$\gamma n \to \pi^- p$ process in ^{4}He and ^{16}O

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Nuclear transparencies for the fundamental process $\gamma n \to \pi^- p$ on ^{4}He and ^{16}O have been calculated using nucleon configurations obtained from realistic ground-state wave functions by the Monte Carlo method. Comparisons between nuclear transparency results using nucleon configurations and the correlated Glauber approximation are made in the case of $(e,e'p)$ on ^{4}He and ^{16}O. Furthermore, nuclear transparencies for the $\gamma n \to \pi^- p$ and $(e,e'p)$ processes have been calculated including a color transparency effect. [S0556-2813(96)03611-4]

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I. INTRODUCTION

During the past decade, interest in hadron propagation has led to many theoretical and experimental studies in nuclear transparency. The classical transparency of a nucleus, to a particle ejected at position $\vec{r}$ with momentum $\vec{p}$, equals the probability that a tube of cross-sectional area σ, parallel to $\vec{p}$ and starting from $\vec{r}$, does not contain any nucleons. This tube is illustrated in Fig. 1(a), and σ denotes the total cross section for scattering of the ejected particle by a nucleon in the nucleus. Analysis using the Glauber multiple scattering theory [1] shows that the nuclear transparency in high-energy reactions is dominated by classical transparency. The transparencies observed in $(e,e'p)$ reactions at MIT-Bates [2] and SLAC [3] are close to the classical transparency.

When the target contains a large number of uncorrelated particles distributed with density $\rho(\vec{r})$, the classical transparency, denoted by the Glauber transparency $t_{\rm G}(\vec{r},\vec{p})$, is given by

$$t_{\rm G}(\vec{r},\vec{p}) = \exp\left\{ -\int_0^\infty ds\,\rho(\vec{r}+\hat{p}s)\sigma \right\}, \tag{1}$$

where $\hat{p}$ is a unit vector along the momentum direction $\vec{p}$. Corrections to $t_{\rm G}$ are due to correlations among the nucleons in the target neglected in arriving at Eq. (1). These have been studied approximately by retaining only the pair correlations between the struck and other (spectator) nucleons [4,5]. Effects of pair correlations among the spectator nucleons [6,7] have also been considered. The correlated Glauber classical transparency that retains only the pair correlations between the struck nucleon and the spectator nucleons is given by

$$t_{\rm CG}(\vec{r},\vec{p}) = \exp\left\{ -\int_0^\infty ds\,g(s)\rho(\vec{r}+\hat{p}s)\sigma \right\}, \tag{2}$$

where $g(s)$ [4] is the pair distribution function of the nucleons inside the nucleus.

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In order to illustrate the absence of quantum effects in the transparencies measured at MIT-Bates [2] and SLAC [3] we consider the knockout of a proton from an orbital $\phi(\vec{r})$ in the nucleus. The outgoing wave is damped with the amplitude

$$a(\vec{r},\hat{p}) = \sqrt{t(\vec{r},\hat{p})}, \tag{3}$$

and the cross section for knockout with missing momentum $\vec{k}$ is proportional to the square of the amplitude

$$\left| \int d^3r e^{i\vec{k}\cdot\vec{r}} \phi(\vec{r}) a(\vec{r},\hat{p}) \right|^2. \tag{4}$$

At large $\vec{q}$ the direction $\hat{p}$ is not very sensitive to $\vec{k}$. The experimental transparencies are obtained from the cross section integrated over the missing momentum $\vec{k}$, given by

$$\int d^3k d^3r' d^3r e^{i\vec{k}\cdot(\vec{r}-\vec{r}')} \phi^*(\vec{r}')\phi(\vec{r}) a(\vec{r}',\hat{p}) a(\vec{r},\hat{p}) = \int d^3r \phi^2(\vec{r}) t(\vec{r},\hat{p}), \tag{5}$$

