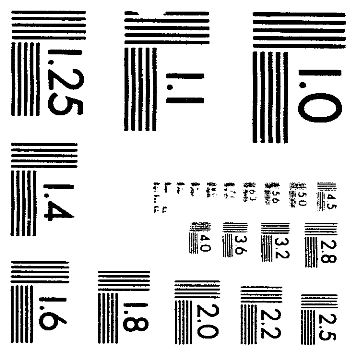

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# Color Transparency

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Abstract

The anomously large transmission of nucleons through a nucleus following a hard collision is explored. This effect, known as color transparency, is believed to be a prediction of QCD. In this talk we discuss the necessary conditions for its occurrence and the effects that must be included in a realistic calculation.

## 1. Introduction

In this talk we consider hard exclusive reactions on a nuclear target. The idea is to use the nucleus to analyze the size (or interactions) of a nucleon immediately before or after a hard interaction. The expectation is that it may be different[1,2] then predicted by the naive Glauber theory. The original motivation behind this was to test a prediction of perturbative QCD and check its validity.

The expectation is that after a hard interaction, interactions with the nucleus will be reduced. This is based on three ideas:

1. A small object is produced in a hard reaction.
2. Small objects interact weakly with the nuclear medium.
3. The expansion time is sufficiently long that the object can exit the nucleus before it expands.

This reduction in the interactions with the nucleus is known as color transparency. It is the first of these three ideas that we really wish to check. However it turns out that is it the third that causes the most uncertainty and unfortunately has the least intrinsic interest. We will consider the three ideas in turn.

## 2. Hard interactions produce small objects

Perturbative QCD based arguments lead to the conclusion that small objects are produced in hard interactions. The idea is quite simple and we refer to Fig. 1a. For all the quarks in the hadron to go in the same direction after a hard interaction the momentum must be shared between the constituents (two in the diagram) of the hadron. The gluon responsible for the sharing is highly virtual and hence can not travel very far. Thus the constituents must be close together in the transverse direction. In fact the size distribution goes like

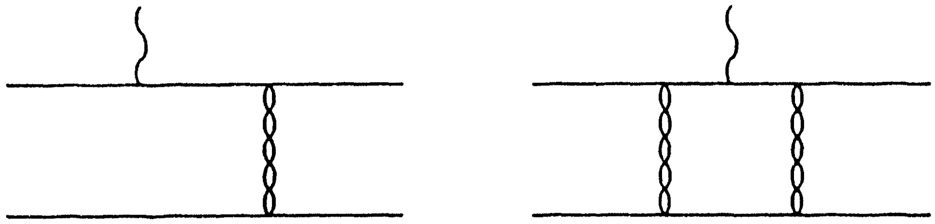

Fig. 1. Perturbative QCD (a) and end point singularity (b) diagrams

$\int \frac{d^2 q_\perp}{(2\pi)^2} \frac{e^{i q_\perp \cdot b}}{q_\perp^2 + (Q/2)^2} \sim \frac{1}{2\pi} \sqrt{\frac{\pi}{2}} \frac{\exp(-Qb/2)}{\sqrt{Qb/2}}$. In the longitudinal direction Lorentz contraction makes the size small.

There are alternate processes that can be imagined to contribute to hard interactions. For example in fig. 1b we show another diagram that can in principle contribute. In this diagram the momentum can be redistributed without any particle being far off shell.[3] This occurs when the spectator has zero momentum and is sometimes referred as an end point singularity. In this case since the particles are all almost on shell we can not use perturbative QCD to estimate this diagram but must use also the confining potential. Naively this diagram does not require the constituents to be close together.

Now the controversy starts. Is this second diagram important? At some energy it must be suppressed. If a charged particle under goes a hard interaction it will bremsstrahlung off photons. Similarly if a color charged object under goes a hard interaction it will bremsstrahlung off gluons. This leads to inelastic processes and not to the exclusive reaction under consideration. The net effect is that this diagram will be suppressed. Actually more is achieved. All processes where the colored constitutions are not close together will be suppressed. This is known as as Sudakov suppression and was discussed by Carlson at this meeting. The only question is at what energy does this suppression occur. There is no consensus on this question.[4,3] Thus this diagram may make a contribution that is not spatially small. If this is dominant we would not see color transparency. One of the interests in color transparency is to see if such diagrams are important. However in the numerical work described in this talk these diagrams will be ignored.

