The concept of color transparency is introduced. This new feature of QCD is characteristic of a gauge theory. It enables strong interactions to be studied in a new domain: scattering amplitudes of transversally small color singlet objects. Experimental data are still few and somehow inconclusive. Future prospects are briefly discussed. This is a frontier problem of QCD which deserves much attention from both theorists and experimentalists in the coming years.

The current lively debate on the nature of the Pomeron reflects our poor understanding of long distance strong interaction physics. Color transparency experiments offer us in this respect a unique opportunity to challenge various theoretical models through their description of the strong interactions of color singlet small objects.

1 The idea

The concept of color transparency has recently attracted much attention. This phenomenon illustrates the power of exclusive reactions to isolate simple elementary quark configurations. The experimental technique to probe these configurations is the following.

For a hard exclusive reaction, say electron scattering from a proton, the scattering amplitude at large momentum transfer $Q^2$ is suppressed by powers of $Q^2$ if the proton contains more than the minimal number of constituents. This is derived from the QCD based quark counting rules, which result from the factorization of wave-function-like distribution amplitudes. Thus protons containing only valence quarks participate in the scattering. Moreover, each quark, connected to another one by a hard gluon exchange carrying momentum of order $Q$, should be found within a distance of order $1/Q$. Thus, at large $Q^2$ one selects a very special quark configuration which can be defined in terms of selected short distance regions of the wave function: all connected

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quarks are close together, forming a small size color neutral configuration. While this is just an important region, quantum mechanically contributing to the process, it is sometimes referred to as a mini hadron. We will use this term freely, with the understanding that the term refers to a region, not a hadron. This mini hadron (like any amplitude selected for its importance) is not a stationary state and evolves until finally one measures combinations of normal hadrons.

Such a color singlet system cannot emit or absorb soft gluons which carry energy or momentum smaller than \( Q \). This is because gluon radiation — like photon radiation in QED — is a coherent process and there is thus destructive interference between gluon emission amplitudes by quarks with "opposite" color. Even without knowing exactly how exchanges of soft gluons and other constituents create strong interactions, we know that these interactions must be turned off for small color singlet objects.

An exclusive hard reaction will thus probe strong interactions in three complementary ways:

- First, selecting the simplest Fock state amounts to the study of the structure of a mini hadron, i.e. the short distance part of a minimal Fock state component in the hadron wave function. This is of primordial interest for the understanding of the difficult physics of confinement.

- Secondly, letting the mini-state evolve during its travel through different nuclei of various sizes allows an indirect but unique way to test how the squeezed mini-state goes back to its full size and complexity, i.e. how quarks inside a color-singlet state rearrange themselves spatially to "reconstruct" a normal size hadron. In this respect the observation of baryonic resonance production as well as detailed spin studies are mandatory.

- Thirdly, the study of the (reduced) final state interactions of the mini hadron with spectator hadrons, through the soft scattering of these latter ones, opens the domain of the strong interactions of small color-singlet objects, much related to Pomeron physics.

2 Present Data

Experimental data on color transparency are very scarce but worth considering in detail. The first piece of evidence for something like color transparency came from the Brookhaven experiment on pp elastic scattering at 90° CM in a nuclear medium [2]. These data lead to a lively debate. The special feature of hadron hadron elastic scattering at fixed angle is that in addition to a clear cut short distance amplitude, there is an infrared sensitive process (the so-called independent scattering mechanism) which allows not so small configurations to scatter elastically. The phenomenon of colour transparency is thus replaced by a nuclear filtering process: elastic scattering in a nucleus filters away the big component of the nucleon wave function and thus its
contribution to the cross-section. Since the presence of these two competing processes had been analysed as responsible for the oscillating pattern seen in the scaled cross-section $s^{10}d\sigma/dt$, an oscillating color transparency ratio emerges. One way ("attenuation method") to understand data is to define a survival probability related in a standard way to an effective attenuation cross section $\sigma_{eff}(Q^2)$ and to plot this attenuation cross section as a function of the transfer of the reaction. One indeed obtains values of $\sigma_{eff}(Q^2)$ decreasing with $Q^2$ and quite smaller than the free space inelastic proton cross section. The survival probability is even found to obey a simple scaling law in $Q^2/A^{1/3}$.

The SLAC NE18 experiment recently measured the color transparency ratio up to $Q^2 = 7 GeV^2$, without any observable increase. This conclusion follows only if the hard scattering part of the process is assumed to be the same as in free space, canceling out in forming the transparency ratio. While this assumption is not needed in the attenuation method, the precision of the data were not sufficient to conclude much using the less model-dependent test. While the majority view is that these data cast doubt on the most optimistic onset of color transparency, emphasizing the importance of a sufficient boost to get the small state quickly out of the nucleus, this conclusion remains tentative and something to be tested.

The diffractive electroproduction of vector mesons at Fermilab and Cern exhibit an interesting increase of the transparency ratio for data at $Q^2 \simeq 7 GeV^2$. In this case the boost is high since the lepton energy is around $E \simeq 200 GeV$ but the problem is to disentangle diffractive from inelastic events.

3 Future prospects

It should by now be obvious to the reader that Color Transparency is just an emerging field of study and that one should devote much attention to get more information on this physics in the near future.

3.1 Experiments

A second round of proton experiments at Brookhaven has been approved and a new detector named EVA with much higher acceptance has been taking data for about one year. Along with other improvements and increased beam type, this should increase the amount of data taken by a factor of 400 allowing a larger energy range and an analysis at different scattering angles. It may also open the field of meson-nucleus reactions.

