**The Search for Color Tranparency**

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The concept of Color Transparency (CT) was introduced two decades ago by Mueller and Brodsky [1], and since has stimulated great experimental and theoretical interest. CT is an effect of QCD, related to the presence of non-abelian color degrees of freedom underlying strongly interacting matter. CT has its most unique manifestation in A(p,2p) or A(e,e′p) experiments at high energies. The basic idea is that, under the right conditions, three quarks, each of which would normally interact very strongly with nuclear matter, could form an object that passes undisturbed through the nuclear medium. A similar phenomenon occurs in QED, where an $e^+e^-$ pair of small size has a small cross section determined by its electric dipole moment [2]. In QCD, a $q\bar{q}$ or $qqq$ system can act as an analogous small color dipole moment.

CT was first discussed in the context of perturbative QCD. Later work [3] indicates that this phenomenon also occurs in a wide variety of model calculations with non-perturbative reaction mechanisms. In general, the existence of CT requires that high momentum transfer scattering takes place via selection of amplitudes in the initial and final state hadrons characterized by a small transverse size. Secondly, this small object should be 'color neutral' outside of this small radius in order not to radiate gluons. Finally, this compact size must be maintained for some distance in traversing the nuclear medium. Unambiguous observation of CT would provide a new means to study the strong interaction in nuclei.

Several measurements of the transparency of the nuclear medium to high energy protons in quasielastic A(p,2p) and A(e,e′p) reactions have been carried out over the last decade. The nuclear transparency measured in A(p,2p) at Brookhaven [4] has shown a rise consistent with CT for $Q^2 \simeq 3$ - 8 $(GeV/c)^2$, but decreases at higher momentum transfer. A more recent experiment [5], completely reconstructing the final-state of the A(p,2p) reaction, confirms the validity of the earlier Brookhaven experiment. The A(e,e′p) measurements at SLAC [6, 7] and at JLab [8, 9] yielded distributions in missing energy and momentum completely consistent with conventional nuclear physics predictions. The extracted transparencies exclude sizable CT effects up to $Q^2 = 8.1$ $(GeV/c)^2$, in contrast to the A(p,2p) results [4]. The measurements rule out several models predicting an early, rapid, onset of CT, but can not exclude models predicting a slow onset of CT.

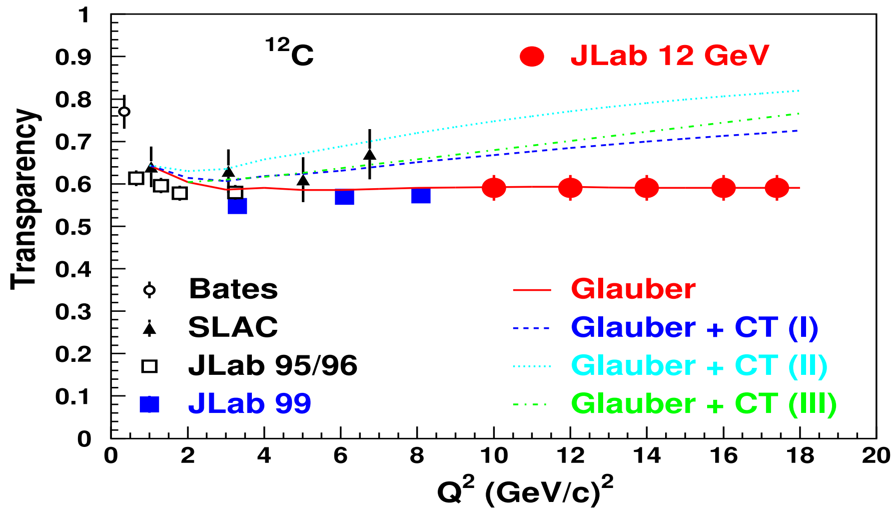


Figure 1: The $Q^2$ dependence of the nuclear transparency. The data are from Refs. [10, 7, 8, 9]. A beam time of about one week is assumed, using the HMS-SHMS magnetic spectrometer combination.

