COLOR TRANSPARENCY EFFECTS IN QUASI-ELASTIC NUCLEAR REACTIONS

GERALD A. MILLER
Physics Department FM-15, University of Washington
Seattle, Washington 98195, USA

ABSTRACT

Previous work on color transparency is reviewed briefly with an emphasis on aspects related to an upgrade of CEBAF.

1. Introduction

My CEBAF talk occurred shortly after submitting a lengthy review on color transparency and the related issues of color fluctuations. Thus the reader is directed to that review for the details. Here I shall be concerned with presenting a brief outline and making a few summary points. The review contains many references, so the reference list here is short.

Usually initial and final state interactions cause absorptive effects which reduce the cross sections. If color transparency CT occurs, such interactions are suppressed at high enough $Q^2$. I discuss some well-known examples of possible reactions: $(e,e'p)$, $(p,pp)$, $(e,e'pp)$ and $(e,e'\Delta^{++})$. The experimental resolution must be good enough to insure that no extra pions are produced and the energy transfer to the recoil nuclear system is small ($\leq 70 - 100$ MeV). This requirement, stringent at high energies, has hindered progress in this field. New measurements at CEBAF and its higher energy version would be of high interest.

CT requires the production of a point-like configuration PLC in two-body reactions. Such PLC do not interact with the residual nucleus. However, even if a PLC is formed, it will expand as it moves through the nucleus. One can express expansion effects in both quark and hadronic bases. Such effects must be included in any realistic estimate of color transparency effects.

The CT idea is based on: small short-lived color singlet objects are produced in elastic hadronic reactions at high momentum transfer $Q^2$ (Sect. 2). Such objects have small interactions with nucleons. The small system is not an eigenstate so, unless its energy is very high, it expands and interacts as it moves through the nucleus, Sect. 3. In addition, careful calculations including various effects present in ordinary nuclear reactions are necessary, Sect. 4. A summary of the implications of color transparency for the proposal of extending CEBAF to higher energies is given in Sect. 5.

2. Is a small system made?

Perhaps the most interesting question is whether or not a small system is made in a high $Q^2$ hadronic exclusive process. The present postulate is that at high $Q^2$,
the matrix elements are dominated by components or configurations that behave as of smaller than average size. Such small-sized configurations or wave packets have been termed point-like configurations PLC.

If one considers asymptotically large values of $Q^2$, perturbative QCD holds and PLC are produced. Eloquent criticisms of early pQCD calculations were put forward by Radyushkin and Isgur and Lewellyn Smith.

But the pQCD arguments and the criticisms thereof were not complete because one must investigate the possible role of low momentum (soft) long wavelength gluons that are radiated as the colored quarks are accelerated. The effects of such radiation can be included via a form factor similar to that introduced by Sudakov, which decreases the probability for elastic scattering of a free fermion. However, for a color singlet system, the gluon radiation contributions cancel if the quarks and gluons making up the system are closely separated. Then significant contributions to the elastic form factor occur mainly for configurations of small size. The so-called Sudakov effects were known early on but numerical evaluations did not occur until recently with the work of Botts, Li and Sterman and now others.

So far we have discussed pQCD calculations. But if one is interested in seeing how color transparency effects grow as $Q^2$ is increased from low values it is necessary to see if non-perturbative calculations also admit a PLC. Several different models have been examined using a new numerical criterion. The result is that the form factor is dominated by PLC within many non-perturbative models. Furthermore, these effects set in at relatively low values of $Q^2$.

3. Time development

Suppose a PLC is produced in the interior of the nucleus. Any non-eigenstate undergoes time development. Here expansion occurs because the starting system is defined to be small. This expansion has been found to be a vital effect for intermediate energies, $P_{lab}$ less than about 20 GeV/c.

We are concerned here with time development in nuclear quasielastic reactions. Consider the (e,e’p) reaction. The virtual photon is absorbed by a proton creating a high momentum object which is ejected from the nucleus. The old fashioned approach is to treat the ejectile as proton. Then the final state interactions are governed by the optical potential $U_{opt}$. If the proton wave function is computed from $U_{opt}$, the proton wave is said to be distorted (from the plane wave approximation). The use of such a wave function in computing cross sections is called the distorted wave impulse approximation DWIA, where the “impulse” refers to the use of the free nucleon-nucleon cross section.

But if the ejected object is a PLC, using $U_{opt}$ is not appropriate. On the other hand, the ejectile expands as it moves through the nucleus, so that one can not simply neglect the soft final state interactions. The need to include this expansion was recognized by Farrar et al. who argued that the square of the transverse size (and therefore the forward scattering amplitude) is roughly proportional to the distance
travelled $Z$ from the point of hard interaction where the PLC is formed.

