CHROMODYNAMICS

A colorful and charming tale of particle physics, which at least some theorists hope is both beautiful and true

BY DIETRICK E. THOMSEN

"Big fish eat little fish, and prey on 'em and bite 'em.
Little fish eat littler fish and so on *ad infinitum.*"

It's not very good poetry, but it could illustrate the dilemma of science in its search for the fundamental building blocks and the ultimate underlying structure of matter. Each time they cut open a fish, scientists find a smaller one inside. It has been clear for decades that what chemists considered the ultimate building block, the atom, was not fundamental at all. More recently physicists have found that what they, perhaps in an access of hubris, had decided to call elementary particles are not the fundamental level either. And lately it is beginning to seem that the structure the physicists developed to deal with that disappointment may in its turn not be the ultimate. It looks like there's an even littler fish inside of it.

To rehash a little bit, the majority of physicists prefer to regard the 100 or more "elementary" particles they have discovered as no longer elementary (with the exception of four of them—more about those in a bit). Underneath this multiplicity of particles, whose existence itself is often evanescent, must lie a simpler structure. For both mathematical and physical reasons theorists came to a small group of entities, which have been dubbed quarks, with a bow in the direction of the most famous Irish wake in English literature.

At first three quarks sufficed for the theorists' imagination. (Indeed it was the line: "Three quarks for Muster Mark" that gave them their name.) The original quarks were called "up," "down" and "strange," and it turned out that various combinations of them and the three corresponding antiquarks could explain the behavior and structure of all the known particles but four. The up and down quarks by themselves could explain garden variety particles like neutrons and protons. The strange quark was necessary to explain the behavior of a class of oddball particles which, because of their behavior had been denominated strange particles.

Recently a fourth quark has entered almost everybody's calculations. It comes about because changes in the theory of the forces that animate the particles (specifically the unified field theory of electromagnetic interactions and the weak subatomic interactions) require the strange particles to behave even more strangely. Namely it introduces certain processes in which their amount of strangeness might otherwise be expected to change but actually does not. (In life it is impossible to be a little bit pregnant, but in physics a particle can be one unit strange or two units strange. If the terminology seems weird, remember that James Joyce is its literary patron saint.)

To account for this new behavior requires a new characteristic of particles, which has been called charm, and along with charm comes a fourth, charmed, quark. Having four quarks is nice for mathematical reasons because a fundamental group of four is more symmetrical than one of three. It is also nice because there are four particles that do not have quarks. The particles that are supposed to be made of quarks are called hadrons, and those of them that can be caught long enough to study show evidence of the kind of internal structure that the quark theory might lead one to expect. The four particles called leptons (the electron, the muon and the two kinds of neutrino) show no evidence of internal structure. They are not supposed to have quarks in them, but are regarded as equally fundamental. Four quarks and four leptons thus make a nice balance. Two different kinds of fundamental entity, each of which comes in four flavors. Very neat.

Now it becomes necessary to color the picture. The reason that theory must color quarks arises from the statistical formulations used to predict the behavior of particles. These come in two kinds, called Bose-Einstein statistics and Fermi-Dirac statistics. As a physicist who once compared physics with hotelkeeping put it, Fermi-Dirac Towers is very exclusive, but the Bose-Einstein Haus is renowned for *Gemütlichkeit.*

What that means is that particles subject to Fermi-Dirac statistics (electrons are an example) obey Pauli's exclusion principle: no two of them with exactly the same values of the properties we have been discussing, the same set of quantum numbers to use the physicists' terminology, can be in the same place at the same time. No double rooms or rollaway beds at Fermi-Dirac Towers. Bose-Einstein statistics allow such crowding together, like a ski-lodge dormitory.

It happens that quarks, by their hypothetical properties, are fermions, members of the class subject to Fermi-Dirac statistics. And that caused a theoretical rub. In many hadrons (neutrons and protons, for example) there are three quarks, and these quarks all appeared to have the same quantum numbers, a direct violation of Fermi-Dirac statistics. The solution to the dilemma was to propose a new quantum number that could make each quark different and so obey the law.

