Momentum Transfer Dependence of Nuclear Transparency from the Quasielastic $^{12}C(e, e'p)$ Reaction

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The cross section for quasielastic $^{12}C(e, e'p)$ scattering has been measured at momentum transfer $Q^2 = 1$, 3, 5, and 6.8 $(\text{GeV}/c)^2$. The results are consistent with scattering from a single nucleon as the dominant process. The nuclear transparency is obtained and compared with theoretical calculations that incorporate color transparency effects. No significant rise of the transparency with Q^2 is observed.

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Mueller and Brodsky [1] have suggested that, at sufficiently high momentum transfer, the final (and initial) state interactions of hadrons with the nuclear medium should be reduced, leading to the phenomenon termed "color transparency." Although the arguments were originally formulated within the context of perturbative QCD (high momentum transfer approximation of the strong interaction), recent work [2] indicates that this phenomenon occurs in a wide variety of model calculations with nonperturbative reaction mechanisms.

The requirements for the existence of color transparency have been discussed recently [2] and are briefly summarized here. First, high momentum transfer scattering should take place via selection of amplitudes in the initial and final state hadrons characterized by a small transverse size (much smaller than the hadron radius). Secondly, this small object should be "color neutral" outside of this small radius in order not to radiate gluons (which would lead to inelasticity). The object, being small and color neutral, would then have reduced inter-

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actions with hadrons in the surrounding nuclear medium ("color screening"). Finally, it is necessary that this compact size be maintained for some distance in traversing the nuclear medium in order that the reduction in the interaction probability be observable.

Various models have been used to estimate the magnitude of this effect at experimentally accessible energies, and the predictions differ considerably. Therefore it is important to establish experimentally the momentum scale required to observe this novel prediction.

An observed energy dependence in large angle quasielastic $A(p,2p)$ scattering at high energies [3] has been interpreted as evidence for color transparency [4]. However, this dependence is strongly correlated with the known oscillation of the free nucleon-nucleon scattering cross section [5], complicating the interpretation. Data from $A(e,e'p)$ can provide additional strong constraints on the momentum transfer (Q^2) dependence of color transparency. In particular, the electromagnetic probe samples the complete nuclear volume; the fundamental electron-proton scattering cross section is smoothly varying and accurately known in this kinematic range; detailed knowledge of the nucleon energy and momentum distribution in a nucleus A has been provided by low energy $A(e,e'p)$ experiments; and the relatively high energy resolution of the experiment allows clean detection of quasielastically scattered protons over a large kinematic range. Here we report on a measurement of the Q^2 dependence of the nuclear transparency of recoiling protons from $^{12}C(e,e'p)$ quasielastic scattering in the momentum transfer region from 1.0 to 6.8 $(GeV/c)^2$. Analysis of data from additional nuclear targets is in progress and will be published in a future paper [6].

Quasielastic $(e,e'p)$ scattering from nuclei involves scattering from the moving, off-shell protons of a finite nucleus [7]. In the plane wave impulse approximation (PWIA) the proton is ejected without final state interactions with 4-momentum $(T'+M,\mathbf{p}')$ from a target nucleus A by exchange of a virtual photon [4-momentum $(\nu,\mathbf{q})$] with the incident electron, leaving an $A-1$ nucleon system B with kinetic energy T_B. In PWIA the coincidence differential cross section for quasielastic $(e,e'p)$ scattering from nuclei is written as [7]

$$\frac{d^6\sigma}{dE'd\Omega_e dT'd\Omega_p} = K\sigma_{ep}^{os} S(E_m,p_m) , \qquad (1)$$

where K is a kinematic factor, σ_{ep}^{os} is the off-shell electron-nucleon scattering cross section, and $S(E_m,p_m)$ is the spectral function, i.e., the probability to find a proton with 4-momentum $(M-E_m-T_B,\mathbf{p}_m)$, where the missing energy $E_m \equiv \nu - T' - T_B$ and missing momentum $\mathbf{p}_m \equiv \mathbf{p}' - \mathbf{q}$. The spectral function is normalized so that $\int_0^\infty \int_{-\infty}^{+\infty} S(E_m,p_m)d^3\mathbf{p}_m dE_m = Z$. Extensive measurements of quasielastic $(e,e'p)$ scattering from nuclei have been made in the low momentum transfer region $Q^2 \le 0.3$ $(GeV/c)^2$ and the spectral function in the single particle region ($E_m < 80$ MeV and $|\mathbf{p}_m| < 250$ MeV/c) has been determined [8]. The presence of final state interactions, where the proton can scatter both elastically and inelastically from the surrounding nucleons as it exits the nucleus, reduces the measured $A(e,e'p)$ cross section. The nuclear transparency, the ratio of the measured cross section to the PWIA prediction, is a direct measure of this reduction. In the limit of complete color transparency, final state interactions vanish and the nuclear transparency approaches unity.

