=43.3$ mb. The corresponding quantities obtained using $\sigma_{CT}(z)$ are given by the dash-dotted and the solid lines. As expected the correlation effects as well as CT increase T. It appears that up to momentum transfer as high as $Q^2 \sim 4$ (GeV/c)^2, NN correlations produce a larger enhancement of T, than CT. Moreover, the effect of CT is somewhat smaller in the CGA than in the standard GA. We remind the reader that the signal useful for an investigation of CT is $\sim 1-T$.

A crude estimate of correlation effects on the nuclear transparency has also been given in Ref. [11], where the function G of Eq. (4) has been approximated with a step function producing a correlation hole of radius 0.5 fm, and an enhancement of less than (10–15)% has been found. The larger correlation effect found in the present calculation is due to the fact that the realistic $G(z)$, shown in Fig. 1, is rather long ranged and its shape can hardly be approximated by a step function of radius 0.5 fm.

The sensitivity of the CGA+CT calculation to the input σ and $G(r)$ is studied for ^{56}Fe. The results obtained on approximating the $G(r)$ by the pair correlation function $g(r)$ are shown by the dash–double-dotted line in Fig. 3. The resulting decrease in T is <0.005 at $Q^2<1$ and ~ 0.025 at $Q^2=10$ (GeV/c)^2. It is likely that the total N-N cross section is reduced, from its free space value of ~ 43.3 mb at $E_{\rm lab}=1.5$ to 4 GeV, in nuclear matter due to Pauli blocking. Simple estimates suggest that σ in matter is ~ 37 mb for $Q^2<3$ (GeV/c)^2, and is not too sensitive to Q^2. The results obtained using this value of σ are shown by the dot–double-dashed line in Fig. 3. It appears that Pauli blocking could increase T by ~ 0.05 even at large values of Q^2.

From this study of the FSI of the struck nucleon in electron-nucleus scattering at high-momentum transfer we conclude that ground-state correlations cause a significant enhancement of the nuclear transparency T in $(e,e'p)$ experiments. It appears to be necessary to take into account such enhancement in order to understand the available measurements [12] of T for low-energy (~ 180 MeV) protons by the $(e,e'p)$ reaction [13,14]. As a consequence, their effect has to be carefully taken into account when studying the possible occurrence of a new phenomenon such as CT. However, it should be possible to separate the effects of CT and correlations by measuring the Q^2 dependence of T. The correlation effects have no Q^2 dependence other than the small variation of σ with proton energy. The CT effect, on the other hand, has a characteristic Q^2 dependence.

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