Nuclear Transparency to Large-Angle *pp* Elastic Scattering

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Large-angle *pp* elastic and quasielastic $(p,2p)$ scattering have been simultaneously observed in hydrogen and each of several nuclear targets (Li, C, Al, Cu, Pb) at incident proton momenta of 6, 10, and 12 GeV/c. The nuclear transparency is the ratio of such a cross section in a nucleus to the free *pp* cross section. The transparency of aluminum increases with incident momentum by more than a factor of 2 from 6 to 9.5 GeV/c and falls significantly between 9.5 and 12 GeV/c. This occurs in a region where the free-proton nucleon-absorption cross section exhibits little energy dependence. QCD predicts an increase in transparency with energy.

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This Letter describes the first results from a program of study at the Brookhaven National Laboratory Alternating-Gradient Synchrotron which investigates the effects of "color transparency." Quasielastic *pp* scattering from each of several nuclei is compared to *pp* elastic scattering in hydrogen at three energies. These data are analyzed with a simple model in which the quasielastic cross section is assumed to factor into the product of three terms, a single-particle nuclear momentum distribution, a free *pp* cross section, and a factor T which we refer to as the transparency of the nucleus. In the absence of Fermi motion the transparency would be

$$T=\frac{(d\sigma/dt)(p\text{-}p\text{ elastic in nucleus})}{(d\sigma/dt)(p\text{-}p\text{ elastic in hydrogen})}. \qquad (1)$$

Data are presented for *pp* elastic and quasielastic scattering near 90° c.m. (center of mass) at incident proton energies of 6, 10, and 12 GeV/c, corresponding to t [(four-momentum transfer)^2] of -4.8, -8.5, and -10.4 GeV^2.

The cross section $(d\sigma/dt)$ for *pp* elastic scattering at large transverse momentum and at fixed c.m. angle is characterized by an s [(center-of-mass energy)^2] dependence which oscillates around the nominal s^{-10} form predicted by the dimensional scaling law of Brodsky and Farrar.[1] The form of this energy dependence can be related to the probability of finding protons with all of their quarks confined to a region of space which is proportional to $1/\sqrt{s}$. This implies that for large s these initial- and final-state protons are very small.

It has been pointed out by Mueller[2] and others that small protons which participate in such processes are characterized by color-charge and color-field distributions confined to ever smaller dimensions as s increases. In high-t quasielastic scattering this implies that the cross section for soft initial- and final-state interactions with other nucleons in the nucleus will vanish as the energy scale increases. It has thus been predicted that at high energy the transparency of nuclei should approach unity. This is in sharp contrast to a more conventional Glauber picture[3] of absorption in which the transparency would be expected to be energy independent.

The apparatus consists of a large-angle magnetic spectrometer with a 4.5° aperture.[4] Large proportional chambers measure the trajectories of recoil tracks opposite the spectrometer. When configured for incident momentum of 10 GeV/c, the spectrometer has $\Delta p/p = 1\%$ and $\Delta\theta = 1$ mr and the recoil-chamber resolution is $\Delta\theta = 5$ mr. Beam and spectrometer Cherenkov counters identified protons.

In this experiment, *pp* elastic scattering in hydrogen and in nuclei were observed simultaneously. Nuclear targets (Li, C, Al, Cu, or Pb) were placed between two CH_2 targets. The nuclear targets were divided into four equal segments and spaced at 3-in. intervals. The CH_2 targets were 2 in. thick. The thickness of each nuclear target was chosen so that the number of nuclear protons was larger by about a factor of 5 than the number of hydrogen protons. Data were collected on all targets at 6 and 10 GeV/c and on C and Al at 12 GeV/c.

The segmented nuclear targets were covered above and below with a scintillation counter backed with a two-layer 1.5-radiation-length lead-scintillator sandwich. This counter, spanning about $\frac{2}{3}$ of the total solid angle for particles leaving the target, intercepted charged tracks or π^0 photons produced out of the two-body scattering plane. Events with hits in more than 2 layers were used for background analysis.