The 12 GeV upgrade at JLab will improve this situation by pushing the measurements to higher values of $Q^2$ where the CT predictions diverge appreciably from the predictions of conventional calculations. The Brookhaven data seem to establish, for nucleon momenta $\geq$ 7 GeV/c, a definite increase in nuclear transparency. Thus, A(e,e$'$p) measurements at $Q^2 > 12$ (GeV/c)$^2$, corresponding to comparable momenta of the ejected nucleon, would unambiguously answer the question whether one has entered the CT region. This would require the highest-momentum spectrometer avaliable, the SHMS. Figure 1 displays both the present status and expected effects of CT in the measurement of nuclear transparency in A(e,e$'$p) experiments, feasible with 11 GeV beams from an upgraded CEBAF.

Alternatively, one can attempt to observe the disappearance of recoil proton events with momenta > 300 MeV/c. As a large fraction of the cross section yield in A(e,e$'$p) in this region originates from recoil protons with lower momenta rescattering, this yield should substantially decrease with the onset of CT, and give a measurable effect at lower $Q^2$ than in the example

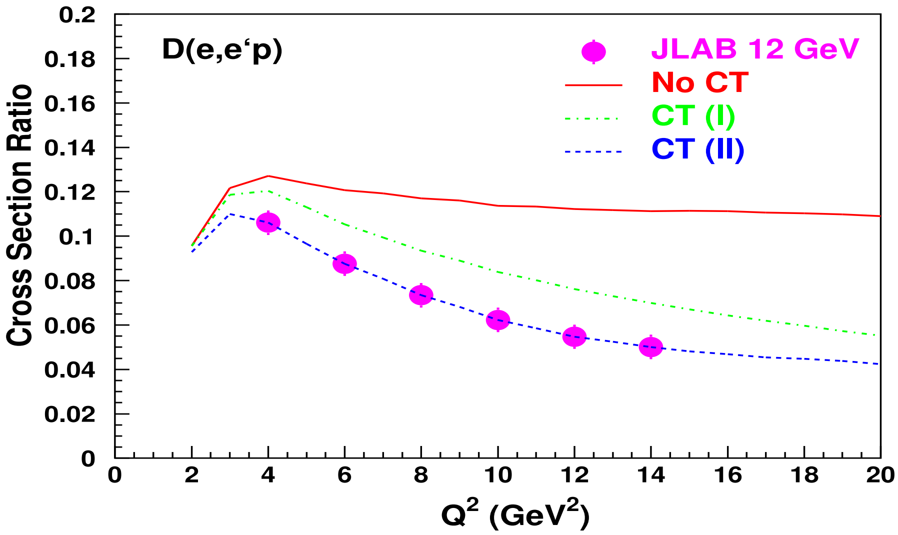


Figure 2: The $Q^2$-dependence of the yield ratio at recoil proton momenta of 400 and 200 MeV/c, respectively, for the D(e,e′p) reaction. A beam time of about one month is assumed.

above. An important advantage of this method is that the effect can be studied using the lightest nuclei (D, $^3$He, $^4$He) for which wave functions are far better known. The suggested experiment would measure the ratio of yields at recoil proton momenta of 400 and 200 MeV/c, respectively. Figure 2 demonstrates the feasibility of such an experiment, again utilizing the SHMS spectrometer to detect the highest nucleon momenta.

Intuitively, one expects an earlier onset of CT for meson production than for hard proton scattering, as it is much more probable to produce a small transverse size in a $q\bar{q}$ system than in a three quark system.

Studies of both the $Q^2$ dependence for a given nucleus and the A-dependence at fixed $Q^2$ will complement each other to provide an unambiguous verification of the onset of CT. Many experiments at $Q^2 \sim$ few (GeV/c)$^2$ have shown indications that CT may be already present [11, 12]. A recent di-jet experiment [13] has reported full CT effects at $Q^2 \simeq 10$ (GeV/c)$^2$. However, in all of these cases the interpretation of the CT signal is rather model dependent.

