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

A. Leksanov, J. Alster, G. Asryan, Y. Averichev, D. Barton, V. Baturin, N. Bukhtyayorova, A. Carroll, S. Heppelmann, T. Kawabata, Y. Maksidi, A. Malki, E. Minina, I. Navon, H. Nicholson, A. Ogawa, Yu. Panebratsev, E. Plasetzky, A. Schetkovsky, S. Shimanskiy, A. Tang, J.W. Watson, H. Yoshida, D. Zhalov

School of Physics and Astronomy, Suckler Faculty of Exact Sciences, Tel Aviv University, Ramat Aviv 69978, Israel, Yerevan Physics Institute, Yerevan 375036, Armenia, Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973, USA, Petersburg Nuclear Physics Institute, Gatchina, St. Petersburg 188350, Russia, Physics Department, Pennsylvania State University, University Park, PA 16801, USA, Department of Physics, Kyoto University, Sakyoku, Kyoto, 606-8502, Japan, Department of Physics, Mount Holyoke College, South Hadley, MA 01075, USA, J.I.N.R., Dubna, Moscow 141980, Russia, Department of Physics, Kent State University, Kent, OH 44242, USA
(November 7, 2018)

The transparency of carbon for (p,2p) quasi-elastic 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.

24.85.+p,25.40.-h,24.10.-i

This paper reports a new measurement of the transparency of the carbon nucleus in the C(p,2p) quasi-elastic 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 quasi-elastic scattering with the EVA detector [2] at the Brookhaven AGS. This cylindrically-symmetric large-angle tracking spectrometer, with a 3 m long super-conducting 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 quasi-elastic 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 characterized by a small missing energy (Q^2) and a reduced four-momentum transfer squared (Q^2). The color transparency prediction is that the fraction of nuclear protons contributing to (p,2p) quasi-elastic scattering should increase from a level consistent with Glauber absorption at low Q^2 to near unity at higher Q^2.

The fundamental sub-process in the quasi-elastic events is a pp interaction. The quasi-elastic events are characterized by a small missing energy (E_F) and momentum (P_F), defined in terms of the initial and final-state energies and momenta E_i and P_i (i=1,2 for beam and target protons and i=3,4 for final-state protons)

\[ E_F = E_i + E_d - E_1 - m_p \]
\[ P_F = P_i + P_d - P_1, \quad m_M^2 = E_F^2 - P_F^2. \]

In the spirit of the impulse approximation, we identify the missing momentum of Equation (1) with the momentum of the nucleon in the nucleus while recognizing that in the transverse direction this relation is spoiled by elastic re-scattering. 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

\[ dE_F \, d^3P_F \rightarrow d^2P_{FT} \frac{da}{\alpha} d(m_M^2) \]

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

\[ \alpha = A \frac{(E_F - P_{Fz})}{M_A} \simeq 1 - \frac{P_{Fz}}{m_p} \]

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 quasi-elastic process produces a broader distribution about the same point. The kinematic cuts used to define event candidates are summarized as follows:

\begin{equation}
|P_{F_T}| < 0.5 \text{GeV/c}; |P_{F_T}| < 0.3 \text{GeV/c}; |1 - \alpha_0| < 0.05 \tag{4}
\end{equation}

\begin{equation}
\alpha_0 \equiv 1 - \frac{\left( \sqrt{(E_1 + m_p)^2 - 4m_p^2} \cos \left( \frac{\theta_1 + \theta_2}{2} \right) - P_1 \right)}{m_p}.
\end{equation}

Taking into account the measurement resolution, our best determination of the light-cone momentum in the kinematic region of interest is obtained by measuring \(\alpha_0\) instead of \(\alpha\) directly. The variable \(\alpha_0\) is an approximation to \(\alpha\) that, for fixed beam energy, depends only on final-state lab polar angles \(\theta_1\) and \(\theta_2\). Simulations indicate that in the kinematic region of interest near \(\alpha = 1\) and near 90° c.m., the difference between \(\alpha_0\) and \(\alpha\) is less than 0.005. In the following analysis, the experimental error in the measurement of \(\alpha\) using the \(\alpha_0\) variable is about 1.5%. This is the same set of cuts used in previously published analysis 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, 14.4) GeV/c, and the c.m. angular range for each beam momentum is from \(\theta_{low}\) to 90° where \(\theta_{low}\) is (86.2°, 87.0°, 86.8°, 85.8°, 86.3°) at each corresponding momentum.