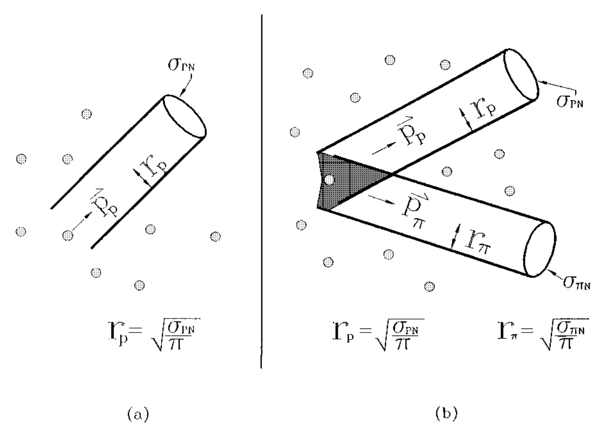

FIG. 1. (a) Tube illustration of classical transparency for a particle ejected from a nucleus at position $\vec{r}$ with momentum $\vec{p}$. (b) Tube illustration of classical transparency for quasifree $\gamma n \to p\pi^-$ process. Both p and π^- are created at $\vec{r}$, and the shaded region indicates the overlap between the proton and the pion exit tubes.

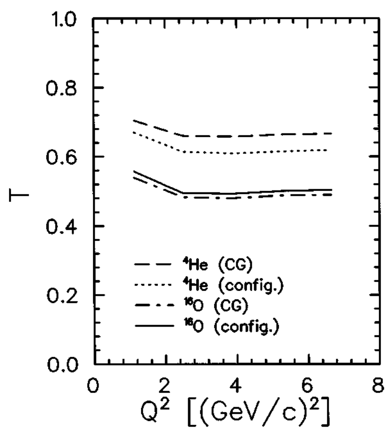

FIG. 2. Nuclear transparencies for the $(e,e'p)$ process in ^{4}He and ^{16}O calculated from nucleon configurations and the correlated Glauber approximation as a function of Q^2. The dashed line is the transparency result for ^{4}He from the correlated Glauber approximation, and the dotted line is from nucleon configurations; the dash-dotted line is the result for ^{16}O from the correlated Glauber approximation and the solid line is from the nucleon configurations.

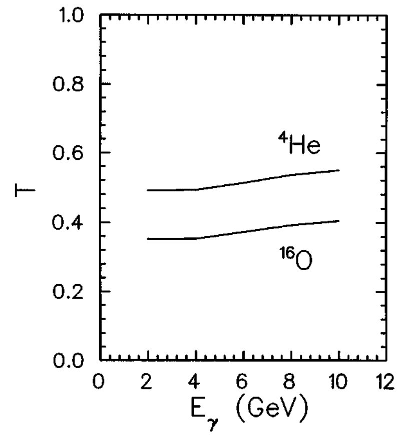

FIG. 3. Nuclear transparency for $\gamma n \to \pi^- p$ process in ^{4}He and ^{16}O as a function of photon energy E_γ for a pion center-of-mass angle of 75° calculated from the nucleon configurations.

which contains only the density distribution $\phi^2(\vec{r})$ of the initial state and the classical transparency.

We report calculations of the classical transparency for the $\gamma + n \to \pi^- + p$ reaction on ^{4}He and ^{16}O. We use configurations obtained by sampling realistic nuclear wave functions by the Monte Carlo method and thus include all correlation effects. Section II describes the importance of the $\gamma + n \to \pi^- + p$ process for nuclear transparency and color transparency studies. The Monte Carlo calculations are discussed in Sec. III. The results for $(e,e'p)$ are compared in Sec. IV with those using approximations based on the density distribution $\rho(\vec{r})$. The possible effects of color transparency for $\gamma + n \to \pi^- + p$ and $(e,e'p)$ processes are also considered.

