Pitfalls in looking for color transparency at intermediate energies

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The problems and uncertainties in the search for color transparency at intermediate Q^2 are considered. We show that conventional (optical) model [distorted wave impulse approximation (DWIA)] predicts a substantial change of the transparency, T, with Q^2 in the kinematics of the NE-18 $(e, e'p)$ experiment, while the color transparency phenomenon may lead to nearly Q^2 independent T. In the case of $A(p, 2p)$ reaction we demonstrate that the conventional optical model well describes the 1 GeV $A(p, 2p)$ data but not the transparency observed at higher energies.We find also that DWIA (with or without color transparency) predicts strong dependence of T on the momentum of the struck nucleon which is consistent with the pattern of the Brookhaven National Laboratory $A(p, 2p)$ data at $p_N = 6$ GeV/c and 10 GeV/c.

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I. INTRODUCTION

The Glauber model is known to be extremely successful in describing the total, elastic, and breakup cross sections of hadron-nucleus scattering at the incident energies from above 800 MeV up to about 10 GeV (for the review see, e.g., Refs. [1–3]). At the same time it has been well understood theoretically long ago that elastic Glauber multiple scattering theory violates unitarity for the high energy processes. This is due to a significant contribution of inelastic diffractive intermediate states. This physics leads to a noticeable inelastic shadowing correction to the total cross sections of the hadron-nucleus scattering [4] which has been observed experimentally, see Ref. [3] for review. Inelastic intermediate states in the eikonal formulas lead to various coherent phenomena.

Based on perturbative QCD it has been suggested that color transparency (CT) phenomenon should take place in quasielastic processes at very high momentum transfer [5, 6]. Subsequent theoretical analysis has found that CT does not arise within the mean-field-based models of nucleons. In the oscillator quark model of hadrons the effective size of the produced quark system in the form factor processes does not depend on Q in the nonrelativistic approach. Furthermore it even increases with Q in the light-cone quantum mechanical models of a nucleon [7]. At the same time theoretical analysis of realistic quark and Skyrmion models of hadrons have found that in the quasielastic processes the effective size of the interacting hadrons significantly decreases with increase of the momentum transfer even in the nonperturbative domain. In the realistic models the decrease is related to incorporation of singular interaction between quarks at short distances. Thus CT is well suited to search for short-range quark-gluon correlations in wave functions of hadrons (for the theoretical discussion and references see recent review [7]). At present experimentalists hunt for CT in both hadron and electron experiments [8–10].

The first preliminary results of the NE-18 experiment at the Stanford Linear Accelerator Center (SLAC) which studied quasielastic knockout reactions $A(e, e'p)$ for $Q^2 \simeq 1.0, 3.0, 5.0, 6.8$ GeV^2 were reported recently [9]. According to the previous theoretical estimates (see, e.g., Refs. [11–15]) in this Q^2 range the effects due to CT are expected to be rather small. So a more careful analysis is necessary of other small Q^2 dependent effects which could mask the CT effects.

We present a more detailed analysis of the $A(e, e'p)$ reaction at intermediate Q^2 taking into account several effects which may influence interpretation of the forthcoming NE-18 data, namely, (i) substantial dependence of the elementary pN total cross section on the initial energy (Q^2) (completely neglected in the previous calculations of transparency) (ii) soft final state interaction in different kinematic ranges of the intranuclear proton momentum, and (iii) effect of suppression of small size configurations in bound nucleons—color screening effect [16, 17].

We will demonstrate that in the kinematics of the NE-18 experiment these effects lead to a rather peculiar Q^2 dependence of the transparency: effect (i) leads to a substantial enhancement of the transparency at $Q^2 \simeq 1$ GeV^2, while effect (ii) noticeably affects transparency in the transverse kinematics studied in Ref. [9]. Effect (iii)

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slows down an increase of the nuclear transparency at intermediate Q^2. Combined, these effects result in a near equal values of nuclear transparency at $Q^2 \simeq 1$ GeV^2 and $Q^2 \simeq 7$ GeV^2.

At the same time the optical model predicts a substantial change of the transparency between $Q^2 = 1$ GeV^2 and higher Q^2 measured in the NE-18 experiment due to a 25% drop of the effective interaction cross section between $T_p = 0.5$ GeV corresponding to $Q^2 = 1$ GeV^2 and $T_p \geq 1$ GeV corresponding to the higher Q^2 points of NE-18.

In a previous paper [13] we combined conventional distorted wave impulse approximation (DWIA) (which uses the realistic Hartree-Fock-Skyrme wave function [18] for the description of the nuclear structure, and the optical limit of the standard Glauber approach [19, 20] for the distortion phenomena), and the quantum diffusion model of expansion of a small size configurations [11] to estimate CT in $A(e,e'p)$ reaction at $Q^2 \geq 6$ GeV^2. We pointed out that uncertainties resulting from insufficient understanding of nuclear effects can be suppressed if one chooses the following strategy.

(i) The nuclear spectral function $S(\vec{k},W)$ [see Eqs. (4) and (5) below] should be measured in sufficiently wide ranges of the missing energies W and the nuclear recoil momenta (i.e. the bound proton momentum k before collision). This would help to justify the use of the sum rule

$$\int d\vec{k} \int dW S(\vec{k},W) = Z. \qquad (1)$$

(ii) The data for effective transparency in the quasielastic reaction, $T_{\rm eff}$, defined as

$$T_{\rm eff} = \frac{Z_{\rm eff}}{Z} = \frac{\int d\vec{k} \int dW S_{\rm eff}(\vec{k},W,Q^2)}{\int d\vec{k} \int dW S(\vec{k},W)}, \qquad (2)$$

should be obtained in a wide range of the momentum transfer (5–6)$\leq Q^2 \leq$ 25–30 GeV^2 since in this Q^2 range the length of expansion of the small size configuration (SC) produced in one-step hard interaction will exceed (or at least become comparable with) the sizes of light and medium nuclei [11, 12, 7]. An additional simplification arises in this case because the momentum of the outgoing nucleon

$$p = Q\sqrt{1+\frac{Q^2}{4m^2}} \qquad (3)$$

falls into the interval $4 \leq p \leq 16$ GeV/c. where the total proton-nucleon cross section, $\sigma_{pN} = 40$ mb, the main parameter determining absorption in DWIA, is practically constant.

