Author: John Koster
Title: The Color Glass Condensate
Abstract: The color glass condensate is a proposed new form of matter present in high-energy hadrons that offers great promise to explain 40 year old puzzles in nuclear physics. This paper will examine the recent theoretical and experimental work on this topic.


HERA


RHIC


LHC

1. Introduction

The Color Glass Condensate is a proposed new form of matter, which is present in all high energy hadrons and has the potential to shed light on many nuclear phenomena from the Quark Gluon Plasma to the origin of proton spin. It is important to note the difference between a Color Glass Condensate (CGC) and the Quark Gluon Plasma (QGP). High energy collisions produce QGP's whereas CGC's describe the structure of a high energy particle. As in the rest of high energy physics, it is the collision of particles that probe the nature and existence of the CGC. If CGC exists it is important to understand that this state is present in the nuclei before the collision. At the present time, there is experimental evidence that suggests the existence of CGC, but the evidence is far from conclusive, and there are different interpretations of the data. The following is a discussion of the reasoning behind the CGC, CGC interpretations of current experimental data, and planned experiments to further probe CGC. What will not be discussed extensively are potential applications of this as of yet unproven theory.

2. Background

For the sake of non-particle physicists, some background in the field will be included before the explanation of the CGC.

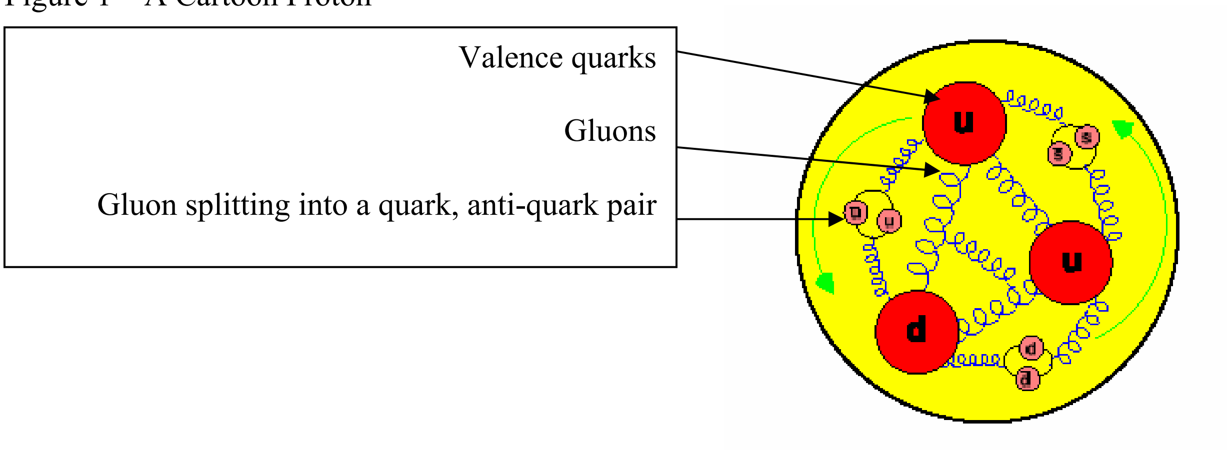
2.1 Partons

The proton and neutron are not the fundamental building blocks of matter. They are built out of particles called quarks. Quarks carry the familiar electric charge (albeit in fractions of the electron charge) and also carry color charge, which is the charge for the strong force. The nature of the strong force prevents experimenters from pulling a proton or neutron apart to directly observe an individual quark. Nonetheless they have found experimental proof that six different kinds of quark exist. These quarks have been named: up, down, charm, strange, top and bottom. Two up quarks, and a down quark are always found inside of a proton. This type of ever-present quark is called a valence quark.

A hadron is made up of quarks. Protons and neutrons are hadrons. They are made up of three quarks each. More exotic particles which have only two valence quarks exist, but will not be discussed in this paper.

