When is a particle?

Particle physics, like poetry, no longer hews to its former rigid rules, hence the standard for accepting quarks as elementary constituents is less severe than the neutrino's was in the 1930's—in fact, we may never see a quark.

Sidney D. Drell

Man's effort to understand what we and our world are made of is one of the greatest adventure stories of the human race. It dates from the beginning of recorded history. Science first flourished 2500 years ago with the quest of the early Greek philosophers for an underlying unity to the rich diversity observed in world around them. They realized that the search for an understanding of Nature at a fundamental level in terms of basic processes and constituents necessarily carried them beyond the sensory world of appearance.

In his essay on Lucretius, George Santayana described the emergence of this idea that "all we observe about us, and ourselves also, may be but passing forms of a permanent substance" as one of mankind's greatest thoughts. We now recognize it as the original search, in its most primitive form, for Nature's conservation laws and elementary particles. However, the early Greek "metaphysicists" predated by two millenia the modern scientific method—with its insistence on experimental observation. In their inquiry they relied purely on rational analysis, free from the discipline of direct observational content. Not surprisingly, therefore, they went off in widely differing directions: Leucippus and Democritus to the concept of indivisible atoms; Anaxagoras to the original bootstrap model of infinitely divisible seeds within seeds, each as complex as the whole, and Anaximander, Pythagoras and Plato to more abstract mathematical concepts of numbers and symmetries.

On occasion since then, scientists have arrogantly alleged that the end of this search for Nature's basic building blocks is in sight. However, such delusions have been short lived, especially in modern times, crumbling midst the debris that emerges from increasingly powerful atom smashers. We have come to appreciate how much richer Nature's imagination is than our own vision of what lies beyond the next frontier, as we explore with ever more powerful and sensitive instruments on ever-shrinking space–time scales. This is particularly true now, after three explosive years of remarkable discoveries of new particles, starting with J/ψ in November 1974; see figure 1. In the wake of these momentous discoveries it is timely to explore what has happened in recent years to our concept of the elementary constituents—the building blocks—of Nature.

Sidney D. Drell is a professor at Stanford University and the deputy director of the Stanford Linear Accelerator Center.

Quarks—fit for the Social Register?

During the past two decades we have come to the point of accepting into the exclusive family of elementary particles a guest who would not have made the Social Register of an earlier generation. i am, of course, referring to the *quark*, which was introduced in 1964 independently by Murray Gell-Mann and George Zweig[1] in their efforts to summarize and systematize the great proliferation of nuclear particles that were being produced by accelerators on the high-energy frontiers of the 1950's. Regularities had been perceived in the masses of these particles as well as in the characteristics of their creation, their interactions and their decays; Gell-Mann and Zweig showed that these regularities, as well as new ones found later, could be accounted for in terms of the simple motions and interactions of just three different kinds of fractionally charged spin-$\frac{1}{2}$ quarks. The quantum numbers of these quarks are shown in table 1. In this scheme, known as SU(3), several hundred hadronic resonances are successfully interpreted as excited states of just two simple quark configurations:

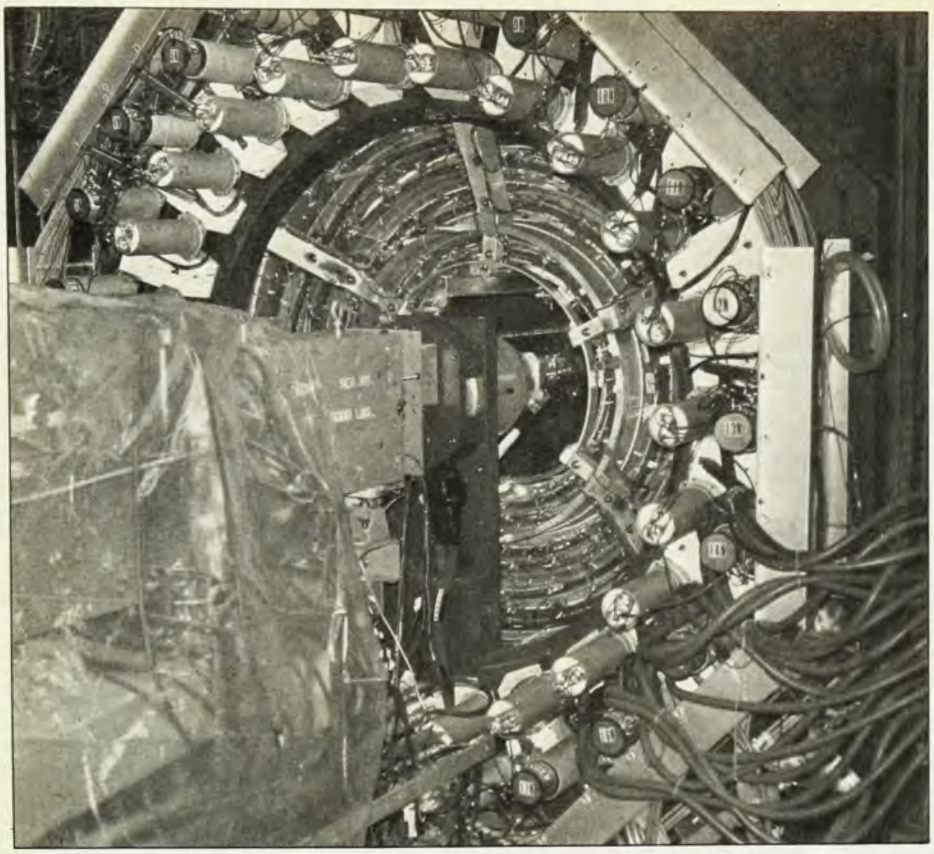
- three quarks (qqq) form a baryon and
- a quark–antiquark pair ($q\bar{q}$) forms a meson.

Table 1 lists the quantum numbers and "flavor" labels—up, down and strange—of the three original quarks. In it Q is their electric charge in units of the proton charge, I_3 is the third component of their isotopic spin and S is their strangeness number.

Because the quark hypothesis made correct predictions, provided a systematic organization of a large mass of data and brought simplicity along with a unifying harmony to our view of Nature, it was a crucial step forward, similar in many ways to the discovery of the nuclear atom by Ernest Rutherford in 1911. The role of quarks in subnuclear spectra is similar to that of electrons in atomic spectra, and that of neutrons and protons in nuclear spectra. What is new, however, is that in contrast in both our atomic and nuclear experience we do not "see" the individual quarks isolated from one another. When we break apart—ionize—an atom, its electrons and its nucleus are clearly evident and are detected in the debris. The same is true when we identify individual protons and neutrons in the debris stripped away in nuclear collisions. How then do we account for our failure to see quarks in the debris of a shattered proton or of any other subnuclear particle? What does this unprecedented experimental situation do to our very concept of an elementary particle?

Indeed, when we now ask what we mean by an elementary particle, we can feel a certain kinship with the modern poet who asks, "When is a poem?" Modern poetry clearly no longer lives by

0031-9228/78/3106-0023 $0.50



The detector, Mark I, with which the "ψ" particle was discovered in 1974 at the Stanford Linear Accelerator Center. The particle was discovered simultaneously at Brookhaven, where it was dubbed "J." The long lifetime and great mass of J/ψ surprised the physics community. The particle's existence decisively supports the concept of charmed quarks. Figure 1

rigid rules of meter and rhyme, and many times even—or should I say especially—the meaning is obscure. As Archibald MacLeish wrote in his poem "Ars Poetica":

"A poem should not mean
But be."

How do we scientists now respond to the question, "When is a particle?"