(iii) Equation (2) should be checked at $1 < Q^2 < 2$ GeV^2 where CT effects are absent. The assumption implicitly made in Eq. (2) is that the nuclear reaction cross section can be factorized as the product of the elementary ep cross section and the nuclear spectral function. In this case expression (2) arises as the ratio of the nuclear $(e,e'p)$ cross sections calculated within the distorted wave approximation and in the plane wave limit under the same kinematic conditions. It is customary to neglect the difference between the elementary ep cross section and the cross section of the electron scattering off a bound proton. We shall not discuss this problem here in detail though we will consider implications of one off-shell effect specific for the interaction with a nucleon in SC—the suppression of the probability of SC in bound nucleons.

If requirements enumerated above are satisfied, one can look for CT in electron experiments with relatively poor resolution in missing energy and recoil momentum. Besides, under these circumstances it would be sufficient to measure the $A(e,e'p)$ cross sections with accuracy of $\approx (5-10)$ %; see, for example, Fig. 1 where results of calculation of the Q^2 dependence of the effective transparency $T_{\rm eff}$ are presented (details of this calculation which is similar to those of Ref. [13] are given below). Indeed since σ_{pN} is practically constant in this kinematics the only reason for $S_{\rm eff}(\vec{k},W,Q^2)$ to depend on Q^2 appears to be color transparency phenomenon — suppression of the soft final state interaction (FSI) of the SC with the residual nucleus.

The second aim of this paper is to extend our calculation [13] to the case of $A(p,2p)$ reactions in the kinematics of the Brookhaven National Laboratory (BNL) high energy experiment [8]. We find that the optical model prediction falls significantly below the BNL data for the nuclear transparency. To check the accuracy of the used optical model we apply it also to the 1 GeV $(p,2p)$ data [22] (where CT effects are obviously absent) and find them to be in a reasonable agreement with the model.

Specific of theoretical description of CT in coordinate space at moderate energies is quantum diffusion [17, 11, 23]. This phenomenon is well known in nonrelativistic quantum mechanics as distortion of wave packet. In the

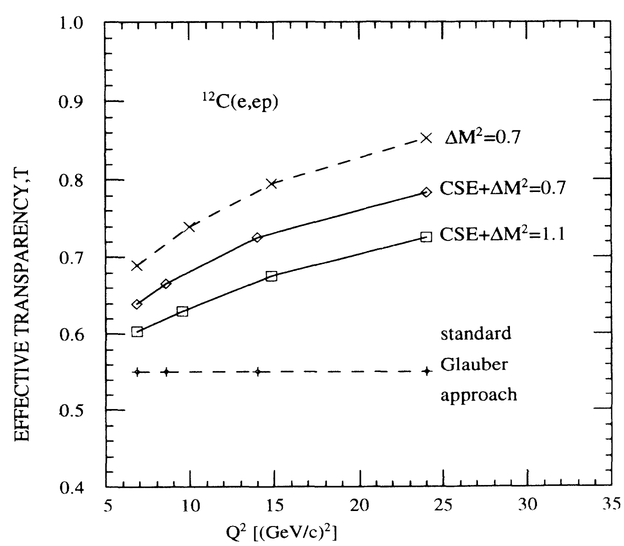

FIG. 1. Effective transparency as a function of Q^2 for the ^{12}C$(e,e'p)$ reaction, calculated in the quantum diffusion model with different values of ΔM^2. The curves labeled CSE include the color screening effect of suppression of SC in bound nucleons.

related phenomenon—the charge transparency in QED—the quantum diffusion has been observed by Perkins in 1956 [24]. In perturbative QCD the quantum diffusion is a property of the leading logarithmic approximation compare the discussion of the reaction of annihilation of e^+e^- into hadrons in Ref. [25]. In nonperturbative regime interpolating formulas for quantum diffusion has been suggested in [11] which is smooth interpolation between well-understood perturbative QCD regime and multiperipheral approach. It has been demonstrated recently in Ref. [15] that the few baryon resonance model of CT approximation leads to similar results at moderate energies. Thus it seems now that uncertainties in including quantum diffusion effects at moderate energies are not large provided the expansion rate is determined from one experiment.

We demonstrate also that inclusion of the CT and the quantum diffusion effects allows us to understand the magnitude of the transparency observed in the experiment [8] which is significantly larger than the one expected in the Glauber model (though of course not the drop of transparency indicated by the 12 GeV/c data). Previously in Ref. [13] we found a noticeable dependence of $T(k)$ for the $A(e,e'p)$ reactions on k. This dependence was due to rescattering effects and correlation between momentum and space distributions of the nucleons. In the case of the $A(p,2p)$ process the contribution of the surface (edge) is further increased. As a result we find that the DWIA leads to a substantial drop of $T(k_3)$ with increase of $\mid k_3 \mid$(k_3 is the component of the struck nucleon momentum along the beam direction). This trend is consistent with the BNL data [8] at 6 and 10 GeV/c [26].

