Particle Physics: Is the Electron Really a Hadron at Heart?

Whether or not they know much about physics, most people are aware that one of the crowning achievements of high energy research was the discovery of a symmetry to the organization of elementary particles called the "eightfold way."

After the invention of the synchrotron opened up the world of subnuclear particles, new mesons and baryons were found by the hundreds—or thousands, depending on how you counted them. So many particles defied understanding until the theoretical application of a certain unitary symmetry showed that the particles fell into clearly distinguished groups with well-defined relations between them. The eightfold way not only explained the properties of many particles that were known, but it also predicted the existence of a new particle where one member was missing from a group that should have had ten particles in it. When the omega minus was discovered at Brookhaven National Laboratory in 1964, it had exactly the properties expected for the tenth member of the incomplete group. So the discovery of the omega minus spectacularly confirmed the theory that the elementary particles are related by a unitary symmetry, and made one wonder whether there might not be some underlying reason for it.

The reason put forward was that the elementary particles—at least those that undergo the strong interaction—are not really elementary at all, but are made up of still more basic particles with strange properties and strange names. The possibility was widely discussed not only in the scientific literature, but also in magazines such as *The New Yorker*, perhaps because the name was chosen by Murray Gell-Mann from a line in *Finnegan's Wake* by James Joyce, "Three quarks for Muster Mark?" Realizing that the relations among the elementary particles expressed by unitary symmetry would follow naturally from three subnuclear particles, Gell-Mann and George Zweig independently proposed in 1963 that three quarks with fractional charges could be put together in various ways to make up all the strongly interacting particles, or hadrons (see box).

The quark theory has really been a cornerstone of elementary particle theory for the last 10 years. Not only does it explain systematic properties of the multitudes of elementary particles, but it also explains many dynamic results. For instance, at very high energies the likelihood for a meson (consisting of two quarklike particles) to hit a nucleon (consisting of three quarks) is just two-thirds of the likelihood for two nucleons to collide. But some recent results obtained at the electron-positron storage ring, SPEAR, at Stanford University, Stanford, California, seem to cast doubt on quark-like models in both their static and dynamic aspects.

The quark theory has had problems as well as successes, and one of the problems is explaining why quarks have never been seen despite searches of cosmic rays, meteorites, and the mud on the sea floor, in addition to more usual investigations with accelerators. Perhaps quarks are either just mathematical constructions or else are so enormously massive that they have never been knocked loose from a nucleon. But experiments at the Stanford Linear Accelerator Center (SLAC) in 1967 and 1968 strongly supported the notion that the proton was made up of quarks—or at least something like them. When electrons with energies of 20 billion electron volts (Gev) were scattered off protons, an abnormally large number were found scattered at large angles. The result was interpreted as evidence that the proton is composed of a number of hard pointlike particles, called partons, that are free to scatter. The electron-proton scattering study did not determine the fine details of the nucleon constituents, so parton has become a generic term of which many types of quarks could be examples.

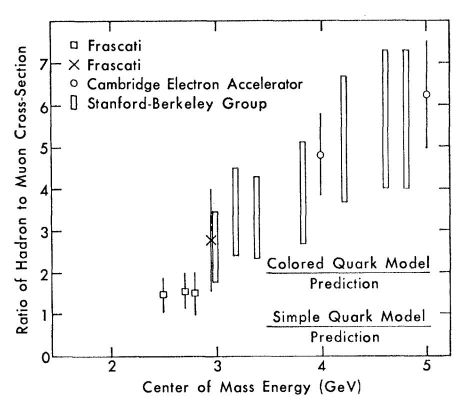


Fig. 1. Data from electron-positron collisions at the Stanford storage ring appear to rule out most theories that have the strongly interacting particles composed of quarks. The simplest quark model predicts that the ratio of hadron production to muon production should be 2/3, independent of energy. More complex models, like the colored quark model, predict values from 2 to 6, but the experimental curve does not seem to be leveling off yet at 5 Gev.