The Hermes detector at HERA is beginning operation. It will enable a confirmation of existing data on $\rho$ meson diffractive production at moderate $Q^2$ values and quite smaller values of energies: $10 \leq \nu \leq 22 GeV$. This experiment might however suffer from the same weakness as the ones from FNAL and CERN since Hermes small luminosity only allows integrated measurements and
Thus cannot assure that diffractive events are not polluted by inelastic events. It seems difficult to envisage in the near future the detection of the recoiling proton.

The $15 - 30 \text{GeV}$ continuous electron beam ELFE project is presently discussed at the European level [12]. Besides the determination of hadronic valence wave functions through the careful study of many exclusive hard reactions in free space, the use of nuclear targets to test and use color transparency is one of its major goals. The $(e, e', p)$ reaction should in particular be studied in a wide range of $Q^2$ up to $21 \text{GeV}^2$, thus allowing to connect to SLAC data (and better resolution but similar low $Q^2$ data from CEBAF) and hopefully clearly establish this phenomenon in the simplest occurrence. The measurement of the transparency ratio for photo- and electroproduction of heavy vector mesons, in particular of $\psi$ and $\psi'$ will open a new regime where the mass of the quark enters as another scale controlling the formation length of the produced meson.

### 3.2 Theory

#### 3.2.1 Large vs Small Nuclei

To the extent that the electromagnetic form factors are understood as a function of $Q^2$, $eA \rightarrow e'(A-1)p$ experiments will measure the color screening properties of QCD. The most straightforward quantity to be measured is the transparency ratio $T_r$ which is defined as:

$$T_r = \frac{\sigma_{\text{Nucleus}}}{Z \sigma_{\text{Nucleon}}}$$  \hspace{1cm} (1)

At asymptotically large values of $Q^2$, dimensional estimates suggest that $T_r$ scales as a function of $A^{\frac{1}{2}}/Q^2$ [5]. The approach to the scaling behavior as well as the value of $T_r$ as a function of the scaling variable determine the evolution from the mini-region to the complete hadron. This interesting effect can be measured in an $(e, e'p)$ reaction that provides the best chance for a quantitative interpretation.

Although color transparency was first mostly considered as an effect to be studied on rather large nuclei, it became recently clear that small nuclei had much to teach us about this physics item. Deuteron electrodesintegration reactions $d(e, e'p)n$ for instance [13], both polarized and unpolarized, is much interesting. The idea is simple; let us examine the case where the virtual photon mostly hit the proton in the deuteron. The neutron momentum distribution is then due to the combination of

- Fermi momentum effects in the initial state;
- final state interactions.

These two components are well known at small $Q^2$. At large $Q^2$, the hard process selects small-sized proton, and the interaction miniproton-neutron is much weaker. This is where Pomeron physics enters, at least if energy is high enough. High $Q^2$ electroproduction data appear then as an unexpected testing bench of soft physics,
with the important bonus of a controlable variable sized hadron scattering on a normal one. Whether the small size justifies completely a perturbative treatment of this small transfer amplitude is still an open question.

The cross section for \(d(e,e'p)n\) may be written as

\[
\frac{d\sigma}{dE_{e'}d\Omega_{e'}d^3p_p} = \sigma_{ep} \ D_d(q,p_p,p_n) \ \delta(q_0 - M_d - E_p - E_n)
\]

where \(D_d(q,p_p,p_n)\) is the joint probability of the initial proton having a Fermi momentum \(p_p - q\) and the final proton (neutron) a momentum \(p_p\) \((p_n)\). A poor energy resolution would restrict the physics to a qualitative observation of color transparency, whereas a very good one would allow a quantitative determination of the miniproton-neutron scattering cross-section as a function of the miniproton size \((i.e. \ Q^2)\), provided one controls and deconvolutes Fermi momentum effects in the deuteron.

Frankfurt et al.\(^{[13]}\) estimate sizable effects at CEBAF energies, which amount to \(Q^2\) values in the range \(\sim 4 \text{GeV}^2 \leq Q^2 \leq 10 \ (\text{GeV}/c)^2\). Prospects are brighter within ELFE conditions.

### 3.2.2 Helicity (non-)conservation

The hadronic helicity conservation rule in hard exclusive reactions \(^{[14]}\) follows from two assumptions:

- quark masses can be neglected;
- valence states (with only fermions) dominate.

These assumptions which asymptotically are quite solid in reactions such as \((e,e',p)\) are less justified in the hadronic case \(^{[15]}\). They are exactly what leads to the result of color transparency. It thus follows that the helicity non-conserving contributions must be filtered away in a nuclear medium. It is thus most interesting, at a given value of \(Q^2\) to compare the nuclear absorption of amplitudes violating the helicity conservation rule. For this measurement to be possible, we must consider cases where such amplitudes are quite large at reasonable \(Q^2\) values. This is not the case for the proton form factor \(F_2\), but maybe for the \(p - \Delta\) transition form factor \(^{[16]}\), measured at \(Q^2 = 3.2 \text{GeV}^2\).

In the case of hadronic reactions, it has been predicted \(^{[15]}\) that the amount of helicity non conservation seen for instance in the helicity matrix elements of the \(\rho\) meson produced in \(\pi p \rightarrow \rho p\) at \(90^\circ\) would be filtered out in a nucleus. Experimental data in free space \(^{[17]}\) yield \(\rho_{1-1} = 0.32 \pm 0.10\), at \(s = 20.8 \text{GeV}^2\), \(\theta_{CM} = 90^\circ\), for the non-diagonal helicity violating matrix element. If the persistence of helicity non- conservation is correctly understood as due to independent scattering processes which do not select mini-hadrons and thus are not subject to color transparency, helicity conservation should be restored at the same \(Q^2\) in processes filtered by nuclei. One should thus observe a monotonic decrease of \(\rho_{1-1}\) with \(A\).
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