A tale of two particles

To appreciate how far we have moved in our modern concept of elementary particles we need look back only to 1930 and the birth of the neutrino. On the historical time scale this is less than 2% of the way back to the earliest Greek metaphysicists of 2500 years ago, but our concepts of "When is a particle?" have evolved considerably during this relatively brief period. Before the neutrino could fully establish its credentials as a socially respectable elementary particle in the 1930's and 1940's, many physicists insisted on seeing it carry away both energy and momentum in proper proportion during beta decay; more conservatively, some insisted on being able to observe its arrival. In today's world of quarks we have apparently discarded such requirements as a standard against which to test the concept of particle. Indeed, according to current dogma we never can nor shall observe isolated quarks or record the emission and absorption of individual quarks. How and why have we come to such a revolutionary new perception of elementary particles? By way of contrast, recall first the story of the neutrino.

The neutrino idea was born in 1930, following the accumulation of experimental data[2] from the microcalorimetric measurements of the average energy of beta particles from radium E. This evidence showed that the average energy of disintegration in the decay equaled the mean energy of the continuous beta spectrum, rather than its upper limit, and that furthermore there was no appreciable accompanying gamma radiation.

Wolfgang Pauli was convinced that these results were very significant. In an open letter to Hans Geiger and Lise Meitner, who were attending a meeting at Tübingen in December of 1930, Pauli pointed out that in beta decay not only the energy but also the spin and the statistics were apparently not conserved. A half integer of angular momentum is missing in beta decay if the beta particle is the only particle emitted.

Incidentally, at this same time an understanding of the spins and statistics of nuclei based on the fledgling quantum theory provided a strong argument against the hypothesis then current that the fundamental constituents of nuclei were protons and electrons. For example, in those days prior to the discovery of the neutron, how could one explain Bose statistics for the N^{14} nucleus if its basic building blocks were in fact 14 protons and 7 electrons!

Emphasizing the importance of spin and statistics, Pauli went on to propose the outlandish idea of introducing a very penetrating, new neutral particle of vanishingly small mass in beta decay to save the situation. However, as Chien-Shiung Wu[2] relates in the fascinating account she prepared as a memorial tribute to Pauli, "... he was most modest and conciliatory in his pleading for a hearing." Admitting that his remedy might appear an unlikely one, Pauli commented in his letter:

> "Nothing venture, nothing win. And the gravity of the situation with regard to the continuous beta spectrum is illuminated by a pronouncement of my respected predecessor in office, Herr [Peter] Debye, who recently said to me in Brussels, 'Oh, it is best not to think about it at all ... like the new taxes.' One ought therefore to discuss seriously every avenue of rescue. So, dear radioactive folks, put it to the test and judge."

Pauli made public his proposal of this strange new particle at the American Physical Society meeting in Pasadena in June 1931. He insisted that the sum of the energies of the beta particle and of the very penetrating neutral particle (or particles) emitted by the nucleus in one process should equal the energy that corresponds to the upper limit of the beta spectrum. In addition to energy, Pauli assumed that linear momentum, angular

Table 1. Quarks and their quantum numbers in SU(3)

Quark flavor	Q	I_3	S
u (up)	2/3	1/2	0
d (down)	−1/3	−1/2	0
s (strange)	−1/3	0	−1

Table 2. Four-quark scheme, SU(4)

Quark flavor	Q	I_3	S	C
u	2/3	1/2	0	0
d	−1/3	−1/2	0	0
s	−1/3	0	−1	0
c (charm)	2/3	0	0	1

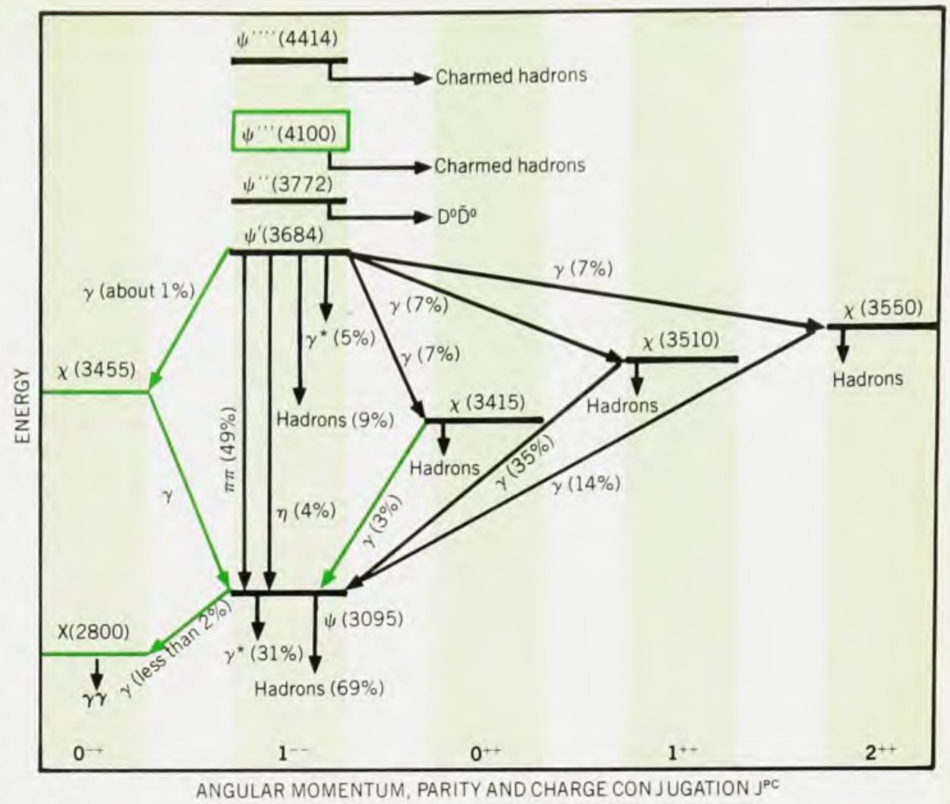
momentum and statistics are conserved in all elementary processes.

In his reverence for conservation laws Pauli adopted a very different approach from Niels Bohr, who had suggested some years earlier that energy and momentum may be conserved only statistically and not in individual nuclear processes. Let me quote here from Bohr's 1930 Faraday Lecture:[3]

> "At the present stage of atomic theory . . . we have no argument, either empirical or theoretical, for upholding the energy principle in the case of beta-ray disintegrations, and are even led to complications and difficulties in trying to do so."

After conceding some difficulties in so radical a departure from the principle of energy conservation, particularly with regard to time reversal, Bohr remarked:

> "Just as the account of those aspects of atomic constitution essential for the explanation of the ordinary physical and chemical properties of matter implies a renunciation of the classical ideal of causality, the features of atomic stability, still deeper-lying, responsible for the existence and the properties of atomic nuclei, may force us to renounce the very idea of energy balance."



The spectrum of charmonium, the bound states of a charmed quark–antiquark pair, showing decay processes of charmonium levels. Particle masses in GeV are in parentheses. Figure 2

Pauli's "radical" conservatism

Pauli's hypothesis of a new unobserved particle met with skepticism, as it was too radical for most physicists to accept with ease. From our present perspective, the "radical" Pauli, with his insistence on maintaining conservation laws—even at the expense of introducing a new and invisible particle—was really the conservative in his approach. Indeed, Pauli was so conservative that he did not publish his proposal. Only after James Chadwick's discovery[4] of neutrons in 1932 and the consequent collapse of the proton–electron picture of nuclei did Pauli put aside the reservations he had about his neutrino hypothesis.

