Energy Dependence of Nuclear Transparency in C(p,2p) Scattering

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The transparency of carbon for $(p, 2p)$ quasielastic events was measured at beam momenta ranging from 5.9 to 14.5 GeV$/c$ at 90° c.m. The four-momentum transfer squared (Q^2) ranged from 4.7 to 12.7 (GeV$/c)^2$. We present the observed beam momentum dependence of the ratio of the carbon to hydrogen cross sections. We also apply a model for the nuclear momentum distribution of carbon to obtain the nuclear transparency. We find a sharp rise in transparency as the beam momentum is increased to 9 GeV$/c$ and a reduction to approximately the Glauber level at higher energies.

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This paper reports a new measurement of the transparency of the carbon nucleus in the C$(p, 2p)$ quasielastic scattering process near 90° pp center of mass (c.m.). These new data verify a surprising beam momentum dependence that was first observed most clearly with aluminum targets in 1988 [1]. While the original result was very provocative, that measurement involved momentum analysis of only one of the two final-state protons, raising some questions about the quality of event selection. We now report on a new measurement of carbon quasielastic scattering with the EVA detector [2] at the Brookhaven AGS. This cylindrically symmetric large-angle tracking spectrometer, with a 3-m-long superconducting solenoid magnet, provided symmetrical momentum and angle reconstruction of the two final-state protons. Initial results with this apparatus [3] emphasized the angular dependence of the transparency at the lower beam momenta of 5.9 and 7.5 GeV$/c$. We now present a newer measurement of the energy dependence of transparency for beam momenta ranging from 5.9 to 14.5 GeV$/c$.

Color transparency refers to a QCD phenomenon, predicted in 1982 by Brodsky [4] and Mueller [5], involving reduction of secondary absorption in proton-nucleus quasielastic scattering. These theorists deduced that when a proton traversing the nucleus experiences a hard collision, a special quantum state is selected. That special state involves the part of the proton wave function that is most "shock resistant" and that tends to survive the hard collision without breaking up or radiating a gluon. This state is also expected to have a reduced interaction with the spectators in the target nucleus. The state is predicted to involve a rare component of the proton wave function that is dominated by three valence quarks at small transverse spatial separation. The color transparency prediction is that the fraction of nuclear protons contributing to $(p, 2p)$ quasielastic scattering should increase from a level consistent with Glauber absorption [6,7] at low Q^2 to near unity at higher Q^2.

The fundamental subprocess in the quasielastic events is a pp interaction. The quasielastic events are characterized by a small missing energy (E_F) and momentum ($\vec{P}_F$), defined in terms of the initial- and final-state energies and momenta E_i and $\vec{P}_i$ ($i = 1, 2$ for beam and target protons and $i = 3, 4$ for final-state protons)

$$\begin{aligned} E_F &= E_3 + E_4 - E_1 - m_p\,, \\ \vec{P}_F &= \vec{P}_3 + \vec{P}_4 - \vec{P}_1, \qquad m_M^2 = E_F^2 - \vec{P}_F^2\,. \end{aligned} \tag{1}$$

In the spirit of the impulse approximation, we identify the missing momentum of Eq. (1) with the momentum of the nucleon in the nucleus while recognizing that in the transverse direction this relation is spoiled by elastic rescattering. Because the 90° c.m. pp cross section strongly depends on one longitudinal light-cone component of the missing momentum, we express the missing momentum in light-cone coordinates with the transformation $(E_F, P_{Fz}) \rightarrow (E_F + P_{Fz}, E_F - P_{Fz})$. The coordinate system takes $\hat{z}$ as the beam direction and $\hat{y}$ normal to the scattering plane. The four-dimensional volume element is

$$dE_F d^3\vec{P}_F \rightarrow d^2\vec{P}_{FT}\,\frac{d\alpha}{\alpha}\,d(m_M^2)\,, \tag{2}$$

where $\vec{P}_{FT}$ is the transverse part of the missing momentum vector. The ratio $\frac{\alpha}{A}$ is associated with the fraction of light-cone momentum carried by a single proton in a nucleus with A nucleons,

$$\alpha \equiv A \frac{(E_F - P_{Fz})}{M_A} \simeq 1 - \frac{P_{Fz}}{m_p}. \quad (3)$$

