

# The Big Bang's Pervasive Plasma: the Quark-Gluon Plasma

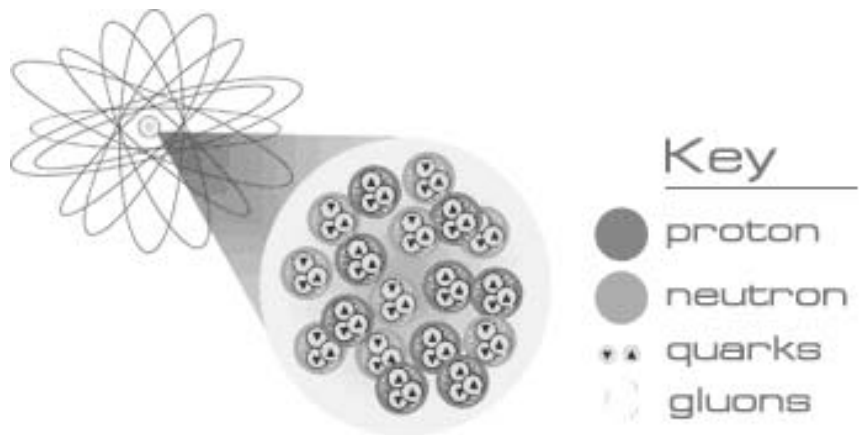
*Michael Sekora*

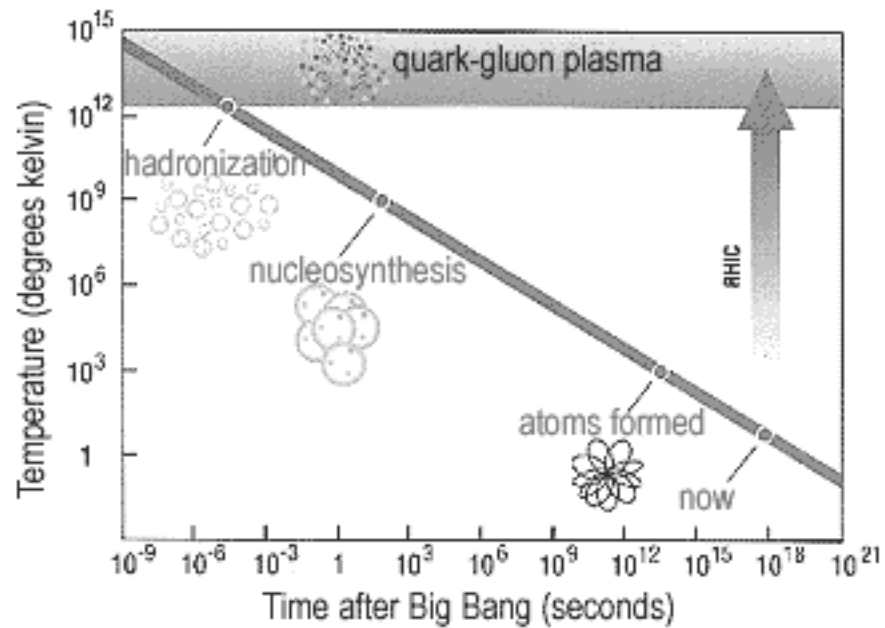
The universe was created twelve to fifteen billion years ago in a massive explosion that physicists term the “Big Bang.”<sup>1</sup> In the first microseconds after the Big Bang, when the temperature and concentration of energy was immensely high, an ancient form of matter pervaded the universe.<sup>2</sup> This form of matter consisted of all quarks and gluons existing freely in a quark-gluon plasma, which existed throughout the universe until  $10^{-5}$  seconds after the Big Bang when the temperature throughout the universe dropped to  $10^{12}$  Kelvins.<sup>3</sup> As the universe expanded and cooled, the quark-gluon plasma underwent hadronization and began to condense and decay into hadrons, strongly interacting particles such as protons, neutron, and pions.<sup>4</sup>

However, all theories pertaining to matter rest on the assumption that many particles such as protons and neutrons found inside an atom's nucleus are made of quarks. Yet, no one has ever succeeded in isolating a free quark.<sup>1</sup>

Quarks are infinitesimal, rattle around inside the proton near the speed of light, and make up just 2 percent of the proton's total mass.<sup>5</sup> They possess a characteristic that physicists call “color,” which is loosely analogous to electric charge.<sup>2</sup> Color generates a color field or chromodynamic field. The quantum of this field, the transmitter of the strong force, is the gluon. Gluons carry most of the proton's energy. And like the photon, which transmits the electromagnetic force, a gluon is massless. Yet, unlike a proton which is made of three quarks, a gluon has charge that allows it to generate its own color field, exert its own strong force, and interact with other gluons.<sup>5</sup> The color field, like the electromagnetic field, can be thought of having two components: color electric and color magnetic.<sup>5</sup> A fast-moving color charge produced by gluons moving at light speed generates a strong color magnetic field.<sup>5</sup> Hence, gluons act as little dipole magnets.

