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THE COLOR GLASS CONDENSATE IN DIS AND HEAVY ION PHYSICS.

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I introduce the concept of the Color Glass Condensate. I discuss the hints that this matter may have been observed in deep inelastic scattering and in experiments at RHIC

1 What is the Color Glass Condensate?

The ideas for the Color Glass Condensate originate in the result for the HERA data on the gluon distribution function shown in Fig. 1(a) [1] The gluon density is rising

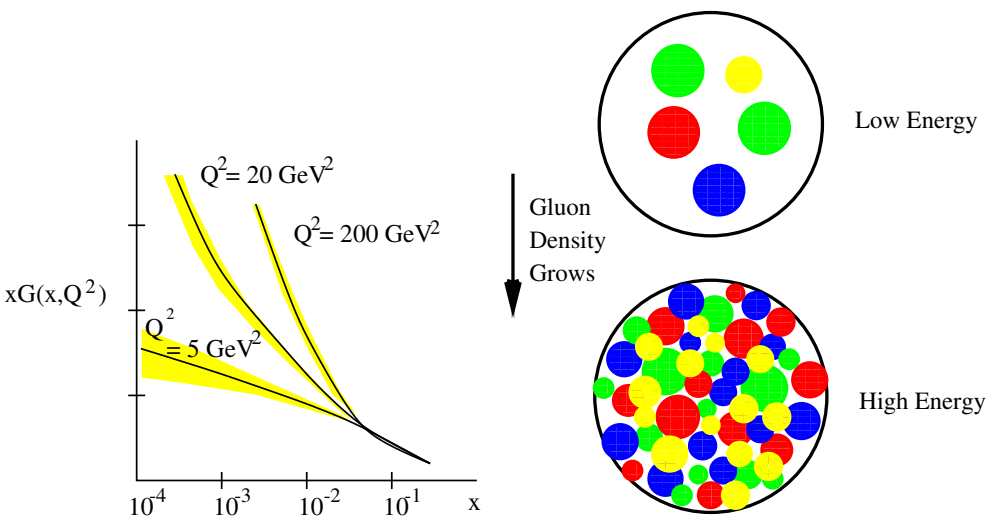

Figure 1. (a)The HERA data for the gluon distribution function as a function of x for various values of Q^2. (b) A physical picture of the low x gluon density inside a hadron as a function of energy.

rapidly as a function of decreasing x. This was expected in a variety of theoretical works,[2]-[4] and has the implication that the real physical transverse density of gluons must increase.[2]-[3],[5]. This follows because total cross sections rise slowly at high energies but the number of gluons is rising rapidly. This is shown in Fig. 1(b). This led to the conjecture that the density of gluons should become limited,

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that is, there is gluon saturation. [2]-[3], [5]

The low x gluons therefore are closely packed together. The strong interaction strength must become weak, $\alpha_S \ll 1$. Weakly coupled systems should be possible to understand from first principles in QCD.[5]

This weakly coupled system is called a Color Glass Condensate for reasons we now enumerate:[6]

- **Color** The gluons which make up this matter are colored.
- **Glass** The gluons at small x are generated from gluons at larger values of x. In the infinite momentum frame, these larger momentum gluons travel very fast and their natural time scales are Lorentz time dilated. This time dilated scale is transferred to the low x degrees of freedom which therefore evolve very slowly compared to natural time scales. This is the property of a glass.
- **Condensate** The phase space density

$$\rho = \frac{1}{\pi R^2} \frac{dN}{dy d^2 p_T} \tag{1}$$

  is generated by a trade off between a negative mass-squared term linear in the density which generates the instability, $-\rho$ and an interaction term $\alpha_S \rho^2$ which stabilizes the system at a phase space density $\rho \sim 1/\alpha_S$. Because $\alpha_S << 1$, this means that the quantum mechanical states of the system associated with the condensate are multiply occupied. They are highly coherent, and share some properties of Bose condensates. The gluon occupation factor is very high, of order $1/\alpha_S$, but it is only slowly (logarithmically) increasing when further increasing the energy, or decreasing the transverse momentum. This provides saturation and cures the infrared problem of the traditional BFKL approach.[7]