Quantum electrodynamics uses the idea of a photon as a force-carrying particle between two charged particles, and similarly quantum chromodynamics uses the idea to construct a force-carrying particle called the gluon. Unlike the electromagnetically neutral photon, the gluon has a color charge. As if that were not enough of a complication, the gluon can split into a quark-antiquark pair. These quarks are known as sea quarks. Together quarks and gluons are known as partons. To help the reader remember these terms I have included a picture of a proton.

Figure 1 – A Cartoon Proton



2.3 Momentum Transfer (Q^2)

The arbitrary scattering event shown in figure 2 shows the initial and final momentum of a particle as p_i and p_f. With these two variables one can define the momentum transfer q as

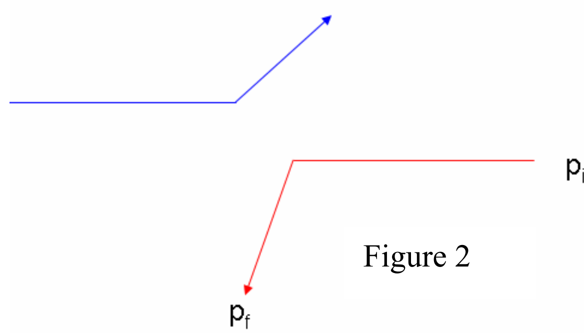


Figure 2

$q = p_1 - p_2 = (q_0, q_1, q_2, q_3)$

Where I have defined a momenta p_j as,

$p_j = (\gamma mc, p_x, p_y, p_z)$

$\quad = (p_{j0}, p_{j1}, p_{j2}, p_{j3})$

With this the invariant quantity q^2 is defined as:

$q^2 = q_1^2 + q_2^2 + q_3^2 - q_0^2$

The literature introduces the variable Q^2 defined as,

$Q^2 = - q^2$

Q^2 characterizes the energy of a collision. The common interpretation of Q^2 is that it corresponds to the wavelength or mass of the probe. Typical units for Q^2 are GeV^2, where the factor of $1/c^2$ has been suppressed.

2.3 The infinite momentum frame and Bjorken x

In the infinite momentum frame the four momentum of a hadron is approximated as $P = (p, 0, 0, p)$. This will only hold when $\gamma >> 1$. James Bjorken proposed the variable x (Bjorken x) to describe the fraction of the momentum carried by a parton inside a hadron, ie $p_{parton} = (xp, 0, 0, xp)$. This variable is commonly called the parton momentum fraction. If a parton collides with another parton, then the final momentum of one of the partons will be:

$p_{parton\ f} = p_{parton\ i} + q$

$p_{parton\ f}{}^2 = x^2\ p_{parton\ i}{}^2 + q^2 + 2x\ p_{parton\ i} . q = m_{parton}{}^2$

$x^2 P^2 = x^2 m_{hadron}^2$. In the limit of $\gamma \rightarrow$ infinity, m_{parton}^2 and m_{hadron}^2 can be neglected. Therefore:

$x = Q^2/2P.q$

3. The Gluon Distribution Function

A partonic distribution function describes the probability density of a parton inside a given hadron as some function of the parton momentum fraction. For example u(x)dx gives the probability finding a up quark with momentum fraction between x and x + dx. The distribution function is not directly observed in experiment. Experimental data is fed into well-accepted QCD calculations to produce the distribution functions. As an illustration of this process, a plot showing results from the ZEUS and H1 experiments, located at the Hadron Electron Ring Accelerator (HERA) accelerator in Germany, is shown in figure 3. This is electron-proton collision data. The uv, dv, g, and S curves correspond to distributions of the valence up quarks, valence down quarks, gluons and sea quarks respectively. Notice the factor of 20 reduction in the size of the gluon and sea quark. It is also important to note that the bands characterize the errors, but do not include all possible errors.

