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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 with ^{2}H, C, Fe, and Au nuclei at momentum transfers $Q^2 = 1$, 3, 5, and 6.8 $(\mathrm{GeV/c})^2$. We extract the nuclear transparency $T(A,Q^2)$, a measure of the average probability of escape of a proton from a nucleus A. Several calculations predict a significant increase in T with momentum transfer, a phenomenon known as color transparency. No statistically significant rise 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 inital 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, *i.e.* 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 four-momentum transfer 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 $(\mathrm{GeV/c})^2$ [2–6]. We present measurements of T for the reaction $A(e,e'p)$ on ^{2}H, C, Fe, and Au nuclei at four-momentum transfer squared $(Q^2) = 1$, 3, 5, and 6.8 $(\mathrm{GeV/c})^2$.

The first experiment to investigate CT was performed

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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 $Q^2 \simeq 3-8\,(\mathrm{GeV/c})^2$, but then decreasing for $Q^2 \simeq 8-11\,(\mathrm{GeV/c})^2$. 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. These ambiguities should play less of a role in $A(e,e'p)$ reactions because of the simplicity of the elementary electron-proton interaction compared to the proton-proton interaction.

The current experiment 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]. Here we discuss aspects that are unique to the present analysis. Kinematics for the data presented here can be found in ref. [10]. Solid targets of 2%, 6%, and 12% radiation length and liquid targets of 4 and 15 cm were used as checks of the radiative corrections. For the nuclear targets, data were taken at quasielastic kinematics (nearly elastic $e-p$ kinematics, with energies adjusted to allow for the binding energy of the proton in the nucleus). The angle of the proton spectrometer was varied to account for the Fermi motion of the initial proton (so-called perpendicular kinematics). At higher Q^2 the angular spread due to this effect is reduced and fewer angle settings are required.

Measurement of the electron and proton in coincidence allows reconstruction of the "missing" energy $E_m \equiv \nu - E'_p + M_p - T_{A-1}$ and momentum $\mathbf{p}_m \equiv \mathbf{p}' - \mathbf{q}$ not accounted for in the detected particles [11]. In the Plane Wave Impulse Approximation (PWIA), these are just the separation energy E_s and momentum $\mathbf{p}$ of the initial proton, which has four-momentum $p \equiv (M_p - E_s - T_{A-1}, \mathbf{p})$. Here $q = (\nu, \mathbf{q})$ is the virtual photon four-momentum transfer ($Q^2 \equiv -q^2$), $p' = (E'_p, \mathbf{p}')$ is the four momentum of the detected proton, and T_{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:

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

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} [12], 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. We assume the dipole and Gari-Krümpelmann [13] forms for the proton elastic form factors G_E^p and G_M^p, respectively, as suggested by SLAC experiment NE11 [14].

Details of the Monte Carlo program used to compute the PWIA cross-section are presented in a previous publication [9]. In the present analysis we use a delta-function for the ^{1}H spectral function and determine the ^{2}H spectral function using the Bonn potential [15]. 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 distribution is calculated using a Woods-Saxon nuclear potential 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 (Reference [11] for C and Fe, Reference [16] for Au). Descriptions of the deepest-lying shells of Fe and Au were taken from a Hartree-Fock calculation [17] since data on these shells are inconclusive. For Fe and Au, the spectral function parameters were varied to provide better agreement with the $Q^2 = 1, 3\ (\mathrm{GeV/c})^2$ data of the present experiment [10]. 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}C [18] and ^{16}O [19] 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 [20] [21], yielding correction factors of $1.22 \pm .06$ for Fe and $1.28 \pm .10$ for Au.

In extracting T, the data are restricted to events where the spectrometer acceptances and the shape of the spectral function are well understood. The acceptance of each spectrometer is restricted to $\pm 5\%$ in momentum fraction, ± 15 mr in in-plane angle, and ± 40 mr in out-of-plane angle. Furthermore, we require $-30 < E_m < 100\,\mathrm{MeV}$ and restrict the range of p_m. By eliminating events with $E_m \gtrsim 140\,\mathrm{MeV} \simeq m_\pi$, we ensure that no inelastic processes have occurred. For ^{1}H and ^{2}H, we use $p_m < 170\,\mathrm{MeV/c}$. For the C and Fe targets we use $p_m < 250\,\mathrm{MeV/c}$, while for Au we use $p_m < 210\,\mathrm{MeV/c}$ because fewer recoil proton angles were measured for this target. For the C, Fe, and Au targets we apply the additional constraint that the angle of $\mathbf{p}'$ with respect to the beam in the horizontal plane is greater than the angle of $\mathbf{q}$. The transparency at each Q^2 is the weighted average of T over the measured proton angles.

