

A-dependence of nuclear transparency in quasielastic $A(e, e'p)$ at high Q^2

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The A -dependence of the quasielastic $A(e, e'p)$ reaction has been studied at SLAC with ${}^2\text{H}$, C, Fe, and Au nuclei at momentum transfers $Q^2 = 1, 3, 5$, and 6.8 (GeV/c) 2 . We extract the nuclear transparency $T(A, Q^2)$, a measure of the average probability that the struck proton escapes from the nucleus A without interaction. Several calculations predict a significant increase in T with momentum transfer, a phenomenon known as Color Transparency. No significant rise within errors is seen for any of the nuclei studied.

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In 1982, Mueller and Brodsky [1] proposed that in wide angle exclusive processes, the soft initial and final state interactions (ISI and FSI) of hadrons in nuclei would vanish at high energies. This effect, originally based on arguments using perturbative QCD, is called “Color Transparency” (CT), in reference to the disappearance of the color forces between the hadrons and nuclei. Evidence for the CT effect can be sought by measurement of the nuclear transparency T , defined as the ratio of the measured cross section to the cross section expected in the limit of complete CT (i.e., no ISI or FSI), as a function of the 4-momentum transfer squared, Q^2 , and nuclear mass, A . For CT to be observable in quasielastic $A(e, e'p)$ scattering, the recoiling proton must maintain its reduced interaction with other nucleons over a distance comparable to the nuclear radius. This is probed directly by measuring the A dependence of T . At low energies, $T < 1$ because of absorption or deflection of the

hadrons by ISI and FSI with the nucleus. As the energy increases, and if CT effects begin to dominate the scattering, T should increase towards unity [2]. Some recent models of CT predict significant increases in T for Q^2 as low as 5 (GeV/c) 2 [2–6]. We present measurements of T for the reaction $A(e, e'p)$ on ${}^2\text{H}$, C, Fe, and Au nuclei at $Q^2 = 1, 3, 5$, and 6.8 (GeV/c) 2 .

The first experiment to investigate CT was performed by Carroll *et al.* [7] using simultaneous measurements of $A(p, 2p)$ and $H(p, 2p)$ reaction rates at Brookhaven National Laboratory. Their results showed T increasing for $Q^2 \simeq 3\text{--}8$ (GeV/c) 2 , but then decreasing for $Q^2 \simeq 8\text{--}11$ (GeV/c) 2 . Because of the subsequent decrease, the rise at lower momentum transfer cannot be taken as an unambiguous signal of CT. Ralston and Pire [6] suggest that the maximum in T is due to a soft process that interferes with the perturbative QCD amplitude in free proton-proton scattering but is suppressed in the nuclear environment. Such ambiguities should be smaller in $A(e, e'p)$ reactions because of the simplicity of the elementary electron-proton interaction compared to the proton-proton interaction.

The experiment reported here was performed in End Station A at SLAC using the electron beam from the Nuclear Physics Injector [8]. Details of the experiment have been published previously [9]. Kinematics for the present data are shown in Table I. Solid targets of 2% (C), 6% (C, Fe, and Au), and 12% (Au) radiation length and liquid targets of 4.0 (${}^1\text{H}$ and ${}^2\text{H}$) and 15.7 cm (${}^2\text{H}$) were used. The angle of the proton spectrometer was varied

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Measurement of the electron and proton in coincidence allows reconstruction of the “missing” energy, $E_m \equiv \nu - E'_p + M_p - K_{A-1}$, and momentum, $\mathbf{p}_m \equiv \mathbf{p}' - \mathbf{q}$, not accounted for in the detected particles [10]. In the Plane Wave Impulse Approximation (PWIA), these are equal to the separation energy E_s and momentum \mathbf{p} of the struck proton, which has initial 4-momentum $p \equiv (M_p - E_s - K_{A-1}, \mathbf{p})$. Here $q = (\nu, \mathbf{q})$ is the virtual photon 4-momentum transfer ($Q^2 \equiv -q^2$), $p' = (E'_p, \mathbf{p}')$ is the 4-momentum of the detected proton, and K_{A-1} is the kinetic energy of the recoiling $A-1$ system.

