Evidence for Free Quarks Won't Go Away

But high-energy theorists ignore the experiment in the hope it will. Several new investigations may settle the issue this year

When quarks were proposed in 1964 to be the fundamental constituents of matter, physicists were understandably skeptical. After all, since Robert A. Millikan's famous oil drop experiments in the early 1900's, everyone believed that the electrical charge of any object was an integer multiple of that of an electron. Yet quarks were given charges of one-third and two-thirds of the electronic charge. They should stick out like a sore thumb, but there was absolutely no experimental evidence for fractionally charged objects.

A little more than a decade later, however, physicists had become converted, although quarks still had not been directly detected. A succession of high-energy accelerator experiments provided circumstantial but convincing evidence that elementary particles like the proton and neutron were in fact composites of more fundamental entities, probably with fractional electric charges. In the meantime, theorists constructing models for the strong nuclear force between elementary particles had to account for the absence of "free" quarks; that is, quarks not forming combinations with other quarks. Although no theory has rigorously proved that quarks are always bound together in this way, "most theorists are convinced that the usual [theory of the strong force] would require total confinement," says Robert Jaffe of MIT.

Upon this scene burst William Fairbank, George LaRue, and Arthur Hebard of Stanford University with their announcement in the spring of 1977 that, after 12 years of trying, they had found two small niobium spheres among the eight measured that had fractional electric charges, possibly residing on their surfaces. Although no one has confirmed their results, in the past 4 years the Stanford group has continued to find more niobium balls containing fractional charges. (James Phillips has since joined the group, and Hebard is now at Bell Laboratories.) The evidence is getting better, not worse as usually happens when unusual phenomena pop up but later quietly drop from sight.

By last summer, the investigators had completed 39 measurements on 13 balls and they saw fractional charges 13 times on five different balls (some were measured more than once). In every case, the charge was either 0, $+1/3$, or $-1/3$. Fairbank presented his group's most recent results in an invited talk to an American Physical Society meeting last month in New York City. Fairbank said that data from eight more measurements on four new balls were not completely analyzed, but that the eight measurements fell into three groups with charges separated by 1/3.

Suppose, suggests Jay Orear of Cornell University, that there was a random background effect that the Stanford group was overlooking. Then, there should be a constant probability for measuring any value of charge between $+1/2$ and $-1/2$. (The way the experiment is conducted, 1/2 is the largest charge value that can be present.) The probability that the investigators just happen to pick out the values 0 and $\pm 1/3$ from this continuous distribution is "only one in a million," says Orear. Gaurang Yodh of the University of Maryland adds that repeatability of the experiment, always seeing either 0 or $\pm 1/3$ as the charge on the niobium balls, is the main strength of the claim for fractional charge.

Observers are quick to point out that even if the Stanford results are accepted as proved, the source of the fractional charge need not necessarily be quarks, but quarks are the only "conventional" particles with this odd property. And, if they are quarks, the impact on elementary particle physics would be enormous. Among other things, the much touted grand unified theories that attempt to absorb all three forces that affect elementary particles (strong nuclear, weak, and electromagnetic) into one mathematical framework would have to be modified, as would the leading quark theory, quantum chromodynamics.

Given the huge potential significance of a free quark sighting, it is perhaps surprising that theorists have not devoted more effort to accommodating the particles into their models. With only a few exceptions, theorists and high energy physicists in general have given a collective, although nervous, yawn to the Stanford experiment. Sheldon Glashow of Harvard University says that he and his theorist colleagues have been known to jump on bandwagons before, but free quarks are just not the direction people want to go right now.

Another sticky point is that Fairbank, the principal investigator in the Stanford group, is a condensed matter (solids and liquids) physicist, and the experiment is quite far removed from the accelerator experiments that high energy physicists are used to. But Warren Johnson, who is working with David Douglass at the University of Rochester to set up a quark search somewhat similar to Fairbank's, says that it is not prejudice that prevents high energy physicists from being more receptive; their background is so different that they have no way to judge the Stanford work. In this light, says Johnson, "it is just good sense to remain skeptical when there is only one experiment."

Fairbank says that work on the Stanford free quark search began after the 1964 proposal of Murray Gell-Mann and (independently) George Zweig, both now at Caltech, that quarks are the constituents of the elementary particles that feel the strong nuclear force (the force that binds the nucleus together). About 1970, Hebard and Fairbank turned up some evidence for fractional charges, but they could not remove all the background forces. When LaRue rebuilt the original apparatus, positive data began to appear consistently, leading to the results published in 1977 and subsequently.