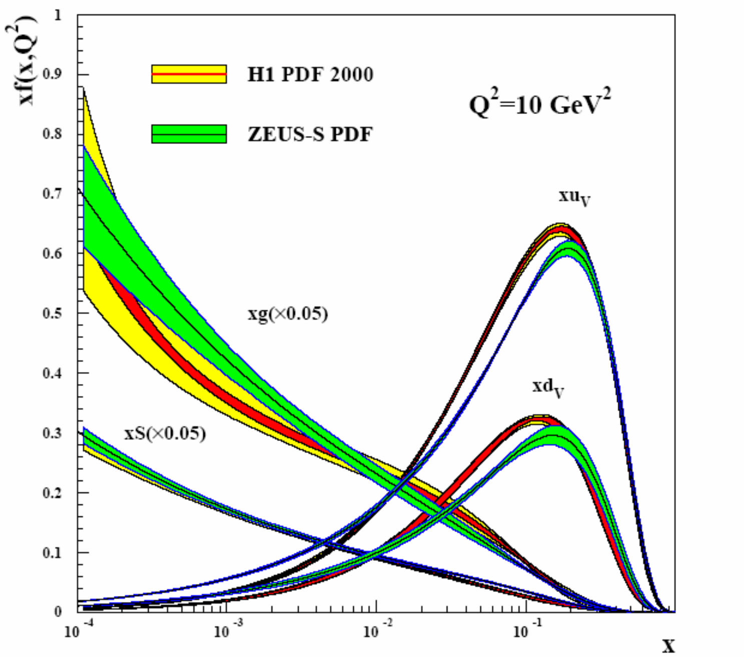


Figure 3 – Plot of x (Distribution Functions) versus the variable x as measured in the ZEUS and H1 experiments. Source: [1]

The rapid rise in occupation of low momentum gluons suggests emergent phenomena may emerge at low momentum fraction.

3.1 Gluon Condensates

It is now time to start the introduction to the CGC. The notation follows that of a paper by Elena Ferreiro [2], but it has been slightly reframed to follow our treatment of superfluids.

Lorentz contraction dictates that a high energy hadron can be viewed as a very thin pancake. In this framework the partons roam in the plane transverse to the direction of motion, but have very little freedom in the direction of motion. [2] Introduces a formula for the transverse gluon size,

$r_T^2 = \alpha_s N_c / Q^2$.
The subscript T indicates a transverse radius
α_s - strong coupling constant
N_c - number of colors.

[2] also defines a gluon density given by,

$\rho = xG(x,Q^2)/ (\pi R^2)$

Now a modification to the notation of [2] is made so as to use the gluon gluon density to give a typical interparticle spacing, d

d = SquareRoot $[R^2 / xG(x,Q2) \pi]$

This has been done to bring in the language of superfluids. When r_T is of the order of d the new phenomena may emerge and a condensate has the potential to be formed. The interparticle spacing becomes small for large values of xG(x,Q2) or when x is small. The literature refers to a saturation scale, $Q_s(x)$. $Q_s(x)$ corresponds to the value of Q^2 where saturation effects become important. Not noted explicitly in the function is a dependence on the atomic weight, A. Presumably, higher atomic weights increase the gluon density, and therefore lower the associated saturation scales. Figure 4 shows that the value of Q^2 heavily affects when saturation becomes important.

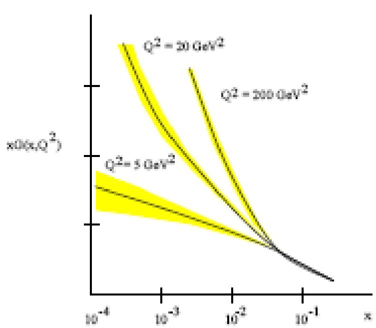


Figure 4 – The gluon distribution function plotted against x for various values of Q^2. Source: [3]

There is current theoretical work on the scaling between x and Q_s^2. This current theoretical work uses the following parameterization,

$Qs = 1GeV (x_0/x)^{\lambda}$

Where $x_0 = 3 * 10^{-4}$, and
$\lambda = 0.25$

The details of x_0 and λ will be discussed in more detail below.

3.2 Gluon Glass
It is now time to finally discuss the full meaning of CGC. The following is a simple explanation given by McLerran in [3] of the glassiness expected in the CGC.