Implicit in this definition is a concept of fast gluons which act as sources for the colored fields at small x. These degrees of freedom are treated differently than the fast gluons which are taken to be sources. The slow ones are fields. There is an arbitrary X_0 which separates these degrees of freedom. This arbitrariness is cured by a renormalization group equation which requires that physics be independent of X_0. In fact this equation determines much of the structure of the resulting theory as its solution flows to a universal fixed point.[6]-[9]

There is evidence which supports this picture. One piece is the observation of limiting fragmentation. This phenomena is that if particles collide at some fixed center of mass energy and the distribution of particles are measured as a function of their longitudinal momentum from the longitudinal momentum of one of the colliding particles, then these distributions do not change as one goes to higher energy, except for the new degrees of freedom that appear. This is true near zero longitudinal momentum in the center of mass frame because new degrees of freedom appear as the center of mass energy is increased. In the analogy with the CGC, the degrees of freedom, save the new ones added in at low longitudinal momentum, are the sources. The fields correspond to the new degrees of freedom. The sources are fixed in accord with limiting fragmentation. One generates an

effective theory for the low longitudinal momentum degrees of freedom as fixed sources above some cutoff, and the fields generated by these sources below the cutoff. A recent measurement of limiting fragmentation comes from the Phobos experiment at RHIC shown in Fig. 2 [10]

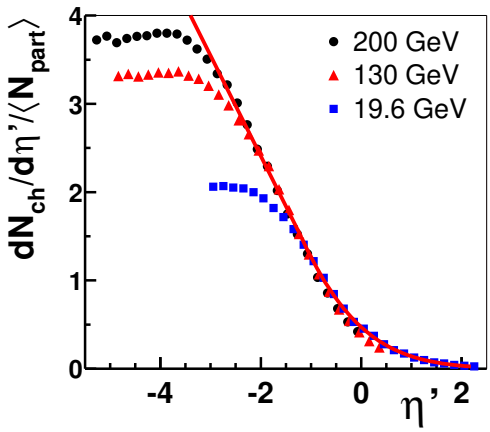

Figure 2. Limiting fragmentation and the RHIC data.

Of course the perfect scaling of the limiting fragmentation curves is only an approximation. As shown by Jalilian-Marian, the limiting fragmentation curves are given by the total quark, antiquark and gluon distribution functions of the fast particle measured at a momentum scale Q^2_{sat} appropriate for the particle that it collides with.[11] The saturation momentum Q_{sat} will play a crucial role in our later discussion. It is a momentum scale which is determined by the density of gluons in the CGC

$$\frac{1}{\pi R^2}\frac{dN}{dy} \sim \frac{1}{\alpha_S} Q^2_{sat} \tag{2}$$

The saturation momenta turns out to depend on the total beam energy because the longitudinal momentum scale of the target particle at fixed x of the projectile will depend upon the beam energy. It is nevertheless remarkable how small these violations appear to be.

The CGC may be defined mathematically by a path integral:

$$Z = \int_{X_0} [dA][dj] exp\left(iS[A,j] - \chi[j]\right) \tag{3}$$

What this means is that there is an effective theory defined below some cutoff in x at X_0, and that this effective theory is a gluon field in the presence of an external source j. This source arises from the quarks and gluons with $x \geq X_0$, and is a variable of integration. The fluctuations in j are controlled by the weight function $\chi[j]$. It is $\chi[j]$ which satisfies renormalization group equations which make the

theory independent of X_0.[8]-[14],[6]. The equation for χ is called the JIMWLK equation. This equation reduces in appropriate limits to the BFKL and DGLAP evolution equations.[4], [15] The theory above is mathematically very similar to that of spin glasses.

There are a variety of kinematic regions where one can find solutions of the renormalization group equations which have different properties. There is a region where the gluon density is very high, and the physics is controlled by the CGC. This is when typical momenta are less than a saturation momenta which depends on x,

$$Q^2 \leq Q^2_{sat}(x) \tag{4}$$

The dependence of x has been evaluated by several authors, [2],[16]-[18], and in the energy range appropriate for current experiments has been determined by Triantafyllopoulos to be

$$Q^2_{sat} \sim (x_0/x)^{\lambda}\ GeV^2 \tag{5}$$

where $\lambda \sim 0.3$. The value of x_0 is not determined from the renormalization group equations and must be found from experiment.