Figure 1 shows the measured transparency as a function of Q^2. Fractional systematic uncertainties 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; 2% for σ_1^{cc} (except for ^{1}H); 2–5% for $S(\mathrm{p}, E_s)$ (solid targets only); and 3–8% for the correlation correction (solid targets only). The ^{1}H results are consistent with the expected $T = 1$ (no absorption). The measured p_m and E_m distributions of the nuclear targets for all Q^2 are also in reasonable agreement [10] with those calculated in the PWIA model using a single spectral funtion for each nucleus (when renormalized at each Q^2 by a single scale factor $= T$), indicating that the PWIA description of quasielastic scattering remains valid at higher Q^2.

Color Transparency is expected to produce an increase in T with increasing Q^2 for the nuclear targets. There is no statistically significant evidence of such an increase in the measured Q^2 range. The rise in the value of T at $Q^2 \leq 1\,(\mathrm{GeV/c})^2$ (including the data from ref. [22]) is at least partially due to the smaller nucleon-nucleon total cross section at momenta $\simeq 1\,\mathrm{GeV/c}$, as has been suggested in Reference [5]. For $Q^2 \geq 3\,(\mathrm{GeV/c})^2$ 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:

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

For this calculation, the nuclear density distributions were taken from Reference [27] and σ_{eff} is the only free parameter. We also assume that the hard scattering rate is accurately determined by our PWIA model, and therefore that any energy dependence of the transparency is due to FSI. Thus our parameterization differs somewhat from that of Ref. [26], where the hard scattering amplitude was also varied as a free parameter. In the limit of complete CT one would expect $\sigma_{eff} \rightarrow 0$. The results of fitting this model to the measured transparency for the C, Fe, and Au targets is shown in Fig. 2. Also shown in Fig. 2 (dashed curve) is a simple $T = A^\alpha$ parameterization, where complete CT would correspond to $\alpha = 0$. The classical attenuation model does a good job of parametrizing the data (somewhat better than the A^α fits) and the fitted values of σ_{eff} are tabulated in Table I where one observes a clear decrease in σ_{eff} at $Q^2 = 1\ (\mathrm{GeV/c})^2$ correlated with an observed decrease in the free nucleon-nucleon cross section. However these cross sections are noticably lower than the free cross sections [28] (36 - 45 mb) for the momentum range of the present experiment. Such a reduction 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. [29]. While the value of σ_{eff} for $Q^2 = 7\ (\mathrm{GeV/c})^2$ shows a slight decrease it is consistent with a constant value for $Q^2 = 3-7\ (\mathrm{GeV/c})^2$. In summary, we have measured the A-dependence of the quasielastic $(e, e'p)$ reaction in the Q^2 range of $1-7\ \mathrm{GeV}^2$ and have seen little 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 Frontieres, 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, 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 (unpub-

