Searching for the Quark-Gluon Plasma

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The search for a new form of matter that may exist at very high energy has been an important research problem in nuclear physics in recent years. Since the emergence of the modern theory of fundamental particles, it is accepted that mesons and the protons and neutrons of ordinary nuclei are composed of quarks held together by force-carrying particles called gluons. At extremely high density or temperature, the mesons and nucleons might dissolve into their fundamental constituents, forming a new kind of matter, called the quark-gluon plasma. In this phase, analogous to ordinary plasmas of ionized gas, the bound quarks would be ionized and free to move about the entire volume of the plasma. This quark-gluon plasma could have interesting properties, particularly if it were a thermodynamically distinct phase. For example, if it had a latent heat of formation, effects of phase separation may appear; if so, phase separation may have played a role in the early evolution of the universe (*1*).

The main event. Streamer chamber photo of a single 200-GeV-per-nucleon sulfur nucleus hitting a sulfur target. Collision products are dispersed by a magnetic field and their tracks are visible as ionization streamers in an intense electric field. A single collision such as this produces a swarm of pi mesons whose momenta reveal properties of the dense interaction region. From the NA35 experiment at CERN. [Courtesy of T. A. Trainor, University of Washington]

The first prediction that the quark-gluon plasma might be a distinct thermodynamic phase of matter was made in the early 1980s (*2*, *3*). The predicted transition temperature was roughly 2×10^{12} K or 150 MeV, which may be within the reach of large accelerators capable of producing collisions of heavy nuclei on nuclear targets. By the latter part of the decade, nuclear beams were available in these accelerators, and experimenters had begun looking for signs of the new form of matter. The larger the nucleus and the higher the bombarding energy, the higher the density that can be made in the collision. However, it has not been easy to obtain detailed information about what goes on in these collisions. The matter produced in the collisions stays together for only a very short time, and all that experimenters can observe is a shower of ordinary particles left over at the end. Nevertheless, much has been learned from study of the characteristics of the particles in violent collisions. The latest findings were presented at a conference last year, "Quark Matter 1993" (*4*). The highest energy experiments (200 GeV per nucleon) were carried out at CERN in Geneva, and lower energy experiments (14 GeV per nucleon) at Brookhaven National Laboratory have also contributed to the search.

The possibility of forming the quark-gluon plasma depends on whether the protons and neutrons interact strongly enough to slow each other down in a collision or whether, at high energy, they just punch through each other with only minor interactions. Only if the nucleons deposit most of their energy in a central zone in the collision would there be enough energy to make the plasma. Earlier experiments seemed quite promising because many more particles were produced than would be expected if protons and neutrons interacted with only a single partner in the collision. It was not known until last year, however, whether nucleons at CERN energies were actually slowed down substantially by the collisions. When a proton collides with an individual proton at high energy, it is hardly deflected by the interaction, although it typically loses half its energy. The CERN experiments showed that in nucleus-nucleus collisions, many of the nucleons are slowed essentially to a stop, making all of their energy available in a central zone (*5*).

With enough energy available to form a new phase of matter, the next question is whether there is anything different about the particles because of their origin in a high-density medium. Specifically, are their abundances, momentum distributions, and correlations different from what one would expect from proton-proton collisions? No striking differences have been found among the particles that are composed of the ordinary "up" and "down" quarks, particles such as protons, neutrons, and pi mesons.

However, the characteristics of other rare mesons did show dramatic differences. In particular, the mesons containing "strange" and "charmed" quarks turned out to be sensitive to the high-density environment. Such mesons are rare because the strange and charmed quarks are massive and not easily produced in single nucleon-nucleon collisions. In the plasma phase, the gluons and ordinary quarks would collide repeatedly with one another, producing more and more of the rarer strange quarks. Thus, nucleus-nucleus collisions would produce more strange mesons, a phenomenon that was observed in experiments at Brookhaven (*6*).

Another rare meson, the *J*/psi particle, was studied in the CERN experiments. This meson consists of a charmed quark bound together with its antiquark partner. Brookhaven's experiments had shown that more strange mesons are produced in nucleus-nucleus collisions, but at CERN, it was discovered that nucleus-nucleus colli-