> *The glassy nature of the condensate arises because the fields associated with the condensate are generated by constituents of the proton at higher momentum. These higher momentum constituents have their time scales Lorentz time dilated relative to those which would be measured in their rest frame. Therefore the fields associated with the low momentum constituents also evolve on this long time scale. The low momentum constituents are therefore glassy: their time evolution scale is unnaturally long compared to their natural time scale. Hence the name Color Glass Condensate.*

Since gluons are the force mediator between quarks, then it follows that gluons must be generated by quarks. As seen in figure 2, quarks on average have significantly higher momenta than typical gluons. Thus by time dilation, the natural time scale of a quark is much slower than that of a gluon. But remember, the gluons are generated by quarks and so the gluons will evolve on the quark time scale. However, the gluon natural time scale is much faster than the quark time scale and so the gluon field can be considered a glassy substance. McLerran's statement implies that even if a gluon was generated by a *low* momentum quark it still must be considered glassy.

But exception can be taken with this view. Nucleons are complicated systems that are not well understood. It is possible that the large number of low x gluons could be generated exclusively by correspondingly low x quarks. If this were the case, then gluon dynamics evolve on the same time scale as that of the quarks. Thus there would be no glassiness in the system.

4. Current Experimental Work
The search for a CGC is an ongoing effort and has developed at two main accelerators: the HERA accelerator in Germany and the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in the USA. The accelerators are significantly different. HERA collides electrons and protons, while RHIC can collide any combination of protons, deuterons, and gold. The different experimental techniques complement each other as experimental issues intrinsic to one collision type may become irrelevant in the other. An unfortunate side effect of the different methodologies is that different signatures are used to look for the CGC.

4.1 HERA Data

The HERA search involves structure functions, which have an important and interesting role in nuclear physics. They are used to transform a scattering event from a point-like particle picture to that of a composite object picture. The distribution functions shown in figure 2 were generated using structure functions. Iancu, et al [4] performed a fit of a structure function called F_2 measured at the ZEUS experiment to their calculations using the CGC. As figure 5 shows their fit compares very favorably to experiment.

