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Studying the Early Universe via Quark-Gluon Plasma

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Abstract

Shortly after the Big Bang, the early universe is a high temperature and high density environment. In order to recreate this state of matter in the laboratory, a little bang was created by colliding heavy ions at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and subsequently at the Large Hadron Collider (LHC) at CERN. From the most energetic collision at RHIC, the created temperature is estimated to be at least 221 MeV, where the quarks in the nucleon will no longer be confined and a new state of matter, quark-gluon plasma (QGP), is formed. Detailed studies of the QGP, reveal that QGP has the lowest "shear viscosity to entropy ratio" which is close to the lowest bound determined from quantum mechanics. This makes QGP the "most perfect fluid" in universe. The measured properties of QGP should also provide constraints for theoretical models of the early universe.

Keywords: Quark-Gluon Plasma, Perfect Fluid

The universe we know began with a Big Bang. In the first few micro seconds after the Big Bang, the universe was a high temperature and high density environment. Then the primordial fireball starts to cool off. As time passed, the system expanded and cooled, during which, the universe evolved through several phases. At a temperature above the critical temperature of Quantum Chromodynamics (QCD), the quarks and gluons are deconfined, which is a phase known as quark-gluon plasma. When the temperature crosses the QCD critical temperature, a QCD phase transition occurs and quarks are confined and hadronized into mesons and baryons. As the cooling proceeds, the universe cooled to the temperature of the cosmic background radiation, T = 2.73K. Therefore, recreating the conditions of the early universe allows one to study the properties of the quark-gluon plasma, which in turn provides important information on the evolution of the early universe.

In the world around us, all quarks are confined in the form of baryons, such as protons and neutrons. According to QCD, the strength of the interaction between quarks is described by the strong coupling constant. The magnitude of the strong coupling constant is small when the momentum exchange is large at high energy, which is also known as "asymptotic freedom." One might imagine that for small QCD coupling constants, or when the temperature is high, quarks and gluons would be deconfined and move freely as a gas, or as a quark-gluon plasma (QGP). To create a quark-gluon plasma in laboratory, one needs to achieve the deconfinement energy which has only existed in the early universe.

QCD predicts that at a critical temperature, a phase transition from hadronic gas to quark gluon plasma will occur, causing a sudden increase in the number of degree of freedom when transitioning from the hadron gas phase to the QGP phase. One calculation from lattice QCD, shown in Fig. 1 [1], indicates a sudden increase in the ratio of the energy density over the fourth power of the temperature, a phase transition, at the critical temperature, T_c. The high temperature phase is known as the "quark-gluon plasma" [2]. The critical temperature, T_c, is estimated to be 175 MeV from these lattice QCD calculations.

There are two methods to achieve the condition of small QCD coupling constant in laboratory. First, one can "heat up" the nucleon. Second, one can reduce

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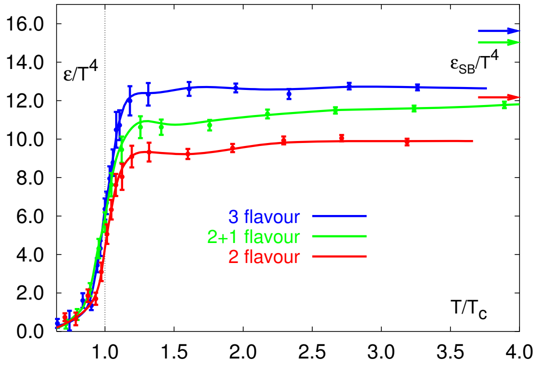

Figure 1: Energy density, ε, as a function of temperature from Lattice QCD calculations [1]. The energy density increases rapidly when T > T_C.

the distance between the quarks, i.e. "squeeze" the nucleon. Both of these conditions can be achieved by colliding large nuclei at relativistic energies and creating a high temperature and high energy density environment. This is accomplished at the Relativistic Heavy Ion Collider (RHIC) located in Brookhaven National Laboratory, where gold (and copper and uranium) nuclei are collided at upto 200 GeV per nucleon pair ($\sqrt{s_{NN}}$ = 200 GeV). Starting in 2010, the Large Hadron Collider (LHC) at CERN has collided lead nuclei at even higher energies ($\sqrt{s_{NN}}$ = 2.76 TeV).