II. THE $\gamma N \to \pi^- P$ PROCESS

For high energy exclusive reactions at large transverse momentum, the constituent counting rule predicts [8]

$$d\sigma/dt \propto \frac{1}{s^{n-2}}, \tag{6}$$

where s, t are the Mandelstam variables, and n is the total number of elementary fields; in case of photopion production from nucleon, $n=9$. Experimentally, the constituent counting rule behavior has been observed in $\gamma p \to \pi^+ n$ process at photon energies above 2 GeV [9]. This energy dependence of the cross section predicted by the constituent counting rule for $\gamma n \to \pi^- p$ can be tested experimentally at CEBAF [10] using a deuterium target. The $\gamma n \to \pi^- p$ process on nuclei is the simplest quasifree process involving two charged final-state hadrons. By detecting both final state hadrons from the quasifree $\gamma n \to \pi^- p$ process, the energy dependence of the transparency effect is maximized compared with a single-hadron process such as $(e,e'p)$, $(e,e'\pi)$ at comparable kinematics. Because the final state consists of two charged hadrons, one can use the existing magnetic spectrometers to define the quasifree process. Thus, the photopion reaction $\gamma n \to \pi^- p$ is an excellent candidate to study transparency in nuclei [10].

There are two dominating diagrams contributing to the quasifree $\gamma n \to \pi^- p$ process from a nuclear target. In the small t region, the incident photon fluctuates into a ρ meson that couples to the nucleon inside the nucleus. In the large t region, the diagram in which the incident photon couples directly to the nucleon inside the nucleus dominates because of the rapid decrease in the nucleon form factors with momentum transfer. The cross section will be proportional to the transparency of the nucleus to the ejected proton and pion. In the remainder of this paper, we focus on the large t $[|t| \geqslant 1.0\ (\mathrm{GeV}/c)^2]$ region where the classical transparency should be relevant.

The quasifree $\gamma n \to \pi^- p$ reaction from light nuclei provides an excellent process to search for enhancement of nuclear transparency due to reduced final-state interactions (FSI) by effects such as color transparency (CT) [11] for three reasons. In the region where the cross section obeys the constituent counting rule the proton and pion are likely to be created in their simplest constituent quark states. Secondly, the two-quark structure of the pion is more likely to be produced in a pointlike configuration (PLC) state as compared to a nucleon with a three-quark structure. Finally, detecting both the final-state proton and pion, enhances the CT effect above that in either the $(e,e'p)$ or $(e,e'\pi)$ reaction at comparable kinematics. For future CEBAF upgraded energies (8–10 GeV) [12], the CT effect might be observed experimentally by choosing light nuclei so that the hadronic expansion lengths for both the proton and the pion are comparable to the nuclear size.

III. TRANSPARENCY CALCULATIONS

The quasielastic $A(e,e'p)$ process is probably the simplest process for studying nuclear transparency both experimentally and theoretically. First, we discuss the nuclear transparency calculation for the $(e,e'p)$ process in nuclei. The nuclear transparency T for the quasifree $A(e,e'p)$ reaction is expressed as

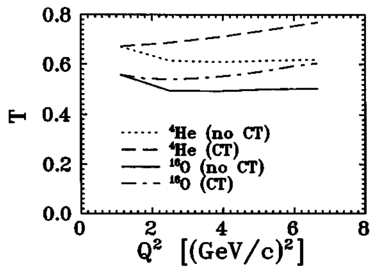

FIG. 4. Nucleon configuration calculations for the $(e,e'p)$ process for ^{4}He and ^{16}O both with and without a color transparency effect. The long-dashed line is ^{4}He$(e,e'p)$ with CT effect and the dotted line is without CT effect; the dash-dotted line is ^{16}O$(e,e'p)$ with CT effect and the solid line is ^{16}O$(e,e'p)$ without CT effect.

$$T=\frac{1}{Z}\int \rho_p(\vec{r})P(\vec{r})d^3r, \tag{7}$$

where $\rho_p(\vec{r})$ is the proton density, Z is the total number of protons in the nucleus, and $P(\vec{r})$ is the probability for the proton, originating at $\vec{r}$, to escape without final-state interactions. When only the correlation effects between the struck proton and the spectator nucleons are considered, $P(\vec{r})=t_{\rm CG}(\vec{r},\hat{p})$, as given by Eq. (2). We denote the transparency thus obtained as the ''correlated Glauber'' approximation $T_{\rm CG}$.

