Quark-Gluon Plasma

Can quarks get out of the bag and into the soup? Experiments seek a new state of matter: an unstructured mix of matter's most fundamental structural elements.

By DIETRICK E. THOMSEN

Quarks and gluons are reuniting nuclear physics and particle physics. It's nowhere near as difficult as reuniting the ancient supercontinent Gondwanaland: Nuclear physics and particle physics were never oceans apart, but over the last few decades distinct specialties have developed. Now, groups of nuclear physicists are going to one of the world's foremost particle-physics laboratories, CERN in Geneva, Switzerland, to use its most powerful accelerator, the Super Proton Synchrotron (SPS), to energize not protons but atomic nuclei. Their goal is to make a quark-gluon plasma, an unusual state of matter that interests both groups fundamentally.

Years ago, both nuclear and particle physics were studied in the same accelerators. These machines drove energized protons or electrons against atomic nuclei, and researchers could study both nuclear structure and individual particles in the results of such collisions. As accelerator energies went up, studies using the higher-energy machines concentrated more and more on individual particles, their relations with one another and their internal structure, if any. Studies of nuclear structure remained at the lower energies, and the two specialties, particle physics and nuclear physics, gradually differentiated themselves.

The current theory of the structure of subatomic particles, which comes mainly from high-energy studies, proposes that there are two kinds of fundamental objects, quarks and leptons. Each of the six kinds of lepton is itself a subatomic particle: electrons, neutrinos, etc. Of the more than 100 remaining varieties of subatomic particle, each is made up of two or three quarks, of which there are also six varieties. Within the structures they build, quarks are held together by particles called gluons, which embody the force that sticks the quarks to each other.

A curious thing about this gluon force is that the farther apart two quarks get, the *stronger* the force between them becomes. Quarks thus tend to stay as close together as they possibly can; in fact, they are supposed to be unbreakably bound within the structures of the particles they make up. One way of describing this situation is to say that a proton or a neutron or some other kind of particle is a bag, in which the constituent quarks are confined, and they cannot get out. A theory called quantum chromodynamics (QCD) has grown up to describe the gluon force and how quarks act under its influence.

Quarks also influence nuclear physics. They are the constituents that make up the neutrons or protons, and so have secondary effects on nuclear structure, but they also seem to have primary effects. Within a nucleus the bags seem to be somewhat leaky: Quarks can relate to each other through the bags, so to speak. Several experiments have shown that there are situations when a nucleus made of a neutron and proton can look like a collection of six quarks rather than an identifiable neutron and proton. According to QCD theory, if a nucleus gets extremely hot and dense, the bags should disappear entirely, and what should remain is an unstructured soup of quarks and gluons, without any recognizable neutrons or protons present.

Under the broken line is CERN's SPS, where high-energy nuclei will collide.

Illustrations: Lawrence Berkeley Lab.

Such a soup is called a quark-gluon plasma. It is a new state of matter and a very fundamental one, probably representative of things that happened in the very beginning of the universe. Physicists want to see whether it exists.

To get nuclear matter to the temperature and density needed to produce a quark-gluon plasma, experimenters accelerate ions to high energies and then bang them against other atoms in targets. The heavier the elements used, the better the chance of reaching the proper conditions. These are truly atom-smashing experiments. The collisions produce "fireballs" of nuclear matter, in which, under proper conditions, a quark-gluon plasma might appear.

The ions are atoms with some or most of their electrons removed. In principle, therefore, any machine that accelerates positively charged protons should be able to handle ions. In practice it takes some rather painstaking adjustment to make the operation practical, but more important, the accelerator chosen must have an injection system that can handle the ions. Not every proton accelerator has one.

Of existing ion accelerators, two of the most energetic – the Bevalac at the Lawrence Berkeley (Calif.) Laboratory (LBL) and the Synchrophasotron at Dubna, USSR – are both converted proton accelerators. Although experiments with them and their less energetic congeners have shown many surprising phenomena, they do not seem to reach the threshold for a quark-gluon plasma. The interested physicists started looking for something more energetic.

CERN was the obvious choice, Howel Pugh of LBL told SCIENCE NEWS. CERN has three high-energy proton accelerators, and it has an injector capable of handling fairly heavy ions. One of these accelerators is the Intersecting Storage Rings (ISR), an apparatus that would be capable of accelerating two beams of ions and colliding them head-on. Such an arrangement would be able to put much more of the expended energy into the "center of mass," where it would be available to increase the temperature and density of the collision fireball than the more usual method of accelerating one beam of ions and striking it against a stationary target. So LBL and the Los Alamos (N.M.) National Laboratory proposed colliding-ion experiments in the ISR.