The time development of the PLC can also be obtained by modeling the ejectile-
nucleus interaction as $\hat{U} = -i\sigma(b^2)\rho(R)$, where $b^2$ represents the transverse separation
of the quarks and $\rho(R)$ is the nuclear density at a distance $R$ from the nuclear center. Then one can assume a baryonic basis and compute the relevant matrix elements
of $\sigma(b^2)$. Jennings and Miller solved the Lippman-Schwinger equation using an
exponentiating procedure. Greenberg and Miller showed that exponentiation is often
a very accurate approximation. A more elaborate approach was taken later by using
measured matrix elements for deep inelastic scattering and diffractive dissociation.
In this case, an approximate linear growth of the PLC cross section with distance is
obtained.

Still another approach involves treating the baryon-nucleon amplitude in terms
of a finite number of baryonic states. Then the baryon-nucleon $T$-matrix can be
represented as an $N \times N$ matrix. The eigenvalues of such a matrix are an example of
the Good-Walker diffractive eigenvalues. The absence of interactions required for
complete color transparency can only be obtained if the $T$-matrix has at least one
state of eigenvalue 0, the PLC, but several different papers use two state models
without satisfying this condition.

4. Relevant data

It is natural to consider the $(e,e'p)$ and $(p,pp)$ processes for color transparency
searches. The first published experiment aimed at color transparency was the BNL
$(p,pp)$ work of Carroll et al. The only other one published is the SLAC $(e,e'p)$
NE18 experiment. We discuss each.

4.1. The BNL $(p,pp)$ experiment

Proton beams of momenta $p_L$ were 6, 10 and 12 GeV/c aimed at a target consisting
of CH$_2$ interleaved with nuclei. The experimental setup used was that for proton
hydrogen elastic scattering at a center of mass angle of 90°. For the hydrogen target,
identifying an elastic scattering event requires detecting the outgoing momentum of
one proton and the angle of the other. This is not sufficient for nuclear scattering
because of the Fermi motion of the bound proton. However, information from veto
counters was used to suppress inelastic events.

The data were originally plotted with an effective beam momentum, $P_{\text{eff}}$. It is
better to use $-k_z$, the component of the momentum of the struck nucleon calculated in
the plane wave impulse approximation. The $z$-axis is defined by the beam direction.
The DWIA describes similar data at intermediate energies of $E_p = 1$ GeV with accuracy of better than 20%.
However the BNL data are considerably above the DWIA
results, see Figs. 9 and 10 of Ref. [1].

The observed large value of the ratio of the cross section to its value in Born
approximation indicated the presence of a large transparency effect, but the apparent
drop at 12 GeV/c caused considerable discussion. The color transparency models
which include expansion effects naturally produce an increase of the transparency consistent with the one observed in the BNL experiment at 6 and 10 GeV/c.

The possible nuclear results depend on the pp elastic scattering data. The energy dependence of the 90° angular distribution is of the form of $1/s^{10} R(s)$ where $R(s)$ oscillates between 1 and 3 over the energy range of the BNL experiment. Ralston and Pire, suggested that the energy dependence is caused by an interference between an amplitude which produces a PLC, and a soft one which involves a large or blob-like configuration BLC. Another mechanism is that of Brodsky and de Teramond. It is natural to discuss high $Q^2$ elastic proton-proton scattering in terms of configurations of different sizes. Separating the contributing configurations into two, a PLC and a BLC is only a simple first step.

Effects of the Fermi motion in treating the expansion process were evaluated, and big numerical effects were obtained. The result was that it became possible to construct a model which is able to describe BNL data at all energies. The solid curves of Fig. 10 of Ref. [1] show the full calculation of Ref. [26] including the Ralston-Pire interference effect. Keeping the experimental uncertainties in mind, the agreement between theory and experiment is rather good.

4.2. The SLAC $(e,e'p)$ experiment

If color transparency effects observed at BNL are real they should be manifest in reactions other than $(p,pp)$. Thus the recent measurement of the $(e,e'p)$ reaction made at SLAC and the possibility of future work at CEBAF are very exciting. The NE18 collaboration measured cross sections for $^{12}$C, Fe and Ag targets for momentum transfers $Q^2$ of 1, 3, 5 and 6.8 GeV$^2$. We quote results presented recently for $^{12}$C. The available data and the related theory are shown in Fig. 11 of Ref. [1].

The NE-18 experiment has made a significant achievement in observing the quasi-elastic $(e,ep')$ reaction at $Q^2$ between 1 and 7 GeV$^2$. One is now faced with the task of assessing the data. The results of Ref. [20] are that no significant rise of the transparency with $Q^2$ is seen. Early predictions depended on the unknown expansion rate. This is still unknown but is now better constrained by the $(p,pp)$ data. One is now in a much better position to ask for the SLAC experiment: how large can one expect CT effects to be? One way to see is to compare the data with DWIA calculations, another way is to use models consistent with the BNL data to compute CT effects for the $(e,e'p)$ reaction.