We define the nuclear transparency T as the ratio of the measured coincidence rate to the rate calculated in the PWIA. The PWIA quasielastic cross section is [11]

$$\frac{d^6\sigma}{dE'_e d\Omega_{e'} dE'_p d\Omega_{p'}} = p' E'_p \sigma_1^{cc} S(\mathbf{p}, E_s). \quad (1)$$

Here $dE'_e d\Omega_{e'}$ and $dE'_p d\Omega_{p'}$ refer to the outgoing electron and proton, respectively. The nuclear structure is characterized by the spectral function $S(\mathbf{p}, E_s)$, the probability density for finding a proton with separation energy E_s and 3-momentum \mathbf{p} . The electromagnetic interaction is specified by σ_1^{cc} [11], the square of the elastic scattering amplitude of an electron and a moving off-shell proton. Other forms for this amplitude, including the on-shell value, have been tested with little ($\leq 2\%$) effect on the measured T . The dipole form for G_E^p and the Gari-Krümpelmann [12] form for G_M^p are assumed.

Details of the Monte Carlo program used to compute the PWIA cross-section were presented in a previous publication [9]. In the present analysis, we use a delta function for the ${}^1\text{H}$ spectral function and determine the ${}^2\text{H}$ spectral function using the full Bonn potential [13, Table II]. For the solid targets, we use Independent Particle Shell Model (IPSM) spectral functions; the energy levels are characterized by a Lorentzian energy profile (due to the finite lifetime of the one-hole state), and the momentum distributions are calculated using Woods-Saxon nuclear potentials with shell-dependent parameters. The Lorentzian and Woods-Saxon parameters are determined from fits to spectral functions extracted from previous $A(e, e'p)$ experiments (Ref. [10] for C and Fe, Ref. [14] for Au). Descriptions of the deepest-lying shells of Fe and Au were taken from a Hartree-Fock calculation [15] since data on these shells are inconclusive. For Fe and Au, the spectral function parameters were varied to provide better agreement with the $Q^2 = 1$ and $Q^2 = 3$ (GeV/c)² data of the present experiment [16]. The uncertainty in the spectral function parameters results in 2% systematic uncertainties in T for C, 3% for Fe, and 5% for Au. The IPSM spectral function does not include the effects of short-range nuclear correlations, which move strength to p_m greater than the Fermi momentum. The measured T

must be corrected by the ratio of $\int S d^3p dE_s$ for the correlated and the IPSM spectral functions, integrated over the measured E_m and p_m range. For C, the correction factor is 1.11 ± 0.03 , inferred from ${}^{12}\text{C}$ [17] and ${}^{16}\text{O}$ [18] spectral functions that include the effects of correlations. For Fe and Au we use a correlated nuclear matter spectral function corrected for finite nucleus effects [19,20], yielding correction factors of 1.22 ± 0.06 for Fe and 1.28 ± 0.10 for Au.

The data used to extract T are restricted to a kinematic region where the spectrometer acceptances and the shape of the spectral function are well understood. The acceptance of each spectrometer is restricted to $\pm 5\%$ of the central momentum, ± 15 mr in in-plane angle, and ± 40 mr in out-of-plane angle. Furthermore, we require $-30 < E_m < 100$ MeV (negative E_m account for finite resolution effects) and restrict the range of p_m . By eliminating events with $E_m \gtrsim 140$ MeV $\simeq m_\pi$, we ensure that no inelastic processes have occurred. For ${}^1\text{H}$ and ${}^2\text{H}$, we use $p_m < 170$ MeV/c. For the C, Fe, and Au targets, we use a range in p_m that provides uniform coverage over all Q^2 : $0 < p_m < 250$ MeV/c [21] for Fe and C and $0 < p_m < 210$ MeV/c for Au because fewer recoil proton angles were measured for this target. The transparency at each Q^2 is the weighted average of T over the proton spectrometer angle settings. The resulting T is insensitive at the $\sim 5\%$ level to variations in the above kinematic limits.

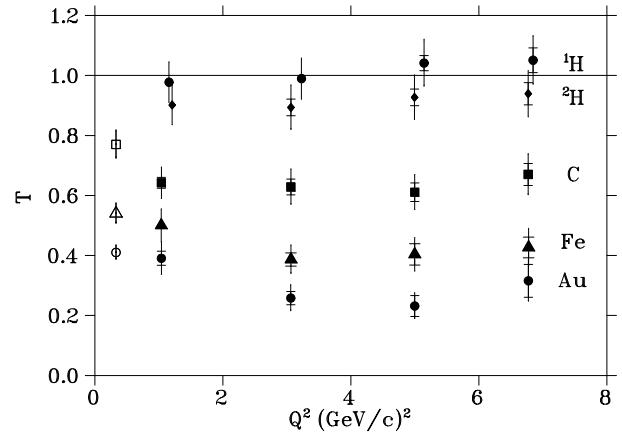


Figure 1. Nuclear transparency for $A(e, e'p)$ as a function of Q^2 . The inner error bars are the statistical uncertainty, and the outer error bars are the statistical and systematic uncertainties added in quadrature. The points at $Q^2 = 0.33$ (GeV/c)² are from Ref. [22] for C, Ni and Ta targets.