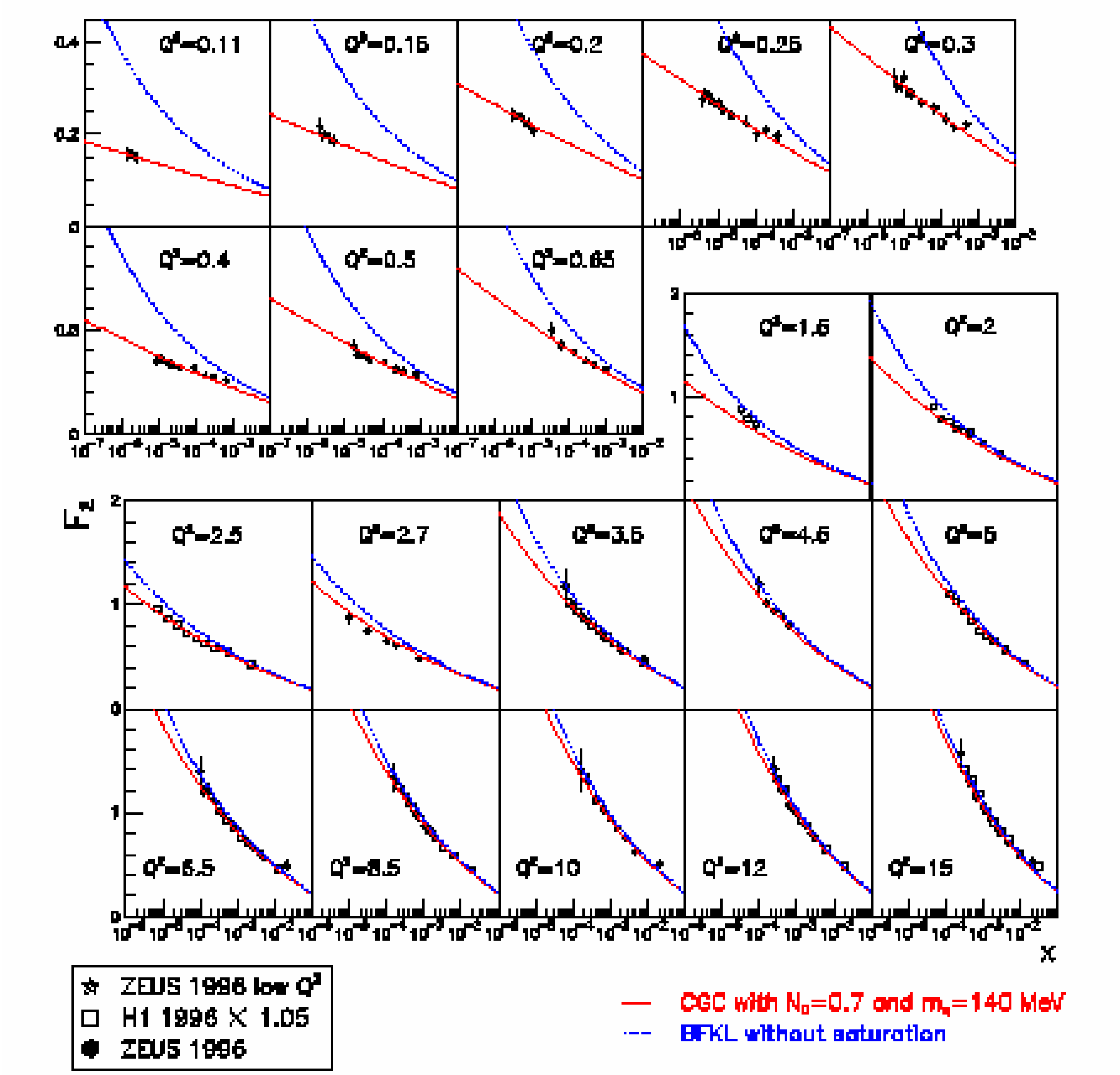


Figure 5 – Experimental Data from the ZEUS, and HERA experiments shown in black. A CGC based fit in red, and a BFKL without saturation fit in blue. Source: [4]

The fit used three parameters: R_p (proton radius), and the previously mentioned x_0 and λ. For the purposes of the fit λ was treated as a free parameter, and was adjusted to give the best fit. From the fit of the data, the value of λ was found to lie between 0.25 and 0.29. λ can also be calculated using perturbation theory [5] and is found to lie between 0.27 and 0.30 with a 15% uncertainty.

4.2 RHIC Data

At the RHIC facility co four experiments, BRAHMS, PHENIX, PHOBOS and STAR, are producing data on the CGC search. Since each experiment is unique, covering all the data would take multiple papers and so only the BRAHMS experiment will be covered as an example. This experiment is chosen, since from a literature review, the data seems to give the clearest hint of CGC-like behavior.

Since the physics program at RHIC is quite diverse not every possible type of collision is run each year. The most interesting hadron on hadron collision for the CGC is a deuteron (each with a nucleus of one neutron and one proton) with gold. It is believed that this type of collision avoids some of the complications present in other types of collision. The most recent data available comes from the 2003 run. As in the HERA data, the theory and experiment match up favorably.

The quantity R_{dAu} is roughly the ratio between the number of particles produced in a deuteron (d) on gold (Au) collision with that of a proton on proton collision as a function of two variables. Its exact definition is given below

$$R_{\mathrm{pA}} \equiv \frac{1}{A} \frac{dN_{\mathrm{pA}}/d^2p_\perp d\eta}{dN_{\mathrm{pp}}/d^2p_\perp d\eta}$$

Source: [6]

$p_\perp$ is simply defined as the momentum perpendicular to the beam axis.

The variable η defined as
$\eta = -\ln(\tan[\theta/2])$
Where θ is defined as the angle measured from the beam axis.
N_{xy} stands for the number of particles produced in a collision of nuclei x and nuclei y.