Relevant DWIA calculations must satisfy certain criteria: (1) compute the relevant observable $T(A)$ according to the experimental acceptance; (2) use nuclear wave functions which reproduce the nuclear density and spectral function; (3) include the energy dependence of $\sigma$. Calculations satisfying these criteria are shown in Fig. 11 of Ref. [1] along with calculations including color transparency effects consistent with the BNL results.

The net result is that calculations which predict substantial color transparency effects for the $(p,pp)$ reaction do not predict much color transparency in the regime of $Q^2$ available to the NE18 experiment. The $(e,e'p)$ reaction is inherently simpler
than the (p,pp) reaction so it is imperative to push the (e,e’p) measurements to higher values of $Q^2$, say up to 12 or 15 GeV$^2$. Observing substantial effects would be possible.\footnote{16}

4.3. Rescattering vs. time development

The problem in looking for CT 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 CT at intermediate values of $Q^2$ it is necessary to suppress this expansion. If one studies a process where the produced system can only be produced by an interaction in the final state, a double scattering event, then the color coherent effects would be manifest as a decrease of the probability for final-state interactions with increasing $Q^2$. One could then observe an effect decreasing from the value expected without CT (Glauber-value) to zero. Thus, the measured cross section is to be compared with a vanishing quantity so that the relevant ratio of cross sections runs from 1 to infinity. The first calculations\footnote{27} show that substantial CT effects are observable in the $(e,e'pp)$ reactions on $^4He$ targets. Such experiments can be done at CEBAF. It would be important to do these experiments at low $Q^2$, say 4 to 6 GeV$^2$ to establish the effects and then to confirm them by going to higher values of $Q^2$.

Another idea involves pionic degrees of freedom. Probing a nucleon at intermediate momentum transfers ($Q^2$ about a few GeV$^2$) may produce a small system without a pion cloud\footnote{14,15}. This cloud-stripping effect can be studied by considering processes that require a pion exchange to proceed. An 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. Calculations are now in progress\footnote{28}. This could be a new kind of transparency that involves pions, so the name “chiral transparency”\footnote{14} was invoked.

5. Spin Dependent Color Transparency

Bill Greenberg’s thesis included a detailed study of effects which can be observed by measuring the polarization of the outgoing proton. I will discuss the principal results of this work\footnote{29}.

Our procedure was to treat the vector nature of the photon and the spin of the proton and photon explicitly by describing the initial bound proton and the ejected wave packet as four-component Dirac spinors. Such effects, ignored in previous calculations, yield several results.

(1) The use of Dirac based optical potentials in the “standard calculation” (ignoring CT) leads to smaller cross sections than predicted before. This model dependence, which arises from the different radial form used in the optical potential, means that
one must be wary of claims that color transparency can be observed by finding small differences between data and the magnitude of a DWIA prediction.

(2) The normal component of the ejectile polarization, which vanishes in the limit of full CT, is found to approach zero very slowly as the energy increases. Finding color transparency by measuring the polarization of the outgoing proton will be very difficult at any foreseeable energy.

(3) The presence of the $1H_{11/2}$ orbital, causes the normal-transverse response in $^{208}Pb$ to be sensitive to color transparency effects at quite low momentum transfers $\sim 1$ GeV/c. There is a similar effect in $^{120}Sn$.

(4) The four-component nature of our formalism, allows us to determine that our calculations are roughly consistent with current conservation, except when the momentum $k_z$ of the struck nucleon is greater than about 150 MeV/c. Here the $z$ direction is that of the virtual photon. More generally, we argue that attempts to enhance color transparency effects by measuring cross sections for large values of $k_z$ are risky. One needs to check that the relevant predictions satisfy the current conservation.

6. Implications for CEBAF at higher energy

Studying the $(e,e'p)$ reaction at high $Q^2$ represents an excellent opportunity to observe color transparency. One should not be discouraged by the NE18 results. Calculations which predict substantial color transparency effects for the $(p,pp)$ reaction do not predict much color transparency in the regime of $Q^2$ available to the NE18 experiment. The $(e,e'p)$ reaction is inherently simpler than the $(p,pp)$ reaction so it is imperative to push the $(e,e'p)$ measurements to higher values of $Q^2$, say up to 12 or 15 GeV$^2$. If the effect is not seen at 15 GeV$^2$, it can regarded as inconsequential.

Using double scattering reactions $(e,e'pp)$ and $(e,e'\Delta^{++})$ would allow a measurement of color transparency effects at modest values of $Q^2$, from 1 or 2 up to about 6 GeV$^2$. It would be important to do these experiments to establish the effects and then to confirm them by going to higher values of $Q^2$.

Observing color transparency in $(e,e'\vec{p})$ measurements would be very difficult at any momentum transfer. Such measurements are sensitive to interesting nuclear structure effects, but there is no urgent need to do these at higher energies.

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