The Stanford experiments were similar to the experiments Rutherford performed when he discovered the nucleus of the atom. Rutherford found that when alpha particles passed through a gold foil many were deflected. The large deflections were evidence that the positive charge in the atom was located at a point rather than being diffused throughout the atom. The experimental results from SLAC also had the property of scaling—that is, the distribution of scattered electrons at one accelerator energy was related to the distribution at another energy in a very simple way. The quark model and the property of scaling, as explained by the parton model, were both sturdy and central props in the framework of particle physics.

The surprise that knocked out the props from both important theories at once is an elegant experiment that examines the results when an electron and positron annihilate and produce pure energy, which subsequently appears as a shower of particles and antiparticles. The experiment makes it possible to study the hadrons from a particularly simple starting point, since the electrons and positron are in the class of leptons, or those particles that do not respond to the strong interaction. The results are so unusual that physicists are already suggesting new ways of viewing matter in order to understand them. Not only do the results contradict the quark and parton models, but they look almost as if protons had collided. In other words, leptons seem to be showing the sort of behavior expected from the hadrons. According to Burton Richter at SLAC, the energy density at the point of annihilation is almost as great as in the "big bang" that presumably started the universe, so perhaps it should be no surprise that the physics coming out of this experiment is so different from what has gone before.

The experiments that have upset so many well-founded notions examine the particles produced when beams of electrons and positrons stored in the same ring collide. All the energy of motion and rest mass is converted into a photon, which can decay into hadrons or leptons, so long as equal numbers of particles and antiparticles are produced. The hadrons generated are mostly pions. By very general assumptions, the ratio of hadrons to muons produced in the reaction is a measure of the charge on the quarks that make up the hadrons. Specifically the ratio should be the sum of the squares of the individual quark charges, and should be independent of energy. Experiments at the Laboratori Nazionali, Frascati, Italy, ruled out the simple quark model, which gives a sum of 2/3, and results obtained at the Cambridge Electron Accelerator in Cambridge, Massachusetts, just before it was closed down last year showed that the ratio kept rising with energy to an extent that seemed to rule out all but very complex quark models (Fig. 1). But the Cambridge experimenters did not have time to accumulate very many events (about 100 in all), and the results were so troublesome that the high energy physics community awaited further verification.

With a more sophisticated hadron detector and more intense electron and positron beams, a group of researchers from the Stanford Linear Accelerator and the Lawrence Berkeley Laboratory repeated the Cambridge experiment and found that when their maximum energy, 5 Gev in the center of mass, was reached the ratio was still rising. The storage ring used for the experiments is filled with a compact bunch of electrons from the SLAC accelerator going around in one direction, and a bunch of positrons going in the other direction. After the ring is filled, beams can circulate for 2 to 3 hours before they are degraded. Hadrons are detected by a very large magnetic detector which almost completely surrounds the storage ring at one of the two regions where the electron and positron bunches collide (Fig. 2). Cylindrically shaped wire spark chambers just outside the beam pipe detect the paths of particles produced in the collision. The particles pass through a solenoidal magnetic field, so the energy and type of each particle can be unambiguously identified. SPEAR is a rather modest facility, as high energy physics machines go. It was just completed in the spring of 1972 at a cost of about $5 million, and the hadron detector was completed in summer of 1973 for about $1 million.

Even though there were warnings, the SPEAR result has astounded many high energy physicists, and there is no doubt, in the words of Sidney Drell at SLAC, that "It has the theorists running for cover." The parton model that worked so well for the earlier experiments at SLAC fails completely to explain the current results, even though the processes are very closely related. In fact, most theorists thought that scaling should work even better for colliding beams than in the previous SLAC experiments. Perhaps the partons are not indivisible after all. Anaxagoras, about 450 B.C., suggested that matter