Figure 1 shows the measured transparency as a function of Q^2 . Note that the results for ${}^{12}\text{C}$ differ slightly (2–3%) from those previously published [9], principally due to improvements in the radiative corrections [16]. The ${}^1\text{H}$ results are consistent with the expected $T = 1$ (no absorption), while the ${}^2\text{H}$ transparencies appear to

be systematically below unity by $\sim 8\%$. For the $A > 1$ targets at all Q^2 , the measured p_m and E_m distributions are in reasonable agreement [9,16] with those calculated in the PWIA model. As this comparison is made using a single spectral function for each nucleus (renormalized at each Q^2 by the measured transparency T), it indicates that the PWIA description of quasielastic scattering is valid at $Q^2 \geq 1$ (GeV/c) 2 .

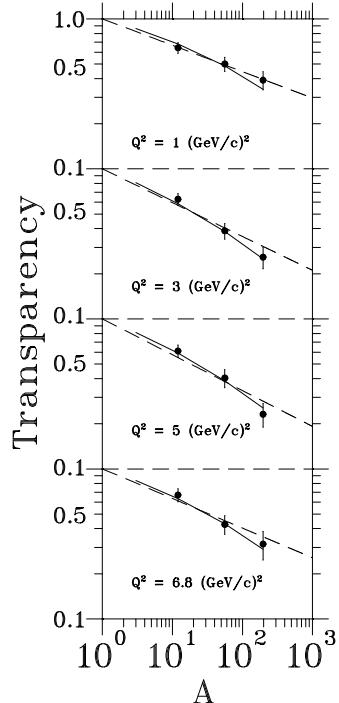
Fractional systematic uncertainties in T include 3% for detection, tracking, and coincidence timing; 5% for spectrometer acceptances; 2% for proton absorption; $\leq 0.9\%$ for charge, target thicknesses, and dead time; 3% for radiative effects; 2% for G_E^p and G_M^p parametrization; 2% for σ_1^{cc} (except for ${}^1\text{H}$); 2–5% for $S(\mathbf{p}, E_s)$ (solid targets only); and 3–8% for the correlation correction (solid targets only). Color Transparency is expected to produce an increase in T with increasing Q^2 for the $A > 1$ targets. There is no evidence within experimental errors of such an increase in the measured Q^2 range. The rise in the value of T at $Q^2 \leq 1$ (GeV/c) 2 (including the data from Ref. [22]) is at least partially due to the smaller nucleon-nucleon total cross section at momenta $\simeq 1\text{GeV}/c$, as has been suggested in Ref. [5]. For $Q^2 \geq 3$ (GeV/c) 2 , the magnitude of the measured T is within the range of the existing Glauber model calculations (i.e., no CT effects) [2–5,23–25]).

To combine the results from different nuclei and improve the sensitivity to CT effects, we can use a simple model for the A -dependence (for $A \geq 12$) of the transparency to obtain an effective nucleon-nucleon cross section (σ_{eff}) for each momentum transfer. This model assumes classical attenuation for the proton propagating in the nucleus with a σ_{eff} that is independent of density:

$$T_{\text{class}} = \frac{1}{Z} \int d^3r \rho_Z(\mathbf{r}) \exp \left[- \int dz' \sigma_{\text{eff}} \rho_{A-1}(\mathbf{r}') \right].$$

In the limit of complete CT, one would expect $\sigma_{\text{eff}} \rightarrow 0$. For this calculation, the nuclear density distributions were taken from Ref. [26] and σ_{eff} is the only free parameter. We also assume that the hard scattering rate is accurately described at each Q^2 by our PWIA model, unlike Ref. [27], where the hard scattering amplitude was also varied as a free parameter. The results of fitting this model to the measured transparency for the C, Fe, and Au targets is shown in Fig. 2 (solid curve). Also shown (dashed curve) is a simple $T = A^\alpha$ parameterization, where complete CT would correspond to $\alpha = 0$. The classical attenuation model provides a reasonable parameterization of the data (somewhat better than the A^α fits) and the fitted values of σ_{eff} are tabulated in Table II, where one observes a decrease in σ_{eff} at $Q^2 = 1$ (GeV/c) 2 correlated with the measured decrease in the free nucleon-nucleon cross section. We note that σ_{eff} is noticeably lower than the free cross section σ_{free} (Table II), as could be expected from quantum effects not accounted for in the classical calculation, as well as

nuclear effects such as Pauli blocking, short-range correlations, etc. [28], which are important effects at lower Q^2 . In addition, the finite experimental acceptance has been shown [5,25] to account for some of this effect. The ratio of σ_{eff} to σ_{free} is consistent with a constant value of 0.68.