The idea of the experiment is delightfully simple, but its execution presents numerous difficulties. The niobium spheres are superconductors. Superconductors have the property that an applied magnetic field cannot fully penetrate the bulk of the material, and this feature can be used to levitate a superconducting body, in this case a niobium sphere. The sphere was in effect supported by a magnetic "spring," which like any spring has a resonant frequency at which it will tend to vibrate if displaced by some force. As the displacing force, the Stanford investigators used an alternating electric field parallel to the vertical magnetic field whose frequency matched the resonant frequency of the "spring." The amplitude of the oscillations should then be directly proportional to any electric charge residing on the niobium ball. Radioactive electron and positron (anti-

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electron) sources in the apparatus enabled the physicists to add or subtract individual electric charges, and in this way the residual charge on a ball could be brought to zero (no quarks present) or $\pm 1/3$ (quarks present). The balls weigh about 0.1 milligram, are just under 0.3 millimeter in diameter, and contain about 5×10^{17} niobium atoms.

Some feeling for the delicacy of the experiment can be gotten from the realization that the electric displacing force is only about a twenty-millionth as strong as the magnetic supporting force. In addition there are two background forces large enough to affect the results. The forces are due to induced and permanent dipole moments on the niobium balls that interact with nonuniformities in the electric field felt by the balls. The background forces mimic fractional electric charges by causing an extra displacement of the balls beyond that due to the applied electric field. Moreover, the background sometimes changes during a run. All in all, it is far from a simple matter to extract a meaningful value of the charge on a ball, although the Stanford group claims an accuracy of about ± 0.01 electronic charge.

Perhaps because of the difficulty of the experiment, no one has tried to duplicate it. The only other report (negative) of a free quark search involving levitation of superconducting niobium balls was a 1969 Ph.D. thesis by Earl W. Johnston at the University of Michigan.

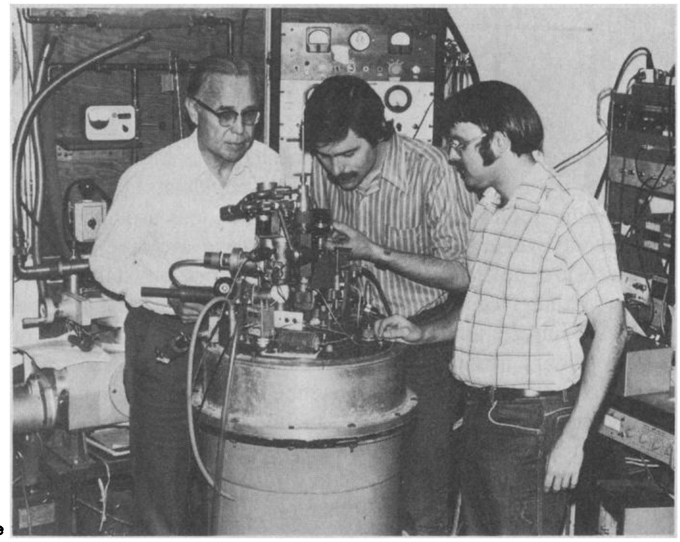
All of this is not to say that there have not been many searches for free quarks, because in fact there have. A rite of passage, as it were, for new high-energy accelerators as they come on-line is seeking the elusive particles among the debris from collisions between elementary particles. Physicists have also looked for free quarks among the showers of particles emanating from the collisions between cosmic rays and gas molecules in the upper atmosphere. Finally, numerous groups have sifted through ocean bottom sediments, seawater, lunar soil, and various earthly rocks and minerals. All such searches have been in vain.

There is, moreover, one experiment with which the Stanford work is often directly compared and which consistently yields no evidence for free quarks. If there is such a thing as a rivalry among free quark hunters, it must be between Fairbank and Giacomo Morpurgo of the University of Genoa and the Italian National Institute for Nuclear Research. Morpurgo says he would like to see free quarks, but the evidence is not there.

Morpurgo and his collaborators began work about the same time as the Stanford group and actually have the first published account of a magnetic levitation quark search experiment. Rather than superconducting niobium at cryogenic temperatures, the Italian physicists started with the highly diamagnetic material, graphite, at room temperature. Like superconductors, normal diamagnetic substances resist applied magnetic fields to some extent and can thereby also be levitated magnetically. By 1970, Morpurgo, Gaetano Gallinaro, and Guido Palmieri had concluded that there were no fractional charges on their graphite. Subsequently, Mauro Marinelli joined the group, Palmieri departed, and the researchers turned their attention to a modified version of their experiment. They decided to concentrate on ferromagnetic materials because more materials could be studied and the sensitivity would be greater.