The CERN management refused, saying the ISR was being closed down and there would be no exceptions. CERN is busy building a huge new accelerator project, the Large Electron-Positron collider (LEP), and is doing it under severe budget constraints. To get LEP, CERN had to make some sharp deals with the 14 nations that jointly own the laboratory, and one of these agreements was that the ISR would be closed.

The CERN management was not being completely negative, however. "They knew they had a fallback position," Pugh says. That was to offer another accelerator, the Super Proton Synchrotron. The SPS has lately been making important new discoveries in particle physics: W and Z particles, exotic unexplained phenomena, etc. However, when LEP starts to run, the SPS will become the injector for LEP. As injection will not exhaust the SPS's beam capacity, the ion experiments could share it. The deal that was made includes just 34 days of running time on the SPS, 17 in November 1986 and 17 a year later. Pugh says this period is enough to get data that will keep them busy a long time analyzing. These are exploratory experiments, and the physicists want to study carefully everything that happens in high-energy nuclear collisions. However, Pugh says, the danger with such a short experimental run is that, should something malfunction, you could lose it all.

Nevertheless, once the deal was cut, physicists from all over the world climbed on the bandwagon, submitting experimental proposals of their own. In addition to two major experiments with large participation by LBL, four others have been accepted. LBL and the Gesellschaft für Schwerionenforschung, or GSI (in English, Society for Heavy Ion Research), in Darmstadt, West Germany, are major participants, jointly supplying the ion source. This includes the actual Electron Cyclotron Resonance (ECR) ion source, built in Grenoble, France, and purchased by GSI, and a special preaccelerator, built at LBL. The two were put together at GSI and are now at CERN. CERN will supply the rest of the accelerating equipment.

The ion first discussed for acceleration in these experiments was oxygen-16. "You'd like to use uranium," Pugh says, but they have to settle for what the equipment can handle. Later it became clear that certain ions heavier than oxygen could work, particularly if they are mixed in the same beam with oxygen. These are magnesium, sulfur and calcium.

It seems now that sulfur and calcium will be used. Beams will be accelerated to two different energies, 200 billion electron-volts (200 GeV) per nucleon and 60 GeV per nucleon. (Neutrons and protons together are called nucleons.)

There are two energy ranges, says Arthur Proskanzer of LBL, where quark-gluon plasmas are possible: the stopping range and the transparency range. In the stopping range, the target stops the projectile, the protons and neutrons of target and projectile are jumbled together in a fireball, and what ultimately comes out of the fireball can no longer be identified as from one or the other.

In the transparency range the projectile goes through the target and comes out somewhat slowed but still identifiable. "The projectile baryons [the neutrons and protons] slow down and continue forward," says Hans Georg Ritter of LBL.

"If we can stop the baryons and build up the temperature and the pressure," Proskanzer says, "the quarks in the baryons will merge and build up a quark-gluon plasma. We want the highest density of quarks to make a quark-gluon plasma."

"And the highest energy density," Ritter adds.

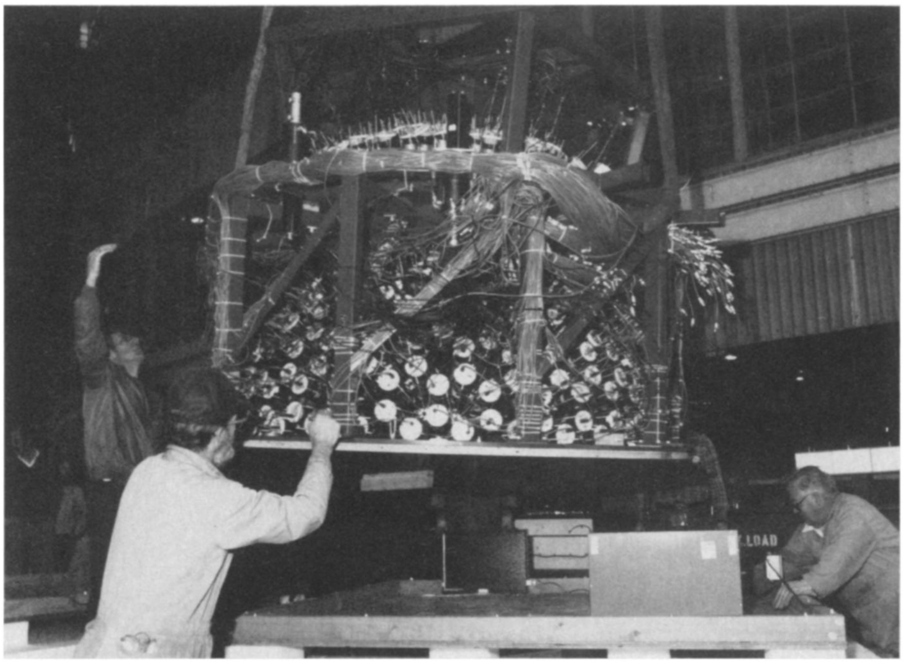
"High density of baryons gives you the quarks in the baryons," explains Proskanzer, "and high energy density gives you temperature that produces quarks thermally by pion production. Each pion we think of as two quarks [which compose the pion]."

