Creation of Quark-gluon Plasma in Celestial Laboratories

R. K. Thakur

*Retired Professor of Physics, School of Studies in Physics
Pt.Ravishakar Shukla University, Raipur, India
21 College Road, Choube Colony, Raipur-492001, India

Abstract

It is shown that a gravitationally collapsing black hole acts as an ultrahigh energy particle accelerator that can accelerate particles to energies inconceivable in any terrestrial particle accelerator, and that when the energy $E$ of the particles comprising the matter in the black hole is $\sim 10^2$ GeV or more, or equivalently the temperature $T$ is $\sim 10^{15}$ K or more, the entire matter in the black hole will be in the form of quark-gluon plasma permeated by leptons.

Key words: Quark-gluon plasma, black holes, particle accelerators
PACS: 12.38 Mh, 25.75 Nq, 97.60 Lf, 04.70−s

1 Introduction

Efforts are being made to create quark-gluon plasma (QGP) in terrestrial laboratories. A report released by CERN, the European Organization for Nuclear Research, at Geneva, on February 10, 2000 said, “A series of experiments using CERN’s lead beam have presented compelling evidence for the existence of a new state of matter 20 times denser than nuclear matter, in which quarks instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely”. By smashing together lead ions at CERN’s accelerator at temperatures 100,000 times as hot as sun’s centre, i.e. at temperatures $T \sim 1.5 \times 10^{12}$ K, and energy densities never before reached in laboratory experiments, a team of 350 scientists from institutes in 20 countries succeeded in isolating quarks from more complex particles, e.g. protons and neutrons. However, the evidence of creation QGP at CERN...
is indirect, involving detection of particles produced when QGP changes back to hadrons. The production of these particles can be explained alternatively without having to have QGP. Therefore, the evidence of the creation of QGP at CERN is not enough and conclusive. In view of this CERN will start a new experiment, ALICE (A Large Ion Collider Experiment), at much higher energies available at its LHC (Large Hadron Collider). First collisions in the LHC will occur in November 2007. A two months run in 2007, with beams colliding at an energy of 0.9 TeV, will give the accelerator and detector teams the opportunity to run-in their equipment, ready for a run at the full collision energy of 14 TeV to start in spring 2008.

In the meantime, the focus of research on QGP has shifted to the Relativistic Heavy Ion Collider (RHIC), the world’s newest and largest particle accelerator for nuclear research, at Brookhaven National Laboratory (BNL) in Upton, New York. RHIC’s goal is to create and study QGP by head-on collisions of two beams of gold ions at energies 10 times those of CERN’s programme, which ought to produce QGP with higher temperature and longer life time thereby allowing much clear and direct observation. The programme at RHIC started in June 2000. Researchers at RHIC generated thousands of head-on collisions between gold ions at energies of 130 GeV creating fireballs of matter having density hundred times greater than that of the nuclear matter and temperature $\sim 2 \times 10^{12}$ K (175 MeV in the energy scale). Fireballs were of size $\sim 5$ femtometre which lasted a few times $10^{-24}$ second. All the four detector systems, viz., STAR, PHENIX, BRAHMS, PHOBOS, detected “jet quenching“ and suppression of “leading particles“, highly energetic individual particles that emerge from the nuclear fireballs in gold-gold collisions. Jet quenching and suppression of leading particles are signs of QGP formation.

Eventually, with plenty of data in hand, all the four detector collaborations - STAR, PHENIX, BRAHMS, PHOBOS - operating at the BNL have converged on a consensus opinion that the fireball is a liquid of strongly interacting quarks and gluons rather than a gas of weakly interacting quarks and gluons. Moreover, this liquid is almost a “perfect“ liquid with very low viscosity. The RHIC findings were reported at the meeting of the American Physical Society (APS) held during April 16-19, 2005 in Tampa, Florida in a talk delivered by Gary Westfall. Thus, it is obvious that the existence of QGP theoretically predicted by Quantum Chromodynamics (QCD) has been experimentally validated at RHIC.

But the QGP created hitherto in terrestrial laboratories is ephemeral, its lifetime is, as mentioned earlier, a few times $10^{-24}$ second, presumably because its temperature is not well above the transition temperature for transition from the hadronic phase to the QGP phase. In addition to this, it is difficult to maintain it even at that temperature for long enough time. However, as shown in the sequel, in nature we have celestial laboratories in the form of
gravitationally collapsing black holes wherein QGP is created naturally; this QGP is at much higher temperature than the transition temperature, and presumably therefore it is not ephemeral. More so, because the temperature of the QGP created in black holes continually increases and as such it is always above the transition temperature.

2 Gravitationally collapsing black hole as a particle accelerator

We consider a gravitationally collapsing black hole (BH). In the simplest treatment a BH is considered to be a spherically symmetric ball of dust with negligible pressure, uniform density \( \rho = \rho(t) \), and at rest at \( t = 0 \). These assumptions lead to the unique solution of the Einstein field equations, and in the comoving co-ordinate system the metric inside the BH is given by

\[
ds^2 = dt^2 - R^2(t) \left[ \frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta \, d\phi^2 \right]
\]

in units in which the speed of light in vacuum, \( c = 1 \), and where \( k = 8\pi G \rho(0)/3 \) is a constant.

