Color Transparency - Color Coherent Effects in Nuclear Physics

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Abstract. Efforts to observe color transparency in $(e,e'p)$, $(p,pp)$ and coherent diffractive $\pi \rightarrow$ two jets reactions are reviewed.

INTRODUCTION

Color transparency is the vanishing of initial and final state interactions, predicted by QCD to occur in high momentum transfer quasielastic nuclear reactions. The nuclear processes $(e,e'p)$ and $(p,pp)$ are examples. The experiments need to be done with good enough resolution so that the basic high momentum transfer reaction (electron-proton or proton-proton) is elastic. The energy transfer to the recoiling nucleus must also be small. If this is the case, the quark-gluon calculation of the process is coherent: one computes the scattering amplitude by adding all of the terms that lead to the same final state. The cross section is the absolute square of that amplitude. Thus color transparency effects are also color coherent effects.

Color transparency occurs [1,2] under the following three conditions:

• To obtain an appreciable amplitude for a high momentum transfer reaction on a nucleon leading to a nucleon, the colored constituents must be close together. Small objects, or point-like-configurations PLCs are produced in high momentum transfer exclusive processes.

• If the quark-gluon constituents of a color singlet object are close together, their color electric dipole moment is small and the soft interactions with the medium are suppressed.

• If the small color singlet can remain small as it moves through the nucleus, it can escape without further interaction.

Understanding each of the above points represents a serious research process; see the review [3]. I make only brief remarks about each item here.
Verifying or disproving the existence of point-like-configurations is the goal of color transparency studies. Originally, studies of perturbative QCD calculations of hadronic elastic form factors showed that the dominant contributions came from configurations which consisted of the fewest possible quarks (and no gluons) each at the same impact parameter. These calculations have been challenged. Frankfurt, Miller and Strikman \cite{4} studied the existence of point-like-configurations within the framework of a wide variety of non-perturbative models. The most realistic models, those which feature correlations between quarks, do admit the existence of a point-like-configuration. But the existence or non-existence of point-like-configurations cannot be decided by theory- experiments are needed.

That point-like-configurations have small forward scattering amplitudes is the least controversial of the three key points. Such an effect occurs in theories such as QED and QCD for which there is a concept of neutrality. The significant experimental evidence for reduced interactions comes from the existence of scaling in low-x deep inelastic scattering, hadron-proton total cross sections (see the review \cite{3}) and in diffractive production of $\rho$ mesons \cite{5}.

The point-like-configuration is not a physical state; it is therefore a wave packet which undergoes time evolution. The point-like-configuration initially has no size, so any evolution necessarily causes expansion. If the point-like-configuration expands while it is in the nucleus, it undergoes typical baryonic interactions and color transparency does not occur even if the point-like-configuration is made. One can estimate \cite{3} the laboratory expansion time in terms of a product of a rest frame expansion time of order 1 fm and a time dilation factor which is expected to be only about 2 for the (e,e’p) experiments done at SLAC and planned at TJNAF and is about 5 or 6 for the (p,pp) experiments at BNL. Expansion effects must therefore be included to interpret these experiments.

**CURRENT (E,E’P) AND (P,PP) DATA**

Color transparency (CT) and color coherent effects have been recently under intense experimental and theoretical investigation. The (p,pp) experiment of Carroll et al. \cite{6} found evidence for color transparency, see Fig. 2 of Ref. \cite{7} while the NE18 (e,e’p) experiment \cite{8} did not. The key feature in the (p,pp) data is the magnitude of the cross section, which is too large to be explained by standard treatments for final state interactions. This experiment was done for $p_L = 6, 10, \text{and } 12 \text{ GeV}/c$, at scattering angles such that $Q^2 = 4.8, 8.6 \text{ and } 10.4 \text{ GeV}^2/c^2$. The expansion times are roughly 3.4, 5.7 and 6.8 fm. No such enhancement was found in the electron scattering data for $Q^2 = 1, 3, 5, \text{and } 7 \text{ GeV}^2/c^2$. These $Q^2$ are reasonably large, but the outgoing proton momenta are 1.1, 2.3, 3.5 and 4.6 GeV/c, so the expansion times take on the small values of about 0.65, 1.3 2.0 and 2.6 fm.

The $Q^2$ of the NE18 experiment seem to be large enough to form a small color singlet object, but the expansion times are small. Thus this failure to observe significant color transparency effects is caused by the rapid expansion of the point
like configuration to nearly normal size (and nearly normal absorption) at the relatively low momenta of the ejected protons \[9\], \[10\]. In particular, models of color transparency which reproduce the (p,2p) data and include expansion effects predict small CT effects for the NE18 kinematics, consistent with their findings, see the discussion and Fig. 11 of Ref. \[3\].

If this interpretation is correct, extending the electron scattering experiments to a \(Q^2 \approx 10 \text{ GeV}^2/c^2\) such that the outgoing proton momentum is about 6 GeV/c should allow the observation of enhanced cross sections.

EVA

The current (p,pp) experiment running at BNL has a new detector EVA \[11\] which should allow much improved measurements. DR. S. Durant, explains in this session how this detector works and presents new preliminary data for \(p_L=6\) and 7.5 GeV/c, taken for quasielastic kinematics such that the initial bound proton is at rest (\(\alpha = 1\)). They find that the ratio of the measured to Born approximation cross sections \(d\sigma/d\sigma_B\) (which is unity if color transparency is fully manifest) rises by about 30% between those two incident momenta.