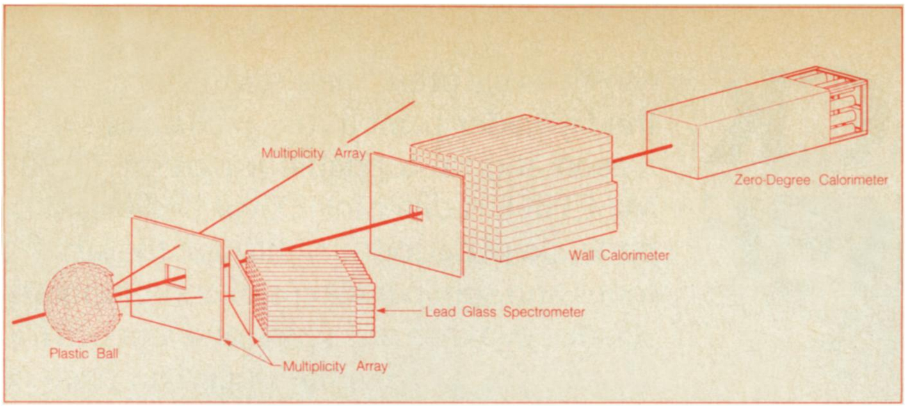
The CERN experiments are thus trying to find the energy region of "maximum stopping." This is important for future accelerator development. If physicists can make an apparatus that will collide uranium against uranium at that energy, says Proskanzer, "that will be the highest density of nucleons one ever will make." He expects that this maximum stopping range may fall somewhere from the energies of the SPS down to those of the Alternating Gradient Synchrotron, a proton accelerator at Brookhaven National Laboratory in Upton, N.Y., that is being converted to an ion accelerator.

If you go on in energy to transparency, Proskanzer says, the passage of the projectile through the target leaves behind a lot of heat, and this will make pions that could in turn make quarks for a quark-gluon plasma. This range ought to be of interest for the Relativistic Heavy Ion Collider that physicists want to build also at Brookhaven.

Proskanzer and Ritter are involved in one of the two original LBL-suggested experiments, which is known as the Plastic Ball experiment, after a particular piece of detecting equipment. There are three main signatures by which the presence of quark-gluon plasma may be known, and the Plastic Ball will concentrate on one of them, high-energy photons (gamma rays). These high-energy photons are produced in the decay of neutral pions, which, in addition to being possible progenitors of a quark-gluon plasma, can also be products of it.

The Plastic Ball is a spherical arrangement of 1,400 lead-glass elements for recording photons, each of which looks at a different part of the target space. The Plastic Ball will almost completely surround the point where the projectile hits


Plastic Ball is about to leave LBL and begin its journey to Geneva.



Nuclei collide inside Plastic Ball. It and downstream detectors record results.

the target. In addition, there will be detectors looking at the multiplicity — the number and variety — of different things coming out of the collision, and in the foward direction there will be a trigger to select events in which nothing comes forward and so presumably the projectile has been completely stopped. In the forward line also will be calorimeters designed to measure the energy of whatever does come forward and so get a "stopping profile," data on the efficiency of stopping, collision by collision. Beside GSI and LBL, the universities of Lund (Sweden) and Münster (West Germany) and Oak Ridge (Tenn.) National Laboratory are collaborating.

Pugh and John Harris of LBL describe the other originally proposed experiment, often referred to as the streamer chamber experiment. For rather complicated theoretical reasons, physicists expect that a quark-gluon plasma will emit a large number of the class of particles called strange particles. The name "strange" was applied in the 1950s, when the first of these particles were found, because their behavior seemed strange at the time. Today it means that they have in their structure a particular kind of quark called (after them) the strange quark. The streamer chamber will look for them.

A streamer chamber is a space filled with gas and bounded by electrodes. Charged particles moving through the gas make a trail of ions. Application of a pulse of half a million volts for 10 nanoseconds accelerates the ions toward one of the electrodes. As they move, they make first an avalanche of similar ions and then a streamer about a centimeter long. The streamers are photographed, and measurements of the photographs identify the particles that passed.