One of the most crucial questions in the study of heavy-ion collisions is the temperature of the matter created at RHIC. One direct method to determine this temperature is via the measurement of the direct photons thermally emitted from the quark-gluon plasma. The temperature of the QGP can be extracted from the slope of the spectra of the thermal photons.

It is predicted that the major source of direct photons for $1 < p_T < 3$ GeV/c is the thermal radiation from the QGP. But in this p_T range, there is a large background of hadronic decay photons. Since any photon production process has a sub-process of producing virtual photons, which decay to electron-positron pairs, one can measure the virtual photons as a proxy of real photons by requiring the mass of the electron pairs to be larger than the mass of the π^0 to suppress the background. PHENIX has measured low mass di–electrons in Au+Au and p+p collisions ($m_{e^+e^-} < 0.3$ GeV/c^2 and $1 < p_T < 5$ GeV/c) [3].

An excess photon yield for $1 < pT < 3$ GeV/c is found in central Au+Au collisions compared to p+p collisions as shown in Fig. 2. After fitting an exponential function, $Ae^{-p_T/T}$, to the spectra of this excess, or

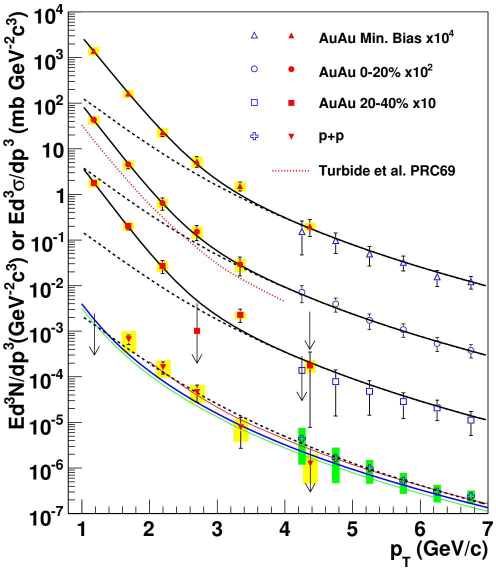

Figure 2: Spectra of direct photon of p+p and Au+Au collisions in various centralities [3]. The direct photon spectra in p+p collisions is well described by pQCD calculations. There is an enhancement of the photon yield in Au+Au collisions compared to scaled p+p spectra between p_T = 1-3 GeV/c.

the thermal radiation, the slope of the exponential is extracted as $T = 221 \pm 19^{stat} \pm 19^{syst}$ MeV, which is well above the critical temperature expected from lattice QCD. In other words, quark-gluon plasma has been created in the highest energy Au+Au collisions at RHIC.

There are several interesting properties of this new type of QCD matter. Here we focus on the azimuthal angular distributions of the charged particles emitted from the QGP. Fig. 3 is a cartoon of a typical collision geometry with non-zero impact parameter. When two gold nuclei collide with each other at a non zero impact parameter, it creates almond-shape colliding area in the transverse plane. The energy released in this colliding volume is high enough to melt the nucleons and form the quark-gluon plasma. After the collision, this volume starts to expand. If the quarks and gluons weakly interact, or behave like gas, the QGP will expand uniformly in all directions. If the interaction between quarks and gluons is large, coupled with the pressure gradient created upon collision, the plasma will expand along its short axis and create an azimuthal anisotropy. The system expands rapidly after collision, so this anisotropy is the largest at the beginning of the collision, and disappears at the end of the expansion. Therefore, this anisotropy tells us the information about the initial state