Recently the $A(e,e'p)$ reactions were considered in Ref. [27] (see also Ref. [28]) within the two-component hadronic basis model [29], which, in contrast to this paper, does not satisfy the CT constraints derived in [15]. Besides they assumed that the rescattering amplitude is $\sim \delta(q)$ where q is the momentum transfer (we thank Miller for confirming this point). They also stated that for the $A(p,2p)$ reaction their model leads to a monotonous decrease of $T(k_3)$ from the values above 1 at negative k_3 to small $T_{\rm eff}(k_{\rm eff})$ close to $T_{\rm eff}(k_{\rm eff})_{\rm DWIA}$, which they assume to be k independent. This is markedly different from the effect of correlation of the coordinate space density and the momentum distribution which we discuss and which leads to a maximum of $T_{\rm eff}(k)$ at $k_3 = 0$.

II. STANDARD DWIA FOR QUASIFREE KNOCKOUT REACTION

First, let us summarize the formalism of the standard DWIA using the $A(e,e'p)$ reaction as an example. [The formalism for the $A(p,2p)$ reactions is a straightforward generalization.] One has to use a number of approximations for the spectral function: The nuclear structure must be described by the single-particle shell model, the nondiagonal transitions of the residual nucleus due to the inelastic FSI must be neglected, finally the quenching effects and the effects of the short-range repulsion between nucleons are also neglected. It is not difficult to deduce exact formulas but in practice the approximations enumerated above are generally used (see, e.g., Refs. [19, 20]). The uncertainty of calculations does not exceed $(10-20)\,\%$, especially, when the sum rules for the spectral function are used.

So, we can write the effective spectral function as

$$S_{\rm eff}(\vec{k},W,Q^2) = \sum_i \Phi_i(\vec{k},Q^2) g_{ii}(W), \tag{4}$$

where i denotes the total set of the shell model quantum numbers. g_{ii} are given by

$$g_{ii}(W) = \langle A|a_i^\dagger \delta(H+W-W_A^0)a_i|A\rangle, \tag{5}$$

where H is the nuclear Hamiltonian, W_A^0 is the nuclear ground state energy, and a_i is an annihilation operator for a proton in the shell-model state i. Since we neglected the contribution of nondiagonal transitions due to FSI, g_{ii} does not depend on Q^2. The FSI is taken into account in the distorted momentum distribution of the protons in nucleus

$$\Phi_i(\vec{k},Q^2) = \left| \int d\vec{r} \exp(-i\vec{k}\cdot\vec{r})\Psi_i(\vec{r}) D_{\vec{p}}(\vec{r},Q^2) \right|^2, \tag{6}$$

where Ψ_i is the single-particle wave function. We have used here wave functions calculated within the Hartree-Fock-Skyrme approximation [18] which describes very well the shapes of the $A(p,p'p)$, $A(p,p'n)$ reactions at $E_p = 1$ GeV, see review in Ref. [21].

The quantity $D_{\vec{p}}(\vec{r},Q^2)$ represents the distortion factor arising due to soft multiple interaction of the fast particle with the residual nucleus. It is reasonable to use at high energy ($p_N \geq 1$ GeV/c) the eikonal approximation

$$D_{\vec{p}}(\vec{r},Q^2) = \exp\left(-\frac{iE}{\hbar p}\int_0^{+\infty} V(\vec{r}+\tilde{p}s)ds\right). \tag{7}$$

The integral should be carried out over the trajectory of moving particle and $V(r)$ can be described in the optical limit of the Glauber approach as

$$\begin{aligned} -\frac{2E}{\hbar p}{\rm Re}V(r) &= \alpha_{pN}\sigma_{pN}\rho(r), \\ -\frac{2E}{\hbar p}{\rm Im}V(r) &= \sigma_{pN}\rho(r), \end{aligned} \tag{8}$$

where $\rho(r)$ is nuclear density, σ_{pN} elementary proton-nucleon cross section, and

$$\alpha_{pN} = \frac{{\rm Re}f_{pN}(0)}{{\rm Im}f_{pN}(0)}. \tag{9}$$

Since the model discussed above does not take into account short-range correlations in the wave function, it is natural to ask about the accuracy of the approximation used. Two neglected effects work in the opposite directions—quenching of the low momentum strength due to short-range correlations tends to lower the cross section as compared to our estimate, whereas the local repulsion ("hole" around the struck nucleon) tends to increase the cross section [for $A(e,e'p)$ by about $\approx$(10–

20)% [13, 14]]. Basically, these two effects lead to an overall renormalization of the cross section which weakly depends on the incident energy. To check the accuracy of this model we repeated the analysis of the BNL data on $^{12}C(p,2p)^{11}B$ reaction at $E_p = 1$ GeV [22]. In the calculation we used the effective cross sections of pN interaction at $E_p = 0.5$ GeV of 30 mb [30] which includes effects of Fermi blocking. For E_p=1.0 GeV we neglected the Fermi blocking and used $\sigma_{\rm tot}(pN) = 43$ mb [2]. The errors for these values of $\sigma_{\rm tot}(pN)$ is about 0.5 mb. This calculation agrees reasonably well with the data, see Figs. 2(a) and 2(b). This indicates that the accuracy of our absolute predictions of the nominal (Glauber model) value of transparency in $(p,2p)$ reactions is about 20%. (Note that this model underestimates quenching by about 10%.) Thus there is an extra renormalization factor ≈ 1.1 when one considers the region of small nucleon Fermi momenta.