There is also a region of very high Q^2 at fixed x, where the density of gluons is small and perturbative QCD is reliable. It turns out there is a third region intermediate between high density and low where there are universal solutions to the renormalization group equations and scaling in terms of Q^2_{sat}.[17] In this region and in the region of the CGC, distribution functions are universal functions of only $Q^2/Q^2_{sat}(x)$. The extended scaling region is when

$$Q^2_{sat} \leq Q^2 \leq Q^4_{sat}/\Lambda^2_{QCD} \tag{6}$$

2 Why is the CGC Important?

The Color Glass Condensate is a new universal type of matter:

- **Matter:** The separation between the gluons in the CGC is small compared to the size of the system. Due to Lorentz time dilation, the lifetime of this matter is long compared to natural time scales.
- **New:** This matter can only be probed at high energy, and it may be produced in ultrarelativistic nuclear collisions.
- **Universal:** The CGC is universal independent of the type of hadron which generated it. Universality of this matter implies it is of fundamental interest.

The Color Glass Condensate is a theory of:

- The origin of glue and sea quarks in hadrons.
- The origin and nature of cross sections and particle production.
- The distribution of valence quantum numbers at small x.
- The initial conditions for the matter which evolves into the Quark Gluon Plasma at RHIC.

3 What does a high energy hadron look like?

In Fig. 3, a hadron is shown in its rest frame and as viewed from the infinite

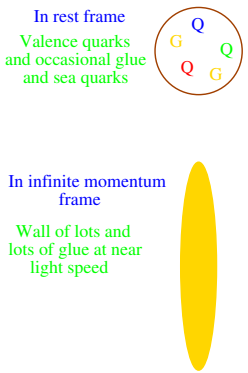

Figure 3. A hadron is shown at rest and in the infinite momentum frame.

momentum frame. The picture does not look Lorentz invariant. This is because the hadron is made of many different Fock space components, some containing valence quarks and a few gluons and sea quarks and some containing valence quarks plus many sea quarks and gluons. At low energies, one is sensitive to matrix elements which involve the valence quarks and a few gluons and sea quarks. For high energy collisions, typical matrix elements involve the valence quarks plus many sea quarks and gluons. At high energies, the hadron appears as if it is a gluon wall.

Of course the Color Glass Condensate description is Lorentz invariant. In fact, there is a very subtle duality of description. If one views the hadron in the infinite momentum frame, one is scattering from high density of gluonic matter. In the rest frame of the hadron, where the probe has very high energy, the Color Glass Condensate appears through coherent multiple scattering of the probe valence quarks. One can prove these descriptions are mathematically equivalent.[19]-[20]

The form of the fields associated with the CGC can also be easily seen. In the infinite momentum frame, the entire hadron is Lorentz contracted into a small region of $x^- = t - z$. The glassy nature of the fields makes them independent of the light cone time $x^+ = t + z$. Therefore the only large component of $F^{\mu\nu}$ is $F^{i+} \sim \partial/\partial x^- A^i$. A little algebra shows that

$$\vec{E} \perp \vec{B} \perp \vec{z} \tag{7}$$

In Fig. 4, these fields are shown. They correspond to the Lienard-Wiechart potential for a boosted electron, except that they are colored and they have a random polarization and color.

The density of gluons per unit area defines a momentum scale, the saturation momenta,

$$\frac{1}{\pi R^2}\frac{dN}{dy} \sim \frac{1}{\alpha_S}\, Q^2_{sat}(x) \tag{8}$$

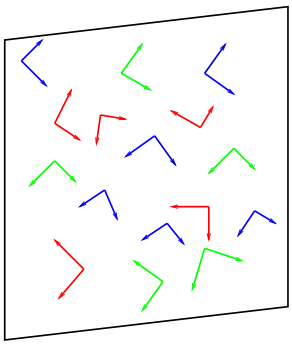

Figure 4. The distribution of colored fields within the CGC.

We insert the extra factor of $1/\alpha_S$ because the fields are classical, and therefore their density should scale in this way. This form is guaranteed because the system is almost scale invariant. Small violations of scaling arise because α_S is measured at Q_{sat}.

