EVIDENCE FOR OBSERVATION OF COLOR TRANSPARENCY IN pA COLLISIONS USING GLOBAL FIT AND SCALING LAW ANALYSIS

Pankaj Jain and John P. Ralston
Department of Physics and Astronomy
The University of Kansas
Lawrence, KS-66045-2151

ABSTRACT

We review a new systematic data analysis procedure for color transparency experiments and its application to the proton nucleus scattering experiment. The method extracts the hard scattering rate as well as the survival probability for the protons travelling through the nucleus directly from the data. The method requires modelling of the nuclear attenuation in terms of an effective nucleon-nucleon cross section. We can minimize this model dependence by introducing a new scaling law analysis procedure which can yield considerable information with very little theoretical input. With sufficient data the functional forms of the survival probability as well as the hard scattering can be extracted without any theoretical modelling. An analysis of the BNL data of Carroll et al shows clear evidence for observation of color transparency.

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1. Color transparency\(^1\) is a theoretical prediction that under certain circumstances the strong interactions may appear to be effectively reduced in magnitude. Consider an exclusive quasi-elastic process in which an incoming proton knocks a proton out of a nucleus with large momentum transfer without disturbing the rest of the nucleus. If only short distance components of the quark wave function in the proton contribute to this process, then the incoming and outgoing states should have considerably reduced attenuation as they propagate through the nucleus. It would seem that to make a quantitative measurement of the attenuation, one must have a value for the hard scattering rate. In the absence of a normalization of the hard sub-process, only a combination of the hard scattering rate and attenuation rate is measured in an experiment. This has lead to controversies in the interpretation of the data.

Theory at present cannot supply absolute normalizations for exclusive processes, so the scattering rate in an isolated hadron has been used previously as a benchmark for comparison with the nuclear target. The “transparency ratio” \( T(Q^2, A) \) was introduced by Carroll et al\(^2\): it is the ratio of a cross section measured in the nuclear target to the analogous cross section for isolated hadrons in free space. However it has become clear that this ratio is not directly related to the attenuation in the nuclear medium. Any soft components of the hadronic wave function contributing to the free space cross section should be filtered by the nucleus, resulting in the survival of a short distance part of the wave function\(^3\). Therefore the free space cross section may be quite different from the hard scattering cross section inside the nuclear target. If only the hard components contribute to the nuclear hard scattering, we expect that it will be closer to the perturbative QCD (pQCD) predictions. In contrast, the free space fixed angle \( pp \rightarrow pp \) cross section is known to deviate considerably from pQCD, displaying, e.g. oscillations with energy.

In order to avoid making too many assumptions about the hard scattering we recently introduced\(^4\) a more systematic data analysis procedure which does not presume that the hard scattering rate inside the nucleus is known. The procedure is based on fitting the A dependence of the nuclear cross section \( d\sigma_A \) at fixed momentum transfer \( (Q^2) \) to determine the effective attenuation cross section \( \sigma_{eff} \). Assuming that the hard scattering factorizes from the subsequent propagation of the hadron, a transparency ratio \( T(Q^2, A) \) can be written as

\[
T(Q^2, A) = \frac{\frac{d\sigma}{dt}|_{hard, A}}{Z \frac{d\sigma}{dt}|_{free\ space}} P(\sigma_{eff}(Q^2), A) \\
= f(Q^2) \ P(\sigma_{eff}(Q^2), A)
\]

where \( P \) is the survival probability. Here \( f(Q^2) \) is treated as an unknown function which contains information about the hard scattering inside the nuclear target as well as the.
free space scattering. For the BNL fixed target experiment we take $Q^2 = -t \approx s/2$. By fitting the $A$ dependence of $d\sigma_A$ at fixed $Q^2$ we determine the functional dependence of $P$ on $A$. In our application to the BNL $pA \rightarrow p'p''(A-1)$ experiment we used a semiclassical model for the survival probability which assumes exponential attenuation of the protons with effective cross section $\sigma_{\text{eff}}$ as they propagate through the nucleus.