Shortly after the Stanford group published its first claim to having observed fractional charge, Morpurgo and his coworkers reported a negative finding. In measurements on five iron cylinders weighing about 0.2 milligram apiece, the investigators observed no fractional charge to a sensitivity of 2 parts in 10^{19} (less than 2 quarks per 10^{19} iron atoms). At the time, physicists generally assumed that the negative result contradicted the Stanford finding.

A news story that devoted much of its discussion to Stanford and made only a cursory reference to Genoa drew an irate letter to the editor of *Physics Today* from Morpurgo. The published letter and a reply from Fairbank were not cast in the friendliest of terms, with each scientist criticizing details of the other's experiment. A second round of letters appeared in the summer of 1978, but by then relations between the two groups were at least formally more amicable. Fairbank wrote, for example, that "Both experiments were carefully done and are significant contributions to an important problem in physics." Since then, Fairbank has journeyed to Genoa and visited the researchers there, but Morpurgo has been unable to accept an invitation to inspect the Stanford laboratory.



William Fairbank, James Phillips, and George LaRue with their free quark search apparatus.

Frans Alkemae

Marinelli and Morpurgo have continued experimenting with steel balls in place of iron cylinders. Interestingly, they find a continuous distribution of residual charge on the steel balls, which some physicists at first interpreted as fractional charges equal to $\pm 1/3$. But Marinelli and Morpurgo attributed the charges to a surface magnetoelectric force. They were able to devise a procedure to remove this effect and they then found no quarks on any of 55 samples to a level of 6 parts in 10^{20}. When Morpurgo presented these latest data at a high energy physics meeting last summer, he suggested that the surface force might also be influencing the Stanford results. Recently, M. J. Buckingham and Conyers Herring, who are at Stanford but not working with Fairbank, explained the mysterious force and showed that it could not be present in the superconducting niobium experiment because of an essential difference in the geometries of the Stanford and Genoa apparatuses. Morpurgo now agrees that this is indeed the case. The important point for free quarks, however, is that, whatever the cause of the effect, the Genoa group properly removed it and then found no quarks.

The question then becomes, "Can the Stanford and Genoa results both be correct?" Nearly everyone seems to agree that they can. In contrast to the situation in 1977, physicists now believe that free quarks, if they exist, are not uniformly

Looking for a Needle in a Haystack

Where in the world should one look for a quark? Right now, nobody knows, but a few physicists have been thinking about the question, and some ideas are emerging. Almost everybody agrees that, if there are free quarks, there are not very many of them. Most physicists also agree that free quarks probably are not running around loose, but are attached to other entities such as the nuclei of ordinary atoms in minerals of the earth's crust.

To explain the apparent absence of free quarks in nature, theorists have devised the concept of color confinement. Although quarks are electrically charged and thereby feel the electromagnetic force, they also possess an abstract "charge" of another sort that physicists have arbitrarily named color. Color is the source of the force between quarks and is ultimately responsible for the strong nuclear force that binds the nucleus together. Quarks come in three colors. Color confinement means that no physically observable particle can have color. Thus, elementary particles must be made of two quarks (a quark and its antiquark) or three quarks (one of each color) because these combinations are colorless. Actually, there is no rule against free particles bearing fractional charges, as quarks would, as long as they are colorless.

In the first billionth of a second following the Big Bang when the universe was unimaginably hot and dense, quarks rather than the composite elementary particles would have been the only form of strongly interacting matter. And they would have been so forcefully pushed together that physicists talk of a quark soup. Later, as the universe expanded and cooled, the quarks would form pairs and triplets, and the elementary particles would be born. Any free quarks existing today are probably those that somehow escaped this recombination process.

How many free quarks should there be? Robert Wagoner of Stanford University and Gary Steigman of the Bartol Research Foundation at the University of Delaware have used a modified version of quantum chromodynamics, the theory of the force between quarks, to make an estimate. They found that the abundance of free quarks depends on the masses of the particles. As it happens, no one knows how heavy a free quark is, although the failure to observe them in accelerator experiments provides a lower limit. The results of William Fairbank and his colleagues at Stanford suggest there may be about one quark for every 10^{19} to 10^{20} protons in the universe (see story).