The elastic or quasi-elastic 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 was 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-dependant tail of the quasi-elastic 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 quasi-elastic peak at missing momentum of zero with a very smooth background. Noting that because we are cutting tightly only on \(\alpha\), 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. 4, we note that for any selected region of \(\alpha\), the selected four-momentum volume is proportional to \(\Delta P_{F_T}^2 \times \Delta m_3^2\). In a 2D distribution of \(m_3^2\) vs \(P_{F_T}^2\), each equal area corresponds to an equal volume of this momentum space. We introduce the variable \(P^4 \equiv m_3^2 + P_{F_T}^2\), the square of the radial distance from the origin in the \(P_{F_T}^2 \times m_3^2\) plane. Each equal interval in \(\Delta P^4\) 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 Figure 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 CH2. 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 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 quasi-elastic 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 < \(P^4\) < .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 the 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 insures that non-absorptive secondary interactions are included in the event selection. We determine $R_C$ and $R_{CH_2}$, the elastic or quasi-elastic 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

$$T_{CH} = \frac{1}{3} \frac{R_C}{R_{CH_2} - R_C}. \quad (5)$$

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

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

The distribution functions $N(\alpha)$ can be estimated from non-relativistic nuclear momentum distributions. We will refer to $n_C(P)$, a recent parameterization of a spherically-symmetric carbon nuclear momentum distribution by Ciofi degli Atti et al. [9].

The nuclear transparency $T$ measures the reduction in the quasi-elastic 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 $\frac{d^2\sigma}{dt pp}(s)$. In terms of $s$ and $s_0$ defined below,

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

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

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

The energy dependence of $T_{CH}$ (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. Fig. 2(bottom) also shows the comparison to the carbon measurement that was reported in our 1988 paper. The 1988 data have been re-normalized to use the nuclear momentum distributions of Ref. [9]. 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 at 12 GeV/c and above. The Glauber prediction and uncertainty associated with it, as calculated [9], 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%.
transparency. Parameterizing \( R(s) \), 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. 3(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].

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.

This research was supported by the U.S. - Israel Binational Science Foundation, the Israel Science Foundation founded by the Israel Academy of Sciences and Humanities, NSF grants PHY-9804015, PHY-0072240 and the U.S. Department of Energy grant DEFG0290ER40553.

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. In has been argued, however, that in this \( Q^2 \) region the apparent disagreement [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.

![Graph](image)

**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 \( \alpha \) 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\(^{\circ} \) – 90\(^{\circ} \). For the new data, a similar angular region is covered as is discussed in the text. The 1988 data cover 81\(^{\circ} \) – 90\(^{\circ} \) c. m.

[1] A. S. Carroll et al., Phys. Rev. Lett. 61, 1698 (1988).
[2] J. Wu, E. D. Minor, J. E. Passaneau, S. F. Heppelmann, C. Ng, G. Bunce and I. Mardor, Nucl. Instrum. Meth. A 349, 183 (1994).
[3] I. Mardor et al., Phys. Rev. Lett. 81, 5085 (1998).
[4] S. J. Brodsky, Proceedings of the XIII International Symposium on Multi-particle Dynamics-1982, ed. W. Kittel, W. Metzger and A. Stergiou, World Scientific, Singapore (1983), p. 963.
[5] A. Mueller, Proceedings of the XVII Rencontre de Moriond, ed. J. Tran Thanh Van, Editions Frontieres, Gif-sur-Yvette, France (1992), p. 13.
[6] R. L. Glauber, Lectures in Theoretical Physics, ed. W. E. Britin et al., Interscience, New York (1959).
[7] L. L. Frankfurt, M. I. Strikman and M. B. Zhalov, Phys. Rev. C 50, 2189 (1994).
[8] C. Cioci degli Atti and S. Trimula, Phys. Rev. C 53, 1689 (1996).
[9] L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. B 503, 73 (2001).
[10] B. Z. Kopeliovich and B. K. Jennings, Phys. Rev. Lett. 70, 3384 (1993).
[11] G. A. Miller and B. K. Jennings, Phys. Rev. D 44, 692 (1991).
[12] J. P. Ralston and B. Pire, Phys. Rev. Lett. 61, 1823 (1988).
[13] S. J. Brodsky and G. F. de Teramond, Phys. Rev. Lett. 60, 1924 (1988).
[14] E. A. Crosbie et al., Phys. Rev. D 23, 600 (1981).
[15] T. G. O’Neill et al., Phys. Lett. B351, 87 (1995).
[16] L. L. Frankfurt, G. A. Miller and M. Strikman, Ann. Rev. Nucl. Part. Sci. 44, 501 (1994).