Not observing the CT phenomenon casts doubt on the strict applicability

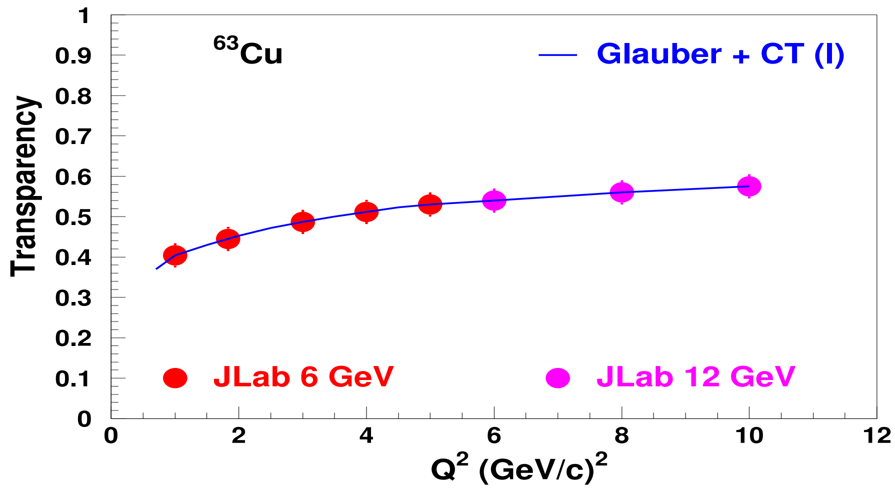


Figure 3: The $Q^2$-dependence of the pion transparency as measured in the exclusive Cu(e,e$'\pi$) reaction. A beam time of about one week is assumed. Note that without the constraint $t \leq 0.5$ GeV/c one can reach $Q^2 = 14$ (GeV/c)$^2$, with similar statistics, assuming a beam time of about one month.

of the QCD factorization theorems recently derived for various deep inelastic exclusive processes. Such factorization theorems are intrinsically related to the access to Generalized Parton Distributions, that in principle allow for a determination of the complete nucleon wave functions. CT is a necessary, but not sufficient, indication of the applicability of the QCD factorization theorems.

Other than the A(e,e$'$p)A-1 reaction the exclusive A(e,e$'\pi$) reaction is the next least model-dependent measurement available to extract an unambiguous signal of CT. For the region of $Q^2 \leq 5$ (GeV/c)$^2$ measurable 40% effects have been predicted. With the HMS-SHMS magnetic spectrometer combination one can measure the pion transparency up to $Q^2 = 10$ (GeV/c)$^2$ at low Mandelstam $t$ ($< 0.5$ GeV/c), or up to $Q^2 = 14$ (GeV/c)$^2$ without this constraint. This is well into the region where the QCD factorization theorems might be applicable. An example of such a measurement is given in figure 3.

# Bibliography

[1] A.H.Mueller, in Proceedings of the Seventeenth Recontre de Moriond Conference on Elementary Particle Physics, Les Arcs, France, 1982, edited by J. Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France,1982); S.J.Brodsky, in Proceedings of the Thirteenth International Symposium on Multiparticle Dynamics, Volendam, The Netherlands, 1982, edited by W. Kittel et al. (World Scientific, Singapore, 1983).

[2] D. Perkins, Phil. Mag. **46**, 1146 (1955).

[3] L.L. Frankfurt, G.A. Miller, and M.I. Strikman, Comments Nucl. Part. Phys. **21**, 1 (1992).

[4] A.S. Carroll *et al.*, Phys. Rev. Lett. **61**, 1698 (1988).

[5] Y. Mardor *et al.*, Phys. Rev. Lett. **81**, 5085 (1998); A. Leksanov *et al.*, Phys. Rev. Lett. **87**, 212301 (2001).

[6] N.C.R. Makins *et al.*, Phys. Rev. Lett. **72**, 1986 (1994).

[7] T.G. O'Neill *et al.*, Phys. Lett. **351**, 87 (1995).

[8] D. Abbott *et al.*, Phys. Rev. Lett. **80**, 5072 (1998).

[9] K. Garrow *et al.*, Submittefd to Phys. Rev. C (2002).

[10] G. Garino *et al.*, Phys. Rev. C **45**, 780 (1992).

[11] M.R. Adams *et al.*, Phys. Rev. Lett. **74**, 1525 (1995).

[12] M. Arneodo *et al.*, Nucl. Phys. **B429**, 503 (1994).

[13] E.M. Aitala *et al.*, Phys. Rev. Lett. **86**, 4773 (2001).