If free quarks do exist, they may well be combined with other more ordinary particles to make a fractionally charged object. But the model taken most seriously by the theory community is that of Alvaro De Rújula of CERN (the European Organization for Nuclear Research near Geneva) and Roscoe Giles and Robert Jaffe of MIT. Their motivation was to find a way of accommodating free quarks within the restrictions of quantum chromodynamics, so that its many successes could be retained. There are eight particles called gluons that are analogous to the photon in electrodynamics and that transmit the color force between quarks. Like the photon, the gluons have no mass and travel at the speed of light. De Rújula, Giles, and Jaffe have proposed that the gluons be given a slight mass. If this were done, they suggested, color confinement need no longer be absolute, and free quarks would be permitted.

A second consequence is that quarks would no longer be pointlike objects as electrons are. Instead, they would become of measurable size and would have an affinity for neutrons. By the time the universe was 3 minutes old, such an extended quark with a mass (for example) 100 times that of a proton could absorb a characteristic number of neutrons (80 in this example), forming a complex object, the "quarkleus." After converting some neutrons to protons by beta decay, the quarkleus could end up as a stable object with an "atomic number" of $35\frac{1}{3}$ and a mass of about 160. As Jaffe says, "it would be a very bizarre isotope." But it could be concentrated in mineral deposits if it had chemical properties similar to that of a metal.

Another bizarre sort of fractionally charged object has been conjured up by George Chapline at the Lawrence Livermore National Laboratory. Protons and neutrons are each made up of three quarks. Atomic nuclei in turn are composed of protons and neutrons. Chapline proposes skipping the protons and neutrons and proceeding directly from free quarks in the earliest moments of the universe to a heavy object consisting of many quarks. There would be no grouping of quarks into threes, and a fractionally charged nucleus-like entity could form. Chapline calculates that the "atomic number" of such an object would have to be greater than 10 (neon) for it to be stable.

At Caltech, George Zweig, the co-inventor of the quark, and Klaus Lackner have been attempting to develop a quark "chemistry." Unrecombined quarks would find protons, neutrons, helium nuclei, or lithium nuclei and form complexes with them. These fractionally charged objects would then evolve as ordinary matter as the universe aged. In particular, the process of nucleosynthesis in stars and supernovas could create heavier quarked nuclei that would then get sucked up into newer stars and their planets. In this way, they could become part of the earth's crust.

A key point, according to Zweig is that the quark would be so tightly bound to the protons and neutrons in the complex that it would look like a single positively charged entity to electrons. The electrons would then settle into orbits determined by this central charge. The chemistry of a quarked atom of this type should be derivable by interpolating between the properties of a normal element and an ion with the same number of electrons but a different nuclear charge. Zweig and Lackner have done this for two properties (electronegativity and a crystal radius). If a quarked atom and a normal element had the same or similar chemical properties, then a good place to look for quarks would be where that element is found.

William Fairbank, Jr., at Colorado State University is also using an interpolation method to calculate the wavelengths of optical transitions in quarked atoms. He then plans to collaborate with Samuel Hurst of Oak Ridge National Laboratory, who has developed a laser spectroscopy technique that can detect single atoms. Fairbank will start looking in seawater for quarked atoms with "atomic numbers" near those of argon, krypton, and xenon (rare gases). The idea is that the leftover fractional charge in the otherwise unreactive object would be strongly attracted to the polar water molecules.—A.L.R.

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distributed over the earth. Because the particles quite possibly are associated with particular atomic species, some physicists believe that they would be as highly segregated as minerals in the earth's crust (see box). It is conceivable that quarks attach themselves to niobium but not to iron.

Several other experiments under way or in preparation could help clarify the question of free quarks. Two of the experiments are similar to the Genoa quark search. In 1974, Klaus Ziock of the University of Virginia had preliminary evidence for fractional charges in measurements of 12 steel balls but was unable to remove all the background forces. After a dry spell in funding, Ziock is gearing up for some further runs starting this month. The second effort is that of Johnson and Douglass at Rochester. Work was started there just after the Stanford group announced its 1977 findings, but meager finances, difficulty in finding graduate students who would gamble on such a high-risk enterprise, and the technological challenges of a complex experiment have slowed progress.