At the Solvay Congress in 1933 Pauli (correctly) conjectured the neutrino to be a massless spin-½ fermion with a penetrating power far greater than that of photons of the same energy. He did this because of conservation laws and in spite of the fact that, as he noted, "experiments do not provide us with any direct proof of this hypothesis"; furthermore, "we don't know anything about the interaction of neutrinos with other material particles and with photons." Pauli argued forcefully against Bohr:

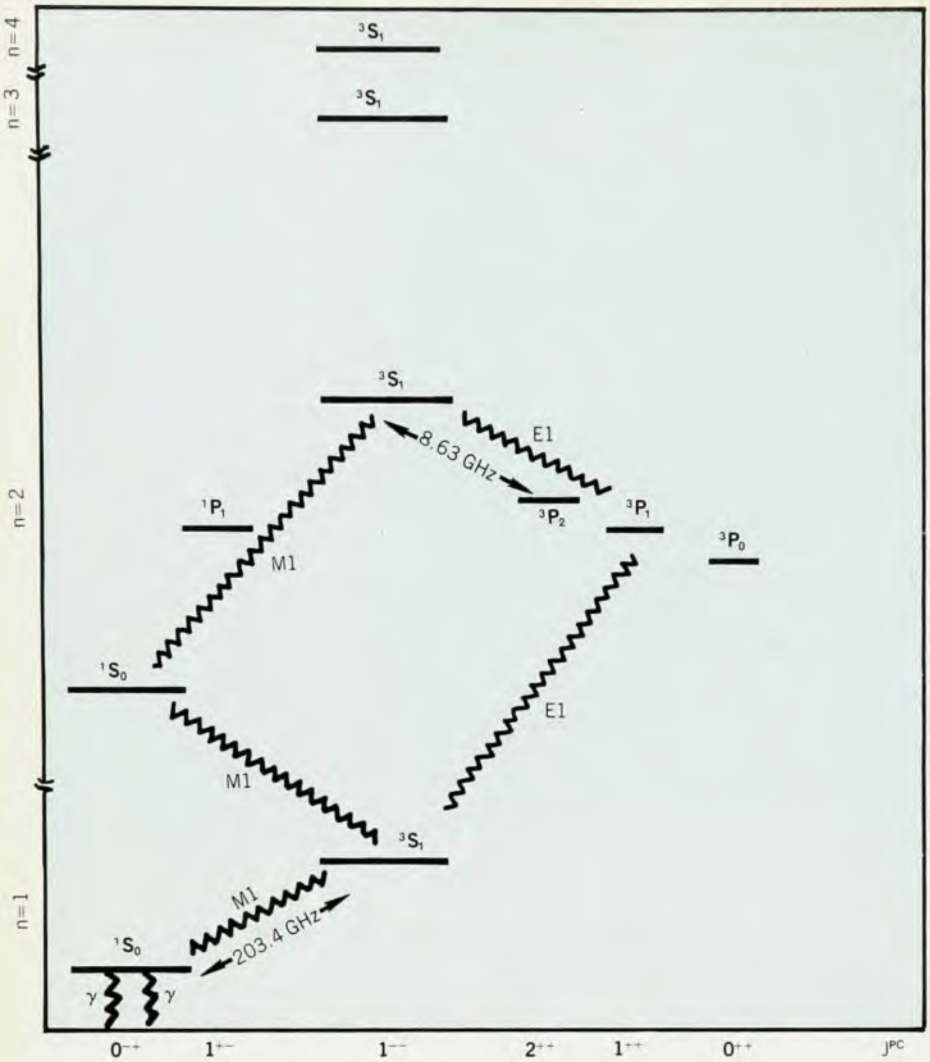
> "The interpretation supported by Bohr admits that the laws of conservation of energy and momentum do not hold when one deals with a nuclear process where light particles play an essential part. This hypothesis does not seem to me either satisfying or even plausible. In the first place the electric charge is conserved in the process, and I don't see why conservation of charge would be more fundamental than conservation of energy and momentum."

Pauli also emphasized the crucial importance of investigating the relation between the energy and momentum carried away by the neutrino by means of sensitive measurements of the amount of nuclear recoil.

Shortly after the close of the discussions at the Solvay Congress, Enrico Fermi[5] gave a quantitative formulation of the neutrino hypothesis, and from 1934 on this hypothesis gained enormous strength from its successful predictions of the energy spectrum and of the angular momentum selection rules in beta processes. However, the evidence for the neutrino was still indirect and would remain so for more than 20 years until it was directly observed as a particle—until the advent of the nuclear reactor there were no intense neutrino sources. As a result, even though all observations and predictions were as if the neutrino were emitted in beta decay, one could still adopt the agnostic stance of weak faith and worry that Nature was simply fooling us. We could invent the neutrino, but did we actually *need* it? Could we do without it?

I remember how real such questions appeared when I entered graduate school at the University of Illinois in Urbana. There I was witness to the first of the series of delicate and ingenious measurements of the nuclear recoils[6] in beta decay that Chalmers Sherwin initiated in 1947. Pauli had judged these measurements to be insurmountably difficult at the Solvay Congress in 1933, but Sherwin accomplished them using a thin-film source of radioactive P^{32} and time-of-flight techniques with then-fast electronics. He clearly demonstrated that the ratio of the missing energy to momentum was given approximately by the velocity of light. Hence within the errors of his measurements the neutrino was, if it indeed existed at all, behaving kinematically as a massless particle.

By then there was in fact little if any doubt about the neutrino, and skepticism on this score was hardly stylish. But I remember vividly a physics-colloquium debate in 1948 between Maurice Goldhaber and Sid Dancoff on whether the neutrino really existed. With a conservative logic that, in these days of confined quarks, seems downright reactionary, Goldhaber advised caution, even in the light of Sherwin's results, and emphasized the importance of looking for evidence of neutrino absorption. After all, we may see it disappear but before all doubts can be removed he advised that we should see the neutrino arrive and hit us over the head—the ultimate litmus test for the full respectability of an elementary particle. To which Dancoff replied, in the spirit of the logical positivist, that we had a respectable wave function, a dignified Dirac wave equation and the unambiguous principles of quantum theory for describing, predicting and analyzing neutrinos in beta processes. What more did we need? The neutrino was in fact no less respectable than, say, the proton!



The energy levels of positronium, e^+e^-, provide an analogy to the charmonium spectrum of figure 2. The first excited levels with n = 2 show fine-structure splitting. Figure 3

No skeptics whatsoever remained eight years later, in 1956, when Clyde Cowan and Frederick Reines[7] used a powerful nuclear reactor as an intense neutrino source and observed its effects. The importance attached by some to being able to detect the arrival as well as the departure of neutrinos is reflected in the 1963 edition of the *Encyclopedia Britannica:*

> "Were it not for the quite convincing experimental evidence of their existence . . . one might regard neutrinos as the necessary but undetectable scapegoats whose subtle function was to permit the application of conservation of energy and momentum to atomic reactions."

I have sketched this history of the neutrino and its development from a radical idea to a respectable particle, in order to contrast and compare it with the current quark theory and dogma. Where do we stand now with the quarks? On one hand, we still lack conclusive evidence of every having "seen" isolated quarks in the laboratory, in spite of many efforts to find them.[8] On the other hand, should we not insist on seeing them if they are indeed the building blocks of the proton? Is such observation not required in the spirit of the modern scientific method, with its primary aim and its central goal, as Herrman von Helmholtz[9] characterized it in paying tribute to Faraday and his work, ". . . to purify science from the last remnants of metaphysics"?

Early in this century the remarkable art of experimentation developed to the extent that it was possible to study the properties of individual atoms. As a result of this fantastic sensitivity of measurement, our entire conception of "seeing" underwent revolutionary changes. On the atomic frontier the most profound and radical change was the realization that it is necessary to take into account the effect of the observation itself on the physical system being observed. This fundamental limitation of the measurement process led to a major revolution in our concept of the elementary particle, driving us beyond classical ideas alone to a quantum description. But there is no uncertainty in what we mean when we say that we *observe* an electron as an elementary particle.

Now that we have come upon the quarks, the situation is very different. Are they objects whose existence can be inferred *only* from the properties of larger, complex structures, such as a proton, in which they are the constituents confined to one another by unbreakable bonds? If quarks are indeed not observed singly or in isolation and if they never get beyond being the "undetectable scapegoats" of the *Encyclopedia Britannica* phrase, will we still attach so central and fundamental an importance to them, or even to the elementary-particle concept itself?

Quarks: the evidence

For the quarks to survive as fundamental there are two possibilities:

- They will be discovered, that is, observed singly. In this case they will constitute the atoms of yet another layer of matter, presumably with an internal structure of their own to be studied by another generation to come.
- They will not be discovered in the same sense as the neutrino was, but they will persist in fulfilling the goal that motivated their being introduced in the first place, of providing a simple basis for the explanation of the observed multiplet structure and properties of subnuclear particles.