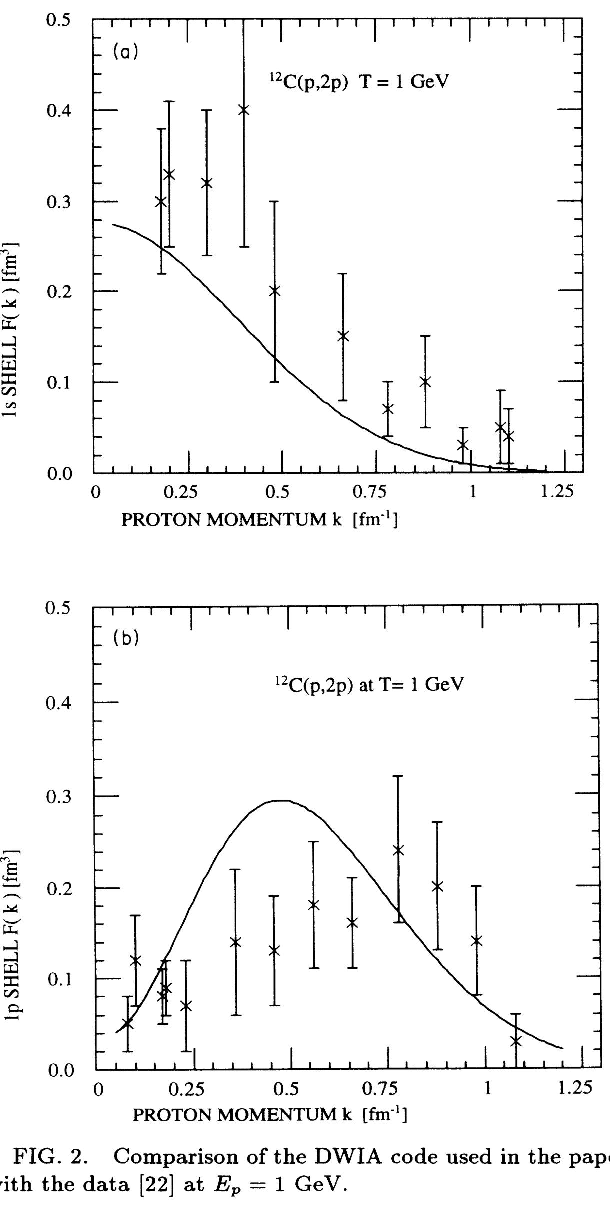

FIG. 2. Comparison of the DWIA code used in the paper with the data [22] at $E_p = 1$ GeV.

III. MODELING OF COLOR TRANSPARENCY EFFECTS

The inelastic intermediate states give a significant contribution in the eikonal formulas for the high-energy processes like $A(p,2p)$. The necessary condition is that the momentum transfer in the rescattering amplitudes should be sufficiently small ($-t \leq \frac{3}{R_N^2}$) and essential longitudinal distances should be large enough, $l \approx \frac{2p_N}{\Delta M^2}$.

Here we concentrate on the intermediate-energy limit when the expansion distance is small. In this case the simplest way to implement the CT is to use instead of the free σ_{pN} a new quantity $\sigma_{\rm SC}^{\rm eff}$ which describes the interaction of a SC with the media. It takes into account both the suppression of interaction in the point where SC is produced and the restoration of soft FSI of the expanding SC with nucleons of the residual nucleus when SC moves along the trajectory in nuclear medium. For very large energies the completeness sum over produced hadron states can be used and the produced configuration can be considered as frozen. As a result a more effective method can be developed—see the discussion in Ref. [31].

There were a several models [11, 12] to consider this phenomenon. We shall use expression obtained in the quantum diffusion model [11]

$$\sigma_{\rm SC}^{\rm eff} = \sigma_{pN}\left\{\left[\frac{s}{l_h} + \frac{\langle n^2k_t^2\rangle}{Q^2}\left(1-\frac{s}{l_h}\right)\right]\Theta(l_h - s) + \Theta(s-l_h)\right\}. \tag{10}$$

Here s is the distance passed by the expanding quark-gluon state along the trajectory from the point of hard interaction, n is the number of constituents in the proton ($n = 3$), and k_t^2 is the average transverse momentum of constituents in the proton [$k_t^2 \simeq (0.350\ {\rm GeV}/c)^2$]. The linear dependence of $\sigma^{\rm eff}$ on the distance from the interaction point follows from analysis of perturbative QCD Feynman diagrams [17,23]. The same pattern is found for the time evolution of the quark-gluon state produced in the e^+e^- annihilation; see, e.g., Ref. [25]. It is assumed in Eq. (10) that the size of configuration in the interaction point decreases as $\frac{1}{Q^2}$. This provides a reasonable approximation for the Q^2 dependence of the transverse size of the nucleon found in the realistic models of the nucleon form factor [7]. In any case the answer is not very sensitive to the actual size in the interaction point as soon as it is much smaller than the average nucleon size. This is because the expansion effects increase the size very fast in the kinematics under discussion. The Landshoff mechanism [32] which is discussed for the pp large angle scattering corresponds to a somewhat slower decrease of the this size $\approx Q^{-0.7}$ [33]. The quantity l_h determines the length of the expansion, i.e., the distance to be passed by the SC from the point of hard interaction in order to become a normal size proton. Estimates of l_h in different models of color transparency lead to the same expression for l_h

$$l_h = \frac{2p}{\Delta M^2}, \tag{11}$$

but predict different values for the parameter ΔM^2. Another "classical mechanics" pattern for expansion of SC corresponding to $\sigma(l) \approx (l/l_0)^2\sigma_0$ [11] is realized in the models where SC is approximated as a superposition of few-nucleon resonances [12, 15]. However, if expansion parameters of this model are adjusted to fit the BNL data [8], the predictions of this model for $T_{\rm eff}$ for $A(e,e'p)$ reaction practically coincide [34] with those of the diffusion model. Thus we will present results only for the quantum diffusion model, Eq. (10).