Elastic pp scattering occurs at a singular point ($m_M^2 = 0$, $P_{FT}^2 = 0$, $\alpha = 1$) in this four-dimensional phase space, while the quasielastic process produces a broader distribution about the same point. The kinematic cuts used to define event candidates are summarized as follows:

$$|P_{Fx}| < 0.5 \frac{GeV}{c}; \qquad |P_{Fy}| < 0.3 \frac{GeV}{c};$$
$$|1 - \alpha_0| < 0.05,$$
$$\alpha_0 \equiv 1 - \frac{(\sqrt{(E_1 + m_p)^2 - 4m_p^2})\cos(\frac{\theta_3+\theta_4}{2}) - P_1}{m_p}. \quad (4)$$

Taking into account the measurement resolution, our best determination of the light-cone momentum in the kinematic region of interest is obtained by measuring α_0 instead of α directly. The variable α_0 is an approximation to α that, for fixed beam energy, depends only on final-state lab polar angles θ_3 and θ_4. Simulations indicate that in the kinematic region of interest near $\alpha = 1$ and near 90° c.m., the difference between α_0 and α is less than 0.005. In the following analysis, the experimental error in the measurement of α using the α_0 variable is about 1.5%. This is the same set of cuts used in previously published analysis [3] where the emphasis was on the c.m. angle dependence of transparency. Here the transparency is analyzed at 5 beam momenta, 5.9, 8.0, 9.1, 11.6, and 14.4 GeV/c. The c.m. angular range is chosen to be similar at each beam momentum, extending from $\theta_{\rm low}$ to 90° where $\theta_{\rm low}$ is 86.2°, 87.0°, 86.8°, 85.8°, and 86.3° at each corresponding momentum.

The elastic or quasielastic event selection procedure involves first the application of the cuts of Eq. (4), associated with three of the four missing energy-momentum relations. In the previous 5.9 and 7.5 GeV/c analysis, the signal/background separation was extracted from the missing-energy distribution. A model for the background distribution, based on observed events with additional soft-track production in the detector provided guidance for the shape of the background distributions. The use of the missing-energy distribution for extraction of signal from background is less satisfactory for this analysis. The missing-energy resolution varies with beam momentum, degrading from about 300 MeV to 500–700 MeV as beam momentum increases. Furthermore, the phase-space available for inclusive-event production falls rapidly to zero as the missing energy approaches zero. Thus, most of the background is under the resolution-dependent tail of the quasielastic signal.

We now describe an improved analysis procedure where the background subtraction utilizes the variation in the density of measured events per unit four-dimensional missing-momentum space, a distribution which shows a sharp quasielastic peak at missing four-momentum of zero with a very smooth background. Noting that because we are cutting tightly only on α, we can observe the peaking signal over background in the remaining three dimensions of momentum space. From the form of the missing four-momentum differential element shown in Eq. (2), we note that for any selected region of α, the selected four-momentum volume is proportional to $\Delta P_{FT}^2 \times \Delta m_M^2$. In a 2D distribution of m_M^2 vs P_{FT}^2, each equal area corresponds to an equal volume of this momentum space. We introduce the variable $P^4 \equiv m_M^4 + P_{FT}^4$, the square of the radial distance from the origin in the $P_{FT}^2 \times m_M^2$ plane. Each equal interval in ΔP^4 also corresponds to an equal volume of missing four-momentum. The motivation for replacing the missing-energy distribution with the P^4 distribution for signal background extraction is the expectation that inclusive background may be a smoother and flatter distribution and the signal will be sharper.