Nuclear transparency (with total errors) as a function of A for each Q^2 . The solid line is a fit using the classical attenuation model discussed in the text and the dashed line is a fit to $T = A^\alpha$.

In summary, we have measured the nuclear transparency of the quasielastic ($e, e'p$) reaction as a function of the nuclear mass A in the Q^2 range of 1–7 (GeV/c) 2 . The measured transparencies for all the $A > 1$ targets, as well as σ_{eff} , are independent of Q^2 for $Q^2 > 3$ (GeV/c) 2 indicating that we have seen no evidence of effects associated with Color Transparency.

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- [1] A. H. Mueller, in *Proceedings of the XVII Rencontre de Moriond, 1982*, edited by J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, France, 1982), p. 13; S. J. Brodsky, in *Proceedings of the Thirteenth International Symposium on Multiparticle Dynamics*, edited by W. Kittel, W. Metzger, and A. Stergiou (World Scientific, Singapore, 1982), p. 963.
- [2] G. R. Farrar *et al.*, Phys. Rev. Lett. **61**, 686 (1988).
- [3] B. K. Jennings and G. A. Miller, Phys. Rev. D **44**, 692 (1991).
- [4] O. Benhar *et al.*, Phys. Rev. Lett. **69**, 881 (1992).
- [5] L. L. Frankfurt, M. I. Strikman, and M. B. Zhalov, Penn. State Univ. preprint, 1993.
- [6] J. P. Ralston and B. Pire, Phys. Rev. Lett. **61**, 1823 (1988).
- [7] A. S. Carroll *et al.*, Phys. Rev. Lett. **61**, 1698 (1988).
- [8] NPAS Users Guide, SLAC Report No. 269, 1984 (unpublished).
- [9] N. C. R. Makins *et al.*, Phys. Rev. Lett. **72**, 1986 (1994).
- [10] S. Frullani and J. Mougey, Advances in Nucl. Phys. **14**, 1 (1984).
- [11] T. De Forest, Nucl. Phys. **A392**, 232 (1983).
- [12] M. F. Gari and W. Krümplemann, Z. Phys. **A322**, 689 (1985).
- [13] R. Machleidt *et al.*, Phys. Rep. **149**, 1 (1987).
- [14] E. N. M. Quint, Ph.D. Thesis, U. Amsterdam, 1988.
- [15] J. W. Negele, Phys. Rev. C **1**, 1260 (1970); J. W. Negele and D. Vautherin, Phys. Rev. C **5**, 1472 (1972).
- [16] T. G. O'Neill, Ph.D. thesis, Caltech, 1994.
- [17] I. Sick, private communication.
- [18] J. W. van Orden, W. Truex, and M. K. Banerjee, Phys. Rev. C **21**, 2628 (1980).
- [19] X. Ji, private communication.
- [20] S. Liuti, private communication.
- [21] $p_m > 0$ corresponds to the angle of \mathbf{p}' with respect to the beam in the horizontal plane being greater than the angle of \mathbf{q} .
- [22] D. F. Geesaman *et al.*, Phys. Rev. Lett. **63**, 734 (1989); G. Garino *et al.*, Phys. Rev. C **45**, 780 (1992).
- [23] A. Kohama, K. Yazaki, and R. Seki, Nucl. Phys. **A536**, 716 (1992).
- [24] A. S. Rinat and B. K. Jennings, TRIUMF Preprint, 1993.
- [25] N. N. Nikolaev *et al.* Nucl. Phys. **A567**, 781 (1994).
- [26] H. de Vries *et al.*, At. Data Nucl. Data Tables **36**, 495 (1987).
- [27] P. Jain and J. P. Ralston, Phys. Rev. D **48**, 1104 (1993).
- [28] V. R. Pandharipande and S. C. Pieper, Phys. Rev. C **45**, 791 (1992).
- [29] A. Baldini *et al.*, *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series, Vol. **I/12b**, edited by H. Schopper (Springer-Verlag, 1987).