To extract the pp elastic signal in hydrogen (CH_2), events are selected for which the spectrometer track has transverse momentum within 30% of the kinematic maximum. From the reconstructed vertex distribution, interactions in the CH_2 are selected [see Fig. 1(a)]. These events are then subjected to a two-body elastic-scattering hypothesis. With the measurement of the beam-track and spectrometer-track four-momenta and the recoil-track direction a missing three-momentum $\mathbf{p}$ is determined. The target proton is then assumed to have four-momentum of the form

$$P=(m_p,p_x,p_y,p_z)=(m_p,\mathbf{p}), \tag{2}$$

with the energy taken to be the proton mass m_p.

To isolate the CH_2 hydrogen signal from inclusive and quasielastic scattering backgrounds, one looks for a sharp peak at $|\mathbf{p}|=0$. The coordinate system is defined so the incident beam is along the z axis and the y axis is normal to the scattering plane. In Fig. 1, the p_z distribution is shown for the CH_2 events [1(b)] and for the pure carbon sample [1(c)] at an incident momentum of 6 GeV/c after a cut on total target momentum $|\mathbf{p}|<1.1$ GeV/c. The resolution in p_z is 10 MeV/c. The hydrogen elastic signal is extracted from the CH_2 events with use of a smooth fit to the background around the sharp hydrogen peak. Measurements with aluminum targets at incident momenta of 6, 10, and 12 GeV/c yielded 1701, 650, and 220 hydrogen elastic events, respectively. The yields on other targets at 6 and 10 GeV/c were 2 to 4 times smaller.

To extract the pp quasielastic signal from scatters in the nuclear targets, the procedure described above is applied to each event and the missing momentum $\mathbf{p}$ is calculated. The quasielastic scattering signal appears in the three-dimensional distribution of the variable $\mathbf{p}$ as an enhancement within about 250 MeV/c of the origin. If the scattering cross section and transparency T were independent of $\mathbf{p}$ then the shape of this quasielastic distribution would be just the shape of the nuclear momentum distribution $F(\mathbf{p})$. To proceed with the analysis we make two assumptions. The first assumption is that the quasielastic cross section factorizes. Noting that the pp elastic cross section has negligible dependence upon t near 90°, we assume that the three-dimensional quasielastic distribution has the form

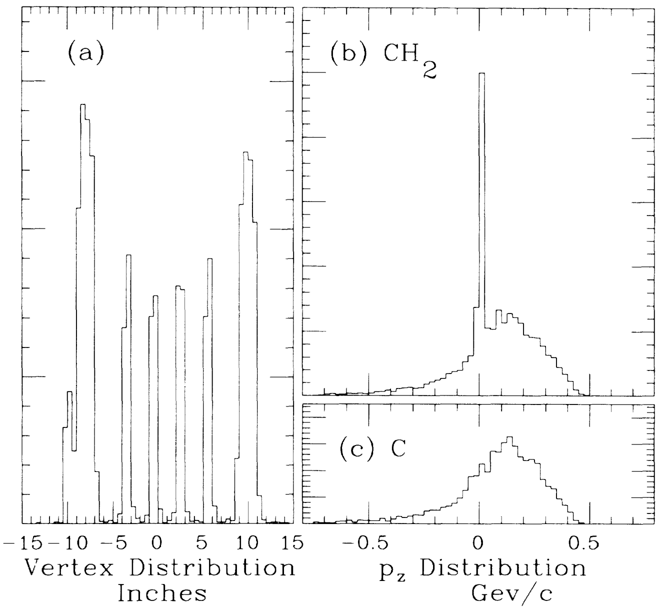

FIG. 1. (a) Reconstructed track vertex distribution along the direction of the incident beam for events with near elastic kinematics. The two outer peaks and four inner peaks are at the location of the CH_2 targets and C targets, respectively. (b) The p_z distribution for events interacting in the CH_2 targets. (c) The p_z distribution for events interacting in the C targets.

$$\frac{d^3N}{dp^3}=N'_{\rm H}T(s)F(\mathbf{p})A(\mathbf{p})\frac{(d\sigma/dt)(s)}{(d\sigma/dt)(s_0)}. \tag{3}$$