The Simplest Quark Model

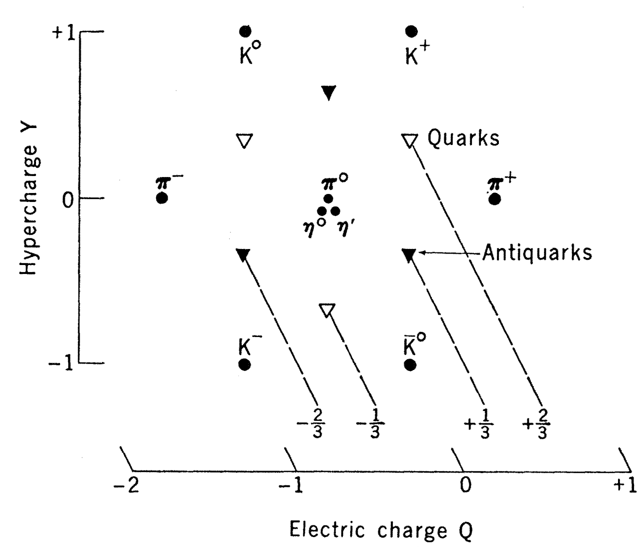
One of the most popular and powerful models of the elementary particles is that they are composed of various combinations of still more basic particles called quarks. The quark hypothesis was suggested after it was discovered that well-defined groups of strongly interacting elementary particles exist, and that the members of a group are nearly equivalent except for charge and hypercharge. (Hypercharge is a special kind of charge, discovered in 1947, which is conserved in strong interactions but not in beta decay.) Not only the existence of various groups, such as the mesons in the figure, but also the relations between the various members of a group are explained by the quark model.

The three quarks have fractional values of the fundamental unit of charge, $+\frac{2}{3}$, $-\frac{1}{3}$, and $-\frac{1}{3}$; and for each quark there is an antiquark with opposite values of charge and hypercharge. Mesons are made up of a quark and an antiquark, while baryons, such as neutrons and protons, are made up of three quarks. Although the multitudes of baryons that have been discovered are not displayed here, they also fall into groups that are symmetric in charge and hypercharge. According to the hypothesis, the proton is composed of two $+\frac{2}{3}$ quarks and one $-\frac{1}{3}$ quark; the neutron is composed of two $-\frac{1}{3}$ quarks and one $+\frac{2}{3}$ quark. (The $-\frac{1}{3}$ quark must be the one with hypercharge $+\frac{1}{3}$, because neutrons and protons have hypercharge 1.)

By combining one of three quarks with one of three antiquarks, nine different possible combinations can be formed, and these correspond to the nine known mesons, including pions π^+, π^0, π^-, which are plotted in the figure by circles. Since the charge and hypercharge of the mesons must be the sum of the values of the constituents, close inspection will establish which quarks and antiquarks make up which mesons. The electric charge scale in the figure is tilted because of its peculiar relationship to the horizontal scale, which is isospin.

—W.D.M.

Symmetry of nine mesons



may be infinitely subdivided, and particle theorists are contemplating the same questions as they try to figure out which of the many possible ways of modifying their theories is most likely to be right. While some postulate that the parton is not pointlike but has a substructure, it must be remembered that the parton—itself a postulated substructure to the proton—has never been observed. Drell thinks that, in retrospect, it should have been more embarrassing to theorists that no fragment representative of the parton was ever seen, not even some fossil of the scattered particle such as the correct total charge.

Although the latest experiment will almost surely change the course of a certain class of theoretical ideas, in which way it is probably too early to tell. The word quark means a lot of things to different people, and "You really don't know exactly how the quark fits into the dynamics of things," says J. D. Bjorken at SLAC, who proposed the most widely accepted explanation of scaling.

One explanation why the ratio of hadrons to muons has not yet leveled off is that the experimental energies are not high enough for the quark effects to be observed. If this is true, it seems as if there must be more than three quarks in the "right" model. In addition to the simplest quark model, which gives 2/3 for the sum of squares of the quark charges, at least four others have been suggested. In order to get the proper statistics for baryon states, the basic triplet of quarks can be repeated three times in three different colors, red, white, and blue, which gives a sum of 2. In addition to color, a fourth, or charm, quark with charge 2/3 can be added to the basic triplet to fix up certain problems in the weak interactions. This model gives 10/3. Next, the model of Han and Nambu has three colored triplets, but the quarks have either integer or zero charge. The Han-Nambu model gives 4. Last, the model of Salam puts charm into the Han-Nambu scheme and gives 6 for the sum of squares of the charges. Thus, with increasing color, charm, and complexity, values from 2/3 to 6 can be accommodated.