Obviously, the value of ΔM^2 is very important. One can expect complete CT only if $R_A\Delta M^2 \leq 2p$. An estimate of ΔM^2 in the constituent quark model leads to the values of ΔM^2 in the range $0.7 \leq \Delta M^2 \leq 0.9$ GeV^2 [11]. Another natural scale for ΔM^2 is the distance between the nucleon resonances which is given by the inverse slope of the nucleon Regge trajectory, $\alpha_N'^{-1} \approx 1.1$ GeV^2. It is worth emphasizing here that continuum dominates both in the ^{1}H(e,e') process and in the diffraction dissociation of the nucleon. Therefore the use of one resonance state, N^* [for example, $N^*(1680)$], for the estimate of $\Delta M^2 = M_{N^*}^2 - M_N^2$ can be considered merely as an illustration.

An optimistic value of $\Delta M^2 \approx 0.7$ GeV^2 would give an opportunity to search for color transparency at intermediate $Q^2 \geq 5$ GeV^2 as follows from Fig. 1. A more pessimistic value of ΔM^2 close to 1.1 GeV^2 would make chances of observing CT quite marginal up to $Q^2 \geq 10$ GeV^2.

The CT phenomenon at intermediate Q^2 is additionally suppressed by a specific QCD effect which was ignored so far in the numerical analyses of CT (though it was pointed out in [17]). In QCD the probability of SC in a bound nucleon is smaller than in a free nucleon. This is due to the color screening effect in nuclei [16, 17]. The physics of this suppression is quite transparent: The potential for the interaction of a bound nucleon in a small size quark-gluon configuration with nearby nucleons is smaller than for a nucleon in an average configuration. Since the NN potential is, on average, attractive such small configurations lead to smaller binding. Therefore they are energy unfavorable and should be suppressed as indicated by the Le Châtieler's principle. This suppression factor

$$\delta(k) = \left(1 + \frac{\frac{k^2}{m_p} + 2\epsilon_A}{\Delta E}\right)^{-2} \tag{12}$$

has been estimated in Ref. [17] using the closure approximation. Here $\epsilon_A \approx 8$ MeV is the mean binding energy. The parameter ΔE was estimated to be in the range 0.6 – 1 GeV with the lower value preferable for description of the EMC effect at $x \geq 0.5$. So we will take $\Delta E = 0.6$ GeV in the following analysis. We will use an interpolation formula:

$$\tilde{\delta}(k) = \Theta(Q_0^2 - Q^2) + \Theta(Q^2 - Q_0^2) \times \left\{1 + \left(1 - \frac{Q_0^2}{Q^2}\right)\frac{\frac{k^2}{m_p} + 2\epsilon_A}{\Delta E}\right\}^{-2} \tag{13}$$

to account for the nuclear color screening effect at intermediate Q^2 where the size of interacting configurations is smaller than the normal one. This effect can be included by modifying the momentum distribution as

$$\tilde{\Phi}(\vec{k}, Q^2) = \tilde{\delta}(k)\Phi(\vec{k}, Q^2). \tag{14}$$

Our analysis [17] of the ^{2}H(e,e') SLAC data at $x \geq 1$ and large Q^2 indicates that $Q_0^2 \approx 2$ GeV^2. Results of these calculations are presented in Fig. 1 for C$(e,e'p)$. The curve marked by "*diamonds*" shows the effective transparency obtained with suppression of SC in bound protons taken into account and with values of parameters $\Delta M^2 = 0.7$ GeV^2, $\Delta E = 0.6$ GeV, and $Q_0^2 = 2$ GeV^2; "*boxes*" display effective transparency with correction $\delta(k)$ included and the value $\Delta M^2 = 1.1$ GeV^2 and "*pluses*" are the standard Glauber approximation without CT. The suppression of the probability of SC in the bound proton diminishes the effect of CT by $\approx 10\%$ at all considered Q^2. (We choose here nucleon momenta, k, to be in the same range as in the NE-18 experiment. If the averaging is performed over all nucleon momenta, the discussed effect suppresses nuclear transparency by about $\approx 20\%$.) So the color screening effect would not hamper the interpretation of the data at $Q^2 \gg Q_0^2$; it would be masked, to large extent, by the uncertainties of the DWIA calculations. However, it would be important if one has to match nuclear transparency at $Q^2 \leq Q_0^2$ and at $Q^2 \geq Q_0^2$ which is just the case for the NE-18 experiment (see below). The additional ($\approx 10\%$) suppression may appear due to the increase of ΔM^2 up to 1.1 GeV^2. It would result in a very small difference from the standard Glauber results at intermediate Q^2.

IV. TRANSPARENCY FOR THE $(p, 2p)$ REACTION IN THE KINEMATICS OF [8]

First, let us apply the formalism described above to the analysis of the BNL data [8], which show some evidence for CT. Our results are presented in Figs. 3 and 4. Evidently the nuclear transparencies reported for $p_{\rm inc} = 6$ and 10 GeV/c are much larger than the nominal Glauber model prediction, which as we emphasized above cannot be moved up by more than 30%. One can see also that the CT model with $\Delta M^2 \approx 0.7$ GeV^2 allows one to explain the magnitude of enhancement, even though in this case results of calculation for the Al$(p, 2p)$ process are systematically below the data. Nevertheless, because of rather limited statistics of the BNL experiment one cannot exclude that the parameter ΔM^2 could be increased up to the value 1.1 GeV^2. One should also remember that in this experiment only momentum of one of the protons has been measured, while for the second proton only the angle has been measured. So there is a possibility of a background due to two-step processes like production of a slow baryon resonance in reaction $pN \to N^*N$ at small t with