We know that there exist simple general laws that explain the rich diversity of Nature; this is our fundamental faith as scientists. If the quarks are indeed not observed directly, their survival as vital ingredients in the structure of matter will depend on how successful the quark idea is in unifying, simplifying and correctly predicting diverse observations, and thereby leading us to such general laws. At least from today's perspective, the quarks seem to have done enough for particle physics that there is little danger of their fading away with the ether. In brief, what is the evidence most strongly supporting quarks?

The original quark idea was put forward to explain why baryons occur with the observed multiplet structure of an octet of spin $1/2$ and a decuplet of spin $3/2$, and why mesons form nonets of spin zero or one. General features of the hadronic mass spectra, their transition matrix elements and such static properties as baryon magnetic moments, could be understood in terms of their quark content, three quarks for baryons and a quark–antiquark pair for mesons. What emerged was an intuitively simple picture of relatively light point-like quark constituents moving approximately as independent particles within a hadron.

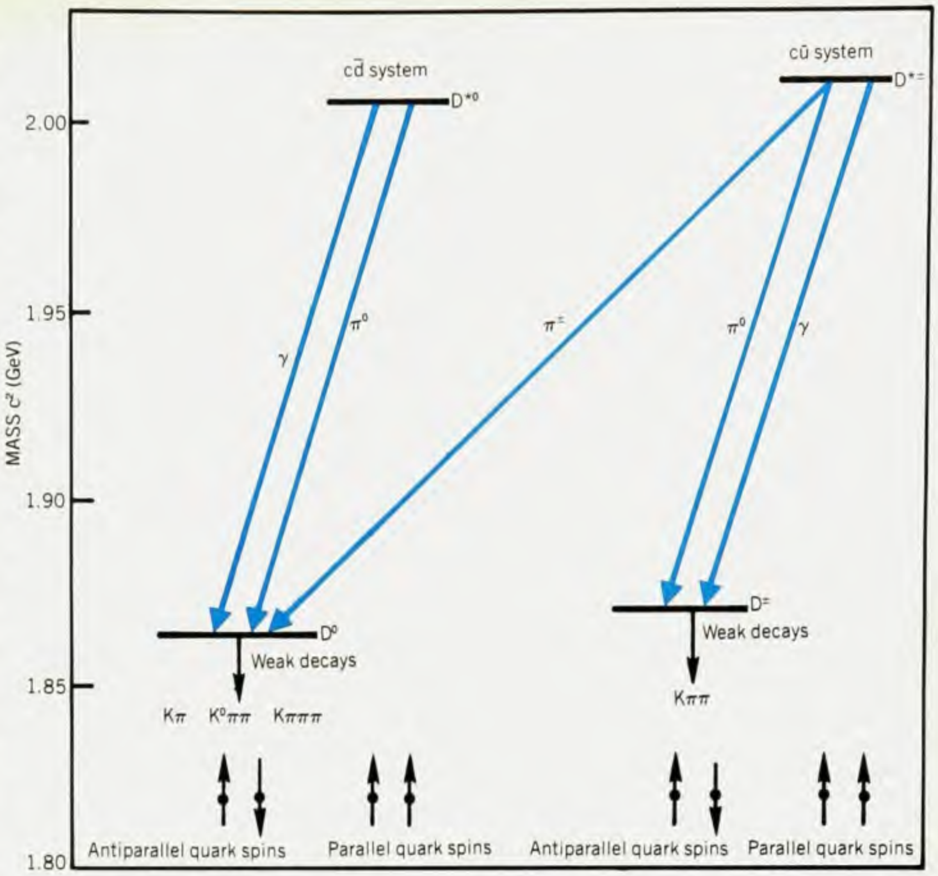
We had to pay a price for these successes. At the very outset it was realized that a successful classification scheme for the three-quark baryonic spectra required that the quarks be assigned to *symmetric* configurations. This was in apparent violation of the heretofore sacred relation between spin and statistics that requires half-integral spin particles such as quarks to be in *antisymmetric* configurations.

The way out of this dilemma was to assign to the quarks a new quantum number, dubbed color,[10] which could take any one of three values, and to require the baryon wave functions to be antisymmetric in color. This effectively triples the number of quarks, and is therefore reminiscent of Pauli's original proposal for the neutrino. He also introduced a new particle, in part to satisfy the requirements of statistics in beta decay. The added quantum number of color introduces the possibility of many additional but unobserved states, corresponding to hadrons of different colors.

To remove this difficulty we must insist that the three quarks forming a baryon are in an antisymmetric color-singlet state. Similarly, the quark–antiquark pair composing a meson must form an anticolor pair, with each color occurring in equal parts. All hadronic states that fail to hide their color are ruled out. An explanation of why Nature is color-blind is fundamental to a complete theory of quarks. Although a theoretical derivation of color blindness still remains to be given, we can correctly and simply describe the observed spectra with no unwanted states by insisting that color remain Nature's secret.

The existence of point-like constituents within the hadron also provided a basis for understanding the observed character of hard, very inelastic high-energy collisions between two hadrons, or between the hadron and an electron, a neutrino or a muon. The nature of the observed scattering patterns between an electron and a proton, for example, required the existence of strong local electromagnetic charges and currents due to point-like constituents within the proton, which were presumably the quarks.[11] (They play the same role as the nucleus in Rutherford scattering.) Specifically, the constituents of the proton scatter the incoming high-energy electrons in high-momentum-transfer collisions as if they themselves had no inner structure, and as if they were relatively light and essentially unbound.

The high-energy inelastic scattering measurements further emphasize the enigma of unobserved quarks. We resort to quark constituents for the most direct and simple interpretation of the observed scattering pattern. However, the proton or neutron, smashed hard and shattered into bits and pieces in the collision, does not spill out quarks in its debris—just other normal hadronic states of mesons and baryons.



New Mesonic states, the D's and D*'s, are formed when a charmed quark binds with an ordinary uncharmed antiquark. The diagram shows the spectroscopy of the four particles. Figure 4

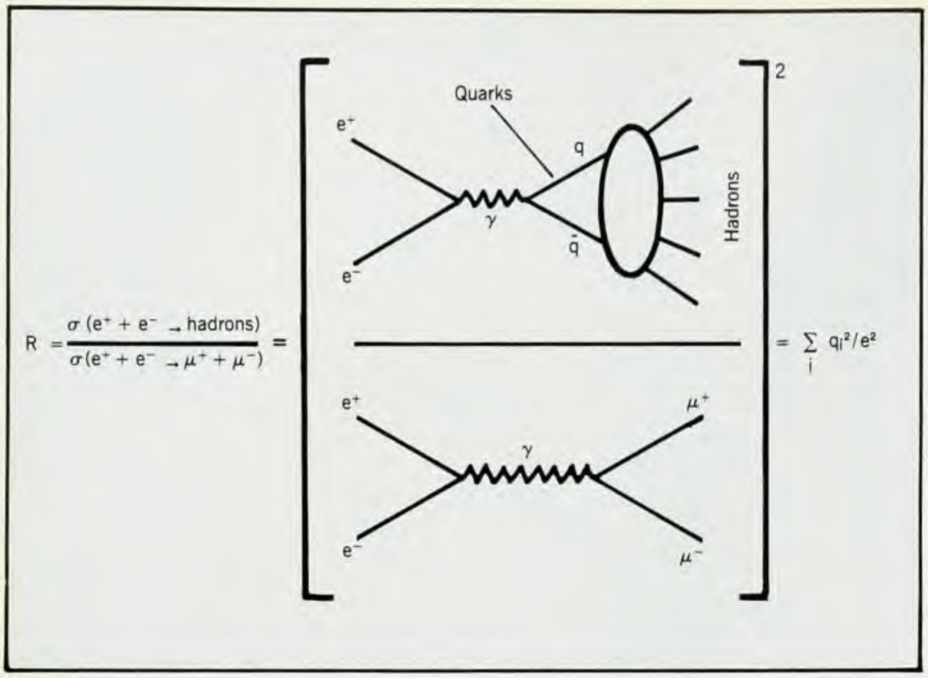
The charm of J/ψ

Unquestionably the most important recent evidence that decisively supports the quark picture was provided by the new discoveries of charmed matter, beginning with the J/ψ close to four years ago.[12] It sent an explosive shock through the scientific community because, on the subnuclear scale of times, it was an almost stable, very narrow, resonance that could not be accommodated in the existing quark scheme. These properties differentiated it from the hundreds of other hadronic resonances with typical decay widths for 10–100 MeV unless they are suppressed by selection rules. The J/ψ, however, was found to have a total decay width of only 70 keV and a mass of 3095 MeV.