Rather than explain away the rising curve in Fig. 1 by saying that the experimental energy is not yet high enough to observe asymptotic phenomena, theorists can explain the curve by saying that new particle channels are being opened up for the first time

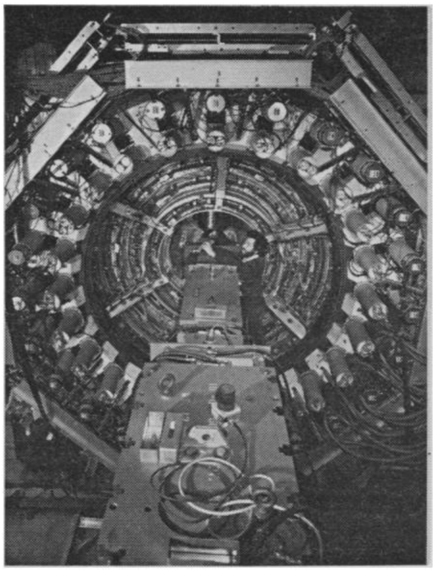


Fig. 2. The system for detecting hadrons produced at the Stanford electron-positron storage ring, SPEAR. A large solenoidal magnet encloses four cylindrical spark chambers, which in turn enclose the beam pipe.

at these energies, and that the ratio will decrease at higher energies once the resonance is passed. The new channels could be colored quarks or charmed quarks or fancier quarks; they could be leptons, heavier than ever observed before, that ultimately decay into hadrons and so enhance the hadron-muon ratio. The problem with this interpretation of the data is that from the lowest to the highest energy there is very little change in the distribution of hadrons in the SPEAR experiments. The distribution is very nicely thermodynamic and independent of energy, except for the ratio of charged to neutral particles. At 3-Gev center of mass energy (1.5 Gev in each beam), about two-thirds of the available energy is found in charged particles, which is expected because pions, π^+, π^0, and π^-, should be produced in equal numbers. But at 5-Gev the fraction of available energy emerging in charged particles has decreased to one-half. According to Bjorken, this change is the only evidence that favors the "opening channel" explanation.

With the easy explanations apparently ruled out, what other interpretations can be given? The other guesses that have been made would be truly revolutionary for physics, if proved correct. The process may not be proceeding through an intermediate, photon, stage at all, but it may be an example of some new force that interacts directly between leptons and hadrons. That may not be likely, but it is not ruled out yet. Speculation that the electron might really have a hadron core would be even more revolutionary, if true. The evidence for this idea is that the distribution of pions from the electron-positron collisions at SPEAR is almost identical to the distribution of pions produced at 90° by collisions of proton beams at the Intersecting Storage Rings at CERN [*Science* **178**, 852 (1972)] or at equivalent angles in experiments at the National Accelerator Laboratory. The major difference is that the number of pions is smaller by 10^6 for lepton collisions.

The fact that the distributions of hadrons is generally thermodynamic (except for the ratio of neutral to charged particles) is also suggestive of proton collisions. The theory of quantum electrodynamics works extremely well for lepton interactions, but no experiment requires it to apply for distances smaller than 5×10^{-15} cm. Such considerations lead to the speculation that the electron may actually be sensitive to the strong interaction within the very tiny radius of 10^{-16} cm (a radius that would account for the factor of 10^6 noted above). The speculation has passed the point of idle talk, and is being seriously discussed in the scientific journals. Is there really a hadron at the heart of the electron?

Although the results of the colliding beams experiments contradict the parton model in almost all its aspects, they don't prove that quarks don't exist. Physicists who favor quarks and partons have often divided into separate camps, particularly on the question of whether the two sorts of particles were equivalent, and those who favor quarks point out that it is only the pointlike nature of quarks—the extreme singularity—that has been questioned.

Since the discovery of the omega minus 10 years ago, many people have felt that data from high energy experiments was proliferating faster than success at understanding it, and that somehow the science that was supposed to be most fundamental had run out of good leads to answer the most important questions. The SPEAR results challenge such well-entrenched theories that the results may change the course particle physics has been following. Further experiments with electron-positron collisions at higher energies, which will be available at SPEAR after this summer, and other experiments that test scaling—such as muon-proton scattering—should tell what is really happening.—WILLIAM D. METZ