An additional contribution is shown in fig. 3. This is known as the Landshoff term and should contribute to proton-proton scattering. Like the end point singularity it should be suppressed by Sudakov effects. Again we do not know at what energy this suppression will occur. However one thing we do know is that the proton-proton 90° scattering data is not given by the $S^{-10}$ predicted by perturbative QCD but rather oscillates around this value.[5] The interference between the Landshoff term and the perturbative QCD term will generate such an oscillation.[5] Other sources for the oscillation have been suggested. For example Brodsky[6] has suggest that the wiggles arise from the opening of the strangeness and charm thresholds. With this approach is he is able to fit both the cross-section and spin observables. It is also possible to fit the spin observables with the Landshoff term as shown by Carlson et al.[7] Both approaches to describing the oscillations have two interfering terms one of which is the perturbative QCD term and other which presumably does not have a small spatial size. We thus expect the second term to have normal distortions. This, as we will see later, has a significant impact on the observed color transparency. In principle the (p,2p) reaction on

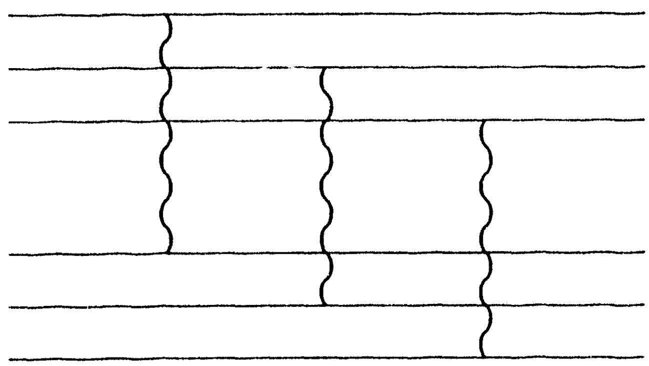

Fig. 2. The Landshoff diagram

a nucleus can distinguish between these two alternatives but currently neither the data nor theory are sufficiently precise.

## 3. Small Objects Interact Weakly

A gluon will only interact strongly with a colorless object only if its wavelength is less then or approximately equal to the color separation. Thus for small objects we expect the interactions to be small. Other processes, for example pion exchange, must also be considered. This has been done by Strikman et al[8] who argues that all interactions are suppressed for small objects. Even the Skyrme model predicts small objects interact weakly.[9] This is the best founded and least controversial of the three assumptions needed to get color transparency.

## 4. The Expansion Time

### *4.1. Small Objects Expand Rapidly!*

Let us consider the form factor in the laboratory frame. The photon four momentum is $(q_0, \vec{q})$. The outgoing (on shell nucleon) has four momentum $(E_q, \vec{q})$ with $E_q^2 - \vec{q}^{\,2} = m^2$. The on shell condition leads to $Q^2 = \vec{q}^{\,2} - q_0^2 = \vec{q}^{\,2} - E_q^2 - m + 2mE_q = 2m(E_q - m) \approx 2mq$ The small object produced has transverse size the order of $1/Q$ hence transverse momenta the order of $Q$ and is off shell by amount $\sqrt{Q^2 + q^2} - \sqrt{m^2 + q^2} \approx Q^2/2q = m$. Thus it lives for a time $1/m$ and can travel a distance of $c/m \approx 0.2$fm. With this kinematics a small object will expand rapidly for any incident energy! This problem must be overcome if we are to have color transparency. As we will see shortly the solutions comes from considering the complete problem.

This example also gives a warning for other problems. Never assume that the frozen approximation is valid just because the incident energy is large. It must be checked in every case.

Even if the above estimate is off by an order of magnitude the expansion is still too fast. The argument relies on just the uncertainty principle so it should be quite robust. The important point is that the small object is far off shell so non-quantum treatments are of no use.