Monte Carlo configurations are snapshots of the positions of nucleons in a nucleus. The nucleons are distributed with the probability $|\Psi|^2$, where Ψ is the ground-state wave function, and thus contain all the correlations included in Ψ. It is straightforward to calculate the classical transparency from the configurations by neglecting the small effect of motion of the spectator nucleons during the reaction. Let $t_{i,I}$ be the transparency for the quasifree $A(e,e'p)$ reaction on nucleon i in configuration I; we have

$$t_{i,I}=P_{i,I,p}, \tag{8}$$

where $P_{i,I,p}$ equals one if for all particles $j\neq i$ that have $\vec{r_{ij}}\cdot\hat{p}<0$, or $r_{ij}{}^2-(\vec{r_{ij}}\cdot\hat{p})^2>(\sigma_{pN}/\pi)$ in the configuration I. Otherwise $P_{i,I,p}=0$. The nuclear transparency is just the average value of $t_{i,I}$ for all i over many configurations I. For the $\gamma n\rightarrow\pi^-p$ reaction on nucleon i in configuration I, we have

$$t_{i,I}=P_{i,I,p}P_{i,I,\pi}, \tag{9}$$

where $P_{i,I,\pi}$ is the transparency for the final-state pion produced from nucleon i in configuration I, and it is calculated in the same way as $P_{i,I,p}$.

The ^{4}He configurations were obtained from Wiringa's variational wave function [13], which explains the observed ^{4}He charge form factors. It thus gives a realistic $\rho(r)$ and contains correlations generated by the Argonne v_{14} model of nuclear forces. The microscopic many-body theory of ^{16}O is not yet as accurate as that of ^{4}He. The optimum variational wave function does not reproduce the observed charge form factor satisfactorily [14]. The ^{16}O configurations are obtained from a model wave function due to Pieper [15] that reproduces the observed ^{16}O charge density [16] and contains realistic correlations.

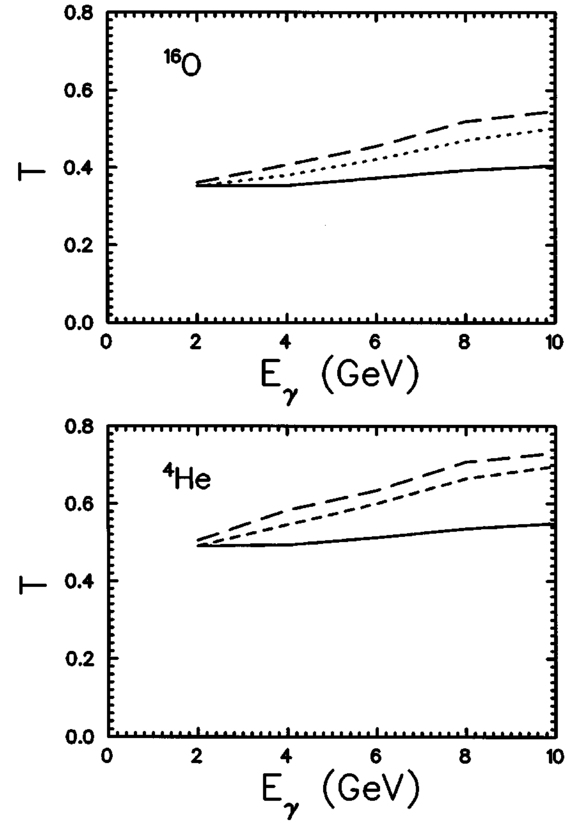

FIG. 5. Transparency calculations for $\gamma n\rightarrow\pi^-p$ process on ^{4}He (lower panel) and ^{16}O (upper panel) with and without CT effects calculated from nucleon configurations. The solid line is the result without CT effect, the dashed line is the result with CT for $\Delta M^2_{\pi^-}=0.7$ (GeV)^2, and the long-dashed line is for $\Delta M^2_{\pi^-}=0.3$ (GeV)^2; $\Delta M^2_p=0.7$ (GeV)^2 is used in both cases.