In Fig. 1 we show the histogram of P^4 for the data sets taken at 5.9 and 11.6 GeV/c for both carbon and CH_2. These events were selected to have exactly two charged tracks and to pass the cuts described in Eq. (4). To verify that the background P^4 distribution is smooth near $P^4 = 0$, we also study a class of tagged inclusive events

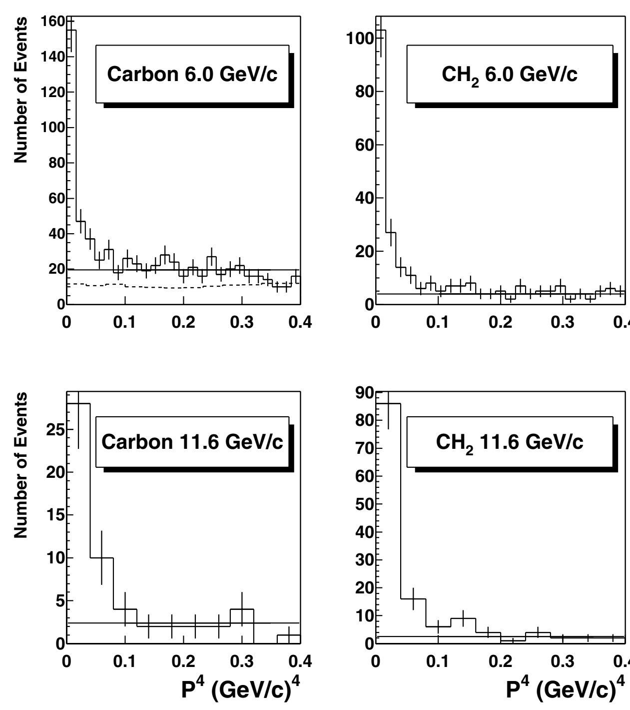

FIG. 1. The P^4 distributions of carbon and CH_2 events that satisfy the cuts defined by Eq. (4). Distributions at beam momenta of 5.9 and 11.6 GeV/c are shown. The solid line indicates the constant background level from fits to the off-peak region. In the upper-left frame, the dashed line indicates the distribution obtained when the data selection cuts are applied to the tagged background events discussed in the text.

that satisfy the same selection cuts but also produce soft charged tracks in the spectrometer inner chambers. The tagged inclusive distribution for 5.9 GeV$/c$ carbon data is plotted with a dashed line. For these tagged background events, the distribution in P^4 is constant to within about 10%. The number of such tagged background events observed at 11.6 GeV$/c$ is too small to analyze but the few events seen are again consistent with a flat distribution. The distribution of tagged background events represents our best determination of the distribution of the inclusive background under the quasielastic peak, for which no extra charged tracks are observed. We can conclude that this selection process, including the cuts of Eq. (4), does not induce an enhancement in the background near $P^4 = 0$.

For extraction of transparency, a constant background level is fit to the distribution in the region $0.15 < P^4 < 0.35$. The background under the peak in the $0 < P^4 < 0.1$ region ranges from 15% to 25% of the signal at different beam energies. We estimate the systematic error in the determination of background to be about 25% resulting in systematic errors in the extracted signals of about 5%. This compares favorably with the 1988 analysis where the background was typically greater than 100% of the signal. We also note that there is no systematic difference in the transparency obtained from this analysis of the P^4 distribution as compared to the analysis of the missing-energy distribution used in previous publications. However, the background for the missing-energy analysis is a larger fraction of the signal, and the background shape is poorly determined for data at higher beam momentum.