4 Experimental Evidence in Support of CGC

In this section, I discuss the accumulated evidence from HERA and RHIC, and elsewhere, in support of the hypothesis of a Color Glass Condensate.

4.1 Geometrical Scaling

Geometrical scaling is the observation[21]-[22] that the deep inelastic cross section for virtual photon scattering as a function of Q^2 and x is really only a function of

$$\sigma^{\gamma^* p} \sim F(Q^2/Q^2_{sat}) \tag{9}$$

where the saturation momentum is taken to be

$$Q^2_{sat} \sim (x_0/x)^\lambda \ 1GeV^2 \tag{10}$$

and $\lambda \sim 0.3$ and $x_0 \sim 10^{-4}$. This scaling works for $x \leq 10^{-2}$ and for the available data in Q^2. The data is shown in Fig. 5

It is straightforward to understand why this scaling works for the small $Q^2 \leq Q^2_{sat}$. This is the region of the CGC, and there is only one dimensionful scale which characterizes the system: the saturation momentum.[16] The surprise is that there is an extended scaling window for $Q^2_{sat} \leq Q^2 \leq Q^4_{sat}/\Lambda^2_{QCD}$.[17] This can be proven analytically. As well, one now has reliable computation of the dependence on x of the saturation momentum, that is, one knows the exponent approximately λ from theory, and it agrees with what is seen from the geometrical scaling curve.[18] What is not determined from the theory of the CGC is the scale x_0, and this must be found by experiment. This comes from the boundary conditions for the renormalization group equations.

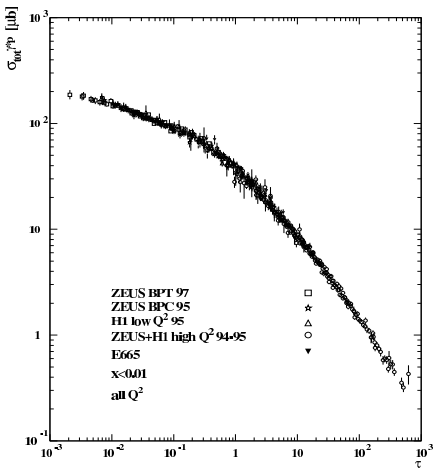

Figure 5. The cross section $\sigma^{\gamma^* p}$ as a function of the scaling variable $\tau = Q^2/Q_{sat}^2$.

4.2 The Structure Function F_2

Using the dipole description of the virtual photon wavefunction, the structure function F_2 can be related to the gluon distribution function which arises from the CGC. One can compute and compare to data. There are 3 unknown parameters in this description: the hadron size, the scale x_0 and the quark mass. In addition, the parameter λ which controls the energy dependence of the saturation momentum is determined by experiment to better accuracy than it is currently known theoretically.[16]-[24] The results for the description of the data are remarkably good for $x \leq 10^{-2}$ and $Q^2 \leq 45\ GeV^2$.[24]

One should note that this description includes both the high and low Q^2 data. Descriptions based on DGLAP evolution can describe the large Q^2 points. The CGC description is very economical in the number of parameters which are used.

4.3 Diffraction and Quasi-Elastic Processes

The CGC provides a description of the underlying structure of gluonic matter inside a hadron. As such, it should be sensitive to probes of the transverse extent of this matter, which can be experimentally studied in diffraction and related quasi-elastic particle production.[25]

For diffraction by a virtual photon, a good theoretical first principles computation is only available for small mass states which are produced by the virtual photon.[26]-[33]. The agreement is good for small masses, and even reasonable for large masses.

There are additional computations of quasi-elastic ρ meson production and J/Ψ production[32]-[33].