The experiment was performed at the Stanford Linear Accelerator Center and used the Nuclear Physics Injector. Data were taken with the pulsed beam duty factor of 2×10^{-4}, and the beam energy resolution ranged from $\pm0.1\%$ to $\pm0.2\%$. The targets consisted of 2% and 6% radiation lengths of ^{12}C. The scattered electrons were detected using the 1.6 GeV/c spectrometer [9] and identified in a detector stack of three drift chambers (each with two wire planes), two plastic scintillator hodoscopes, a lead glass shower counter, and a CO_2 gas Cherenkov detector. The electron momentum resolution was 0.15% over the momentum acceptance of $\pm5\%$. The recoiling protons were detected using the 8 GeV/c spectrometer [10] with a detector stack of ten multiwire proportional chambers and a 3-plane hodoscope system. The proton momentum resolution was 0.15% over the momentum acceptance of $\pm5\%$. Cuts of ±15 and ±40 mrad were placed on the in-plane and out-of-plane angles in both spectrometers. The coincidence performance of the double arm system was checked at each momentum transfer setting by measuring $^1H(e,e'p)$ scattering from a liquid hydrogen target. The double arm coincidence timing resolution (FWHM) was $\simeq 600$ ps. The FWHM resolution in missing energy (momentum) ranged from 8 MeV (28 MeV/c) at $Q^2 = 1$ $(GeV/c)^2$ to 20 MeV (44 MeV/c) at $Q^2 = 6.8$ $(GeV/c)^2$.

The experiment used perpendicular kinematics, where, at each Q^2, the recoil proton momentum is fixed and a distribution in proton scattering angle θ_p is measured (see Table I). The kinematics were chosen to cover the region $-25 < E_m < 140$ MeV and $0 < p_m < 250$ MeV/c [11] at each momentum transfer.

The PWIA prediction needed for the calculation of the transparency was obtained using Eq. (1). The single particle spectral function, normalized to Z, was generated with energies and widths of 16.2 and 5 MeV for the $1p$ shell, and 38.1 and 20 MeV for the $1s$ shell [7]. The missing momentum distributions were generated using a

TABLE I. Kinematics for the $^{12}C(e,e'p)$ measurements.

Q^2 [$(GeV/c)^2$]	E_e (GeV)	E'_e (GeV)	p' (GeV/c)	θ_e (deg)	θ_p (deg)
1.04	2.02	1.39	1.20	35.5	43.4,46.2,49.0,51.8,54.6
3.06	3.19	1.47	2.45	47.7	27.7,30.5,33.3
5.00	4.21	1.47	3.54	53.4	20.9,22.6
6.77	5.12	1.47	4.49	56.6	15.9,17.3

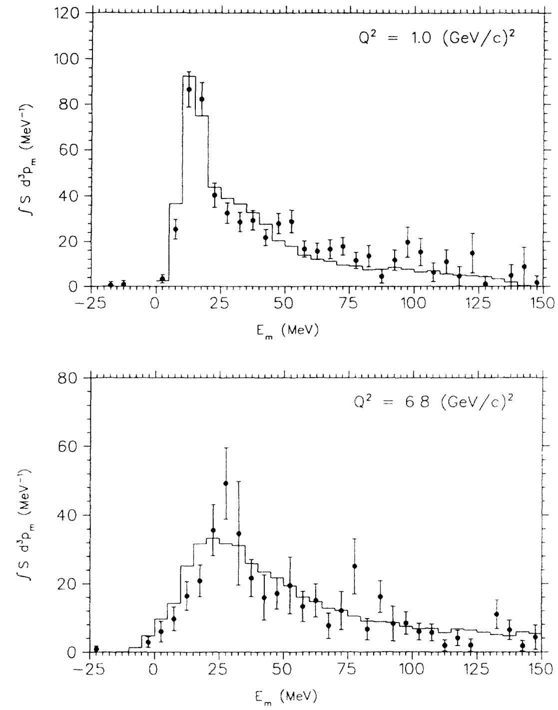

FIG. 1. The missing energy distributions at $Q^2 = 1$ and 6.8 $(\mathrm{GeV}/c)^2$. The solid line is the PWIA model normalized to the data. The error bars on the data are statistical only. Radiative effects are taken into account by the model. A 5 MeV energy shift has been applied to the model at $Q^2 = 1$ $(\mathrm{GeV}/c)^2$ to account for uncertainties in the spectrometer optics.

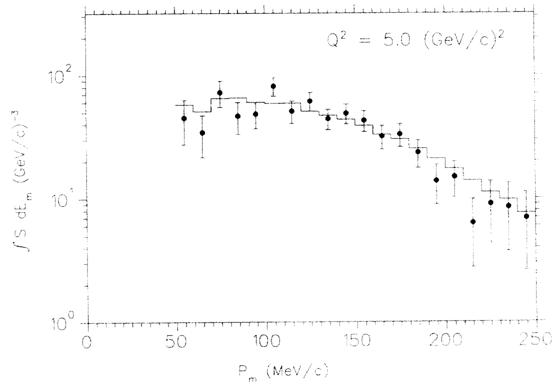

FIG. 2. The missing momentum distributions at $Q^2 = 5$ $(\mathrm{GeV}/c)^2$. The solid line is the PWIA model normalized to the data. The error bars on the data are statistical only. Radiative effects are taken into account by the model.