I ran our \[7\] program for this situation (before the meeting) and the results are displayed in Fig. 1. The effects of color transparency lead to an enhancement over the usual treatment of initial and final state interactions (labelled initial, final state interactions). The (p,pp) reaction is more complicated than the (e,e'p) reaction because the PLC involves all six quarks at the same point. One expects other configurations to contribute. The simplest way to account for such is to assume that the PLC is complemented by another configuration of average size, which we call the blob-like configuration. Two models of such configurations are in the literature \[12,13\]. Here we use the version of Ref. \[13\]. In our treatment such effects are not extremely important \[7\] for the kinematics of the earlier experiment \[7\], but seem to stand out at \(\alpha = 1\). Including them leads to a more rapid rise with \(p_L\) as indicated by the preliminary data. Future data taken at higher energies will be very interesting.

VICTORY OVER THE EXPANSION ENEMY?

The practical problem in looking for color transparency effects in experiments at \(Q^2\) from about one to a few GeV\(^2\) is that the assumed PLC expands rapidly while propagating through the nucleus. To observe color transparency at intermediate values of \(Q^2\) it is necessary to suppress the effects of wavepacket expansion. The propagation distances are small for the the lightest nuclear targets, but then, the transparency is close to unity and the effects of CT in \((e,e'p)\) reactions tend to be small. However, if one studies a process where the produced system can only be produced by an interaction in the final state, the color coherent effects would be manifest as a decrease of the probability for final-state interactions with increasing
FIGURE 1. Color transparency at quasielastic kinematics
$Q^2$. Thus, the measured cross section would be compared with a vanishing quantity, the relevant ratio of cross sections would vary between unity and infinity and, a big signal could be possible. The first calculations [14] showed that substantial CT effects are observable in the $(e,e'p)$ reactions on $^{4}$He targets. Later calculations [15] showed that substantial effects of color transparency are possible to observe using the deuteron as a target in the process $e\, d \to e'\,pn$. Such experiments are planned to run at the Jefferson Lab [16].

Another idea involves pionic degrees of freedom. For some reactions involving nucleons, the initial and final state interactions are expected to be dominated by exchanges of pions. These interactions are also hindered in high momentum transfer nuclear quasielastic reactions because the probability for a PLC to emit a quark-anti-quark pair is suppressed by color neutrality. The vanishing of pion exchange interactions has been called [4] “chiral transparency”.

One example is the quasielastic production of the $\Delta^{++}$ in electron scattering - the $(e,e'\,\Delta^{++})$ reaction. The initial singly charged object is knocked out of the nucleus by the virtual photon and converts to a $\Delta^{++}$ by emitting or absorbing a charged pion. But pionic coupling to small-sized systems is suppressed, so this cross section for quasielastic production of $\Delta^{++}$’s should fall faster with increasing $Q^2$ than the predictions of conventional theories. The first calculations [17] indicate that large effects are possible.

**COHERENT NUCLEAR DIFFRACTION OF HIGH ENERGY PIIONS INTO TWO JETS**

Consider a coherent nuclear process in which a high-energy pion undergoes diffractive dissociation into a $q\bar{q}$ pair of high relative transverse momentum $\vec{k}_\perp$ but the nucleus remains intact. This is a very simple way to select a PLC in a hadronic projectile [18].

If the final $q\bar{q}$ pair carries of all of pion’s energy, only the $q\bar{q}$ component of the light-cone wave function is needed for calculations. In this case, only the small sized pionic configurations pass through the nucleus without absorption. Observing high $k_\perp$ jets insures that only small $q\bar{q}$ separations are involved [18]. The jets we consider involve high (greater than about 1 GeV/c) but not very high values of $k_\perp$ less than about 3 or which is a huge enhancement factor for heavy nuclei. 5 GeV/c (for currently accessible energies).

The small sizes and the large beam momentum greatly simplify any computations of the matrix elements. The large beam momentum insures that the momentum transfer to the high momentum $q\bar{q}$ system is transverse, so the $q\bar{q}$-nucleon interaction is essentially independent of the longitudinal momentum of $q\bar{q}$ pair. Furthermore, the effects of expansion should be negligible.

The dominance of configurations of small size is a key feature of PQCD predictions for coherent diffraction of pions into two jets. Thus, even in a nuclear target, color screening implies that the coherent $q\bar{q}$ system can only weakly interact. In
leading-logarithmic approximation and in the light-cone gauge only two gluons connect the pion - two jet system with the nucleus. Thus the hadronic system propagating through the nucleus suffers no initial-state or final-state absorption, and the nuclear dependence of the $\pi + A \rightarrow 2 \text{jets} + A$ forward amplitude will be approximately additive in the nucleon number $A$, so the cross section would be proportional to $A^2$, a huge enhancement for heavy nuclei. The Fermilab experiment E791 [19], using a 500 GeV pion beam, will measure an integral over $t$ so that the expected $A$ dependence is $A^{4/3}$. Preliminary indications [19] are that this coherent process could be measurable.

Although the vector meson (two jets) suffers no final state interactions, the forward amplitude is not strictly additive in nuclear number since the gluon distribution itself is shadowed. This effect must be taken into account at very high energies; see the discussion in [3].

**QUANTUM INVISIBILITY**

This manuscript summarizes some of the methods that researchers are using to observe color transparency or color coherent effects. A clear and convincing signal of color transparency would represent the discovery of a new physical phenomenon. Initial and final state interactions are the bane of a nuclear physicist’s everyday existence- their disappearance would be a surprise indeed.

Initial and final state interactions, which usually cause the nucleus to act similarly to a black disk, can be said to cast a shadow behind the nucleus. Only visible objects can cast a shadow, so that color transparency is a quantum invisibility.

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