4.4 Qualitative Understanding of Total Hadronic Cross Sections

The elastic and total cross section as a function of energy and are believed to grow as $ln^2(E)$. To understand this behaviour, imagine that we take some probe and try to penetrate the hadron. The cross section is defined by the impact parameter at which the hadron become opaque. We expect that at fixed x, the impact parameter distribution of matter inside a hadron fall off at large b like $e^{-2m_\pi b}$. At fixed impact parameter, we expect that the number of gluons grows as $(x_0/x)^\lambda$. Setting

$$(x_0/x_{min})^\lambda \; exp\,(-2m_\pi b) \sim 1 \tag{11}$$

gives

$$\sigma \sim b^2 \sim ln^2(1/x_{min}) \sim ln^2(E) \tag{12}$$

Here x_{min} is the minimal value of x accessible for some energy E and goes as $x_{min} \sim \Lambda_{QCD}/E$.

This simple physically motivated picture give the expected $ln^2(E)$ growth of the total cross section. It has proven difficult to make these simple arguments rigorous.[34]-[35].

5 Heavy Ion Collisions

The collision of two ultrarelativistic heavy ions can be visualized as the scattering of two sheets of colored glass, as shown in Fig. 6. [36]-[39] At very early times after

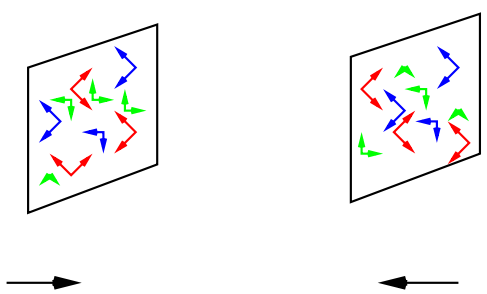

Figure 6. A collision of two ultra-relativistic nuclei.

the collision the matter is at very high energy density and in the form of a CGC. As time goes on, the matter expands. As it expands the density of gluons decreases, and gluons begin to propagate with little interaction. At later times, the interaction strength increases and there is sufficient time for the matter to thermalize and form a Quark Gluon Plasma. This scenario is shown in Fig. 7, with realistic estimates for energy density and time scales appropriate for the RHIC heavy ion accelerator.

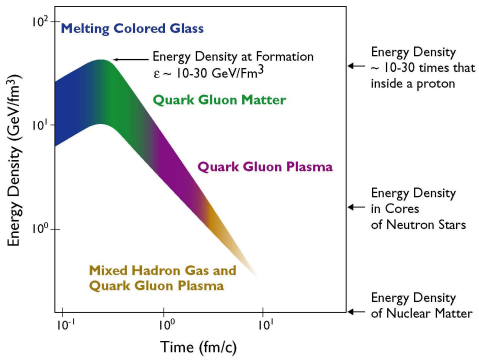

Figure 7. The evolution of a heavy ion collision at RHIC energy.

5.1 The Multiplicity

The CGC allows for a direct computation of the particle multiplicity in hadronic collisions. If one naively tries to compute jet production, the total multiplicity is infrared divergent. This follows because of the $1/p_T^4$ nature of the perturbative formula for gluon production

$$\frac{1}{\pi R^2}\frac{dN}{dyd^2p_T} \sim \frac{1}{\alpha_S}\frac{Q_{sat}^4}{p_T^4} \tag{13}$$

In the CGC, when $p_T \leq Q_{sat}$, this formula is cutoff. This means that the total gluon multiplicity goes as

$$\frac{1}{\pi R^2}\frac{dN}{dy} \sim \frac{1}{\alpha_S}\,Q_{sat}^2 \tag{14}$$

One can compute the proportionality constant and before the RHIC data appeared, predictions were made for the gluon multiplicity.

These predictions and computations of the dependence of multiplicity on centrality and rapidity agree remarkably well with the RHIC data.[40]-[46]

5.2 High p_T Particles

There is now a vast literature on high p_T particle production in pp, pA, and AA collisions.[47]-[65] The Color Glass Condensate describes effects in the small x region of the hadron wavefunction, and provides a theory of shadowing for nuclei. The predictions of this theory are in good qualitative and semi-quantitative agreement with the RHIC data. Experiments at the LHC and at proposed facilities such as eRHIC may provide crucial tests of the Color Glass Condensate.

6 Summary

The Color Glass Condensate provides a theory of the structure of wee partons inside of all hadrons. There is a wide range of data from DIS and heavy ion experiments

which suggest that this description has merit. Future experiments which probe smaller x and high energy scales may turn the optomistic interpretation of existing data into a strong and compelling case for the CGC.

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