TABLE I. Kinematics of the experiment. E is the beam energy, E' and θ_e are the momentum and angle setting of the electron spectrometer, and θ_p is the angle setting of the proton spectrometer. The momentum of the proton spectrometer was set equal to the virtual photon 3-momentum q . The ^1H data were taken at elastic scattering kinematics with the same E and E' as the solid targets.

Q^2 (GeV/c) 2	Targets	E (GeV)	E' (GeV)	θ_e (deg)	θ_p (deg)
1.04	C, Fe, Au	2.015	1.39	35.5	43.4, 46.2, 49.0, 51.8, 54.6
1.21	^2H		1.36	38.8	35.9, 39.1, 41.3, 43.5, 46.7
3.06	C, Fe Au ^2H	3.188	1.47	47.7	27.7, 30.5, 33.3 27.7, 30.5 27.7
5.00	C, Fe Au ^2H	4.212	1.47	53.4	20.9, 22.6 20.9 19.5
6.77	C, Fe Au ^2H	5.120	1.47	56.6	15.9, 16.7, 17.3 16.7 15.9

TABLE II. Measured transparencies (with total errors) for C, Fe, and Au. Also shown are the results of the fits to the A-dependence shown in Fig. 2. σ_{free} is the average of the free p-p and p-n total cross sections from Ref. [29].

Q^2 (GeV/c) 2	T_{C}	T_{Fe}	T_{Au}	α	σ_{eff} (mb)	σ_{free} (mb)
1.04	0.64 ± 0.05	0.50 ± 0.05	0.39 ± 0.05	-0.18 ± 0.02	22 ± 3	37 ± 4
3.06	0.63 ± 0.06	0.39 ± 0.05	0.26 ± 0.04	-0.23 ± 0.02	32 ± 3	44 ± 3
5.00	0.61 ± 0.06	0.40 ± 0.06	0.23 ± 0.04	-0.24 ± 0.02	32 ± 4	43 ± 3
6.77	0.67 ± 0.07	0.43 ± 0.06	0.32 ± 0.07	-0.20 ± 0.02	27 ± 4	42 ± 3

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$$\frac{d^6\sigma}{dE'_e d\Omega_{e'} dE'_p d\Omega_{p'}} = p' E'_p \sigma_1^{cc} S(\mathbf{p}, E_s). \quad (1)$$

Here $dE'_e d\Omega_{e'}$ and $dE'_p d\Omega_{p'}$ refer to the outgoing electron and proton, respectively. The nuclear structure is characterized by the spectral function $S(\mathbf{p}, E_s)$, the probability density for finding a proton with separation energy E_s and 3-momentum \mathbf{p} . The electromagnetic interaction is specified by σ_1^{cc} [11], the square of the elastic scattering amplitude of an electron and a moving off-shell proton. Other forms for this amplitude, including the on-shell value, have been tested with little ($\leq 2\%$) effect on the measured T . The dipole form for G_E^p and the Gari-Krümpelmann [12] form for G_M^p are assumed.

Details of the Monte Carlo program used to compute the PWIA cross-section were presented in a previous publication [9]. In the present analysis, we use a delta function for the ${}^1\text{H}$ spectral function and determine the ${}^2\text{H}$ spectral function using the full Bonn potential [13, Table II]. For the solid targets, we use Independent Particle Shell Model (IPSM) spectral functions; the energy levels are characterized by a Lorentzian energy profile (due to the finite lifetime of the one-hole state), and the momentum distributions are calculated using Woods-Saxon nuclear potentials with shell-dependent parameters. The Lorentzian and Woods-Saxon parameters are determined from fits to spectral functions extracted from previous $A(e, e'p)$ experiments (Ref. [10] for C and Fe, Ref. [14] for Au). Descriptions of the deepest-lying shells of Fe and Au were taken from a Hartree-Fock calculation [15] since data on these shells are inconclusive. For Fe and Au, the spectral function parameters were varied to provide better agreement with the $Q^2 = 1$ and $Q^2 = 3$ (GeV/c) 2 data of the present experiment [16]. The uncertainty in the spectral function parameters results in 2% systematic uncertainties in T for C, 3% for Fe, and 5% for Au. The IPSM spectral function does not include the effects of short-range nuclear correlations, which move strength to p_m greater than the Fermi momentum. The measured T

must be corrected by the ratio of $\int S d^3p dE_s$ for the correlated and the IPSM spectral functions, integrated over the measured E_m and p_m range. For C, the correction factor is 1.11 ± 0.03 , inferred from ${}^{12}\text{C}$ [17] and ${}^{16}\text{O}$ [18] spectral functions that include the effects of correlations. For Fe and Au we use a correlated nuclear matter spectral function corrected for finite nucleus effects [19,20], yielding correction factors of 1.22 ± 0.06 for Fe and 1.28 ± 0.10 for Au.

