THE COLOR GLASS CONDENSATE RHIC AND HERA*

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In this talk, I discuss a universal form of matter, the Color Glass Condensate. It is this matter which composes the low x part of all hadronic wavefunctions. The experimental programs at RHIC and HERA, and future programs at LHC and eRHIC may allow us to probe and study the properties of this matter.

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1. Introduction

The Color Glass Condensate is the limiting and universal form of gluonic matter which composes the low x part of a hadron wavefunction as the density of gluons becomes large. It controls the typical generic features of high energy processes in collisions as diverse as eA, pA, pp or AA. It provides us with a simple description of these features in terms of the properties of the Color Glass.

In this talk, I shall try to answer the following questions:

- What is a Color Glass Condensate?
- Why is it important for hadron–hadron interactions and for RHIC?
- How does it describe lepton–hadron interactions?
- What might we learn about the Color Glass Condensate from further experimental study?

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1.1. *The Color Glass Condensate*

To understand this new form of matter, it is convenient to imagine a hadron in a reference frame where it has very large longitudinal momentum. We will be interested in the constituents of the hadron wavefunction which have small longitudinal momentum in this frame of reference. These low momentum constituents are produced by the high momentum ones. Because the high momentum constituents appear to have time scales which are Lorentz time dilated compared to their natural scales, and since they induce the low momentum fields associated with the low momentum particles, the low momentum fields evolve very slowly compared to their natural time scale. Hence the term, Color Glass, since the fields are composed of color gluons, and glass because the time scale for evolution of these low momentum fields is much longer than their natural time scale. These fields live on a two dimensional sheet because of the Lorentz contraction of the high energy hadron. We shall argue in the following paragraphs that the phase space-density of these fields becomes large and forms a condensate [1].

The fields on the two dimensional sheet turn out to be similar to the Lienard–Wiechart potentials of electrodynamics. They correspond to plane waves as in the Weizsacker–Williams approximation of electrodynamics, except that they have color. They have their color electric field perpendicular to their color magnetic field and both perpendicular to their direction of motion, $\vec{E}^a \perp \vec{B}^a \perp \vec{z}$. They have a random color. This is shown in Fig. 1.

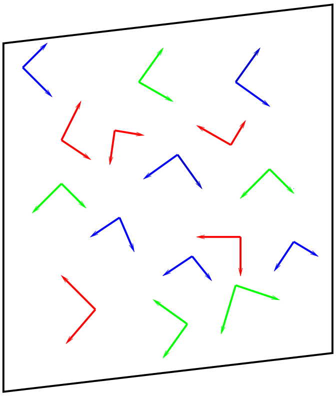

Fig. 1. The Color Glass Condensate.

The gluon structure function $xG(x, Q^2)$ is experimentally measured to increase at small x. In the reference frame where the hadron is very fast, x is the ratio of a constituent energy to the projectile energy. The gluon distribution is shown in Fig. 2(a). Note the rapid increase in $xG(x, Q^2)$ as a function of x for small x. This is the origin of the "small x problem".

This means that the piece of the hadron wavefunction relevant for small x processes has an increasing density of gluons. In Fig. 2(b), we look at a hadron headed along the beam direction. As x decreases, the density of gluons increases.

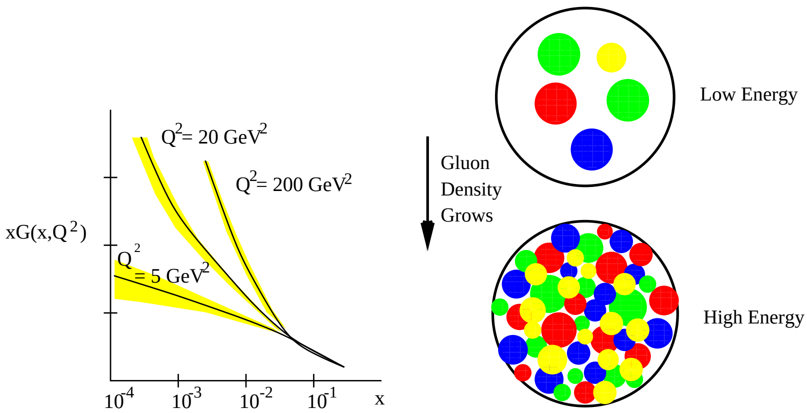

Fig. 2. (a) The gluon structure function as a function of x for various Q^2. (b) The increase in density of gluons as x decreases.

