Effect of Jet Quenching on the Thermodynamics of Quark Gluon Plasma

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Research Article

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ABSTRACT

Heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) results a hot system at energy density. This would result a fluid matter where collective flow is observed at zero viscosity. The suppression of jets are observes in the form of mach cones. This suppression indicates strongly coupled plasma where thermal fluctuations in the plasma characterize the high energy density of the medium. This results in color confinement phase of the quark gluon plasma. The suppression of both light (u, d, s) and heavy (c, b) hadrons is observed at large transverse momenta.

INTRODUCTION

The study of ultra-relativistic heavy ion collisions at RHIC offers the possibility concerning for instant the state of matter called quark gluon plasma at very high temperature and density. We propose to consider strongly coupled classical non-relativistic plasmas to learn about qualitative features of the strongly coupled quark gluon plasma [1].

The Relativistic Heavy Ion Collider (RHIC) began colliding nuclei at ultra-relativistic energies in 2000 to investigate the properties of hot, dense QCD. RHIC accelerates and collides a range of nuclei from protons to gold (Au) at centre-of-mass energies up to $\sqrt{s}$=500 GeV for p + p and $\sqrt{s_{NN}}$=200 GeV for Au+Au. The Large Hadron Collider (LHC) heavy ion program will explore further into the high energy density regime of QCD. The LHC will collide nuclei at a top energy of $\sqrt{s_{NN}}$=7 TeV for Pb+Pb with ALICE, ATLAS and CMS expected to participate in heavy ion data taking.

The jet quenching and this suppression occurs when partons travels through hot and dense plasma with a consequence suppression of high momentum particles are observed in Relativistic Heavy Ion Program at RHIC [2-4] of the energy loss of these partons. This energy loss is deposited in the hot dense medium or absorption of the radiated gluons which leads to the collective effect i.e., formation of a mach cone. The redistribution of the jet energy and momentum is reflected in the correlations of particles associated with the jet [5].

Particles evaluated in gluon matter with large transverse momentum more than the QCD scale $\wedge_{QCD}$ when $\wedge_{QCD} \sim 0.2$ GeV in QCD estimation. The hard probe produced in a very short time scale $\tau_0 = 1/\mathrm{p_T} \sim 0.1 fm/c$ when partons scattered with large transverse momentum, they signify to such hard probes. At large $\mathrm{p_T}$, partons split into quark-antiquark pairs and subsequently radiating gluons.

The data obtained at RHIC confirms that the quark gluon plasma produced in a strongly interacting medium. But the absolute value of viscosity to entropy ratio η/s leads to the weak coupling medium which is based on HTL approximation. This approximation clears the frame of weakly coupled quasi particles with partons. In jet quenching, the particles belongs to jet are excited and correlation have been observed. The shock waves in the form of Mach cones are formed. These shock waves are associated with quasi-particles. The Mach shocks generated due to partonic jets propagating through a deconfined strongly interacting matter. The QGP expands both radially and longitudinally which deform the shock waves. In hydrodynamics, matter in the form of fluid can only generate and propagate shock waves which can be described by quasi particle picture. Thus shock waves can create entropy in the system [6]. There is a general relation between jet parameter $\hat{q}$ and coffecient of viscosity η for weakly coupled partonic plasma.

Non-relativistic plasma is said to be strongly coupled if the value of Coulomb coupling parameter $\Gamma = q^2 / dT$ is larger than 1 and the plasma exist in liquid form if the coulomb coupling parameter is lower than the value one [7,8].