On neglecting mutual interactions the energy \( E \) of any one of the particles comprising the matter in the BH is given by \( E^2 = p^2 + m^2 > p^2 \), in units in which again \( c = 1 \), and where \( p \) is the magnitude of the 3-momentum of the particle and \( m \) its rest mass. But \( p = \frac{\hbar}{\lambda} \), where \( \lambda \) is the de Broglie wavelength of the particle and \( h \) Planck’s constant of action. Since all length in the collapsing BH scale down in proportion to the scale factor \( R(t) \) in equation (1), it is obvious that \( \lambda \propto R(t) \). Therefore it follows that \( p \propto R^{-1}(t) \), and hence \( p = aR^{-1}(t) \), where \( a \) is the constant of proportionality. From this it follows that \( E > a/R(t) \). Consequently, \( E \) as well as \( p \) increases continually as \( R \) decreases. It is also obvious that \( E \) and \( p \to \infty \) as \( R \to 0 \). Thus, in effect, we have an ultrahigh energy particle accelerator, so far inconceivable in any terrestrial laboratory, in the form of a gravitationally collapsing BH, which can, in the absence of any physical process inhibiting the collapse, accelerate particles to an arbitrarily high energy and momentum without any limit.

What has been concluded above can also be demonstrated alternatively, without resorting to the general theory of relativity, as follows. As an object collapses under self-gravitation, the inter-particle distance \( s \) between any pair of particles in the object decreases. Obviously, the de Broglie wavelength \( \lambda \) of any particle in the object is less than or equal to \( s \), a simple consequence of Heisenberg’s uncertainty principle. Therefore, \( s \geq \frac{\hbar}{p} \). Consequently, \( p \geq \frac{\hbar}{s} \) and hence \( E \geq \frac{\hbar}{s} \). Since during the gravitational collapse of an object \( s \) decreases
continually, the energy $E$ as well as $p$, the magnitude of the 3-momentum of each of the particles is the object increases continually. Moreover, from $E \geq \frac{h}{s}$ and $p \geq \frac{h}{s}$ it follows that $E$ and $p \to \infty$ as $s \to 0$. Thus, any gravitationally collapsing object in general, and a BH in particular, acts as an ultrahigh energy particle accelerator.

It is also obvious that $\rho$, the density of matter in the BH, continually increases as the BH collapses. In fact, $\rho \propto R^{-3}$, and hence $\rho \to \infty$ as $R \to 0$.

3 Creation of quark-gluon plasma inside gravitationally collapsing black holes

It has been shown theoretically that when the energy $E$ of the particles in matter is $\sim 10^2$ GeV ($s \sim 10^{-16}$ cm) corresponding to a temperature $T \sim 10^{15}$ K, all interactions are of the Yang-Mills type with $SU_c(3) \times SU_{I_W}(2) \times U_{Y_W}(1)$ gauge symmetry, where $c$ stands for colour, $I_W$ for weak isospin, and $Y_W$ for weak hypercharge; and at this stage quark deconfinement occurs as a result of which the matter now consists of its fundamental constituents: spin 1/2 leptons, namely, the electrons, the muons, the tau leptons, and their neutrinos, which interact only through the electroweak interaction; and the spin 1/2 quarks, $u$(up), $d$(down), $s$(strange), $c$(charm), $b$(bottom), $t$(top), which interact electroweakly as well as through the colour force generated by gluons. In this context it may be noted that, as shown in section 2, the energy $E$ of each of the particles comprising the matter in a gravitationally collapsing BH continually increases, and so does the density $\rho$ of the matter in the BH. During the continual collapse of a BH a stage will be reached when $E$ and $\rho$ will be so large and $s$ so small that the quarks confined in the hadrons will be liberated from the infrared slavery and acquire asymptotic freedom, i.e., the quark deconfinement will occur. This will happen when $E \sim 10^2$ GeV ($s \sim 10^{-16}$ cm) corresponding to $T \sim 10^{15}$ K. Consequently, during the continual gravitational collapse of a BH, when $E \geq 10^2$ GeV ($s \leq 10^{-16}$ cm) corresponding to $T \geq 10^{15}$ K, the entire matter in the BH will be in the form QGP permeated by leptons.

One may understand what happens eventually to the matter in a gravitationally collapsing BH in another way as follows. As a BH collapses continually, gravitational energy is released continually. Since, inter alia, gravitational energy so released cannot escape the BH, it will continually heat the matter comprising the BH. Consequently, the temperature of the matter in the BH will increase continually. When the temperature reaches the transition temperature for transition from the hadronic phase to the QGP phase, which is predicted to be $\sim 170$ MeV ($\sim 10^{12}$ K) by the Lattice Gauge Theory, the entire matter in the BH will be converted into QGP permeated by leptons.
It may be noted that in a BH the QGP will not be ephemeral like what it has hitherto been in the case of the QGP created in terrestrial laboratories, it will not go back to the hadronic phase, because the temperature of the matter in the BH continually increases and, after crossing the transition temperature for the transition from the hadronic phase to the QGP phase, it will be more and more above the transition temperature. Consequently, once the transition from the hadronic phase to the QGP phase occurs in a BH, there is no going back; the entire matter in the BH will remain in the form of QGP permeated by leptons.

4 Conclusion

From the foregoing it is obvious that a BH acts as an ultrahigh energy particle accelerator that can accelerate particles to energies inconceivable in any terrestrial particle accelerator, and that the matter in any gravitationally collapsing BH is eventually converted into QGP permeated by leptons. However, the snag is that it is not possible to probe and study the properties of the QGP in a BH because nothing can escape outside the event horizon of a BH.

5 Acknowledgment

The author thanks Professor S. K. Pandey, the Co-ordinator of the Reference Centre at Pt. Ravishankar Shukla University, Raipur of the University Grants Commission’s Inter-university Centre for Astronomy and Astrophysics at Pune. He also thanks Mr. Laxmikant Chaware and Miss Leena Madharia for typing the manuscript.

References

[1] S. Weinberg, Gravitation and Cosmology (John Wiley & Sons, New York, 1972), 342.
[2] P. Ramond, Ann. Rev. Nucl. Part.Sc., 33 (1983) 31.