The phase space density of gluons is

$$\rho = \frac{1}{\pi R^2} \frac{dN}{dy d^2 p_{\rm T}} \,, \tag{1}$$

where R is the hadron size, $p_{\rm T}$ is the transverse momentum of a constituent, and $y \sim \ln(1/x)$. The high density of gluons is generated dynamically and is caused by an instability, which is proportional to the density. The instability is stabilized when the density of partons becomes large enough so that interactions of order $\alpha_{\rm QCD}\eta^2$ become of the order of the linear instability. Here $\eta = \int d^2 p_{\rm T} \rho$. This requires that

$$\eta \sim Q^2_{\rm sat}/\alpha_{\rm QCD} \,. \tag{2}$$

The factor of Q^2 arises because we consider densities per unit area, and $Q^2_{\rm sat}$ carries this dimension. This $Q_{\rm sat}$ is called the saturation momentum. The factor of $\alpha_{\rm QCD}$ is the strong coupling strength of QCD. When $Q_{\rm sat} \gg \Lambda_{\rm QCD}$, we expect that $\alpha_{\rm QCD} \ll 1$, so that the system becomes a high density Bose Condensate.

The name Color Glass Condensate arises therefore because

- **Color**

  The gluons are colored.

- **Glass**

  The natural time scale for the evolution of the gluon field is Lorentz time dilated. This is like a glass which is a liquid on long times scales but a solid on short ones.

- **Condensate**

  The phase space density is as large as it can be.

1.2. Space time evolution of heavy ion collisions

A collision of two sheets of Colored Glass is shown in Fig. 3.

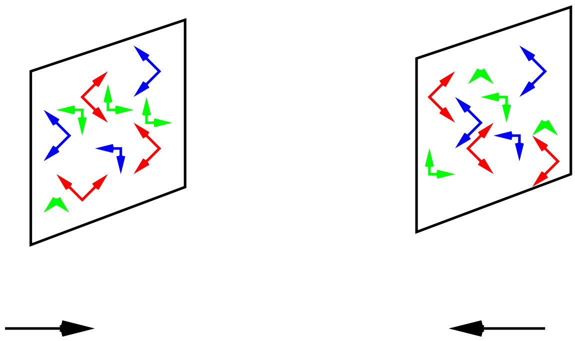

Fig. 3. High energy nucleus-nucleus collisions.

This is the picture of nucleus–nucleus collision which arises from the Color Glass Condensate [2].

The time evolution of the matter produced in these collisions is divided into several stages:

- **Initial conditions**

  For $t < 0$, the two sheets approach one another. The Color Glass is frozen in each nucleus.

- **Melting the Color Glass**

  During the time $0 < t < t_{\rm form}$, the Color Glass melts into quarks and gluons. It is estimated that $t_{\rm form} \sim 1/Q_{\rm sat} \sim .1$–$.3$ Fm/c at RHIC energy. The energy density of the matter at formation is somewhere around $\varepsilon_{\rm form} \sim Q^4_{\rm sat}/\alpha_s \sim 20$–$100$ GeV/Fm^3.

- **Thermalization**

  During the time $t_{\rm form} < t < t_{\rm therm}$, the matter expands and thermalizes. Typical thermalization time is estimated to be $t_{\rm therm} \sim .5$–1 Fm/c.

- **Hydrodynamic expansion**

  The system expands as a thermal system until a time of decoupling which is typically about $t_{\text{decoupling}} \sim 10$ Fm/c at RHIC energy. Here the matter presumably starts as a Quark Gluon Plasma, evolves through a mixed phase of hadrons and Quark Gluon Plasma and eventually becomes a gas of pions. In this stage, most of the physics interesting for studies of the phase transition or cross over between Quark Gluon Plasma and ordinary hadronic matter takes place.

One can use this description to relate experimentally measured multiplicities to energy density as a function of time. The result is shown in Fig. 4. We see that energy very high energy densities are achieved. One can also use the Color Glass Condensate picture to compute multiplicity distributions as a function of the centrality of the collision and as a function of rapidity, with agreement with results from RHIC. One may even be able to explain the observed suppression of jets relative to incoherent pp scattering [3].