Quenching Effect

There are many charge particles within the plasma that can influence many others nearby quasi particles. This sets a sphere of influence. Such a sphere around the charge particle through which it can influence nearby many quasi particles is called a Debye sphere. The radius of Debye sphere is represented by the Debye mean free path λ_d. This Debye mean free path is also called the Debye screening length. The number of quasi particles influenced by Debye sphere is given by Plasma parameter $\wedge = 4\pi n\lambda_d^3$. The relation between shear viscosity η and Debye mean free path λ_d of quasi particles with momentum *p* in the medium is,

$$\eta = C\rho(p)\lambda_d \tag{1}$$

The Casimir invariant for gluon is equal to *c*=1/3 and momentum *p*=3*T* for collection of thermal massless particles and the Debye length $\lambda_d = 1/m_D$ where m_D is the Debye screening mass. Therefore,

$$\eta \sim C \times \rho \times 3T \times \lambda_d \tag{2}$$

Using the relation $s \sim 3.6\rho$ for a gas of free massless bosons, ratio of shear viscosity to entropy relative to Debye mean free path may be derived as,

$$\frac{\eta}{s} \approx \frac{3 \times \frac{1}{3} T\rho\lambda_d}{3.6\rho} \tag{3}$$

$$\approx \frac{T\lambda_d}{3.6}$$

$$\approx 0.27T\lambda_d \tag{4}$$

Using relation $\lambda_d = 1/md$ where m_D is the Debye screening mass, the entropy to density ratio becomes,

$$\frac{\eta}{s} \sim \frac{0.27T\lambda_d}{m_d} \tag{5}$$

This shows that the large value of Debye mass for quasi-particles, there will be a small value of entropy to density ratio η / s and it is considered to be bounded by the quantum limit $\eta / \mathrm{s} \geq 1/4\pi$.

The perturbative distribution in QCD always shows the interaction between hard jets and strongly coupled plasma medium. But at the short distance, there is a weak QCD coupling and the partonic excitation reduced and finally dies. The Debye screening mass $1/m_d \sim 1/\mathrm{g}T$ is very short in perturbative QCD at weak coupling. Therefore, we can approximate the relations,

$$\frac{0.27T}{m_D} \sim \frac{0.27T}{\mathrm{g}T} \tag{6}$$

Or,

$$\frac{\eta}{s} \sim \frac{0.27T}{\mathrm{g}'} \tag{7}$$

Where, g' is the ratio between potential energy to the kinetic energy per particle of the medium i.e., $\mathrm{g}' \sim e^2 n^{1/3} / T$. Therefore for weak coupling,

$$\frac{\eta}{s} \sim \frac{0.27T}{e^2 n^{1/3}} \tag{8}$$

Where, e is electric charge on the quasi particle and *n* is number density of quasi particles. For weak interaction $\mathrm{g}' \ll 1$, which is also bounded by the limit $\eta / s \geq 1/4\pi$.

We can find the equation for jet quenching parameter $\hat{q}$ weakly coupled plasma which ultimately confirmed the quasi-particle dominated quark gluon plasma. The equation of shear viscosity to entropy ratio [9] is,

$$\frac{\eta}{s} \approx 3.75C\frac{T^3}{\hat{q}} \tag{9}$$

Comparing equations, we get

$$3.75C\frac{T^3}{\hat{q}} = 0.27T\lambda_d \tag{10}$$

After solving and rearranging the equation gives the quenching parameter,

$$\hat{q} \approx 4.6\frac{T^2}{\hat{q}} \tag{11}$$

This relation shows that the jet quenching is large for small value of mean free path or Debye screening length and for large value of temperature.

CONCLUSION

The result is nearly equal to the lower bound limit for η / s and lies within the range of shear viscosity to entropy ratio. The result is conflict with the RHIC observation. But the quark gluon plasma at RHIC is thought to be considered as strongly coupled regime and cannot be described as weakly coupled or quasi particle plasma. Also, quenching parameter $\hat{q}$ continuous to increases with temperature which suggested that $\hat{q}$ may be broadly applicable as a coupling strength of quark gluon plasma. Therefore we generally observed the following relation holds for strong or weak coupled plasma:

$$\hat{q}\begin{Bmatrix}\geq\\<\end{Bmatrix}4.6\frac{T^2}{\lambda_d}\begin{cases}\text{weakly couped plasma}\\\text{strongly coupled plasma}\end{cases}$$

The relation confirmed that the value of shear viscosity to entropy ratio is generally small as the jet quenching is high.

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