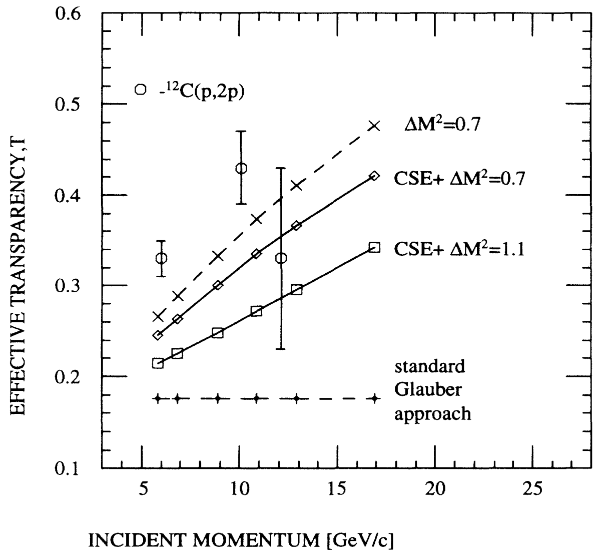

FIG. 3. Effective transparency as a function of $p_{\rm inc}$ for ^{12}C$(p,p'p)$ reaction, calculated in the quantum diffusion model with different values of ΔM^2. The curves labeled CSE include the color screening effect. The data are from Ref. [8].

subsequent large angle elastic rescattering of N in the process $Np \to Np$. To suppress this background much better energy-momentum resolution is necessary. Having these experimental uncertainties in mind it is not clear exactly what range of the intranuclear proton momentum should be accounted for in calculations to make reasonable comparison with experimental data. The above results were obtained by integrating over a wide range of the energies of the recoil system in order to exhaust the sum rules. The data [8] were analyzed also for different intervals of the longitudinal component of the struck nucleon momentum, k_3. The extracted $T_{\rm eff}$ was plotted as a function of $p_{\rm eff}$ which is related to the invariant energy of the two outgoing nucleons $s' \approx s(1+\frac{k_z}{m_p})$ as $p_{\rm eff} \approx (s-2m^2)/2m$.

In order to analyze $T_{\rm eff}$ at fixed $p_{\rm inc}$ as a function of the momentum of the struck nucleon it is necessary to take into account correlations between spatial and momentum distributions of the nucleons. Indeed, nucleons with low momenta are more likely to be near the nuclear surface. Thus it is easier to knock them out in the $A(p,2p)$ reaction if the CT effect is small enough as it is the case experimentally. The observed increase of $T_{\rm eff}$ is illustrated in Fig. 5 where a small change of $T_{\rm eff}(p_{\rm eff})$ due to color screening effect is also included. It should be emphasized here that effect of absorption due to expansion of SC's does not depend practically on $p_{\rm eff}$ for fixed $p_{\rm inc}$. In fact, the projectile contraction does not change at all, while the change of the momenta of outgoing nucleons is also marginal. In the models where one considers interference between the amplitudes dominated by large and small interquark distances [35, 36] plotting $T_{\rm eff}$ as a function of $p_{\rm eff}$ is more illuminating, though one still has to disentangle more conventional mechanisms of the variation of $T_{\rm eff}$ with k_z.

As a first step, to estimate the magnitude of the discussed effect in the kinematics of the BNL experiment [8] we calculated $T_{\rm eff}(p_{\rm eff})$ with appropriate k_s cuts for $p_{\rm inc}$ = 10 GeV/c—dashed curve in Fig. 6. Note also, that the parametrization of the cross section adopted in Ref. [8] did not include the flux factor $(1+\frac{k_z}{m_p})$. Presence of the flux factor in the complete expression for the differential cross section follows from the superposition principle and the calculation of the relevant Feynman di-

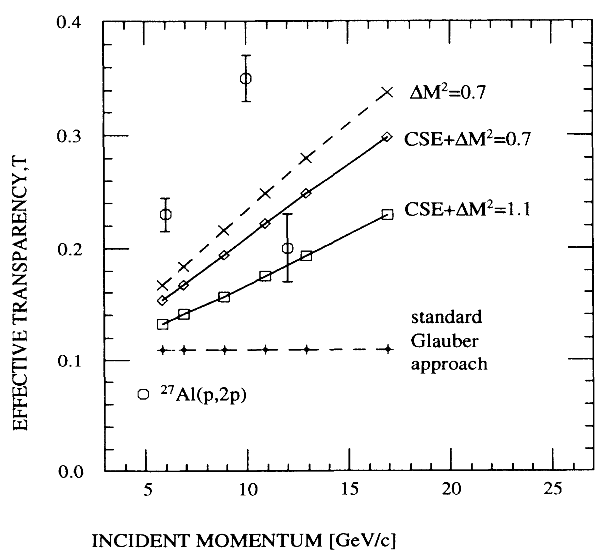

FIG. 4. Effective transparency as a function of $p_{\rm inc}$ for the ^{27}Al$(p,p'p)$ reaction, calculated in the quantum diffusion model with different values of ΔM^2. The curves labeled CSE include the color screening effect. The data are from Ref. [8].