By following this procedure we can determine $\sigma_{\text{eff}}(Q^2)$ and $f(Q^2)$ at each $Q^2$. Since $\sigma_{\text{eff}}(Q^2)$ and the normalization $f(Q^2)$ are free, the fit to the data may or may not show that these parameters vary with energy. The global fit to the BNL data shows evidence for observation of color transparency: $\sigma_{\text{eff}} = 17 \pm 2 \text{ mb} (12 \pm 2 \text{ mb})$ at the $Q^2$ values of 4.8 GeV$^2$ (8.5 GeV$^2$). By use of the intermediate $Q^2$ data points reported for the Aluminum target we determine $\sigma_{\text{eff}} \approx 2.2 \text{ GeV}^2/Q^2$, a rate of decrease in agreement with the pQCD predictions. The plot of $\sigma_{\text{eff}}$ deduced from data is shown in Fig. (1).

The fit also shows that the hard scattering inside the nuclear medium goes down with energy at a rate faster than $(Q^2)^{-10}$. Instead, the hard scattering rate is in agreement with the pQCD prediction which goes roughly like $\alpha_{\text{10}}(Q^2)/(Q^2)^{10}$.

The above procedure can be made even more model independent by using the scaling law for data analysis. As introduced in Ref. [6], the scaling law was assumed to apply in electroproduction to the transparency ratio. (At that time it was believed that one had to assume the hard scattering rate cancelled out in the ratio.) Now it is clear that the scaling law is instead valid for the survival probability. Basically it says that the survival probability is a function of a dimensionless variable. The important dimensionless variable that it can depend on is the effective number of nucleons encountered by the protons as they propagate through the nucleus. This is proportional to the length of the nucleus ($A^{1/3}$) times the nuclear density $n$ times the effective nucleon-nucleon cross section $\sigma_{\text{eff}}$. If the cross section goes like $1/Q^2$ then the survival probability is a function of the dimensionless quantity $nA^{1/3}/Q^2$.

We need to experimentally determine whether this law is satisfied or not. We consider the survival probability to be a function of $Q^2/A^\alpha$ and determine $\alpha$ from the experimental data. The basic complication in this determination is the fact that the experimentally measured transparency ratio $T$ involves an unknown function $f(Q^2)$, where $f(Q^2)$ is the ratio of the hard scattering in the nuclear medium to the free space scattering. With a good data set over a range of the $Q^2$ and $A$ plane one can nevertheless extract functional forms for both $f(Q^2)$ and the survival probability $P$ by fitting $T = f(Q^2)P(Q^2/A^\alpha)$. This is attractive because of its model independence: no theory needs to be used to model $P$, which is simply determined by the best fit. However, the present data is limited since it is available only at two energies for several $A$. We therefore take a somewhat different approach here to check the scaling law with the present data. We assume that the hard scattering inside the nuclear medium satisfies the short distance pQCD predictions. This
is based on the idea of nuclear filtering and is supported by the global fit\(^4\) and by the fact that the cross section in the nuclear target does not show any oscillations\(^3\). We therefore set the average hard scattering cross section in eq. (1) to be \(Z\) times the short distance perturbative QCD prediction\(^7\), which is given by

\[
\frac{d\sigma}{dt_{pQCD}} \approx (\alpha_s(Q^2/\Lambda_{QCD}^2))^{10s^{-10}} f(t/s) .
\]

(In the above expression we have ignored the anomalous dimension which is found to make a very small difference in the results.) We can then calculate \(f(Q^2)\) and take it out of the transparency ratio to yield the survival probability. The survival probabilities for three different values of \(\alpha\) are plotted in fig. 2. The data points are circles \((Q^2 = 4.8\ GeV^2)\), squares \((Q^2 = 8.5\ GeV^2)\) and crosses \((Q^2 = 10.4\ GeV^2)\). It is clear from the figure that \(\alpha = 1/3\) is favored over other values of \(\alpha\). This clearly shows that the data satisfies the scaling law which can therefore be used effectively for analysing future color transparency experiments.

There remains one subtlety. Although the scaling law procedure is quite explicit about the functional dependence on the two variables \(Q^2\) and \(Q^2/A^2\), the ansatz (1) has a symmetry: the data and fit are unchanged under \(f(Q^2) \rightarrow f(Q^2)/K, P(Q^2/A^2) \rightarrow KP(Q^2/A^2)\), where \(K\) is any constant. The absolute magnitudes of the survival probability (or the hard scattering) and the effective attenuation cross section are therefore not determined by this method.

In summary, a systematic global fit shows evidence for observation of color transparency. Our results also show that the data obeys the expected scaling behavior. It will clearly be of great interest to analyze future color transparency experiments by using both methods.

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