The data used to extract T are restricted to a kinematic region where the spectrometer acceptances and the shape of the spectral function are well understood. The acceptance of each spectrometer is restricted to $\pm 5\%$ of the central momentum, ± 15 mr in in-plane angle, and ± 40 mr in out-of-plane angle. Furthermore, we require $-30 < E_m < 100$ MeV (negative E_m account for finite resolution effects) and restrict the range of p_m . By eliminating events with $E_m \gtrsim 140$ MeV $\simeq m_\pi$, we ensure that no inelastic processes have occurred. For ${}^1\text{H}$ and ${}^2\text{H}$, we use $p_m < 170$ MeV/c. For the C, Fe, and Au targets, we use a range in p_m that provides uniform coverage over all Q^2 : $0 < p_m < 250$ MeV/c [21] for Fe and C and $0 < p_m < 210$ MeV/c for Au because fewer recoil proton angles were measured for this target. The transparency at each Q^2 is the weighted average of T over the proton spectrometer angle settings. The resulting T is insensitive at the $\sim 5\%$ level to variations in the above kinematic limits.

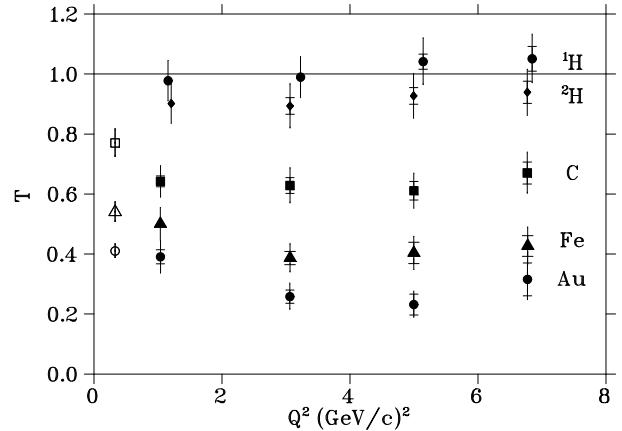


Figure 1. Nuclear transparency for $A(e, e'p)$ as a function of Q^2 . The inner error bars are the statistical uncertainty, and the outer error bars are the statistical and systematic uncertainties added in quadrature. The points at $Q^2 = 0.33$ (GeV/c) 2 are from Ref. [22] for C, Ni and Ta targets.

Figure 1 shows the measured transparency as a function of Q^2 . Note that the results for ${}^{12}\text{C}$ differ slightly (2–3%) from those previously published [9], principally due to improvements in the radiative corrections [16]. The ${}^1\text{H}$ results are consistent with the expected $T = 1$ (no absorption), while the ${}^2\text{H}$ transparencies appear to

be systematically below unity by $\sim 8\%$. For the $A > 1$ targets at all Q^2 , the measured p_m and E_m distributions are in reasonable agreement [9,16] with those calculated in the PWIA model. As this comparison is made using a single spectral function for each nucleus (renormalized at each Q^2 by the measured transparency T), it indicates that the PWIA description of quasielastic scattering is valid at $Q^2 \geq 1$ (GeV/c) 2 .

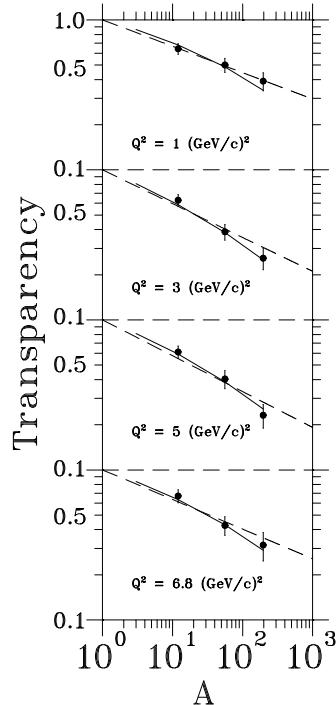
Fractional systematic uncertainties in T include 3% for detection, tracking, and coincidence timing; 5% for spectrometer acceptances; 2% for proton absorption; $\leq 0.9\%$ for charge, target thicknesses, and dead time; 3% for radiative effects; 2% for G_E^p and G_M^p parametrization; 2% for σ_1^{cc} (except for ${}^1\text{H}$); 2–5% for $S(\mathbf{p}, E_s)$ (solid targets only); and 3–8% for the correlation correction (solid targets only). Color Transparency is expected to produce an increase in T with increasing Q^2 for the $A > 1$ targets. There is no evidence within experimental errors of such an increase in the measured Q^2 range. The rise in the value of T at $Q^2 \leq 1$ (GeV/c) 2 (including the data from Ref. [22]) is at least partially due to the smaller nucleon-nucleon total cross section at momenta $\simeq 1\text{GeV}/c$, as has been suggested in Ref. [5]. For $Q^2 \geq 3$ (GeV/c) 2 , the magnitude of the measured T is within the range of the existing Glauber model calculations (i.e., no CT effects) [2–5,23–25].