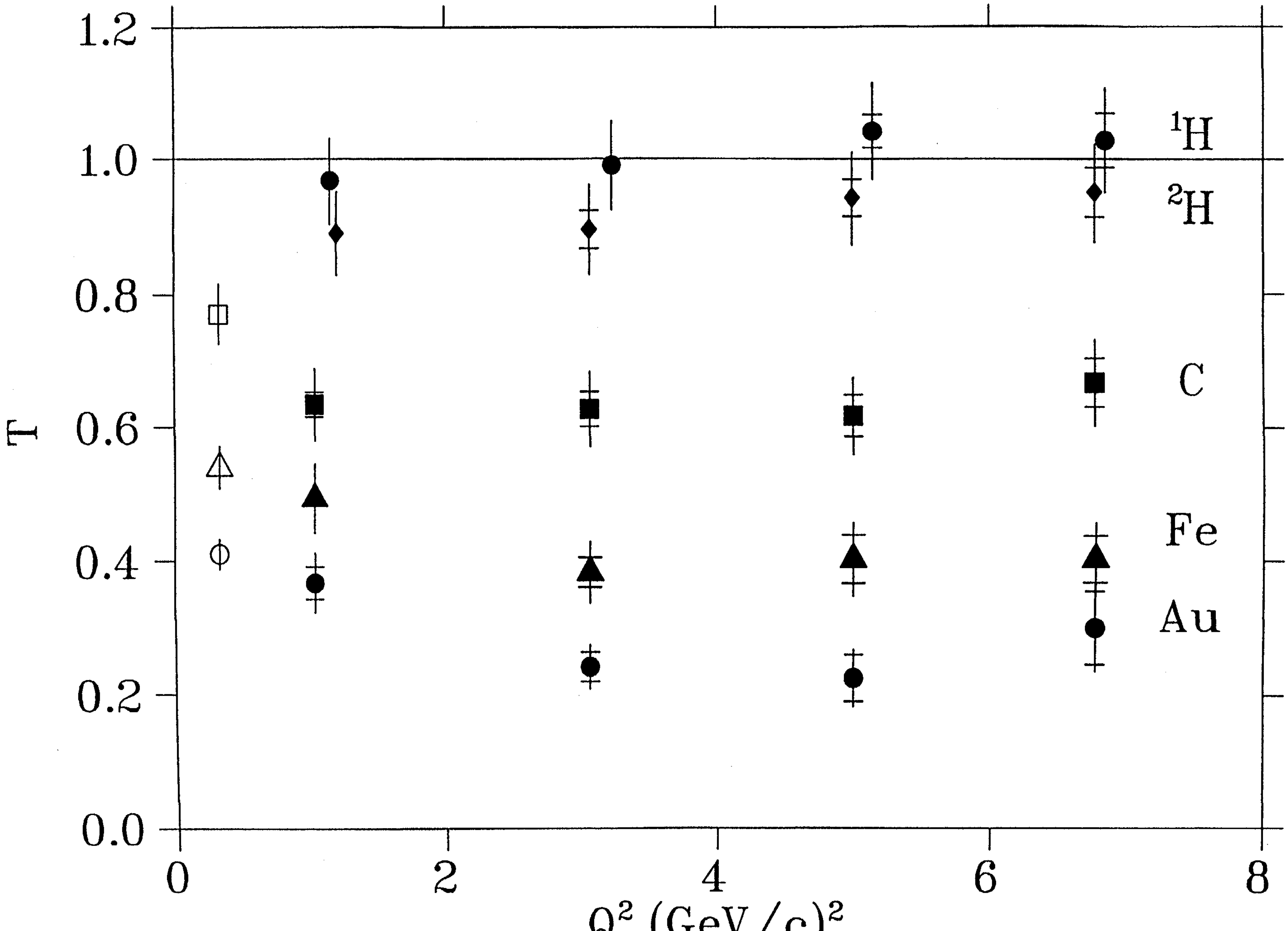
lished).
[9] N.C.R. Makins *et al.*, Phys. Rev. Lett. **72**, 1986 (1994).
[10] T. G. O'Neill, PhD thesis, Caltech (unpublished) (1994).
[11] S. Frullani and J. Mougey, Advances in Nucl. Phys. **14**, Plenum Press, New York 1984.
[12] T. De Forest, Nucl. Phys. **A392**, 232 (1983).
[13] M. F. Gari and W. Krümplemann, Z. Phys. **A322**, 689 (1985).
[14] P. E. Bosted *et al.*, Phys. Rev. Lett. **68**, 3841 (1992); A. Lung *et al.*, Phys. Rev. Lett. **70**, 718 (1993).
[15] R. Machleidt *et al.*, Phys. Rep. **149**, 1 (1987).
[16] E.N.M. Quint, PhD Thesis, U. Amsterdam (unpublished) (1988).
[17] J. W. Negele, Phys. Rev. **C1**, 1260 (1970); J. W. Negele and D. Vautherin, Phys. Rev. **C5**, 1472 (1972).
[18] I. Sick, private communication (1993).
[19] J. W. Van Orden, W. Truex, and M. K. Banerjee, Phys. Rev. **C21**, 2628 (1980).
[20] X. Ji, Priv. Comm.
[21] S. Liuti Priv. Comm.
[22] D.F. Geesaman *et al.*, Phys. Rev. Lett. **63**, 734 (1989). G. Garino *et al.*, Phys. Rev. **C45**, 780 (1992).
[23] A. Kohama, K. Yasaki, and R. Seki, Nucl. Phys. **A536**, 716 (1992).
[24] A.S. Rinat and B. K. Jennings, Preprint 1993.
[25] N.N. Nikolaev *et al.* Nucl. Phys. **A567**, 781 (1994).
[26] P. Jain and J. P. Ralston, Phys. Rev. **D48**, 1104 (1993).
[27] H. De Vries *et al.*, At. Data Nucl. Data Tables **36**, 495 (1987).
[28] 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).
[29] V.R. Pandharipande and S.C. Pieper, Phys. Rev. **C45**, 791 (1992).

FIG. 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 $Q^2 = 0.33$ $(\mathrm{GeV/c})^2$ are from Ref. [22].