Woods-Saxon potential, while the missing energy distributions were described by a Lorentzian with a cutoff at the proton separation energy. For both distributions parameters were obtained from low energy $(e, e'p)$ data [7]. Model sensitivity was tested by varying the parameters, and also by using asymmetric forms for the missing energy distributions via a parametrization of Brown and Rho [12]. The resulting uncertainty on the transparency is 2%. In addition, the model spectral function was corrected for correlation strength not contained in the single particle description by dividing it by the Q^2 independent factor 1.11 ± 0.03, which has been estimated from calculations of ^{16}O [13] and ^{12}C [14]. Calculations [13,15] indicate that correlation strength is only significant well past the Fermi momentum, and so should not modify the form of the single particle spectral function within our acceptance. The off-shell prescription used was σ_{cc1} of de Forest [16], but σ_{cc2} and an on-shell prescription were also used to check model dependences (a variation of 2% in the transparency was found). We used the dipole form for the proton electric form factor, and the parametrization of Gari and Krümpelmann [17] for the proton magnetic form factor. The PWIA Monte Carlo model included the experimental resolution, the spectrometer acceptances, and radiative effects. Radiative effects were calculated in a coincidence framework [18] from the prescription of Mo and Tsai [19], and included the contribution from the recoil proton.

The measured spectral function [determined from Eq. (1) [7]] integrated over the missing momentum vector is compared with the PWIA model at $Q^2 = 1$ and 6.8 $(\mathrm{GeV}/c)^2$ in Fig. 1. The spectral function is integrated over missing energy and compared with the model at $Q^2 = 5$ $(\mathrm{GeV}/c)^2$ in Fig. 2. In both figures, the PWIA model is multiplied by the measured nuclear transparency at each Q^2. The good agreement between the shapes of the data and model validates our assumptions about the $^{12}\mathrm{C}(e, e'p)$ reaction mechanism at high Q^2. There is no evidence for sizable contributions from other processes.

The transparency is defined as the ratio of the number of events measured in the region $\Re$: $[-25 < E_m < 100$ MeV; $0 < p_m < 250$ MeV/$c]$ to the PWIA model prediction (determined for each θ_p and then averaged) for the same region:

$$T(Q^2) \equiv \frac{\sum_{\Re} N_{\mathrm{data}}}{\sum_{\Re} N_{\mathrm{PWIA}}} . \qquad (2)$$

By restricting $E_m < 100$ MeV $< m_\pi$ we ensure that no inelastic processes have occurred.

The results are compared in Fig. 3 with a series of calculations. The extracted transparency for elastic scattering from hydrogen is also shown and is found to be consistent with unity, as expected. The error bars include systematic errors of 6% for hydrogen and 7% for carbon, as well as a model dependence of 4% for carbon. The measured transparencies of Fig. 3 are found to be independent within errors of the E_m upper limit of $\Re$ for values of this limit between 50 and 130 MeV for hydrogen and between 80 and 130 MeV for carbon. The carbon results are compared with two calculations which include color transparency: the naive parton model (dotted) of [20] and the correlated-Glauber/quantum-diffusion model (dashed) of [21]. Cal-

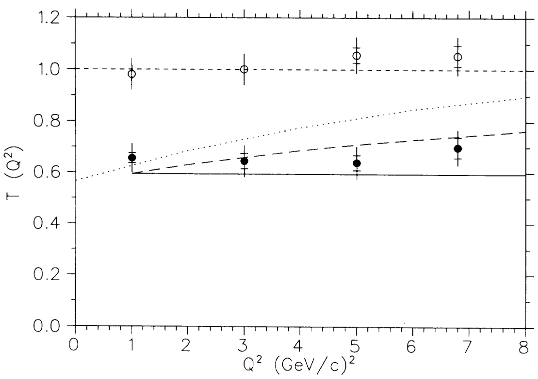

FIG. 3. The measured transparency as a function of Q^2 (hydrogen: open circles; carbon: solid circles), compared with several calculations described in the text. The inner error bars are statistical while the outer are the statistical and systematic errors added in quadrature.

culations [22–24] in the hadronic basis evolution model yield similar results to those of [21]. Conventional calculations which do not include color transparency effects [21,23] typically predict Q^2 independent transparencies and vary in magnitude between 0.55 and 0.65; one such calculation [21] is shown (solid line) in Fig. 3. Clearly, the color transparency predictions with the largest Q^2 dependence are ruled out, although a gradual rise in Q^2 is allowed within experimental error.

In summary, the $^{12}C(e, e'p)$ cross section has been measured over the range $-25 < E_m < 140$ MeV and $0 < p_m < 250$ MeV/c in the momentum transfer range $Q^2 = 1$ to 6.8 (GeV/c)^2. This extends the Q^2 range of these measurements by over an order of magnitude. The distribution of strength is consistent with the impulse approximation for scattering from a single nucleon. The measured transparency ratios are essentially independent of Q^2, indicating the absence of large color transparency effects in this energy range.

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