

# Glueballs

*They are "atoms of color," bound states of the particle that transmits the color force, the strongest force known. A few of them may have been detected in high-energy experiments*

by Kenzo Ishikawa

Is it possible to imagine an atom of light? The photon, the quantum unit of light, is also the carrier of the electromagnetic force that holds together an ordinary atom. Any particle of matter that has an electric charge can emit or absorb a photon; in an atom the electrons are bound to the nucleus by a continual exchange of photons. In an atom of light two photons might be bound to each other by the exchange of additional photons.

As it happens, such an atom cannot be created. The reason is that the photon itself has no electric charge, and so a photon cannot emit or absorb another photon. An analogous bound system may well exist, however, at the next-finer level in the structure of matter. Indeed, it may have been observed already. The analogue of the atom of light is made up of gluons, which are the carriers of the basic force of nature called the strong force or the color force. Ordinarily gluons act to bind together quarks, which are the constituents of protons, neutrons and many related particles. A quark has a property called color charge, and any particle with such a charge can emit or absorb a gluon. In this respect the role of the gluon resembles that of the photon; the two particles are also alike in being massless and in moving at the speed of light. Whereas the photon is electrically neutral, however, the gluon has a color charge. As a result the "glue" that sticks quarks together can also stick to itself. Two gluons should be able to form a composite particle held together by the exchange of other gluons. Physicists have taken to calling such particles glueballs.

If glueballs exist, it should be possible to make them in experiments with the same particle accelerators that give rise to high-energy combinations of quarks. The recent reports that glueballs may have been detected are based on such experiments, but some uncertainty remains about the identification of the particles. The reason for the uncertainty is ironic: it seems these most exotic states of matter are so prosaic in their

outward properties that it is difficult to distinguish them from ordinary particles made up of quarks.

The idea that a force must be carried or transmitted by an intermediary particle is closely related to the much older idea that there can be no action at a distance. The idea of intermediary particles was first incorporated into a quantum-mechanical theory in 1934 by the Japanese physicist Hideki Yukawa. Yukawa was trying to understand the force that binds protons and neutrons in the atomic nucleus, which was then the only known example of the strong nuclear force. He suggested that the force is transmitted by a particle with a mass about 200 or 300 times the mass of the electron.

The basis of Yukawa's estimate of the mass was his hypothesis that the range of a force is inversely proportional to the mass of the particle that mediates it. The interaction between the proton and the neutron was known to have an extremely short range, on the order of  $10^{-13}$  centimeter, which implied a comparatively large mass. In 1947 a particle with a mass about 275 times that of the electron was discovered in cosmic radiation and shown to interact strongly with the proton and the neutron. The particle is called the pi meson and its discovery was a dramatic confirmation of Yukawa's conjecture.

The magnitude of the electromagnetic force between two electrically charged particles is given by Coulomb's law: the force is directly proportional to the product of the charges and inversely proportional to the square of the distance between them. The range of the Coulomb force seems to be infinite, and so according to Yukawa's theory the rest mass of the photon is zero.

Since the gluon also has a rest mass of zero, one would expect the color force mediated by the gluon to be a force of infinite range. In a formal sense the range of the color force may indeed be infinite, but the interactions mediated by gluons have never been observed at a

range of more than about  $10^{-13}$  centimeter, or roughly the same range as the force mediated by the pi meson. The similarity of range is not coincidental: the interaction mediated by the pi meson is thought to be the net result of events that can be described on a finer scale as interactions mediated by gluons, just as an interatomic bond in a molecule is the net result of electromagnetic interactions that are ultimately caused by the exchange of photons between electrons and protons. The observed range of the color force remains puzzling, however, and it now seems that in order to understand the observation it is necessary to postulate the existence of glueballs.

In 1964 Murray Gell-Mann and George Zweig of the California Institute of Technology independently proposed that all particles subject to the strong nuclear force are made up of more elementary constituents: the particles Gell-Mann named quarks. Particles subject to the strong force are called hadrons, and the quark model was introduced in order to classify the proliferating new hadrons being generated in experiments with accelerators. Gell-Mann suggested that all the hadrons in ordinary matter are made up of two flavors, or kinds, of quark, the up, or *u*-flavored, quark and the down, or *d*-flavored, quark. The proton, for example, is made up of two *u* quarks and a *d* quark (*uud*), whereas the neutron is made up of a *u* quark and two *d* quarks (*udd*). A third quark called the strange, or *s*-flavored, quark was invoked to explain the existence of certain particles with strangely long lifetimes. Three corresponding antiquarks were postulated: antiup (*u*), antidown (*d*) and antistrange (*s*). The positively charged pi meson is made up of a *u* quark and a *d* antiquark (*ud*). At least two more quark flavors have since been discovered; they are called charm (*c*) and bottom (*b*).

One distinctive feature of the quark model is that each quark carries a fractional electric charge. The charge of the

$u$  quark is  $+2/3$  (in units of the proton's charge) and that of the  $d$  quark is  $-1/3$ . In a hadron the quarks combine in such a way that the electric charge of the bound system invariably turns out to be an integral multiple of the proton's charge. The charge of the proton itself is  $2/3 + 2/3 - 1/3$ , or  $+1$ ; the charge of the neutron is  $2/3 - 1/3 - 1/3$ , or  $0$ .