We define T_{CH} to be the experimentally observed ratio of the carbon event rate to the hydrogen event rate per target proton for events satisfying the specific set of kinematic cuts given in Eq. (4). The normalization of this ratio depends upon the cuts used and upon the nuclear momentum distribution. However, with the restriction to the region near $\alpha = 1$, the energy dependence of T_{CH} closely tracks the energy dependence of the actual transparency T. The wide range of accepted transverse momentum ensures that nonabsorptive secondary interactions are included in the event selection. We determine R_{C} and R_{CH_2}, the elastic or quasielastic event rates per beam proton and per carbon atom, for sets of data taken at each beam momentum on CH_2 and carbon targets. The experimental ratio, T_{CH}, is

$$T_{\mathrm{CH}} = \frac{1}{3}\,\frac{R_{\mathrm{C}}}{R_{\mathrm{CH}_2} - R_{\mathrm{C}}}\,. \qquad (5)$$

The values of T_{CH} which are plotted in Fig. 2 (top) show a significant beam momentum dependence.

To extract the transparency T, we will also introduce a relativistic nuclear momentum distribution function that specifies the differential probability density per unit four-momentum to observe a particular missing energy and momentum. Implicitly integrating over the missing mass $(m_M)^2$, we characterize the nuclear momentum distribution over light-cone fraction and

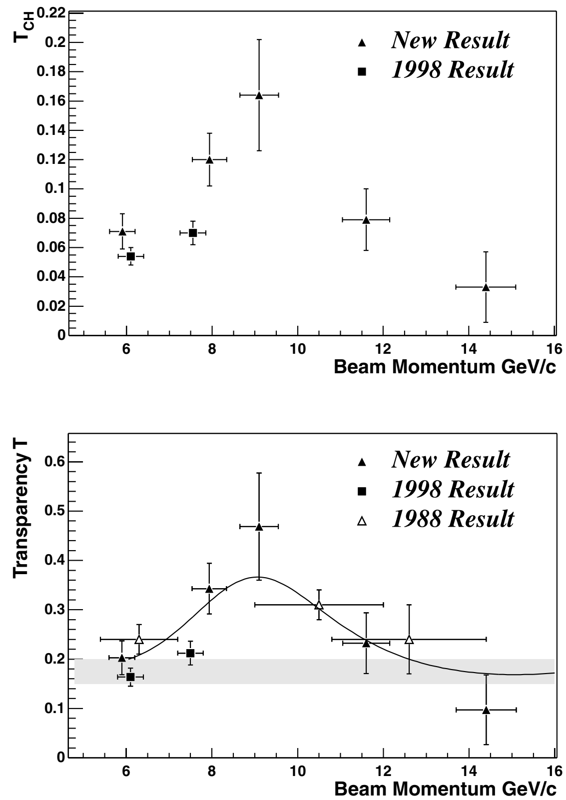

FIG. 2. Top: The transparency ratio T_{CH} as a function of the beam momentum for both the present result and two points from the 1998 publication [3]. Bottom: The transparency T versus beam momentum. The vertical errors shown here are all statistical errors, which dominate for these measurements. The horizontal errors reflect the α bin used. The shaded band represents the Glauber calculation for carbon [9]. The solid curve shows the shape R^{-1} as defined in the text. The 1998 data cover the c.m. angular region from 86°–90°. For the new data, a similar angular region is covered as is discussed in the text. The 1988 data cover 81°–90° c.m.

transverse momentum, $n(\alpha, \vec{P}_{FT})$. We also introduce the integral of this distribution function over the transverse coordinates:

$$N(\alpha) = \iint d\vec{P}_{FT}\, n(\alpha, \vec{P}_{FT})\,. \qquad (6)$$

The distribution functions $N(\alpha)$ can be estimated from nonrelativistic nuclear momentum distributions. We will refer to $n_C(P)$, a recent parametrization of a spherically symmetric carbon nuclear momentum distribution by Ciofi degli Atti *et al.* [8].