Evidently there was a selection rule operating to account for the narrowness of this state. Because the new particle is heavy—weighing more than three times as much as the proton—there is no inhibition in its decay due to threshold effects or lack of phase space. Hence the suppression of its decay can not be explained on kinematic grounds alone. Moreover, the measured quantum numbers of the J/ψ are quite conventional: zero charge, one unit of angular momentum and zero strangeness—just like the photon, which is the source of the J/ψ in electron–positron annihilation. Furthermore, its decay products are familiar particles—predominantly electrons, muons and pions. The narrowness of the J/ψ therefore can not be explained in terms of a selection rule corresponding to the conservation of known quantum numbers.

What then was holding it together for such a long time—about 1000–10 000 times longer than expected? A new quantum number was required above and beyond what could be accommodated in the three-quark scheme, which was now found to be too restrictive. This new quantum number already had been dubbed "charm" by James Bjorken and Sheldon Glashow. Indeed, the existence of a fourth quark with charm had been anticipated by Glashow and his colleagues[13] several years before, as a simple and natural way of theoretically suppressing unobserved weak decays involving a change of strangeness but not of electrical charge between the interacting particles. The easiest way to account for the J/ψ and its long lifetime was to assume it to be a meson made up of a new, massive charmed quark bound to its antiparticle; this is illustrated in table 2.

The value and beauty of such a simple model lies in its predictive power. The successes for this model have been extensive—and although the new discoveries were a shocking surprise, they are now recognized as contributing importantly to the impressive successes of the quark hypothesis. In the decade preceding these new discoveries it was established that every known hadron could be explained as a combination of a quark and an antiquark for the mesons and of three quarks for the baryons. Moreover, all possible combinations of the three "ordinary" quarks correspond to a known hadron, without fail. With the discovery of the J/ψ and its interpretation in terms of the theoretically anticipated fourth, charmed, quark a whole new set of spec-



A schematic picture showing that the ratio R of the cross section for annihilation to hadrons of an electron–positron pair to the cross section for their annihilation to a muon pair is given by the sums of the squares of the quark charges. Figure 5

troscopic levels had to be hunted for and interpreted.

In particular, we should observe a complete spectrum of charmonium,[12] the bound states of a charmed quark–antiquark pair. This is analogous to positronium, with its spectrum of excited states. In fact figure 2 shows how far we have advanced already with charmonium spectroscopy. By way of comparison, figure 3 shows the fine-structure splitting of the first excited levels of positronium with principal quantum number $n = 2$. The $n = 1$ level is much lower in energy, separated by an interval of the order of the rydberg relative to the fine-structure splitting which is smaller by two powers of the fine-structure constant, $\alpha^2 = (1/137)^2$. The energy spacings and branching ratios in charmonium can be understood qualitatively in terms of the binding of a heavy quark-antiquark pair. Detailed analyses of the fine structure reveal information of the shape of their interaction potential.

Furthermore, new mesonic states will be formed when a charmed quark binds with an ordinary uncharmed antiquark, as shown in figure 4. These, the D mesons, have also been observed and fit into the four-quark classification, SU(4). Already there are starts toward the spectroscopy of a charmed quark bound to a strange antiquark, the so-called "F meson," and toward the spectroscopy of charmed baryons.

Natural flavors

A very important parameter for the quark hypothesis is the ratio, R, of the cross sections for an electron–positron pair to annihilate to all possible configurations of hadrons, to the cross section to annihilate to a pair of muons, illustrated by figure 5. Muons, like electrons, are point-like members of that other family of particles known as leptons—particles that do not experience the strong nuclear forces at all. The muons are charged and, of course, interact through the well tested electromagnetic forces. In this context the weak forces are negligible. We believe that when an electron and a positron annihilate to form hadrons at high energy, a single quark–antiquark pair is the intermediary, even though the quarks themselves do not appear in the final states. If the quarks are point-like, their contribution should exhibit the same energy dependence as that found in the production of pairs of point-like muons. The ratio of cross sections therefore should measure the sum of the squares of the quark charges and should be approximately energy-independent.

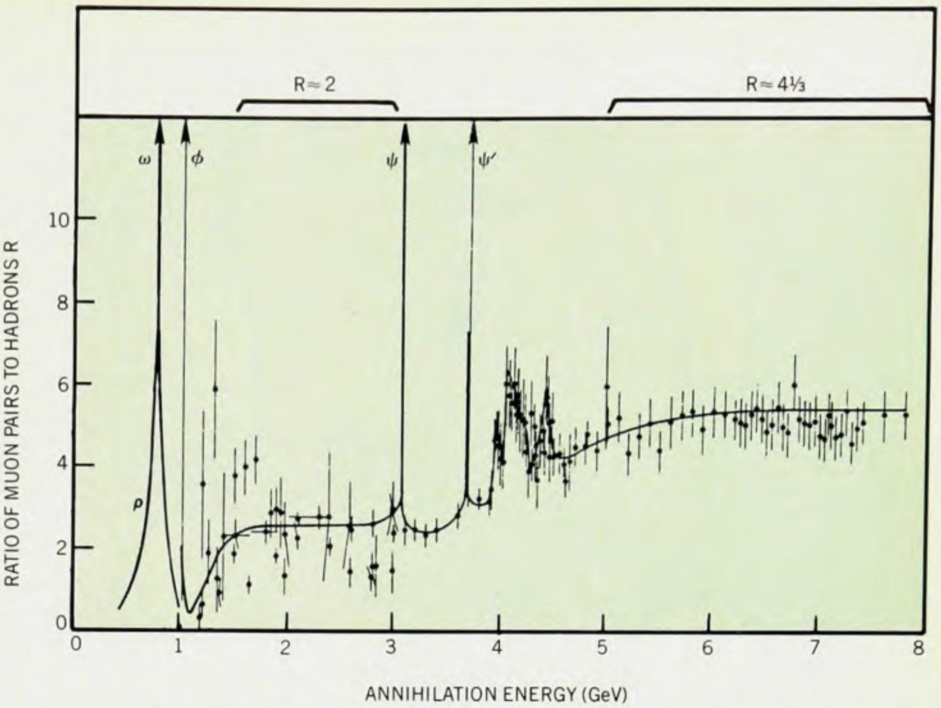
Figure 6, which shows[12] the measured ratio, adds considerable support to the quark picture by showing two regions of approximately constant R. In the lower-energy region, 1.5–3.1 GeV, which is above the individual resonances but below the onset of the new physics, R has a plateau at about $2\frac{1}{2}$. Above the charmonium region, 5–8 GeV, the plateau rises to about 5. The 4–5-GeV region is very rich in new physics associated with the creation of charmed particles, as well as with the creation of pairs of a very likely new heavy lepton, the tau, of mass 1.8 GeV. These values of R provide clues of the greatest importance about the nature and properties of the quarks. As illustrated, they are close to what one predicts for three varieties, called "flavors," of quarks below the region in which charm is excited, as well as for the four flavors (including the charmed quarks) in the higher-energy region, provided each flavor occurs in three colors. Otherwise—without color—there would be a sharp discrepancy of a factor of three.