IV. RESULTS AND DISCUSSION

The transparencies of ^{4}He and ^{16}O to protons ejected in $(e,e'p)$ calculated with the correlated Glauber approximation and from nucleon configurations are compared in Fig. 2. The agreement between the two calculations is better than 8% for ^{4}He and 3% for ^{16}O. Figure 3 shows the calculated nuclear transparencies for the quasifree $\gamma n\rightarrow\pi^-p$ reaction on ^{4}He and ^{16}O as a function of the photon beam energy E_γ, using nucleon configurations. The calculations were performed at a center-of-mass angle for π^- of 75° corresponding to a π^- laboratory angle of 36.7° at a photon energy of 2 GeV and a laboratory angle of 18.4° at a photon energy of 10 GeV. The center-of-mass angle of 75° was chosen to maximize the transparency effect for the $\gamma n\rightarrow\pi^-p$ process. The measured total p-N and π^--N cross sections were used in the calculations and were taken from Ref. [17]. In the $\gamma n\rightarrow\pi^-p$ reaction, the opening angle between the two final-state hadrons becomes smaller as the energy of the incident photon beam increases for a fixed center-of-mass angle of the final state pion. The overlap between the pion and proton exit tubes [Fig. 1(b)] increases, and thus transparency also increases with E_γ. Because of this effect the product of $t_{\rm CG}(\vec{r})$ for proton and pion underestimates the joint probability of the proton and pion to escape, and it is not used.

The quantum diffusion model [18] was used to include the color transparency (CT) effect in the transparency calculation. According to this model, the total hadron-nucleon cross section is modified in the following way:

$$\sigma_T^{\rm eff}=\sigma_0\left\{\left[\frac{z-z'}{l_h}+\frac{\langle n^2t^2\rangle}{Q^2}\frac{(z-z')}{l_h}\right]\theta(l_h-z)+\theta(z-l_h)\right\}, \tag{10}$$

where n is the number of constituent quarks in the hadron, and it is two for pion and three for nucleon. $\sqrt{t^2}=0.350$ (GeV/c) [18], is the average transverse momentum of a quark inside a hadron. l_h is the hadronic expansion length (from a pointlike configuration to its normal size) and $l_h \simeq (2p/\Delta M^2)$ in the quantum diffusion model, where p is the momentum of the final-state hadron in the reaction. ΔM^2 is the mass squared difference between the hadron in PLC and in its normal state. Although this quantity is not known for either the pion or the proton, values of 0.7 (GeV)^2 for the proton and 0.25 (GeV)^2 for the pion are used in Ref. [18].

The NE18 [3] results of the nuclear transparency measurements do not rule out the possibility of CT effect because of the large errors associated with the measurements and also because of the theoretical uncertainties in the predictions. For example, models based on CT sum rules and quark-hadron duality [19] predict that the effect is smaller by approximately a factor of two than given by the quantum diffusion model used here. In the momentum transfer region of a few (GeV/c)^2, it is also possible that FSI are reduced due to the loss of meson clouds of the struck nucleon. Our use of the quantum diffusion model here is purely to provide an estimate of the increase in transparency due to a specified reduction in FSI.

The nucleon configuration calculations for $(e,e'p)$ from ^{4}He and ^{16}O with and without the CT effect are shown in Fig. 4. A value of $\Delta M_p^2=0.7$ (GeV/c)^2 was used in the quantum diffusion model for the CT effect in Fig. 4. Figure 5 shows the transparency results for quasifree $\gamma n\rightarrow\pi^- p$ process on ^{4}He (lower panel) and ^{16}O (upper panel) using the configuration method with and without CT effects. The solid line is the result without CT, the long-dashed line is the result for $\Delta M_{\pi^-}^2=0.3$ (GeV/c)^2 and the dashed line is for $\Delta M_{\pi^-}^2=0.7$ (GeV/c)^2; $\Delta M_p^2=0.7$ (GeV/c)^2 is used in both cases. The calculations were performed at a pion center-of-mass angle of 75°. The effect of CT on this process is sizable for both ^{4}He and ^{16}O at E_γ larger than 4 GeV.

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