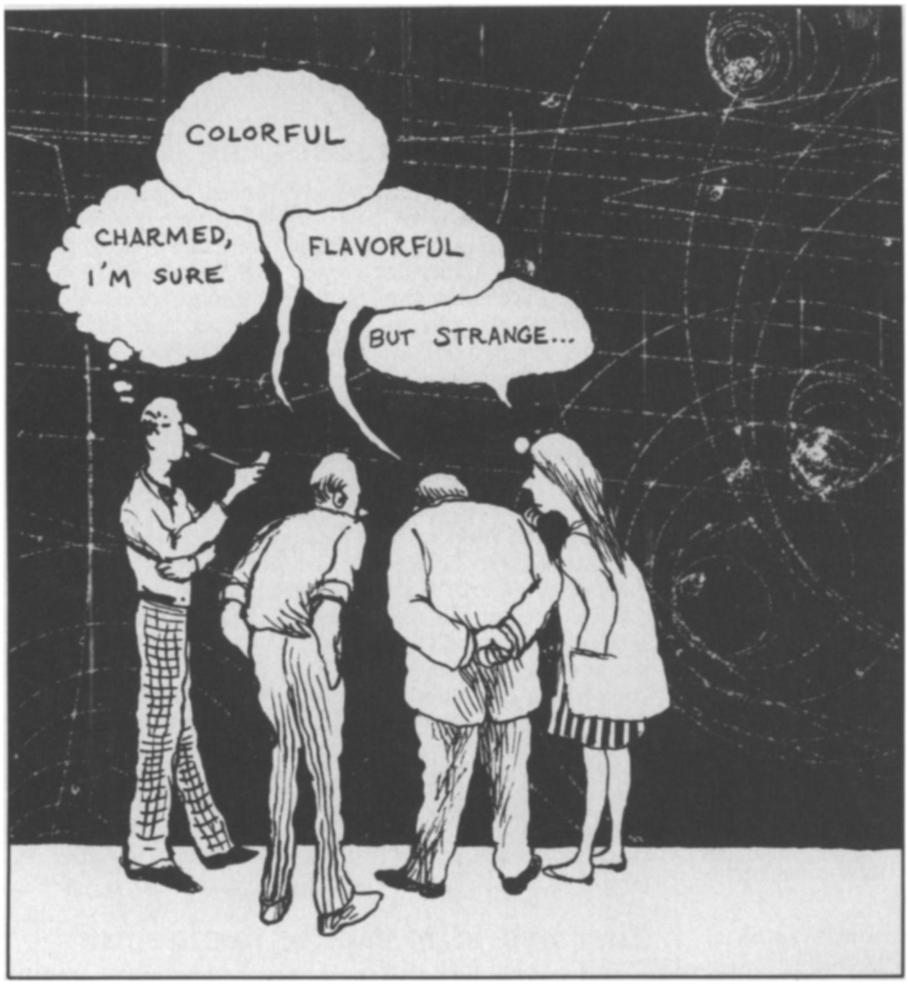
The triadic structure of neutrons and protons makes this new quantum number a bit special. Since neither neutron nor proton shows any such exotic property, the sum of the new quantum number over neutron or proton must be zero. Yet the structure requires something that has three different aspects, which, taken together, yield neutrality. A bipolarity with positive and negative like electricity would not do. Some kind of triangular symmetry was necessary.

What was hit upon was an analogy to the primary colors. Mixing red, blue and yellow in equal proportions gives white or colorlessness. So the new quantum number was called "color." (For reasons possibly of patriotism, American, French or British as you please, theorists tend to say "red, white and blue" rather than "blue, yellow and red.")

Color turned out to be more fundamental than simply a device for getting around Fermi-Dirac statistics. It could serve, in analogy to electric charge, as a kind of charge that would be the source of the forces that held quarks together inside the hadrons. As the theory developed, theorists postulated intermediate particles that would carry the force between quarks. These intermediaries are called gluons. The whole theory is called chromodynamics and it introduces an important change in how physicists regard the class of force they call the strong interaction.

The strong interaction first manifested itself as the force that holds protons and neutrons together in an atomic nucleus. It was later seen to exist among all hadrons. Physicists tended to believe that the force between neutrons and protons was the fundamental manifestation of the strong interaction. Now with chromodynamics they are beginning to see the nuclear binding force as a secondary manifestation of chromodynamics.

A parallel from electromagnetism will help clarify the point. The fundamental



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and strongest manifestation of electric force is between two charged bodies, for example, the force that binds electrons into orbit around an atomic nucleus. But there are weaker, secondary electromagnetic interactions between neutral bodies, for example, the forces that prevent atoms from interpenetrating each other. On these secondary forces are built all of our solid structures. Because of them, books do not pass through bookshelves, and human bodies do not pass through walls.