This rapid expansion is actually useful. It means that we can use factorization. The hard interaction is over and done with before the particle has time to move one nucleon radius

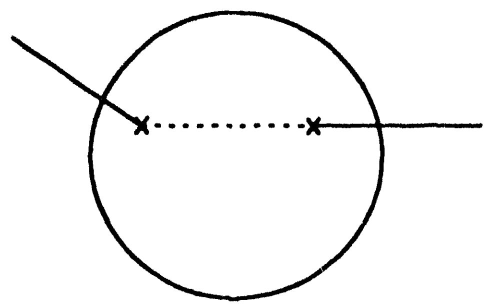

Fig. 3. First order correction term

and interact with the other nucleons.

### 4.2. *Perturbative Treatment*

To see how rapid the expansion time is we treat the interactions with the medium as a perturbation. In fig. 3 we show the first order correction to the amplitude. For color transparency this term should vanish.

Notice that we have two interactions. First we have the hard interaction that makes the small object. Second we have the interaction with nuclear medium. This second interaction give the final state interactions. It must also convert the small object to the nucleon that is observed in the detector.[10,11]

The contribution to the amplitude to second order can be written:

$$\begin{aligned} \mathcal{M}_\alpha &= B_\alpha + ST_\alpha. \\ B_\alpha &= \langle \vec{p}| T_H(Q)|\alpha\rangle = F(Q^2)\langle \vec{p} - \vec{q}|\alpha\rangle, \\ ST_\alpha &= \langle \vec{p}| U\, G\, T_H(Q)|\alpha\rangle, \end{aligned} \tag{1}$$

where $B_\alpha$ is the Born amplitude, $F(Q^2)$ the nucleon form factor, and $\alpha$ labels the nuclear state. Notice the form of the second term; it has $U$, $G$ and $T$. If $G$ were not there we would have $UT$ which is zero (or at least small) since this is just the statement that a hard interaction produces a weakly interacting object. The expansion is in the propagator $G$. The propagator depends on both the internal degrees of freedom and center of mass coordinate. We use a spectral representation of $G = \sum_m \int d^3q' |n, \vec{q}' > /(E_0(q) - E_n(q') + i\epsilon) < n, \vec{q}'|$ where $n$ denotes the intrinsic excited states and $q'$ is the center of mass momentum. The condition to have just $UT$ is that we can use closure on the sum over intermediate states $n$. The hard interaction produces very high energy intermediate states $n$ which by them self would not permit the use of closure. However $U$ prefers low lying states and if we are lucky will cut off the sum at sufficiently low energies to permit the use of closure. Thus the expansion time is more a property of $U$ then of $T$ (although of course both are involved). This is a useful observation since there are other reactions such as total cross-sections that allow the study of $U$.[12] In fact[13] for the total cross-section calculation the frozen approximation is not good. This is quite worrying for color transparency.

An alternate way of looking at the problem is as follows: The energies can be written as $E^* = \sqrt{m_m^2 + q^2}$ and $E = \sqrt{m_0^2 + q^2}$. Thus the intermediate state is off shell by $\Delta E =$

$E^* - E \approx (m^{*2} - m^2)/2q$ and travels a distance $R = 2q/(m^{*2} - m^2)$. Transparency requires that the nuclear size must be less then $R$. As with the closure argument the whole question of expansion time comes down to which states are important.

If we take a simple harmonic oscillator model[10,11] and use $U \propto r^2$ only two states will appear in the sum since $r^2$ only connects the ground state to ground state and the second excited state. This is an interesting example since it shows that it possible to get the cancellation in the scattering amplitude with only two states in spite of the fact we need many states to get a small size. The second point is that it is $U$ that cuts off the sum.