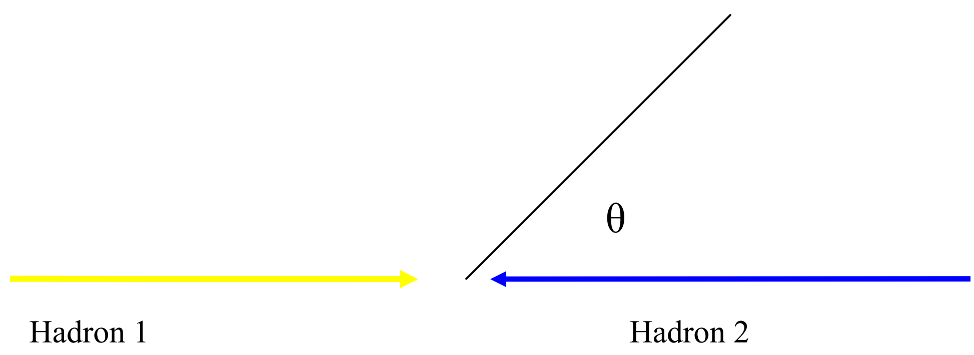


Figure 6 – A Definition of the scattering angle, θ.

With definitions out of the way we can look at data from the BRAHMS experiment.

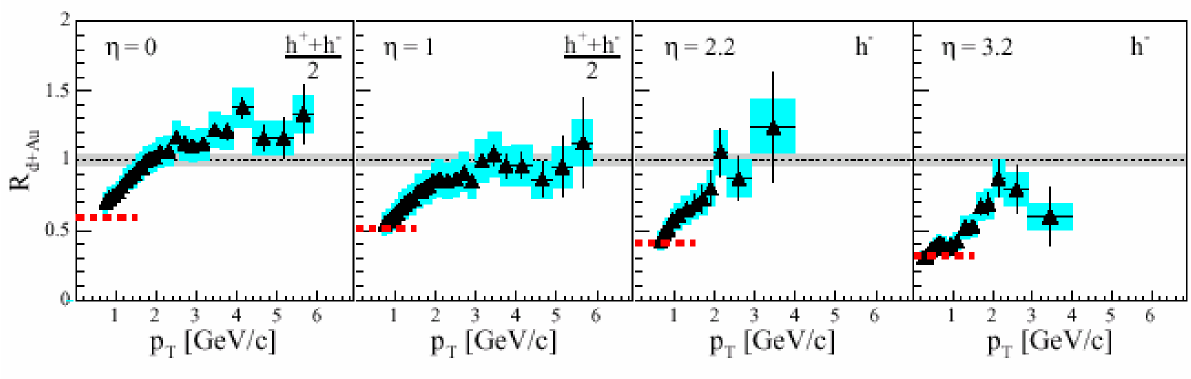


Figure 7 – Data from the BRAHMS Experiment. Source: [6]

Theorists who work on CGC's say that the plots are consistent with the qualitative predictions of the CGC theory. [1, 3, 7]

4.3 Future Experiments

More experiments on the CGC are planned at RHIC. The two large experiments, PHENIX and STAR, are currently building detectors to explore the forward kinematic region. Forward refers to particles which lie close to the beam axis. Looking at particles in this kinematic region will allow cleaner measurements. Both the STAR and PHENIX detectors should be completed by late 2006.

The Large Hadron Collider (LHC) at CERN in France is scheduled to start operation in 2007. This new accelerator will go to higher energies than RHIC.

A proposed upgrade to RHIC called eRHIC would add an electron accelerator to RHIC. eRHIC would allow further explorations of the CGC.

5. Conclusion

Experimentalists and theorists are aggressively pursuing the color glass condensate. If experimentalists find confirmation of a color glass condensate it would be extremely interesting, and would simplify the calculations done by theorists in high energy collisions. If, however, the theory of CGC's is disproved, the question of high gluon densities at low x in nucleons would remain a mystery.

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