Similarly, the fundamental aspect of the chromodynamic force is taken to be that between quarks of different colors. The forces that bind neutral-color neutrons and protons into nuclei are considered secondary as are the interhadronic forces by which hadrons affect each other's motion.

It seems to be generally conceded that it is impossible to break hadrons into their constituent quarks, which would then come out exhibiting their colors, or to materialize gluons. But there are secondary ways to look for confirmation of the color hypothesis. One of these is in the collision and annihilation of beams of accelerated electrons and positrons.

These electron-positron collisons should create both hadrons and leptons. When such experiments were first set up in storage-ring facilities it was thought that the ratio of hadrons produced to leptons produced would be constant over a long range of energies of the colliding particles. The value of this constant would tell whether the color hypothesis was true and in which of its detailed ramifications. The experiments found constant levels, but they found more than one, and in between constant levels they found even bigger surprises: sudden narrow peaks in which the hadron production went up enormously. These peaks are resonances, and they indicate the creation of new particles of fleeting existence that gather up the available energy and form channels for much easier and extremely more copious hadron production. These resonances are the famous psi particles (SN: 5/8/76, p. 293), and theorists seized on them as examples of the working of charm. The psi particles are supposed to contain both charm and anticharm, so that overall they are neutral with respect to it, and do not display charm openly or "nakedly." Just recently, a new particle has been found in the electron-positron collision experiments that seems to display naked charm and thus would form a much stronger experimental argument for the concept (SN: 6/5-12/76, p. 356).

Meanwhile, between the resonances, the hadron-lepton ratio exhibits flat stretches that do not represent the same value, but rise in stepwise fashion as the energy goes up. This indicates to some theorists that other new quantum numbers beyond charm and color are at work. At least two. Beyond charm and color, says one theorist, come "truth" and "beauty." These would require two new quarks, a true, or maybe truthful, quark and a beautiful one. We would then have six quarks: u, d, s, c, t and b.

There is also another reason why six quarks are desirable. The new experiments have found what appears to be a new lepton, the so-called U particle, which is exceptionally heavy for a lepton and may be one of the things the newer theories of lepton physics are looking for. According to the lepton economy, if the U exists, then there should be a U neutrino to go with it. That makes six leptons. With six fundamental units on the lepton side of the fence, physicists have an incentive to seek six on the hadron side, six quarks.

Now it is time to do a little arithmetic. The six quarks are the most fundamental manifestations of hadronic matter, but the three colored states that each can take are only slightly less fundamental. Three times 6 is 18. Furthermore, there are 18 corresponding antiquarks. Makes 36. On the lepton side, 6 leptons and 6 antileptons add 12 more. The total of 48 begins to look too numerous and complex to be the truly ultimate fundamental building blocks. So physicists are beginning to talk of quark spectroscopy as in the early part of the century they talked of atomic spectroscopy, and are beginning to think there is maybe a still lower level.

In an after-lunch speech at the recent meeting of the American Physical Society, Sidney Drell, assistant director of the Stanford Linear Accelerator Center, put it in terms of the disagreement between the ancient Greek philosophers Demokritos and Anaxagoras. Demokritos believed that if one examined the structure of matter one would eventually come to fundamental unstructured objects out of which everything else was made. These he called *atomos,* uncuttable. It has long been clear that what chemists chose to call "atoms" are not the *atomos* of Demokritos, nor are the particles physicists discovered in the atomic nucleus. For a while physicists had thought that in quarks they had come at last to the *atomos.* Now they are not sure, and some say maybe Anaxagoras was right. His picture of material structure was a series of nested seeds. In one seed is a smaller one, inside that yet a smaller one and so on *ad infinitum.*

Whether Demokritos or Anaxagoras be correct, and whether, if the former, we shall ever reach the true *atomos* remain open questions. Benjamin W. Lee, who leads the theorists at the Fermi National Accelerator Laboratory, and who spoke at the same festivity as Drell, is pessimistic about seeing an answer in his lifetime—and he is still quite a young man. Perhaps the last word should be given to St. Paul (who also said it in Greek): "Now we see through a glass, darkly; then we shall see face to face." ☐