Unfortunately the oscillator model is not necessarily a good approximation. However there is some experimental data available. We need $\langle n|T_H(Q)|n=0\rangle$ which is related to the transition form factor (or the nucleon form factor for n=0). We also need $U_{N,m}(\vec{B}, Z)$ which is related to diffractive disassociation. Unfortunately what we need are matrix elements for specific states while all we have experimentally are cross-section for fixed mass $m$. Assuming the matrix elements are just square roots of cross-sections and add coherently gives contributions at very large mass $m$. However we know that the hard interaction and diffractive dissassociation produce different states at the same energy (the pion multiplicities are different) so we introduce a cutoff[14] which we constrain by requiring that color transparency is exact in the closure limit. It is quite worrying that the rather add hoc cut off is all that makes color transparency work.

In some calculations the extreme frozen approximation is used where all effects of the expansion are ignored. In the hadron matrix element approach this does not happen and we can not imagine a reasonable scenario where it would be valid at the energies under discussion. There are simply not the necessary states at very low energy.

## 5. Results

So far we have considered just the results to first order in perturbation theory. We take the higher order terms approximately into account using an exponentiating technique.[11] The approach has been checked numerically and found quite accurate.[15]

The results are shown in fig. 4. There is little transparency in the $Q^2$ range of the SLAC experiment.[16] The results from that experiment, presented at his workshop, fall between the two limits for different cuts off given in this figure and are thus nicely in agreement with our calculations. The results are also in the same ball park as the Brookhaven results.[17]

So far we have considered only quasifree kinematics. This, of course, is optimized for nucleon production. Since color transparency arises by a cancellation between nucleon and resonant states we can enhance color transparency by shifting off the quasi-elastic peak in a direction to optimize for the production of excited states. This can be done by varying the Bjorken $x_B$ or by transferring momentum to the residual nucleus as in the Brookhaven experiment. This should have been obvious from the beginning but we did not realize it until it was pointed out by Boris Kolepiovich[18] who discussed in the context of the role of Fermi motion (see also Bianconi[19]).

The $x_B$ dependence is shown in fig. 5. Only the values of $x_B$ near one should be taken seriously. For comparison with experiment it is probably better to do as in fig. 5b and just compare above the quasi-elastic peak with below the quasi-elastic beak.

So now we come to our final calculation.[13] We include in this calculation the basic color transparency, the distributed mass with a power law cut off, the Landshoff term as

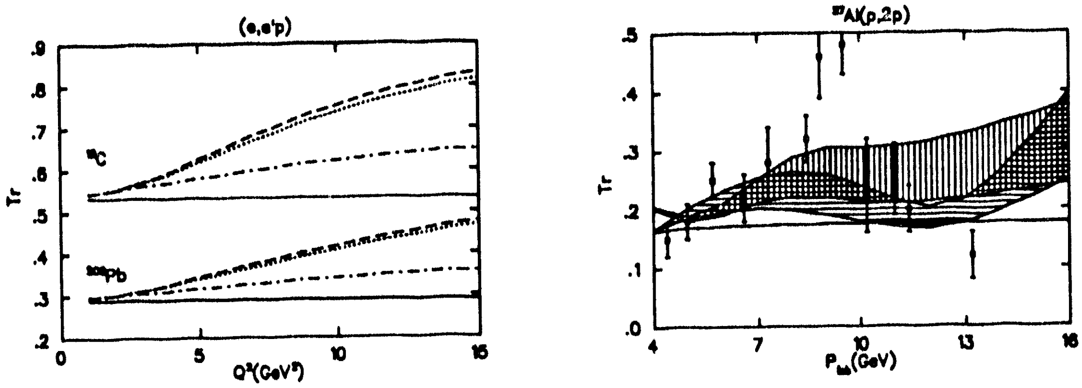


Fig. 4. (a) The transparency, $Tr$, for the $(e, e'p)$ reaction. The solid line represents the standard Glauber calculation ($\sigma_{eff} = \sigma_p$). The lines are as follows dashed: sharp cutoff $g(M_X^2)$, dotted: eq. (5) with $M_1 = 1.44GeV$, dash-dot: power law $g(M_X^2)$. (b) Energy dependence of the transparency $Tr$. The data points are from Carroll et al..[17] The area shaded vertically is obtained from the mechanism of Ref.[5] and amplitude of Ref..[7] The area shaded horizontally is obtained from the mechanism of Ref..[6] In each case the upper bound uses the sharp cutoff for $g(M_X^2)$ and the lower bound a power law. The solid curve assumes no color transparency.