The theory of how nuclear particles are composed of quarks and gluons is Quantum



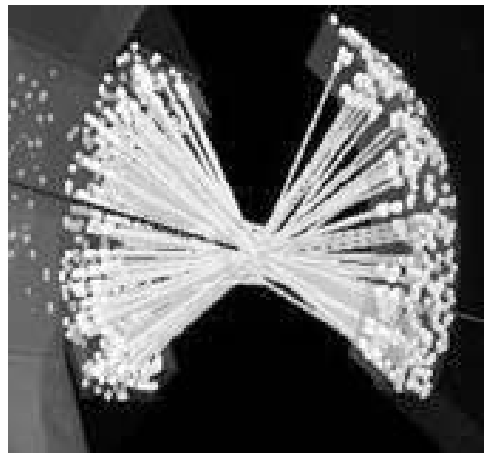


Chromodynamics (QCD), developed in 1973 by MIT Professor Frank Wilczek as a graduate student at Princeton University.<sup>5</sup> QCD is a quantum field theory, which is founded on three main premises: relativity, where energy can be converted to mass, and vice versa<sup>5</sup>; the vacuum containing numerous energy fields, with energy constantly exhibiting itself as virtual particles that manifest and annihilate in less than  $10^{-20}$  seconds; and the premise that the force two subatomic particles exert on one another is created in part by the subatomic particles.<sup>5</sup> These subatomic particles are exchanging virtual particles, which comprise the quantum of the quantum field. This exchange of virtual particles is parallel to what occurs when two charged particles such as an electron and a proton interact. Here, the electron and proton exchange a virtual photon, which comprises the quantum of the electromagnetic field.<sup>5</sup> The theory that describes these interactions is Quantum Electrodynamics (QED), developed by Richard Feynman.

In QED each electron is enveloped by a cloud of photons that exist as virtual particles. Also enveloping each electron are other electrons paired with positrons, the electron's

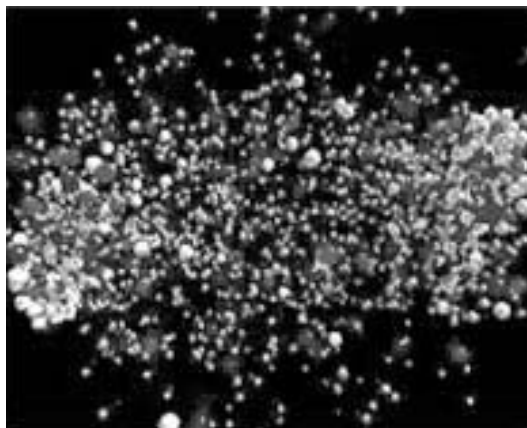
positively charged antimatter twin. This shroud of electron/positron pairs forms a screen that partially cancels the electron's field as seen from the outside of this screen.<sup>5</sup> Conversely, from the inside of this screen the electron's field seems stronger than expected.<sup>5</sup> This phenomenon is termed "screening."

QCD is closely modeled after QED. However, the quantum chromodynamic virtual particles, the gluons, produce a type of screening that is opposite to the type of screening produced by the quantum electrodynamic virtual particles, the photons.<sup>5</sup> The screening that occurs in QCD is termed "antiscreeing" because it is opposite to that of QED. In QCD, gluons envelop a quark and align themselves parallel to the color field as would magnets.<sup>5</sup> Instead of weakening the color field as photons would do to the electromagnetic field, gluons strengthen the color field.<sup>5</sup>



If one quark manages to get inside another gluon cloud, it feels only a feeble attraction.<sup>5</sup> However, the farther away a quark moves, the more it feels the added pull of the gluons.<sup>6</sup> These gluons are manifested from gluons emitted by other gluons and by gluons materializing into virtual quark-antiquark pairs, which

exchange more gluons.<sup>5</sup> The strong force that holds quarks and gluons together inside nuclear particles is analogous to a rubber band connecting two balls. The strong force becomes stronger as quarks stray farther apart and becomes weaker as quarks come together.<sup>7</sup>



process known as hadronization.<sup>1</sup> These hadrons continue to interact with each other as long as the particle density remains high.<sup>1</sup> Yet, these interactions are mediated by the strong force and occur only at a very short range.<sup>1</sup> As further expansion occurs,