To combine the results from different nuclei and improve the sensitivity to CT effects, we can use a simple model for the A -dependence (for $A \geq 12$) of the transparency to obtain an effective nucleon-nucleon cross section (σ_{eff}) for each momentum transfer. This model assumes classical attenuation for the proton propagating in the nucleus with a σ_{eff} that is independent of density:

$$T_{\text{class}} = \frac{1}{Z} \int d^3r \rho_Z(\mathbf{r}) \exp\left[-\int dz' \sigma_{\text{eff}} \rho_{A-1}(\mathbf{r}')\right].$$

In the limit of complete CT, one would expect $\sigma_{\text{eff}} \rightarrow 0$. For this calculation, the nuclear density distributions were taken from Ref. [26] and σ_{eff} is the only free parameter. We also assume that the hard scattering rate is accurately described at each Q^2 by our PWIA model, unlike Ref. [27], where the hard scattering amplitude was also varied as a free parameter. The results of fitting this model to the measured transparency for the C, Fe, and Au targets is shown in Fig. 2 (solid curve). Also shown (dashed curve) is a simple $T = A^\alpha$ parameterization, where complete CT would correspond to $\alpha = 0$. The classical attenuation model provides a reasonable parameterization of the data (somewhat better than the A^α fits) and the fitted values of σ_{eff} are tabulated in Table II, where one observes a decrease in σ_{eff} at $Q^2 = 1$ (GeV/c) 2 correlated with the measured decrease in the free nucleon-nucleon cross section. We note that σ_{eff} is noticeably lower than the free cross section σ_{free} (Table II), as could be expected from quantum effects not accounted for in the classical calculation, as well as

nuclear effects such as Pauli blocking, short-range correlations, etc. [28], which are important effects at lower Q^2 . In addition, the finite experimental acceptance has been shown [5,25] to account for some of this effect. The ratio of σ_{eff} to σ_{free} is consistent with a constant value of 0.68.



Nuclear transparency (with total errors) as a function of A for each Q^2 . The solid line is a fit using the classical attenuation model discussed in the text and the dashed line is a fit to $T = A^\alpha$.

In summary, we have measured the nuclear transparency of the quasielastic $(e, e'p)$ reaction as a function of the nuclear mass A in the Q^2 range of 1–7 (GeV/c) 2 . The measured transparencies for all the $A > 1$ targets, as well as σ_{eff} , are independent of Q^2 for $Q^2 > 3$ (GeV/c) 2 indicating that we have seen no evidence of effects associated with Color Transparency.