$N'_{\rm H}$ is the number of events observed in hydrogen ($N_{\rm H}$) multiplied by the ratio of nuclear protons to hydrogen protons in the target (5.1 for aluminum). $F(\mathbf{p})$ is a probability distribution normalized so that the integral over all $\mathbf{p}$ equals unity. $A(\mathbf{p})$ is the acceptance normalized to the hydrogen acceptance. The final term is the ratio of the off-shell cross section to the hydrogen cross section at s_0 (the nominal c.m. energy squared for hydrogen). The second assumption prescribes a specific method for calculating the ratio of the off-shell cross section to the hydrogen cross section in Eq. (3). The assumption used is to calculate s with the struck-proton four-momentum determined with Eq. (2) and to use the free-pp-cross-section energy dependence to calculate the ratio in Eq. (3). To lowest order in p/m, s is a function of p_z only. The p_x and p_y dependence of Eq. (3) is very nearly that of the distribution $F(\mathbf{p})$. The p_z dependence reflects the extreme s dependence of the pp cross section. The number of elastic events within some range of p_z given by $p_a<p_z<p_b$ is $N(p_a,p_b)$ and is related to transparency T by the expression

$$\frac{N(p_a,p_b)}{N'_{\rm H}}=T\int_{p_a}^{p_b}dp_z\left[\int\int dp_x\,dp_y\,F(\mathbf{p})A(\mathbf{p})\frac{(d\sigma/dt)(s)}{(d\sigma/dt)(s_0)}\right]. \tag{4}$$

TABLE I. The elements in Eq. (4) tabulated for the aluminum data sets at three incident-beam momenta P_0 and for several bins in p_z ($p_a < p_z < p_b$). The number of hydrogen events detected (N_H) for the incident momenta 6, 10, and 12 GeV/c were 1701, 650, and 220, respectively. The effective beam momentum P_{eff} and transparency T have been calculated for each table entry. Systematic errors for T have not been included. P_0, p_a, p_b, and P_{eff} are given in units of GeV/c.

P_0	p_a	p_b	P_{eff}	$N(p_a,p_b)$	$\int_{p_a}^{p_b} dp_z[\ldots]$	T
6	−0.2	0.0	6.6	322	0.17	0.22 ± 0.04
6	0.0	0.1	5.7	721	0.31	0.25 ± 0.03
6	0.1	0.2	5.0	800	0.52	0.18 ± 0.03
6	0.2	0.3	4.4	400	0.29	0.15 ± 0.03
10	−0.2	0.0	11.0	158	0.22	0.25 ± 0.06
10	0.0	0.1	9.5	384	0.25	0.48 ± 0.05
10	0.1	0.2	8.4	481	0.45	0.32 ± 0.04
10	0.2	0.3	7.3	450	0.49	0.28 ± 0.06
12	−0.2	0.0	13.2	25	0.17	0.12 ± 0.04
12	0.0	0.1	11.4	65	0.29	0.20 ± 0.04
12	0.1	0.2	10.2	100	0.35	0.24 ± 0.08
12	0.2	0.3	8.8	140	0.26	0.46 ± 0.07

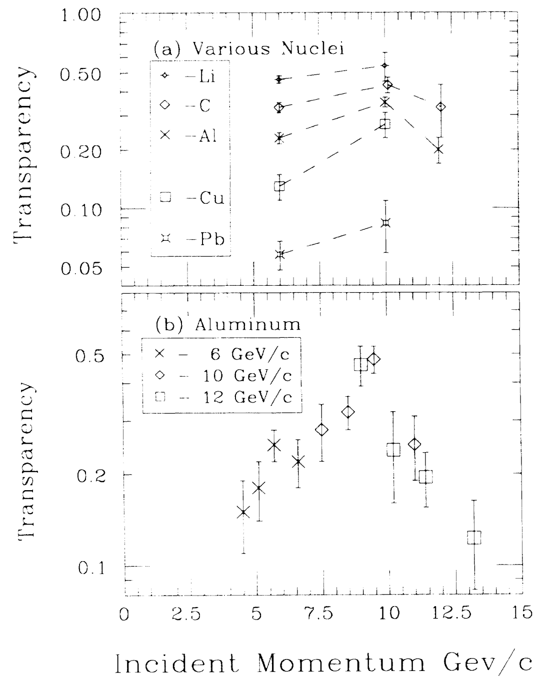

FIG. 2. (a) The transparency vs beam momentum for various nuclear targets selected for -0.2 GeV/$c < p_z < 0.1$ GeV/c. (b) The transparency data points from Table I plotted vs effective incident momentum.