These results thus represent a triumph for the hypothesis of color triplets of quarks. On a descriptive level the quark hypothesis evidently accounts very well for a broad set of observations. Furthermore—does anyone seriously doubt that R will increase onto a higher plateau when the total energy of the colliding electrons and positrons exceeds 9.4 GeV, the threshold for producing the upsilon meson recently discovered at Fermilab? The upsilon is believed to be a bound quark–antiquark pair like charmonium, but built of yet another new flavor of quark pairs.

By now we have had such a proliferation of quark degrees of freedom—presumably at least fifteen, five flavors times three colors—that it can hardly be said they they are entering a very exclusive Social Register!

If we look back once more to the 1930's, we recall that the neutrino became a strong, and to most a persuasive, candidate for the Social Register of elementary particles long before it was seen, when Fermi provided it with effective and indisputable theoretical credentials. There is optimism, at least among many theorists, that quarks have also been gaining the dignity of a pedigree during the past few years. The reason for this optimism is recent theoretical progress that has identified important features of successful quark dynamics in a well defined class of quantum field theories known as nonabelian gauge theories.[10,14] These are generalizations, pioneered in 1954 by Chen Ning Yang and Robert Mills, of the precisely tested and unfailingly successful theory of quantum electrodynamics (QED). The photons, which are the vector quanta of QED, are themselves electrically neutral; this is characteristic of an abelian gauge theory. In non-abelian gauge theory the vector quanta, dubbed "gluons," are themselves also charged. The gluons can exchange this charge between sources, or between one another. In the theory of quarks and gluons known as "quantum chromodynamics" (QCD), the color quantum number plays the same role as the electric charge in QED. In QCD an octet family of colored gluons replaces the single photon of QED as the messenger of the color electric and magnetic fields.

The case for QCD, pioneered in 1973 by H. David Politzer, and by David Gross and Frank Wilczek, is based on the crucial observation that such theories can lead to forces between the quarks, mediated by gluons, that grow weaker at short distances. This behavior is known as "asymptotic freedom." As illustrated in figure 7, it contrasts with the familiar forces of electromagnetism, which grow even stronger than the $1/r^2$ of the Coulomb law at short distances when quantum effects—in particular vacuum polarization—are included. Asymptotically free forces between quarks provide a basis for explaining the observed behavior of the hard collisions, such as Bjorken scaling, which look like scattering from almost free, point-like light quarks within the hadrons. These forces must remain in effect for large separations, however, so that the quarks that behave as almost free at short distances on the scale of hadronic sizes will be confined and can not be pulled apart. Further, the theory must allow only the formation of color-singlet states, to account for the observed spectra and quark structure of hadrons. In QCD the simplest quark configurations that can form color-singlet states are just the observed ones with three quarks or a quark–antiquark pair.



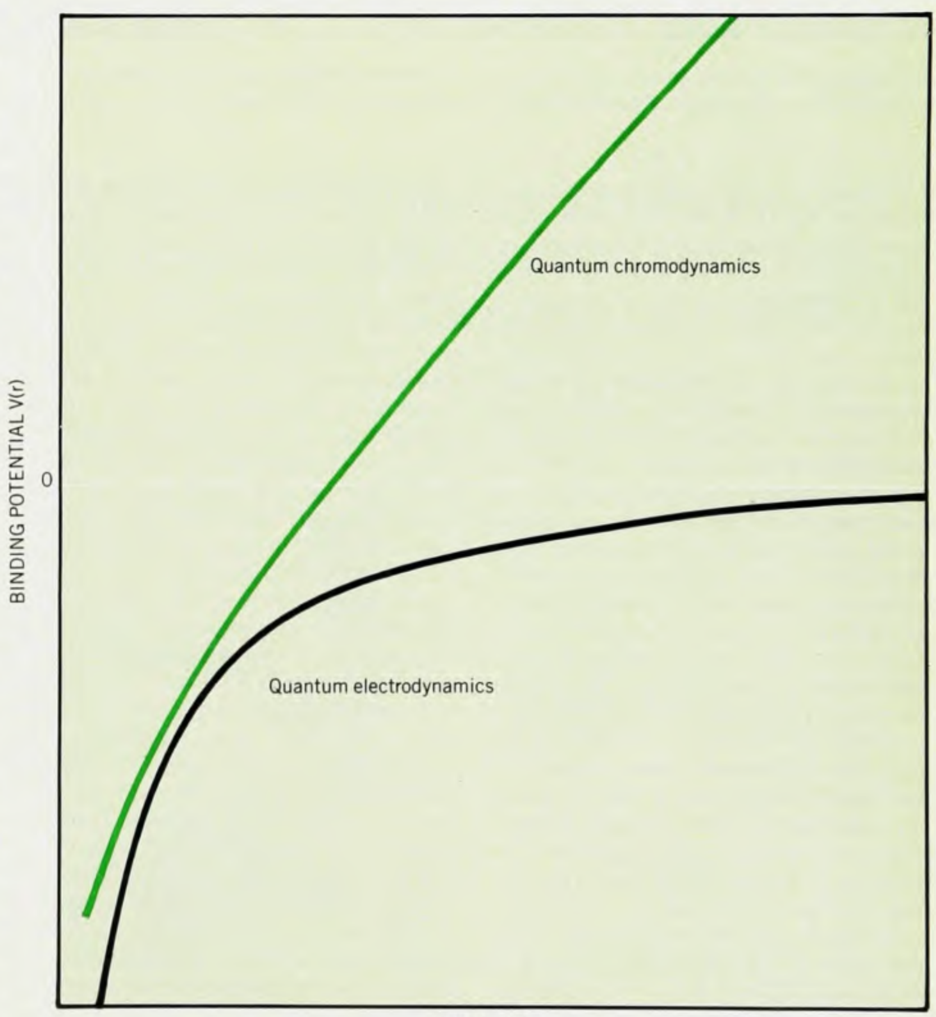
The experimental data for the ratio R of figure 5 show two plateaus consistent with the calculation indicated there. One of them is near $R \approx 3\,[(2/3)^2 + (1/3)^2] = 2$, and the other ratio is near $R \approx 2 + 3\,(2/3)^2 + 1 = 4\,1/3$. The lower-energy region has three flavors and the higher-energy region, where charm is excited, has four flavors plus the heavy tau lepton. Figure 6