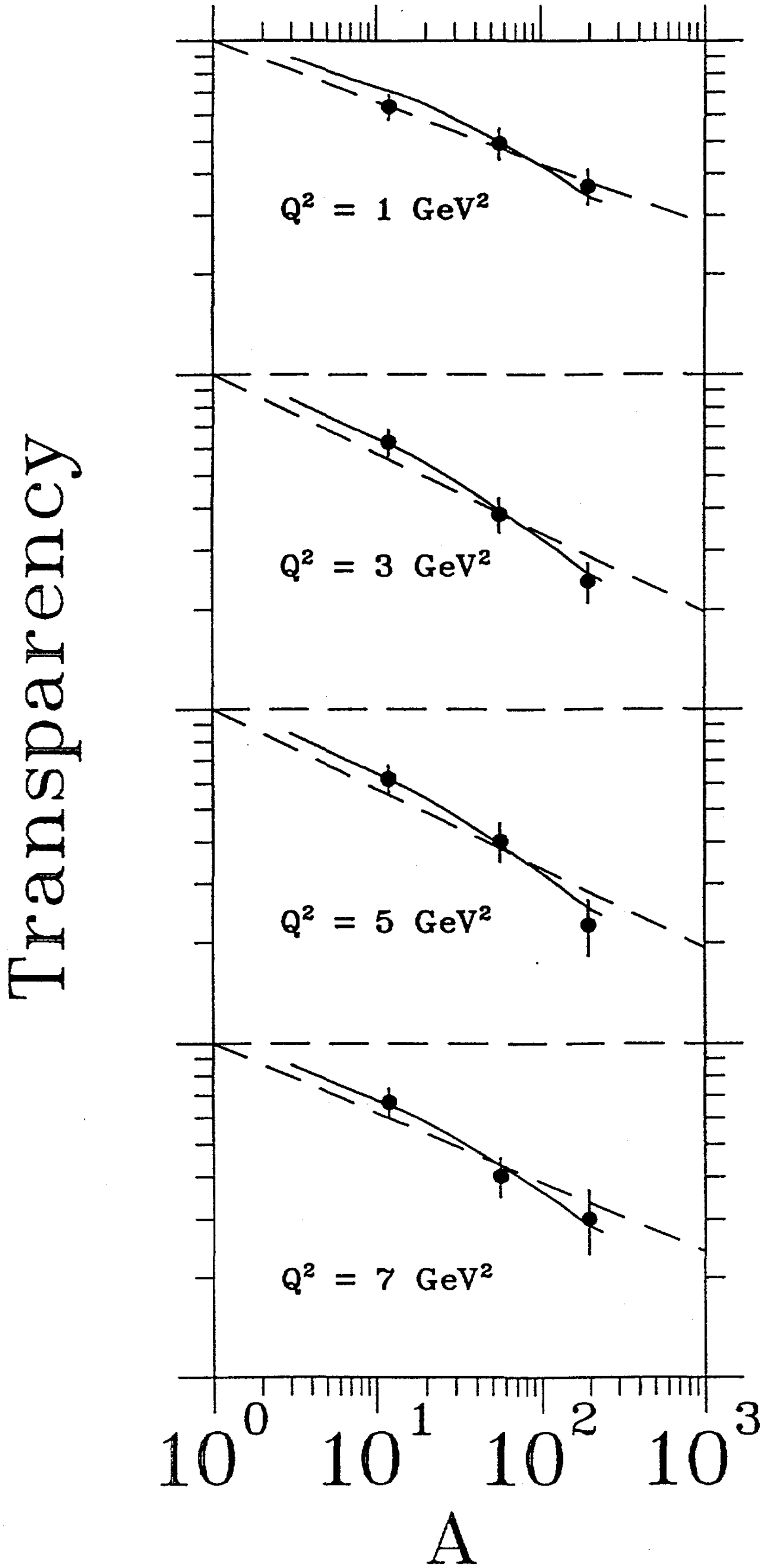
FIG. 2. Nuclear transparency as a function of A for each Q^2. The solid line is a fit using the classical attenuation model discussed in the text, and the dashed line is a fit to $T = A^{\alpha}$.

TABLE I. Measured transparencies 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 proton-proton and proton-neutron total cross sections from Ref. [28].

Q^2 $(\mathrm{GeV/c})^2$	T_C	T_{Fe}	T_{Au}	α	σ_{eff} (mb)	σ_{free} (mb)
1.04	0.63±0.05	0.49±0.05	0.37±0.04	-0.17±0.02	20±2	37±4
3.06	0.63±0.06	0.38±0.04	0.24±0.03	-0.24±0.02	28±3	44±3
5.00	0.62±0.06	0.40±0.05	0.23±0.04	-0.24±0.02	29±3	43±3
6.77	0.67±0.06	0.40±0.05	0.30±0.06	-0.21±0.02	25±3	42±3



1.2
1.0
0.8
0.6
0.4
0.2
0.0
T
0
2
4
6
8
Q² (GeV/c)²
¹H
²H
C
Fe
Au



Transparency
Q² = 1 GeV²
Q² = 3 GeV²
Q² = 5 GeV²
Q² = 7 GeV²
10⁰
10¹
10²
10³
A