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- [1] A. H. Mueller, in *Proceedings of the XVII Rencontre de Moriond, 1982*, edited by J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, France, 1982), p. 13; S. J. Brodsky, in *Proceedings of the Thirteenth International Symposium on Multiparticle Dynamics*, edited by W. Kittel, W. Metzger, and A. Stergiou (World Scientific, Singapore, 1982), p. 963.
- [2] G. R. Farrar *et al.*, Phys. Rev. Lett. **61**, 686 (1988).
- [3] B. K. Jennings and G. A. Miller, Phys. Rev. D **44**, 692 (1991).
- [4] O. Benhar *et al.*, Phys. Rev. Lett. **69**, 881 (1992).
- [5] L. L. Frankfurt, M. I. Strikman, and M. B. Zhalov, Penn. State Univ. preprint, 1993.
- [6] J. P. Ralston and B. Pire, Phys. Rev. Lett. **61**, 1823 (1988).
- [7] A. S. Carroll *et al.*, Phys. Rev. Lett. **61**, 1698 (1988).
- [8] NPAS Users Guide, SLAC Report No. 269, 1984 (unpublished).
- [9] N. C. R. Makins *et al.*, Phys. Rev. Lett. **72**, 1986 (1994).
- [10] S. Frullani and J. Mougey, Advances in Nucl. Phys. **14**, 1 (1984).
- [11] T. De Forest, Nucl. Phys. **A392**, 232 (1983).
- [12] M. F. Gari and W. Krümplemann, Z. Phys. **A322**, 689 (1985).
- [13] R. Machleidt *et al.*, Phys. Rep. **149**, 1 (1987).
- [14] E. N. M. Quint, Ph.D. Thesis, U. Amsterdam, 1988.
- [15] J. W. Negele, Phys. Rev. C **1**, 1260 (1970); J. W. Negele and D. Vautherin, Phys. Rev. C **5**, 1472 (1972).
- [16] T. G. O'Neill, Ph.D. thesis, Caltech, 1994.
- [17] I. Sick, private communication.
- [18] J. W. van Orden, W. Truex, and M. K. Banerjee, Phys. Rev. C **21**, 2628 (1980).
- [19] X. Ji, private communication.
- [20] S. Liuti, private communication.
- [21] $p_m > 0$ corresponds to the angle of \mathbf{p}' with respect to the beam in the horizontal plane being greater than the angle of \mathbf{q} .
- [22] D. F. Geesaman *et al.*, Phys. Rev. Lett. **63**, 734 (1989); G. Garino *et al.*, Phys. Rev. C **45**, 780 (1992).
- [23] A. Kohama, K. Yazaki, and R. Seki, Nucl. Phys. **A536**, 716 (1992).
- [24] A. S. Rinat and B. K. Jennings, TRIUMF Preprint, 1993.
- [25] N. N. Nikolaev *et al.*, Nucl. Phys. **A567**, 781 (1994).
- [26] H. de Vries *et al.*, At. Data Nucl. Data Tables **36**, 495 (1987).
- [27] P. Jain and J. P. Ralston, Phys. Rev. D **48**, 1104 (1993).
- [28] V. R. Pandharipande and S. C. Pieper, Phys. Rev. C **45**, 791 (1992).
- [29] A. Baldini *et al.*, *Total Cross Sections for Reactions of High Energy Particles*, Landolt-Börnstein, New Series, Vol. I/12b, edited by H. Schopper (Springer-Verlag, 1987).

TABLE I. Kinematics of the experiment. E is the beam energy, E' and θ_e are the momentum and angle setting of the electron spectrometer, and θ_p is the angle setting of the proton spectrometer. The momentum of the proton spectrometer was set equal to the virtual photon 3-momentum q . The ^1H data were taken at elastic scattering kinematics with the same E and E' as the solid targets.

Q^2 (GeV/c) 2	Targets	E (GeV)	E' (GeV)	θ_e (deg)	θ_p (deg)
1.04	C, Fe, Au	2.015	1.39	35.5	43.4, 46.2, 49.0, 51.8, 54.6
1.21	^2H		1.36	38.8	35.9, 39.1, 41.3, 43.5, 46.7
3.06	C, Fe Au ^2H	3.188	1.47	47.7	27.7, 30.5, 33.3 27.7, 30.5 27.7
5.00	C, Fe Au ^2H	4.212	1.47	53.4	20.9, 22.6 20.9 19.5
6.77	C, Fe Au ^2H	5.120	1.47	56.6	15.9, 16.7, 17.3 16.7 15.9

TABLE II. Measured transparencies (with total errors) for C, Fe, and Au. Also shown are the results of the fits to the A -dependence shown in Fig. 2. σ_{free} is the average of the free p-p and p-n total cross sections from Ref. [29].

Q^2 (GeV/c) 2	T_C	T_{Fe}	T_{Au}	α	σ_{eff} (mb)	σ_{free} (mb)
1.04	0.64 ± 0.05	0.50 ± 0.05	0.39 ± 0.05	-0.18 ± 0.02	22 ± 3	37 ± 4
3.06	0.63 ± 0.06	0.39 ± 0.05	0.26 ± 0.04	-0.23 ± 0.02	32 ± 3	44 ± 3
5.00	0.61 ± 0.06	0.40 ± 0.06	0.23 ± 0.04	-0.24 ± 0.02	32 ± 4	43 ± 3
6.77	0.67 ± 0.07	0.43 ± 0.06	0.32 ± 0.07	-0.20 ± 0.02	27 ± 4	42 ± 3