QCD demands that a quark-gluon plasma exists at certain energy densities. Since the mid-1980s, researchers have sought to create a quark-gluon plasma, which would be the densest, hottest matter ever observed in a laboratory and possibly the densest, hottest matter in the universe.<sup>2,8</sup> By using particle colliders to compress nuclei at sufficiently large densities and temperatures, individual protons and neutrons will overlap and dump an enormous amount of energy into a very small volume.<sup>1,4,8</sup> This collision creates a fireball intense enough to melt protons and neutrons, and allows quarks and gluons to circulate freely as they would deep inside a proton or neutron.<sup>4,5</sup> However, the quarks and gluons circulate within a much larger volume, forming a quark-gluon plasma.<sup>4,5</sup>

The heavier the ions, the greater the volume over which energy is released in the collision.<sup>1</sup> The ions of choice are lead and gold.<sup>1</sup> Their atomic weights are 207 atomic mass units and 197 atomic mass units, respectively, and they collide with energies around 3.5 TeV.<sup>1</sup> Large amounts of energy are squeezed into a very small space, resulting in high energy density, which is approximately 3-4 GeV/fm<sup>3</sup> at temperatures of 240 MeV.<sup>1</sup> The buzz of colliding nucleons is as dense as 100 nuclei packed into the space of one nucleon.<sup>7</sup> Its temperature is expected to soar to 100,000 times that of the sun's core.<sup>7</sup> This should free quarks and gluons into a small bubble of quark-gluon plasma. The result is similar to a hot gas at high pressure. It rapidly explodes, simultaneously expanding and cooling.<sup>1</sup> This problem of the laboratory fireball rapidly expanding and cooling makes the quark-gluon plasma survive only momentarily.<sup>5</sup> At an energy density of 1 GeV/fm<sup>3</sup> and a temperature of 180 MeV, quarks and gluons condense into hadrons through a

these interactions cease at an energy density of 50 MeV/fm<sup>3</sup> and a temperature of 100–120 MeV.<sup>1</sup> The particles that are left travel outward toward detectors placed around the reaction zone.

The first research team to approach the creation of a quark-gluon plasma worked at the Super Proton Synchrotron at the European Center for Nuclear Research (CERN) in Geneva, Switzerland. In February 2000, these investigators smashed lead nuclei flying at nearly light speed into other nuclei at fixed targets.<sup>2</sup> The CERN team received the first glimpse of the quark-gluon plasma. However, there were some flaws in their data: They did not identify convincing signals in their search for direct evidence such as gamma rays that physicists expect the quark-gluon plasma to emit.<sup>2</sup>

Shortly after the CERN team received its intriguing results, a more powerful particle collider became operational. This Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, New York, collides two beams of gold ions head-on as they travel at nearly the speed of light.<sup>9</sup> The RHIC smashes nuclei together with 10 times greater energy than the Super Proton Synchrotron at CERN.<sup>2,8</sup> The results being collected at RHIC are the most reliable results pertaining to the quark-gluon plasma. Recently, researchers have seen the first clear indication of conventional matter dissolving into free-roaming quarks and gluons.<sup>10</sup> Scientist collided pairs of gold nuclei at high energies and observed the particles that sprayed from the impact point. They detected fewer particles from the collisions than the Standard Model of Particle Physics predicts. This suggests that a tiny blob of unbound quarks and gluons may have been created.<sup>10</sup>

Understanding the quark-gluon plasma is

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very significant. Verifying its existence would allow physicists to comprehend the structure of nuclear particles and the phase transition that is thought to have occurred when the primordial quark-gluon plasma cooled to form today's nuclear particles.<sup>5</sup> If the particle colliders necessary for creating the quark-gluon plasma reveal any irregularities in the plasma-to-matter transition, this may shed light on the formation of the first magnetic field, the formation of the first elements, and even a type of undetected dark matter, or "strange matter."<sup>7</sup> Experiments might yield the first evidence of this proposed strange matter, which is the unseen substance astronomers suspect make up almost 90 percent of the universe. If bubbles in the cooling of the quark-gluon plasma are large enough, and if they chill in just

the right way, some of the plasma might condense into the previously mentioned strange matter because they contain many strange quarks. Lastly, it has been theorized that the quark-gluon plasma may exist in the cores of neutron stars. A neutron star consists of the dark remains of a star that underwent a supernova explosion and collapsed on itself under gravity's influence. Neutron stars pack approximately the mass of the sun inside a sphere 10 kilometers across.<sup>10</sup> A sugar cube-size piece would weigh over a billion tons.<sup>10</sup> Yet, the core of a neutron star is even denser. According to Krishna Rajagopal and Frank Wilczek of MIT, it is in the dense, hot core of a neutron star that subatomic components of protons and neutrons get smashed into a soup called a quark-gluon plasma.<sup>10</sup> ■

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