Color confinement

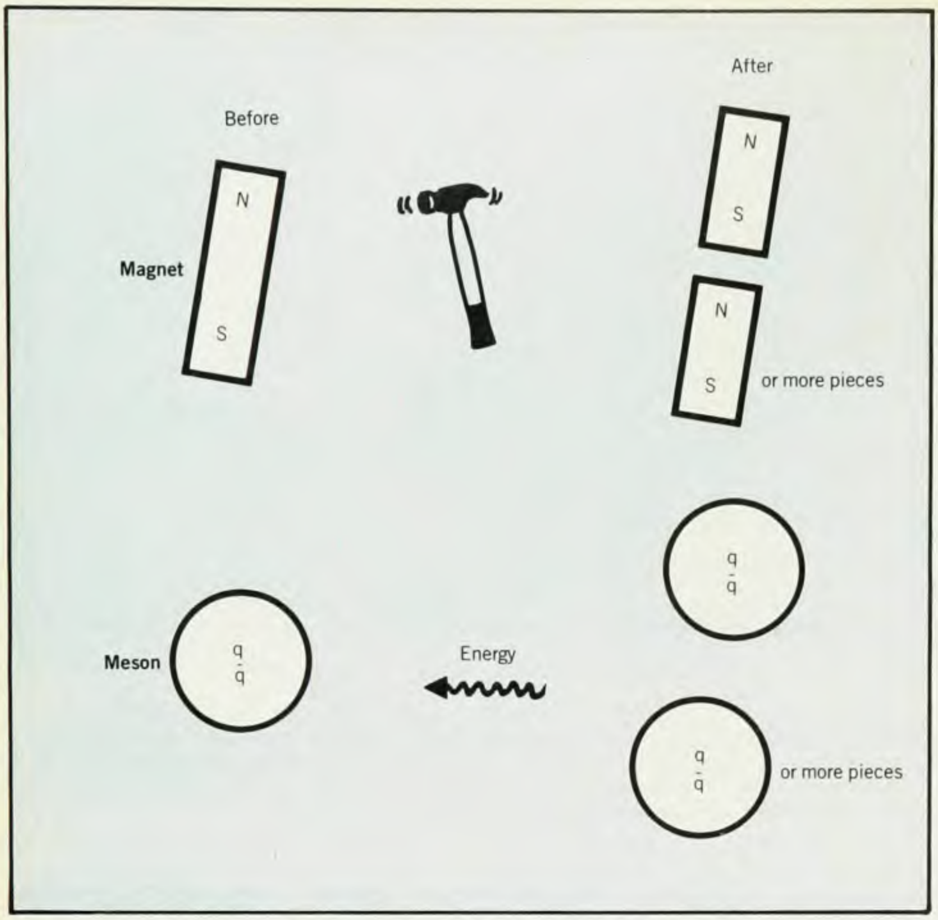
In the framework of quantum chromodynamics, quark confinement becomes synonymous with color confinement. This is the other basic ingredient in addition to asymptotic freedom that we want to find in QCD if it is to form the basis of a fundamental dynamical theory of hadrons in terms of gluons and of quark constituents. The theoretical challenge to prove whether or not QCD actually confines is formidable because of the difficulty in solving—or even attempting to solve—quantum field theory when the forces are strong and we can not resort to weak-coupling perturbative treatments.

With an appropriate dash of the theorists' optimism, let us suppose for a moment that these technical challenges will be surmounted and a convincing case made for color confinement in QCD. We may even further imagine that approximately correct mass spectra will be calculated for the hadrons; this includes understanding why the pion is much lighter than all other hadrons. How compelling will this make the case for quarks as elementary fundamental constituents of the hadron?

The case for quarks might appear more compelling than that of the neutrino back in 1934, because we now see all the elements of a grand synthesis in place. The quantum chromodynamics to which we have turned for a theory of hadrons is a non-abelian local gauge theory of the same formal structure as the one introduced in unifying the weak and electromagnetic interactions. Steven Weinberg discussed this in his article in the April 1977 issue of PHYSICS TODAY. The strong, the electromagnetic and the weak interactions have very different characteristics, such as their ranges and strengths, as studied at present laboratory energies. It has been conjectured,[15] starting with the pioneering work in 1967



The binding potential in quantum chromodynamics, mediated by gluons, exhibits asymptotic freedom and confinement, in contrast to the electromagnetic potential. Figure 7



The way quarks break is analogous to the way a bar magnet breaks. Just as the magnet does not break into isolated poles, the meson does not break into isolated quarks. Figure 8

of Weinberg and Abdus Salam, that the difference between the weak and electromagnetic interactions is a consequence of a partially broken symmetry for the weak processes. The intermediate vector mesons of the weak interactions acquire large masses due to the symmetry breaking; only at truly high energies exceeding these masses— thought to be in the range of 70 GeV or higher—will the common characteristics of the weak and electromagnetic interactions be apparent. Some predictions of this approach to a unified theory of weak and electromagnetic processes have already been verified, in particular, neutral-current effects in neutrino scattering.

A further extension of the symmetry considerations underlying the gauge theories to the strong interactions puts the quarks on the same basis as the leptons. The difference between these derives from the fact that quarks carry the color quantum number—the charge of the strong interactions—whereas leptons do not and are immune to the strong forces. Hence leptons, in contrast to quarks, are not confined by the requirement that color remain Nature's secret. Such a picture is very attractive. It provides a giant step toward one of the principal goals of modern physics: a unified understanding of all the basic interactions in Nature.

Were we to achieve such a theoretical synthesis, the case for admitting quarks to the Social Register as the hadron's basic constituents would clearly be very strong. However, recalling our earlier discussion of the neutrino, do we no longer care that we are now identifying as fundamental constituents of hadronic matter things that, in contrast to all our prior experience, can not even in principle be isolated and observed? When *is* a particle? Are we now willing to say, as a variation of Archibald MacLeish's lines, that in contrast to a poem a particle need not be, but should mean?

The burden of proof for quarks is very different from the original argument for the neutrino. Whereas the neutrino was postulated to protect energy, momentum and spin conservation laws, which involve observable space-time properties, no conservation laws *require* quarks. However, the quarks do present the very strong operational credentials I have described—both experimental and theoretical.

What troubles me most about accepting quarks as the fundamental hadronic constituents is quite simple and has nothing to do with their confinement and Helmholtz's dictum "to purify physics from the last remnants of metaphysics." It is that we already have so many quark degrees of freedom—at least five flavors in each of three colors. The Social Register of particles surely must be more exclusive than that if it is to be valued and honored as it was in those good old days!

Break a meson, make two quarks

Having said this, I have a sneaky suspicion that quarks may turn out to be somewhat like magnetic poles, and nothing more.[16] When broken in two, a bar magnet becomes, not isolated north and south poles separated from one another, but two magnets, each with its own north and south poles. As many have noted, this is very similar to what happens when a meson made of a quark and an antiquark is smashed apart, as shown in figure 8. The debris of the shattered meson consists not of isolated quarks but of more mesons, each with its own quark and antiquark. This is not a literal analogy, of course, because the non-abelian color gauge theory also allows baryons made of three quarks to be formed in color-singlet states. Nevertheless, it is sufficiently close and accurate to be a useful guide.

Our curiosity and present plight with quarks may not be very different from that of an inquisitive mariner at sea some ten centuries or so ago. In a moment of calm on a passage he might have viewed a compass needle—a spare one, I hope!—with idle bafflement or scientific curiosity, and tried to break it apart to separate the two ends with opposite properties, that is, the north pole from the south pole. But to no avail, for with each breaking of the compass needle he ended up with an additional one having both a north and south pole. The understanding of this impossibility to isolate single magnetic poles came only when, in 1820, André Ampere explained magnetism in terms of electric currents. In fact, a fundamental theory of magnetism at the atomic level in terms of the currents of circulating and spinning electrons was achieved only in this century on the basis of modern quantum theory.

Perhaps the quarks are not the fundamental particles of hadron dynamics, just as magnetic poles are but phenomenological manifestations of amperian currents. Presumably they will remain no less important for the description and understanding of subnuclear processes than bar magnets are for understanding a lot of the physics of magnetism. The quarks have done too much already to be forgotten and discarded. If, however, there are underlying dynamics, the whole question of the meaning of confined constituents as elementary particles will disappear. Whether or not the analogy with magnetism has any merit, the notion of a new "elementary structure" underlying the quarks destroys the very attractive idea of a quark–lepton parallel unless we similarly modify and elaborate our picture of leptons. This hardly appears to be an attractive prospect now, particularly be-

THE MOST DEPENDABLE PART OF OUR RADIATION DETECTOR IS MADE OF PAPER.

Our warranty.

Which guarantees for one full year the reliability of the Channeltron® 4700 and 4800 Series continuous dynode electron multipliers.

One full year.

No other maker of radiation detectors would dare make that claim. Their products simply go down too fast. And too often.

Galileo's Channeltron 4700 and 4800 Series are more dependable because we gave them a stable dynode surface that can be exposed to air under normal use without degrading. That means more up time for your experiments. And less frustration.

What's more, we can deliver our Channeltrons fast. In fact, they're on the shelf now, waiting for your order.

For more information about the Channeltron 4700 and 4800 Series, Channeltron electron multiplier arrays, custom assemblies with associated electronics, or our warranty, write Galileo Electro-Optics Corporation, Galileo Park, Sturbridge, MA 01518. Or better, call us at (617) 347-9191.

Galileo Electro-Optics Corp.