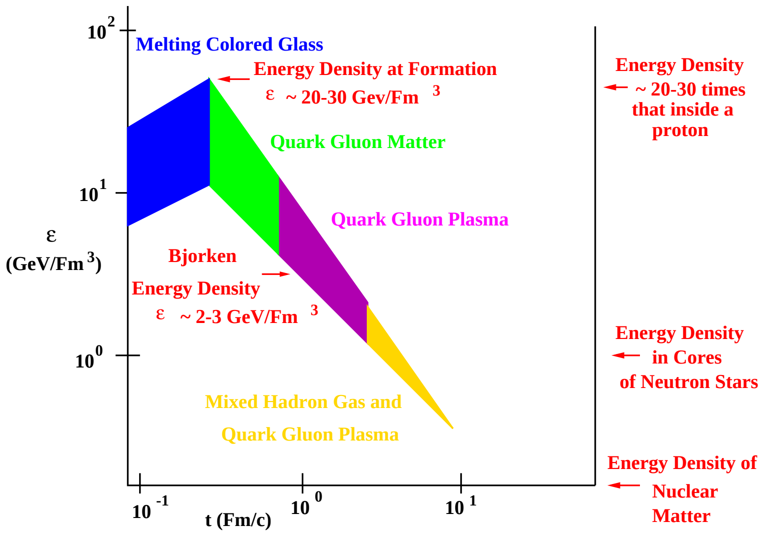

Fig. 4. Bounds on the energy density as a function of time in heavy ion collisions.

2. The Color Glass Condensate and lepton–hadron scattering

Due to lack of space, I will enumerate the successes of the Color Glass Condensate for the description of deep inelastic scattering data.

- The very successful Golec-Biernat Wusthoff model which describes deep inelastic inclusive and diffractive data arises naturally as an approximate description [4]. A fuller treatment requires an impact parameter integration and can describe diffractive vector meson production [5].
- Unitarity is naturally and simply preserved in the Color Glass Condensate description. The Froissart bound is saturated [6].
- Geometric scaling is a consequence of the Color Glass Condensate, out to very large values of Q^2 [7].
- Universality as a function of gluon multiplicity per unit area allows the use of nuclei to produce the Color Glass Condensate at lower energies than would be possible for pp collisions [8].

3. The Color Glass Condensate and further experimental study

Again for reasons of space, I enumerate only a few possibilities:

- The comparison between AA collisions and pA collisions can isolate effects due to the initial state (Color Glass Condensate) from those due to later times (Quark Gluon Plasma).
- The proton fragmentation region of pA scattering allows a probe of the low x part of the nuclear wavefunction.
- Low and intermediate Q^2 studies of both deep inelastic and diffractive scattering in ep collisions can isolate the saturation scale and test the theory.
- eA scattering allows the production of the highest gluon densities at fixed energy and therefore is an excellent place to test theoretical predictions of the Color Glass Condensate

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REFERENCES

[1] L.V. Gribov, E.M. Levin, M.G. Ryskin, *Phys. Rept.* **100**, 1 (1983); A.H. Mueller, Jian-wei Qiu, *Nucl. Phys.* **B268**, 427 (1986); L.D. McLerran, R. Venugopalan, *Phys. Rev.* **D49**, 2233 (1994); 3352 (1994); E. Iancu, A. Leonidov and L. D. McLerran, *Nucl. Phys.* **A692**(2001); E. Ferreiro, E. Iancu, A. Leonidov, L.D. McLerran, *Nucl. Phys.* **A703**, 489 (2002).

[2] A. Kovner, L.D. McLerran, H. Weigert, *Phys. Rev.* **D52**, 6231 (1995); 3809 (1995); A. Krasnitz, R. Venugopalan, *Phys. Rev. Lett.* **84**, 4309 (2000); *Nucl. Phys.* **B557**, 237 (1999); A. Krasnitz, Y. Nara, R. Venugopalan, *Phys. Rev. Lett.* **87**, 192302 (2001).

[3] For a recent review of RHIC results, see L. McLerran, `hep-ph/0202025`.

[4] K. Golec-Biernat, M. Wusthoff, *Phys. Rev.* **D59**, 014017 (1999); **D60**, 114023 (1999).

[5] S. Munier, A.M. Stasto, A.H. Mueller, *Nucl. Phys.* **B603**, 427 (2001).

[6] E. Ferreiro, E. Iancu, K. Itakura, L. McLerran, `hep-ph/0206241`.

[7] A.M. Stasto, K. Golec-Biernat, J. Kwiecinski, *Phys. Rev. Lett.* **86**, 596 (2001); E. Iancu, K. Itakura, L. McLerran, *Nucl. Phys.* **A708**, 327 (2002); A. Mueller, D.N. Triantafyllopoulos, *Nucl. Phys.* **B640,** 331 (2002).

[8] The Electron Ion Collider (EIC) Whitepaper, BNL-68933-02/07-REV.