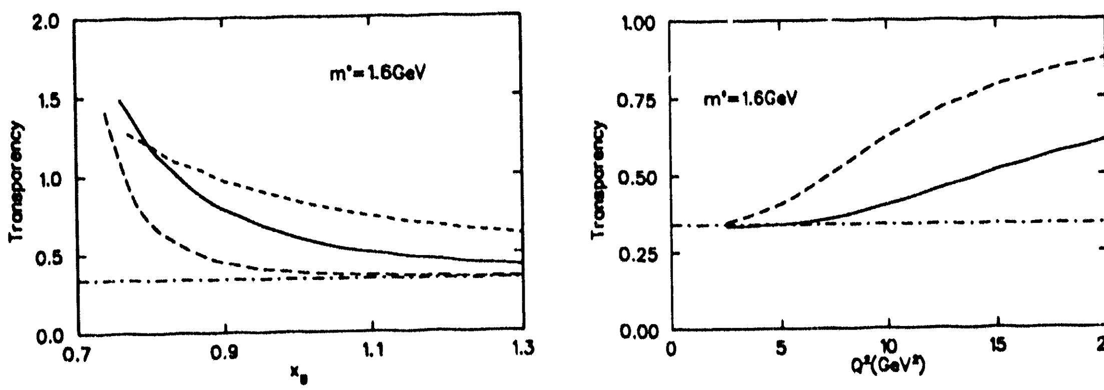


Fig. 5. (a) The nuclear transparency as a function of $x_B$. The curves correspond to $Q^2$ of 7 GeV$^2$ (long dashed curve), 15 GeV$^2$ and 30 GeV$^2$. The dash-dotted curve is the Glauber model. (b) The nuclear transparency as a function of $Q^2$. The solid curve is for $x_B < 1$ while the dashed curve is for $x_B > 1$. The dash-dotted curve is the Glauber model.

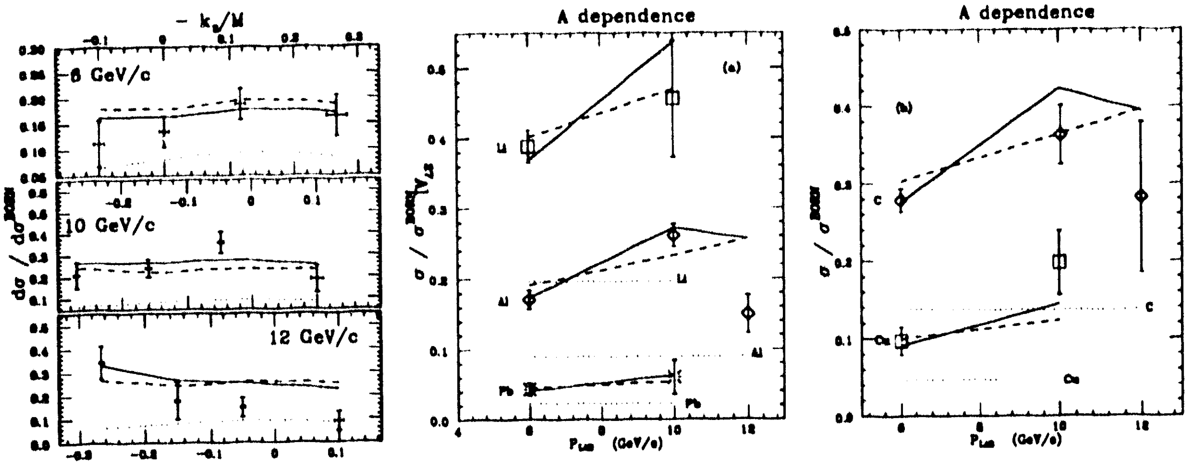


Fig. 6. Transparency for (p,2p). Solid-curve full calculation, dashed-curve without the Ralston-Pire effect, dotted-curve Glauber.