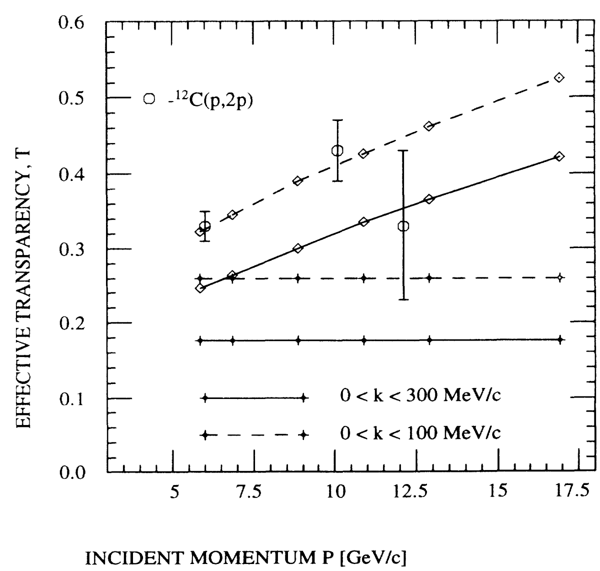

FIG. 5. Dependence of the effective transparency on the momentum of the struck nucleon as a function of $p_{\rm inc}$. Effect of color transparency is calculated for ΔM^2 = 0.7 GeV^2 including the color screening effect. Horizontal curves are the result of the DWIA calculation without color effects.

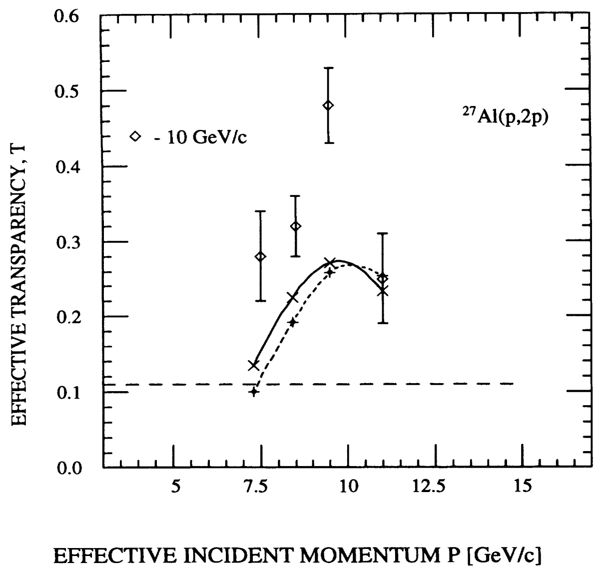

FIG. 6. Effective transparency for the $^{27}\mathrm{Al}(p,p'p)$ reaction at p_{inc} =10 GeV/c calculated as a function of p_{eff} as defined in Ref. [8]. Solid and dashed lines are the result of the calculation including quantum diffusion using Eq. (10) with $\Delta M^2 = 0.7$ GeV^2 and the color screening effect. The dashed curve illustrates an effect of neglecting the flux factor. The horizontal dashed lines are the DWIA result averaged over the nucleon Fermi momenta. The data are from Ref. [8].

agrams [19, 17]. Including this effect results in the solid curve in Fig. 6. The calculated dependence of T_{eff} on p_{eff} is rather similar to the trend of experimental data both at this energy and at 6 GeV/c, although at 12 GeV/c the experimental trend is different: T_{eff} decreases with increase of p_{eff}. One should consider the presented comparison as a preliminary. Further studies involving direct comparison of the theoretical formulas with the measured differential cross sections are necessary. This may result in a modification of extracted values of T_{eff} from the data, since the analysis of Ref. [8] among other things included fitting of the nuclear wave function to the experimental data, while here all effects were normalized to the theoretical spectral function.

V. TRANSPARENCY FOR THE KINEMATICS OF NE-18

Finally, let us consider the possibilities of observing the CT effect in the NE-18 experiment carried out at SLAC [9]. Results of this experiment for the values of transparency are expected to be published in the near future. So it is interesting to analyze the effect of CT in $(e,e'p)$ in the kinematic conditions of NE-18. The measurements were done at the momentum transfer Q^2= 1, 3, 5, and 6.8 GeV^2 using a number of target nuclei: H, D, C, Fe, and Au. Evidently, there is no reason to expect any CT effect at Q^2=1 GeV^2. However, if the data analysis aimed at searching for CT effect in the discussed Q^2 range would include this point, further complication arises. Actually, one has to take into account the dependence of the proton-nucleon cross section on the momentum of outgoing protons. Namely, at $p \approx 1$ GeV/c (which corresponds to $Q^2 \approx 1$ GeV^2) the total proton-nucleon cross section is $\sigma \approx 36$ mb [30]. Then $\sigma_{\mathrm{tot}}(pN)$ increases up to $\sigma \approx 43$ mb at $p \approx 2$ GeV/c and slowly decreasing to $\sigma \approx 40$ mb at $p \gg 3$ GeV/c. Moreover, current analyses of the data on pA scattering at $p_N = 1$ GeV/c indicate that a better description of the data is achieved if one accounts for deviations from the Glauber approximation at this rather low energy by renormalizing the free pN cross section downwards to $\sigma_{pN} \approx 30$ mb (see review in Ref. [30]). It is easy to estimate that the $\approx 25\%$ difference in free pN cross sections can compensate an increase of the effective transparency due to CT when comparing $T_{\mathrm{eff}}(Q^2)$ at $Q^2 = 1$ GeV^2 and $Q^2 = 7$ GeV^2. So, the data at $Q^2 = 1$ GeV^2 could be considered only as a reference point to check quality of description of the distortion effects and the nuclear structure within the models and approximations used for analysis.

