Communication

A New Glassy State of Matter: The Color Glass Condensate

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This communication describes a newly reported state of matter: The color glass condensate. Analogies to glass science are made for this nuclear physics discovery.

In response to recent announcements in the international scientific community, we are pleased to give a brief overview of a new experimental claim that the Color Glass Condensate, an additional sixth state of matter, has been observed. The previously known states of matter include solid, liquid, gas, plasma, and the Bose–Einstein condensate. In the traditional use of the words from our field of glass science, this new state of matter is not a glass, has no color, and is not a condensate. These terms only describe the new state through useful analogies to what we commonly think these terms mean. This development is an exciting new result from the Large Hadron Collider (LHC) that is nestled on the Swiss-French border near Geneva.

The proposed new state of matter relies heavily on some of the great ideas of modern physics including length contraction from Einstein’s theory of relativity. This theory has ample demonstrated experimental agreement and predicts that objects contract in the direction of their motion, as seen by stationary observers.

First, we will briefly explain the connotation of each term in the Color Glass Condensate. Afterward, we describe briefly the new results from CERN.

Color

In particle physics, the term color refers to the type of the field in strong interactions that is similar to charge in electromagnetic interactions. Color is associated with the quarks and gluons that are the quanta of the strong nuclear force (SNF) field as photons are for the electromagnetic (EM) field. The term color is just an unfortunate naming convention that has nothing to do with differing wavelengths of visible light. Electric charge comes in two qualities: positive and negative, whereas in Quantum Chromodynamics (QCD, the theoretical framework of strong interactions), a quark’s color is assigned one of the three values: red, green, and blue. An antiquark has one of the three anticolors, called

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antired, antigreen, and antiblue (represented as cyan, magenta, and yellow, respectively). Gluons are mixtures of color and anticolor components, such as red and magenta. Hadrons are composite particles whose total color is zero. Nature accomplishes this by using two or three quarks to form the hadrons. The color is conserved to zero by using a quark-anti-quark pair or three quarks of different colors yielding zero net color.

Glass

In this new state of matter, glass refers to the disordered state of the gluons. The disorder arises, in part, because of a so-called gluon wall that is built as a result of length contraction due to the high relative velocity seen by the colliding particles. The high velocity is with respect to the target particle (the gluon wall) that other particle collides with. In essence, the gluons pile on each other in an amorphous manner as the interaction dimension shrinks as viewed by the incoming particle. Let us assume that the x-axis is in the direction of motion. The shrinkage of the x dimension for the observed particle is described using relativity by:

$$\Delta x = \Delta x_p / \gamma$$

where \(\Delta x\) is the contracted dimension as seen in the opposing particle’s motion toward the observer due to length contraction, \(\Delta x_p\) is the proper length of a particle measured in the particle’s own frame of reference, and \(\gamma\), the relativistic correction, is a number larger than one that is given by

$$\gamma = 1 / \sqrt{1 - v^2/c^2}$$

In Eq. (2), \(v\) is the relative velocity of the two particles, and \(c\) is the speed of light. As \(v\) approaches \(c\), the \(x\) shrinkage can be very large. For example, for \(v = 0.9999c\), \(\gamma\) is about 70.7.

Condensate

In the context of the whole term Color Glass Condensate, condensate refers to the large density of the gluons as they pile up due to length contraction and a resulting coherence in the wave function of the gluons. It is not a chemical condensate in the manner that atoms undergo.

The evidence for the new state of matter is based on highly correlated directions of some of the released particles from 2 million lead–proton collisions observed in the Compact Muon Solenoid (CMS) experiment at the LHC. The same behavior between generated particle pairs was observed in CMS experiments during proton–proton collisions in 2010 (see Fig. 1).

The first discussion on how to interpret the LHC result was focused on the possible formation of a quark-gluon plasma (QGP). A QGP, a hot soup of quarks and gluons, is believed to be the state of the universe shortly after the Big Bang. The wave of QGP created during the heavy ion collisions sweeps some of the resulting particles in the same direction, which explains the two and three particle that correlations have been observed in heavy ion (lead, gold, copper) collisions at the LHC (see Fig. 1), and at the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory. However, based on calculations that protons in the LHC should not create such plasma, the QGP interpretation was dismissed for this mysterious correlation in proton collisions.

The theoretical model proposed by R. Venugopalan to explain this phenomenon suggests that proton–proton collisions produce a liquid-like wave of gluons, known as the Color Glass Condensate, shortly before the particle direction correlation was seen. Although protons consist of three quarks with gluons between them as they gain energy, up to 7 TeV in the LHC, many complementary gluons are added, see Fig. 2. The increase in the number of gluons means a consequent decrease in individual gluon energy, hence creating a very dense medium filled with low energy gluons. This causes the color field to be perceived as a classical field, like the Coulomb field, by the other fast-moving particles. In the rest frame of the target proton, a fast-moving particle sees these classical fields as contracted to sit atop one another and act coherently. This saturated gluon medium is the Color Glass Condensate; the color is due to the color of the gluons, it is a glass because of the random packing of slow gluons in the medium during collisions, and it is a condensate due to phase space density coherence.

The correlated wave functions of the gluon field are the source of the entanglement between two particles generated during the collision. This quantum entanglement manifests itself in the correlated direction
of the particles generated in the collision, which is the experimental evidence for this new state of matter. (the peaks seen in Fig. 1)

In summary, glass shows up where you least expect it—even in the new LHC CMS detector!

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References