fit by Ralston and Pire,[5] and the kinematic effect relating to $x_B$. The results are shown in the next figures. In the calculations the energy dependence is more reliable then the normalization. Also there is an uncertainty in the normalization of the experimental data. In the figure we have therefore shifted the data down by about one standard deviation of the quota experimental normalization error. For the $^{27}$Al data we have not used the conventional presentation employing a $p_{lab}$ effective. Instead we show the data separately at each incident momenta. This is because the effective $p_{lab}$ approach assumes that there is only one energy scale in the problem, namely $S$. Certainly when the expansion time is important this is not correct. Part of the downward slope in the 12 GeV data comes about precisely because of the breakdown of the concept of effective $p_{lab}$. We strongly discourage the use of this concept.

The down turn in the data in fig. 6b and c is due to the Landhoff term (or the threshold effects). We believe that both this term and the proper treatment of the kinematic effects are necessary in order to describe the data.

The agreement while not perfect is certainly at least qualitative. Thus it is possible to describe simultaneously the SLAC and Brookhaven data. That latter give an indication that color transparency has been seen and its main features understood.

In conclusion we think color transparency has indeed been seen at in the Brookhaven experiment. Although it will have to be confirmed by more precise experiments. The SLAC experiment is at too low an energy to see much effect but their results as presented at this conference are consistent with our calculations. It is thus possible to have qualitative agreement with both the SLAC and Brookhaven experiments. More data is however desperately needed.

## 6. Acknowledgments

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## References


1. A.H. Mueller in Proceedings of Seventeenth rencontre de Moriond, Moriond, 1982 ed. J Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, France, 1982)p13.
2. S.J. Brodsky in Proceedings of the Thirteenth intl Symposium on Multiparticle Dynamics, ed. W. Kittel, W. Metzger and A. Stergiou (World Scientific, Singapore 1982,) p963.
3. N. Isgur and C.H. Llewellyn-Smith, Phys. R .. Lett. 52,1080 (1984); Phys. Lett. B217, 535 (1989); G.P. Korchemskii, A.V. Radysushkin, Sov. J. Nucl. Phys. 45,910 (1987) and refs. therein.
4. H.-N. Li, G. Sterman, Nucl. Phys. B381,129,1992
5. J.P. Ralston and B. Pire, Phys. Rev. Lett. 61,1823 (1988). B. Pire and J.P. Ralston, Phys. Lett. 117B,233 (1982) J.P Ralston and B. Pire, Phys. Rev. Lett. 49,1605 (1982).
6. S.J. Brodsky & G.F. De Teramond, Phys. Rev. Lett. 60,1924 (1988).
7. C.E. Carlson ,M.Chachkhunashvili, and F. Myhrer, Phys. Rev. D46,2891 (1992).
8. L. Frankurt and M. Strikman, Phys. Rep. 160, 235 (1988), L. Frankurt and M. Strikman, Nucl. Phys. B250,143 (1985).
9. G. Kalbermann and J.M. Eisenberg, Phys. Lett. B 286,24 (1992).
10. B.K. Jennings and G.A. Miller, Phys. Lett. B236,209 (1990).
11. B.K. Jennings and G.A. Miller, Phys. Rev. D 44,692 (1991)
12. P.V.R. Murthy et al, Nucl. Phys. B92,269 (1975).
13. B.K. Jennings and G.A. Miller, Phys. Lett. B (submitted)
14. B.K. Jennings and G.A.Miller Phys. Rev. Lett. 69,3619 (1992).
15. W.R. Greenberg and G.A. Miller, Phys. Rev. D47,1865 (1993).
16. R. Milner et al., SLAC proposal NE18
17. A.S. Carroll et al. Phys. Rev. Lett. 61 (1988) 1698. M.B. Johnson and L.S. Kisslinger, World Scientific (Singapore, 1989)
18. B. Kopeliovich, priviate communication, B.K. Jennings and B. Kopeliovich, Phys. Rev. Lett. 70,3384 (1993).
19. A. Bianconi, S, Boffi, and D.E. Kharzeev, Phys. Lett. B205,1 (1993), Nucl. Phys. A, (in press).

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