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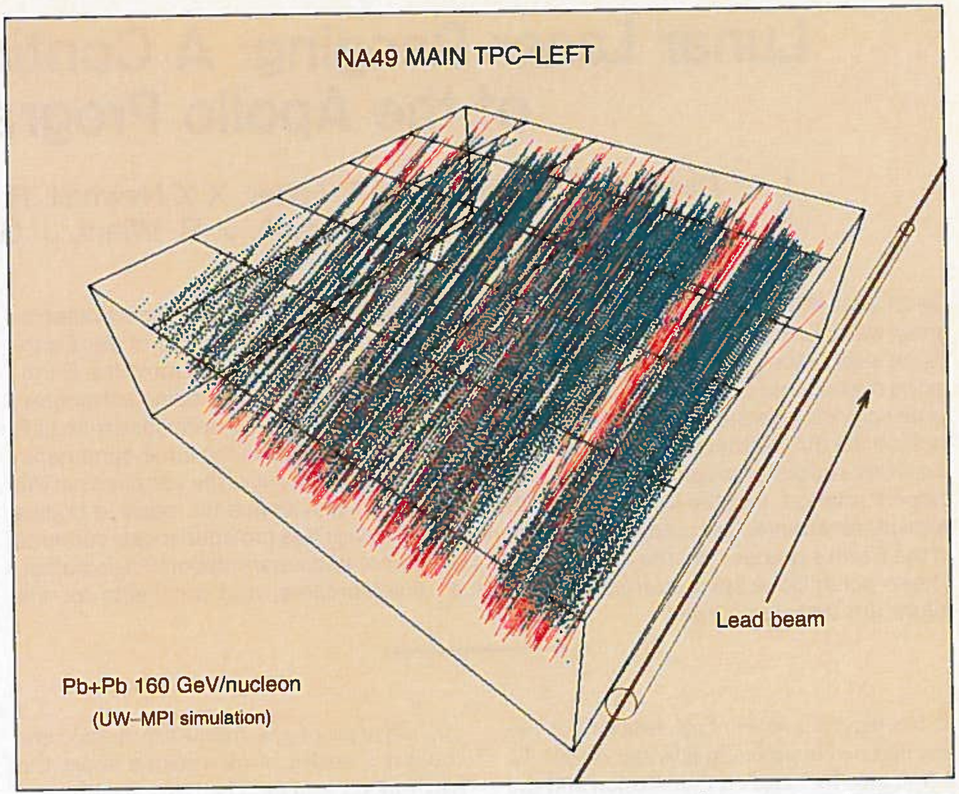
sions produce relatively fewer *J*/psi particles than proton-proton collisions do. The explanation is simple: In the high-density environment of the nucleus-nucleus collision, the number of *J*/psi particles decreases because the presence of other nearby particles disturbs the quark and antiquark in the *J*/psi and easily breaks them apart. The situation is analogous to an ordinary plasma, where the hot environment ionizes the loosely bound electrons on atoms. Of course, after the matter has cooled, the quarks would not be free but would be bound to some ordinary quarks in a different particle. Instead of the *J*/psi, one would see other charmed mesons that contain single charmed quarks. Like the experiments measuring strange particles, the decrease in the number of *J*/psi particles shows that a hot, dense environment is produced (*7*) but does not show specifically that a phase transition has taken place, or that quarks are freely moving in the hot matter. Thus, the existence of the quark-gluon plasma has not yet been proven.

A more specific way to show that matter undergoes a phase transition to a different state would be to measure how long the matter remains as a compact, high-density object. If the particles observed in the detectors were produced immediately, there would not be enough time for a new phase to form. Conversely, if the matter passed into a new phase, it would surely take some time to convert back to ordinary matter. Thus, how long the high-density matter lasts is an important clue to the existence of a phase transition.

However, even a relatively long duration would still be far too short to measure directly: Typically, a collision lasts a few times 10^{-24} s. Fortunately there is an indirect method for inferring the relative emission times of mesons. The method uses the fact that mesons have wave properties just like those of light. The waves can interfere with each other, producing regions of high and low intensity. Just as the interference pattern of light coming from a distant star can be used to infer the diameter of the star (*8*), the interference of two meson waves produces information about the spatial and temporal distribution of the meson source. It is only since 1993, however, that reliable measurements of the source dimensions have been reported for nucleus-nucleus collisions (*9*, *10*). The results are interesting, giving numbers for the dimensions twice as large as would be expected if the matter were created immediately as mesons. Evidently, the matter exists in some other form about twice as long as the collision lasts. However, it is not possible from this measurement to say more specifically what form the matter has.

Plans are under way to produce even higher energies and densities both at CERN and at Brookhaven. At CERN, the experiments will be repeated with beams of lead nuclei, which are about six times heavier than the present sulfur beams. Brookhaven is building a new accelerator that will use colliding beams to increase the available energy by another factor of 10. This accelerator is scheduled to start operation in the late 1990s. Finally, even farther in the future, the Large Hadron Collider project at CERN is designed to accelerate nuclei so that the search for the quark-gluon plasma may be continued at even higher energy.



Tracking the elusive quark-gluon plasma. Calculated tracks in a region 10 meters downstream from the simulated collision of a 160-GeV-per-nucleon lead nucleus with a lead target. These simulations, performed with software being developed at the Max Planck Institute for Physics in Munich and the University of Washington, are in preparation for the NA49 experiment beginning in November 1994. One goal of the experiment is to reconstruct the size of the interaction region by analyzing the momenta of all the pi mesons produced in the collision. [Courtesy of T. A. Trainor, University of Washington]

References

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