The first step in extracting T is to measure the quasielastic signal for events within some range of p_z. This signal is extracted from background by the study of the dN/dp_y distribution for events with $|p_x| < 250$ MeV/c and p_z in the specified range. The details of extracting this signal from background are described elsewhere.[5] The important elements are that the signal is well above background and that the background shape is observed in the subset of data which register hits in the out-of-plane target counters. About half of the background events register double hits in these counters. That background data set, which would include such contamination as soft π^0 production, does not peak around $p_y = 0$. This suggests that such events will not contribute to the signal when background is subtracted.

As an input for this analysis the shape of the underlying nucleon momentum distribution $F(\mathbf{p})$ is required. As reported in Ref. 5, we have measured the projection of this distribution for each target material using these same data. In our evaluation of the integral in Eq. (4), the measured energy-dependent cross section has been used.[6] The acceptance $A(\mathbf{p})$ is determined and folded into the other functions in Eq. (4) with the use of a Monte Carlo program.

The procedure for determining T in Eq. (4) for the aluminum-target data is summarized in Table I. Aluminum data were collected at three different beam momenta P_0 as indicated in the first column. The number of quasielastic events measured in the p_z range $p_a < p_z < p_b$ is shown, as well as P_{eff}, the effective incident momentum corresponding to this p_z range. This result from the integration in Eq. (4) is shown along with the extracted transparency T. To lowest order in p/m_p, $P_{\text{eff}} = P_0[1 - (p_a + p_b)/2mp]$.

Such an analysis is used to extract the transparency for each of the various nuclei studied. For the data in Fig. 2(a) quasielastic signals were extracted in the p_z range -200 MeV/$c < p_z < 100$ MeV/c and plotted against beam momentum P_0. The aluminum transparency data of Fig. 2(b) are plotted against P_{eff} and are taken from Table I.

Errors in Fig. 2 and Table I represent the statistical errors associated with extraction of signals from background. The error bar on the 12-GeV/c carbon point has been increased to 20% to account for observed inconsistencies in extracting the carbon signal in CH_2.

Additional systematic uncertainties must be considered in the overall normalization of transparency and the normalization for a particular target. Theoretical uncertainty in calculating off-shell proton cross sections and uncertainties in the shape of $F(\mathbf{p})$, especially the very high momentum tails of the distribution, give rise to systematic normalization uncertainties. For illustration, if the assumption that m_p is the energy of the struck nucleon [see Eq. (2)] were incorrect by 20 MeV, that would introduce an error in the measured transparency of less than 5%. Neither of these effects generate large energy-dependent uncertainties for a given nuclear target. The target-dependent and target-independent systematic uncertainties in the normalization of the transparency are estimated to be 10% and 25%, respectively. We have not attempted to include theoretical uncertainty associated with the factorization assumption of Eq. (3) in our estimate of systematic errors.

The results, shown in Fig. 2, indicate that the transparency T is indeed energy dependent. The increase in transparency as the incident-beam energy is raised from 6 to 10 GeV/c is seen in all targets. The 12-GeV/c data (Al and C only) show a significant drop in T. The result reported here does not support a monotonic increase in transparency with energy in accordance with dimensional scaling and as predicted by perturbative QCD. However, we emphasize that a conventional Glauber absorption picture does not predict any energy dependence.

It has been noted that the dependence of T upon energy is inversely correlated both with the deviations of the elastic cross sections from the s^{-10} form and with the energy dependence of the spin observable A_{nn}.[7] Brodsky and de Teramond have discussed that relationship in terms of possible dibaryon resonances near the thresholds for strangeness and charm production.[8] This inverse correlation may also be a prediction of the chromo-Coulomb-phase model of Ralston and Pire.[9] The common element in both arguments is that the transparency may reflect the relative importance of hard perturbative versus soft nonperturbative contributions to the cross section.

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