Roger Bland, Jeffrey Royer, and their associates at San Francisco State University also began looking for free quarks after the 1977 announcement from Stanford. The San Francisco State researchers measured the electric field required to halt charged tungsten droplets falling under the influence of gravity (modified Millikan oil drop experiment). Analysis of 69 droplets showed that there was no residual charge (no quarks) for any of the particles; that is, there were no quarks in about 10^{12} tungsten atoms. At New York, the San Francisco group reported on a sample of 100,000 mercury droplets that were measured in a modified version of their original apparatus. The researchers found no quarks in 4×10^{16} mercury atoms. Both purified and native mercury was examined. Further experiments are planned.

An altogether different sort of free quark search is based on the use of an electrostatic (Van de Graaff) accelerator as the front end of a mass spectrometer. One limitation in past studies (negative) of this type is that the mass of the ion carrying a quark is not known, but mass spectrometers are tuned to sort things according to their mass. A concept developed by Ted Litherland and his coworkers at the University of Toronto provides a way to overcome this limitation and is the basis for at least three planned experiments at Toronto, Rochester (Stephen Olsen and David Elmore), and Ohio State University (Richard Boyd). The idea is to remove the magnetic sector of the mass spectrometer and instead use two electrostatic sectors arranged in a particular way. The resulting configuration would, says Olsen, permit ions of every mass to pass through the column but would be very selective for fractional electric charge.

One advantage of such a scheme is that, if a fractionally charged particle was detected, its mass and charge could be determined independently. Another feature is that fractionally charged particles could be collected for experiments of other types, such as optical spectroscopy. One thing high energy physicists would like is a sample of fractionally charged objects to put in accelerator targets in order to determine their properties. A quark would have to obey quantum chromodynamics, for example.

But it is still another type of search that some observers are betting on in the great quark hunt sweepstakes. Work is going on in three places, the Lawrence Berkeley National Laboratory, the Argonne National Laboratory, and the Lawrence Livermore National Laboratory. Two years ago Greg Hirsch and Ray Hagstrom of Berkeley got the idea to use the technology of high-speed ink jet printers to make reproducible, small-sized mercury droplets. The droplets would fall by gravity, but where they landed could be controlled by a horizontal electric field. The droplets would be deflected by the field by an amount proportional to any electric charge on them.

> "It is just good sense to remain skeptical when there is only one experiment."

Fractionally charged droplets would show up in the regular spacings between integer-charged particles. One trick is to make the droplets small enough—10 micrometers in diameter—to be deflected. This problem was solved with the help of Charles Hendricks of Livermore, who is the person in charge of manufacturing the tiny glass Microballoons used as targets in Livermore's laser fusion experiments. Hirsch says that an apparatus built at Berkeley is now operating well enough that integer charges can be easily resolved after the droplets fall about 3 meters. In the meantime, Hagstrom has taken a new position at Argonne where he is working on a much larger apparatus of the same type to be completed by this summer. And Hendricks is building his own machine at Livermore, which should, he says, be working soon.

The main advantage of this droplet approach, says Hagstrom, is that it allows the direct study of relatively large quantities of matter that has not had its quark content threatened by extensive chemical refining. If all the niobium in the 17 balls reported over 4 years at Stanford could be converted to droplet form, the Berkeley apparatus could run it through in less than a minute. Moreover, if quarks are truly present on the niobium balls, Hagstrom estimates, the refining process could have reduced their concentration by a factor of 10^{12}.

In the midst of more quark hunting activity than has been evident for some time, Fairbank is not sitting still. His group has generated several schemes, one of which is a nonsuperconducting, room-temperature experiment that LaRue is readying. But the idea that will be tried first is a new way to analyze the data. It turns out that the researchers do not count every niobium ball that they measure. The background force must be accounted for by comparing the measurements on several balls as a function of their vertical position in the apparatus. Only if the positional dependence of the apparent residual charge stays constant for at least two balls can the background force be properly subtracted out, yielding the true residual charge. When this criterion is not met, no value for the residual charge can be obtained. Some physicists wonder if a bias is introduced when measurements are discarded. In any case, the physics literature is replete with examples of strange effects that extensive scrutiny failed to discredit. Only later did someone show where the original investigators went wrong.

To alleviate such suspicions, it has been proposed (by Hagstrom and Luis Alvarez of Berkeley and independently by Zweig) that a computer program be constructed that allows someone outside the Stanford group to enter arbitrary values of electric charge into the data being analyzed. The Stanford researchers could not discard a ball for having the "wrong" charge because they would not know what value had been added into their data until after the analysis had been completed. At the New York meeting, Fairbank told the audience that future measurements would be analyzed in this way and that such a computer program was in the process of being written. If Stanford does this, said Alvarez, "everyone will believe them."

—ARTHUR L. ROBINSON