Normally, says Pugh, the chamber works in the streamer mode, but in this experiment, the time will be so short that it will have to run by photographing the avalanches. The avalanches give very little light, so image intensifiers made by IT&T at a cost of $125,000 each will amplify the light 4,000 times. They will also give better position resolution than direct photography, an advantage that Pugh says he finds incredible.

These image intensifiers are spin-offs from spy satellites. Another derivative of the spook business is charge-coupled devices (CCDs), light sensors that Harris is building into a monitoring system to watch the streamer chamber's operation. CCDs are arrays of light-sensitive elements that build up digital information about light intensity across a given picture and send it directly to a computer memory. Their largest use in science so far is in astronomy, where their great sensitivity is used to build up time exposures of faint objects.

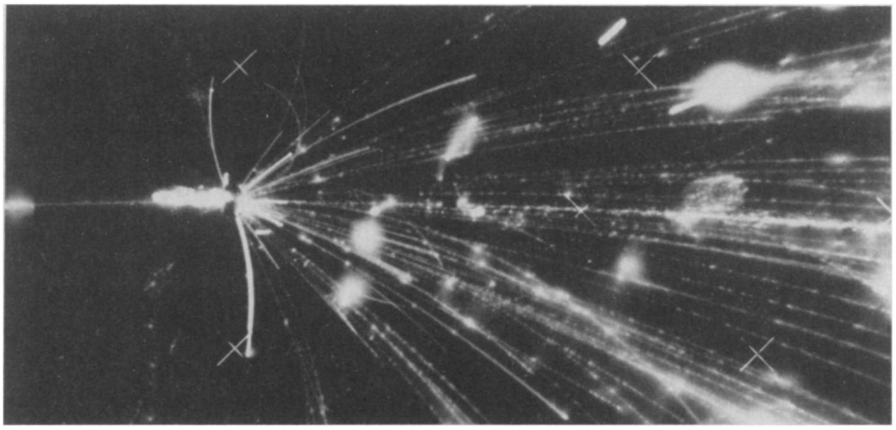
Here they will be used for quick snapshots, about one every 30 seconds. All the data cannot be taken with CCDs, however. The desired events come about once a second, and the analysis of the CCD findings is too slow. The CCDs will give a minute-to-minute check on how well the streamer chamber is doing. "We like to believe that within a few seconds of turning the [accelerator] beam on, we're going to have a snapshot of a quark-gluon plasma," Pugh says. In this experiment, too, there will be other particle detectors and calorimeters to check what comes out in the forward direction and measure the stopping power of the target. The universities of Heidelberg (West Germany), Marburg (West Germany), Frankfurt (West Germany), Warsaw and Athens are in this with LBL and GSI.

One of the later-proposed experiments will look for the third major expected signature of a quark-gluon plasma, correlated pairs of particles called muons. The energy the muons possess in the direction transverse to the motion of the accelerated projectiles will be crucial for identifying those from a quark-gluon plasma, and this experiment, a collaboration of institutions in Norway, France, Switzerland, Spain and Portugal, will use a variety of detectors and calorimeters to compare transverse and longitudinal energies.

Another experiment, by 12 institutions ranging from the Punjab to Pittsburgh and from Athens to Bergen (Norway), will look for strange particles with a time-projection chamber. In this chamber, passing charged particles also make trails of ions in a gas, but here the ions are drawn to wire meshes that collect them as electric charges and measure their time of flight, giving three-dimensional information about where in the chamber they were made. Twelve more institutions, ranging from Tel Aviv and Novosibirsk (Siberia) to Los Alamos (N.M.) and Montreal, will collaborate in measuring the energies of whatever comes out of the collision in any direction and recording both photons and muons.

Finally, a collaboration of the University of California at Berkeley and CERN will look for free quarks. QCD theory says that free-flying quarks cannot exist, and it may seem paradoxical to look for them as part of an effort to confirm QCD by finding a quark-gluon plasma, but all bets need to be covered. Pugh says that as an experimentalist he is willing to entertain the thought that both phenomena might coexist.

If a quark-gluon plasma appears, it will confirm a major prediction of QCD, which is physicists' theory for the organization and structure of matter on the most fundamental level yet investigated, and so it will be a very important result. But Pugh gives the impression that he will be a little disappointed if that's all, if a quark-gluon plasma forms and then promptly cools back to ordinary nuclear matter. It will be much more exciting if the quark-gluon plasma instead leads to structures of matter or kinds of particles unknown up to now and otherwise unobtainable. ☐



Streamer chamber shows particle tracks as bright lines like these.