Circle No. 19 on Reader Service Card

NUPRO Fine Metering Valves let you set and maintain precise flow rates easily, accurately, repeatedly.

Patented

Accurate, repeatable flow adjustment, with rapid set point and excellent stability are the main benefits of using NUPRO Fine Metering Valves in your high-precision systems.

You also have a selection of design and performance features to meet application demands...service ratings to 2000 psi and 400°F, a variety of flow patterns, choice of brass, 316 stainless steel or Monel, and optional vernier handles.

Swagelok® or pipe end connections are available in 1/16″ to 3/8″ sizes.

All models are available from local stocks to meet your system requirements immediately.

MONEL, TM International Nickel
Swagelok TM Crawford Fitting Company

NUPRO®

NUPRO COMPANY
4800 East 345th Street
Willoughby, Ohio 44094

Circle No. 20 on Reader Service Card

cause no one has either seen or theorized creatively as to what these new "elementary structures" might be. On the other hand, the lepton degrees of freedom, along with those of the quark, have also begun to proliferate.

Some physicists were discouraged already 30 years ago with the discovery of the muon, about which I. I. Rabi is quoted as remarking, "Who ordered that?" More recently we have apparently encountered a new, third strain of leptons[12] in the tau, which is also thought to be accompanied by its own neutrino, as are the electron and muon. As we continue to raise our energy frontier, are we fated to meet proliferating families of leptons as well as quarks? Facing this dilemma, Werner Heisenberg proposed a different viewpoint in a lecture on the nature of elementary particles, which he delivered in 1975 shortly before his death.[17] He raised the possibility that we are asking the wrong question in particle physics when we ask what a proton "consists of":

> "I will now discuss that development of theoretical particle physics that, I believe, begins with the wrong questions. First of all there is the thesis that the observed particles such as the proton . . . consist of smaller particles: quarks . . . or whatever else, none of which have been observed. Apparently here the question was asked: What does a proton consist of? But the questioners appear to have forgotten that the phrase 'consist of' has a tolerably clear meaning only if the particle can be divided into pieces with a small amount of energy, much smaller than the rest mass of the particle itself."

Heisenberg is referring here to the fact that in the realm of quarks, in contrast to atomic or even nuclear physics, we are no longer dealing with energies that are but small fractions of the rest masses of the particles themselves. The strong subnuclear forces confining the three valence quarks in the baryon also create many virtual quark pairs and gluons. Retardation effects, as well as the energy-momentum content of the gluon fields that bind the quarks together, will be important. All of these effects and virtual particles—the gluons as well as the fluctuating numbers of quark pairs—must be included in a dynamical description of "life" within the hadrons. When we apply quantum mechanics to a relativistic strong-interaction problem, our basic elements are no longer simply a fixed small number of particles, but field amplitudes that create eigenstates of definite quantum numbers. In view of this, Heisenberg suggested that our quest for simplicity and an underlying level of unification should be formulated in terms of the fundamental currents or symmetries of the theory.

Heisenberg's emphasis on symmetries is reminiscent of the idea of Pythagoras and Plato. Pythagoras first explicitly emphasized the importance of symmetry 25 centuries ago and insisted that ultimately all order is capable of being understood and expressed in terms of number. Plato provided a specific form for this idea by identifying the fundamental symmetries as the basic atoms in his scheme. Dressing his idea in modern garb, we should not so much focus on the problem of the many quark degrees of freedom as seek simplicity in the underlying group structure of the fundamental equations. Perhaps in our quest for simplicity we should follow the lead of Albert Einstein, by incorporating the sources and forces of a unified field theory in the physical geometry of space-time.

The hidden one

The fate of the idea of hidden building blocks can be settled only by experiments, including the very fundamental and difficult quark searches already in progress. Whatever their future fate, the concept of confined quarks already has a distinguished history, which dates back to the classical Greek and Roman times and includes the writings of Leucippus, Democritus, Epicurus and Lucretius. Modern historians of science still debate intensely whether the atoms of Democritus and Leucippus are physically indivisible (because they are solid and impenetrable) or whether they are logically and mathematically indivisible (because they have no parts). Some suggest that both kinds of atoms are to be found in their writings. Apparently a full development of the idea of indivisible elementary atoms consisting of minimal parts that are permanently confined and can not be pulled apart dates to Epicurus, around 300 BC. In a charming article,[18] Julia and Thomas Gaisser refer to the elaboration of this idea by Lucretius, who refers to the *minimae partes* of the indivisible atoms in his great poem, *De Rerum Natura*. Clearly these were the early versions of quarks—or partons, as we sometimes call the minimal parts of the hadrons.

I was so intrigued by these references to confined quarks, or *minimae partes*, in classical philosophy that I found myself also wondering whether Greek mythology could not provide some roots—perhaps even a name—for these hidden basic things. What I came up with after anything but a scholarly, thorough search[19] was the nymph goddess Calypso, referred to as the hidden one, who kept Odysseus confined to her island of Ogygia for seven years after his shipwreck en route home from the Trojan wars. Calypso offered Odysseus immortality if he would share eternal, blissful confinement with her. However, when the gods called on Odysseus to resume his human destiny and his hazardous journey home, he rejected her offer.

Whether quarks will remain mysterious as hidden elementary "calypsons," be understood as phenomenological manifestations of an underlying dynamics or reveal themselves directly to experiment remains for the future. So does the fate of those theorists among us who concern ourselves with quantum chromodynamics, asymptotic freedom and quark confinement. Those theorists who have said that it is impossible to liberate quarks should perhaps look again to Epicurus, the metaphysical father of confined quarks, for a second message that is frequently—and erroneously—attributed to him: Eat, drink and be merry, for tomorrow an isolated quark may actually be found.

* * *

This article is an adaptation of the Richtmyer Memorial Lecture delivered on 24 January 1978, at the San Francisco meeting of the American Association of Physics Teachers. It is a pleasure to thank Maurice Goldhaber and Peter Pesic for valuable discussions during the preparation of this lecture.

References

1. M. Gell-Mann, Phys. Lett. **8**, 214 (1964); G. Zweig, CERN Preprints TH401, 412 (1964).
2. C. S. Wu, in *Theoretical Physics in the Twentieth Century, A Memorial Volume to Wolfgang Pauli* (M. Fierz, V. F. Weisskopf, eds.), Interscience (1960), page 249.
3. N. Bohr, J. Chem. Soc., 349 (1932).
4. J. Chadwick, Proc. Roy. Soc. A **136**, 692 (1932).
5. E. Fermi, Z. Phys. **88**, 161 (1934); Ric. Sci. **2**, Part 12 (1933).
6. C. W. Sherwin, Phys. Rev. **73**, 1219 (1948); **75**, 1799 (1948); **82**, 52 (1951).
7. C. L. Cowan, F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire, Science **124**, 103 (1956).
8. L. W. Jones, Rev. Mod. Phys. **49**, 717 (1977).
9. Reference 3, page 384.
10. R. L. Jaffe, Nature **268**, 201 (1977).
11. J. I. Friedman, H. Kendall, Ann. Rev. Nucl. Sci. **22**, 203 (1972).
12. F. Schwitters, Scientific American, April 1977, page 56; W. K. H. Panofsky, talk presented at the Centennial Meeting of the Mathematical and Physical Societies of Japan (Tokyo, 10 October 1977), SLAC-PUB-2025, Stanford, Calif.
13. S. L. Glashow, Scientific American, April 1975, page 38.
14. Y. Nambu, Scientific American, May 1976, page 48.
15. S. Weinberg, Scientific American, January 1974, page 50; E. Leader, P. G. Williams, Nature **257**, 93 (1975).
16. S. D. Drell, Daedalus, March 1977, page 15.
17. W. Heisenberg, PHYSICS TODAY, March 1976, page 39.
18. J. H. Gaisser, T. K. Gaisser, Am. J. Phys. **45**, 439 (1977).
19. Homer, *The Odyssey*, book 5. □