Our calculations of the effective transparency in $(e,e'p)$ reaction on C, Fe, and Au performed in the kinematics of NE-18 experiment are presented in Figs. 7–9. To show possible effect of the CT we display in these figures results of the standard Glauber approximation and the effective transparency obtained with and without the suppression of SC in the bound proton taken into account. To illustrate the expected Q^2 dependence of T_{eff} we included also the point at Q^2=1.8 GeV^2 where σ_{pN} reaches its maximum, though no data were collected by the NE-18 experiment between $Q^2 = 1$ and 3 GeV^2. There is a chance to observe some increase of the effective transparency due to the CT by comparing T_{eff} at $Q^2 = 3$ GeV^2 and at $Q^2 = 7$ GeV^2 only if the experimental precision is about (2–4) %.

To summarize, we have demonstrated that the Glauber optical model modified to account for the production of small size configurations in hard processes provides a sufficiently reliable way of calculating the nuclear trans-

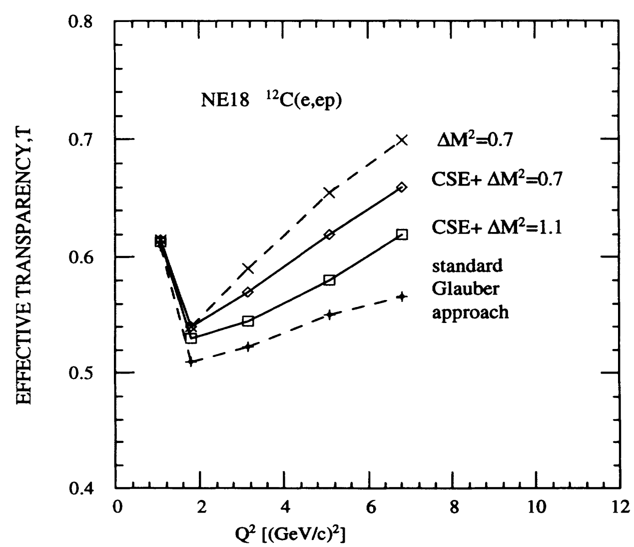

FIG. 7. Effective transparency for the $^{12}\mathrm{C}(e,e'p)$ reaction, calculated in the kinematics of the NE-18 experiment.

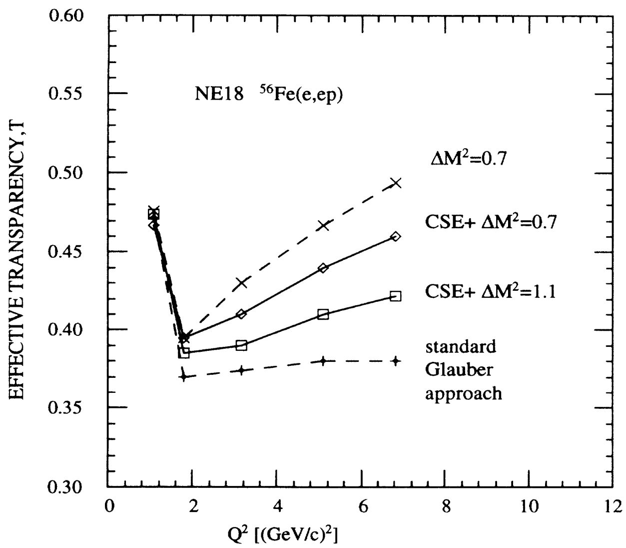

FIG. 8. Effective transparency for the ^{56}Fe$(e,e'p)$ reaction, calculated in the kinematics of the NE-18 experiment. The dot-dashed curves between Q^2 =5 and 7 GeV^2 show the effect of neglecting a different acceptance of the NE-18 experiment at Q^2 = 7 GeV^2.

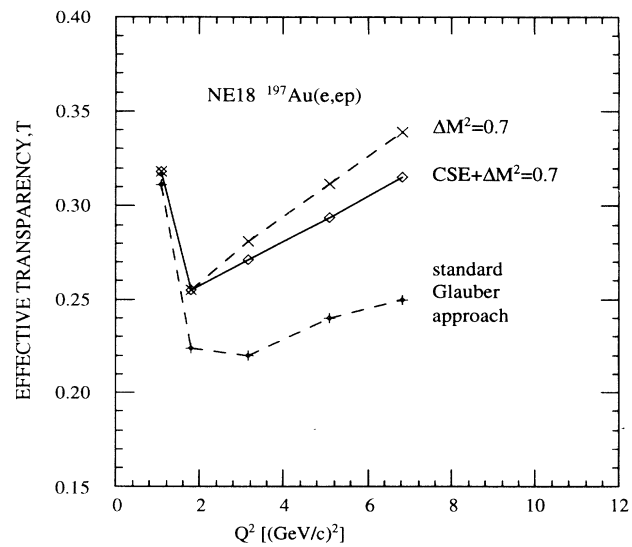

FIG. 9. Effective transparency for the ^{197}Au$(e,e'p)$ reaction, calculated in the kinematics of the NE-18 experiment.

parency in $(p,2p)$ and $(e,e'p)$ reactions. The comparison with the data at E_p = 1 GeV clearly indicates that the nuclear transparency observed in BNL experiment [8] is substantially larger than the Glauber model result. The increase of $T_{\rm eff}$ at $p_{\rm inc}$ = 6 and 10 GeV/c can be explained by the CT effect. However, the same model of the CT when applied to the kinematics of the electron experiment [9] predicts nearly constant nuclear transparency due to the energy dependence of the elementary pN cross section, and the effect of the suppression of SC in bound nucleons. To get further experimental insight into the problem, detailed measurements are necessary of the $(e,e'p)$ reaction at intermediate $Q^2 \approx 2$ GeV^2, and also of the $A(p,2p)$ cross sections at $E_p \approx 2$–4 GeV. Furthermore, better energy resolution has to be employed to suppress contribution of the inelastic double rescatterings. Under these conditions a detailed study of CT effects would be possible at intermediate energies.

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