The nuclear transparency T measures the reduction in the quasielastic scattering cross section in comparison to the elastic cross section due to initial- and final-state interactions with the spectator nucleons. It can be defined in terms of the experimentally observed ratio T_{CH} through a convolution of the fundamental pp cross section with a nuclear distribution function $n(\alpha, \vec{P}_{FT})$ and the pp elastic cross section $\frac{d\sigma}{dt_{pp}}(s)$. In terms of s and s_0 defined below,

$$T_{\rm CH} = T \int d\alpha \int d^2\vec{P}_{FT}\, n(\alpha, \vec{P}_{FT})\, \frac{(\frac{d\sigma}{dt})_{pp}(s(\alpha))}{(\frac{d\sigma}{dt})_{pp}(s_0)}, \quad (7)$$

where the c.m. energy squared for elastic and quasielastic scattering is $s_0 = 2m_p E_1 + 2m_p^2$ and $s(\alpha) \simeq \alpha s_0$.

Because distributions in $\vec{P}_{FT}$ and α will be weighted by the pp cross section, the distribution is skewed toward small α. In the kinematic region of interest, the c.m. energy of the $pp \to pp$ subprocess will be nearly independent of $\vec{P}_{FT}$ but will depend critically upon α.

The energy dependence of $T_{\rm CH}$ [Fig. 2 (top)] and T [Fig. 2 (bottom)] are both presented here. We emphasize that the striking energy dependence of transparency is seen in the simple ratio of event rates without assumptions about the nuclear momentum distribution. Figure 2 (bottom) also shows the comparison to the carbon measurement that was reported in our 1988 paper. The 1988 data have been renormalized to use the nuclear momentum distributions of Ref. [8]. The comparison demonstrates the consistent pattern for a peaking of the transparency at beam momentum of 9 to 10 GeV$/c$, and a return to Glauber levels above 12 GeV$/c$. The Glauber prediction and uncertainty associated with it were calculated using published assumption [9] and is shown as a shaded band in Fig. 2 (bottom). The probability that our new result with carbon is consistent with the band of Glauber values is less than 0.3%, and compared to a best constant fit of 0.24 the probability is less than 0.8%.

Several modifications of the original prediction for energy dependence of color transparency have been discussed [7,10,11]. One model directly applicable to this measurement has been suggested by Ralston and Pire [12]. They noted that the short-distance contribution to the 90° (c.m.) cross section is predicted to have a s dependence of s^{-10}. Other softer contributions to the cross section result in deviations from scaling by as much as a factor of 2. They predict that the interference between these processes produces an oscillatory cross section and transparency. Parametrizing $R(s)$, the ratio of observed pp cross section to the s^{-10} scaling prediction, with their model, Ralston and Pire argue that the energy dependence of transparency should reflect the shape of $R^{-1}(s)$. We have included the curve $R^{-1}(s)$ as the solid line on Fig. 2 (bottom) with arbitrary normalization.

Another perspective on the s dependence was suggested by Brodsky and de Teramond [13]. They suggest that the energy dependent structure in $R(s)$, with excess cross section above 10 GeV$/c$ and the corresponding reduction in the transparency, could be related to a resonance or threshold for a new scale of physics. They point out that the open-charm threshold is in this region. A measurement of transparency with polarized beams and targets should distinguish between these models [14].

Nuclear transparency has been measured with electron beams at SLAC [15] at Q^2 up to 6.8 GeV^2 corresponding to about 8 GeV$/c$ of beam momentum in this $(p, 2p)$ measurement. No clear disagreement with the Glauber model was seen in $(e, e'p)$ measurement. It has been argued, however, that in this Q^2 region the apparent disagreement [7,16] can be explained within a unified model of the time evolution of the interacting proton state. The authors claim that for some choices of model parameters, higher Q^2 is required for observations with electrons.

In conclusion, we confirm the striking energy dependence observed in the 1988 measurement. We have extended the measurement of transparency to higher energy and have shown that the anomalous beam momentum dependence originally observed most clearly in aluminum is similar for carbon targets. While the peaking of transparency in the 8 to 9 GeV$/c$ region corresponds to about twice the Glauber levels, the return to Glauber in the 12 to 15 GeV$/c$ region is established.

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