In this way the electric charge of every hadron known can be accounted for as a sum of quark charges. With the exception of a few somewhat controversial measurements, however, a fractional charge has not been observed in nature. If a particle with a fractional charge could be isolated, it would seem comparatively easy to distinguish it from all the surrounding particles with integer charge. Because of the failure to detect fractional charges, many physicists were at first unwilling to accept the existence of quarks as more than a convenient but fictional device for making predictions about hadrons. As more hadrons were discovered, however, and as more of their features were shown to fit the quark model, the reality of quarks seemed much less at issue. The question was not whether quarks exist but why they are never detected in isolation.

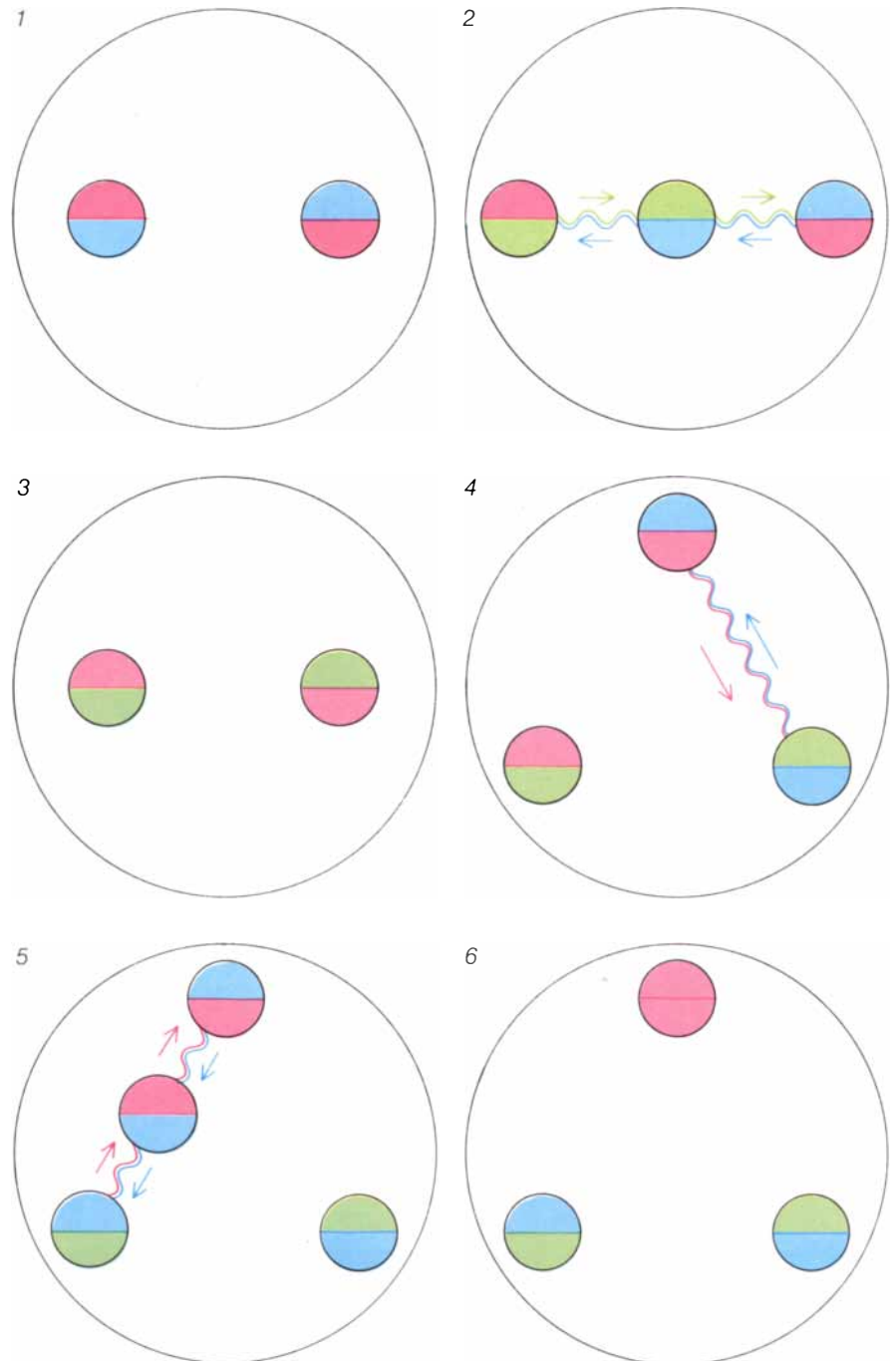
A related issue arises when one considers the spin, or intrinsic angular momentum, of the quarks. The spin of a particle is like the spin of a top except that the spin of the particle is quantized: it must take on integer or half-integer values when it is expressed in fundamental units. Particles whose spin is an integer (such as  $0$ ,  $1$  or  $2$ ) are called bosons; examples are the pi meson (with a spin of  $0$ ) and the photon and the gluon (with a spin of  $1$ ). The energy of a collection of bosons is divided among the individual bosons according to a statistical distribution called Bose-Einstein statistics. Particles whose spin is a half-integer (such as  $1/2$ ,  $3/2$  or  $5/2$ ) are called fermions; the electron, the proton, the neutron and all the quarks are fermions with a spin of  $1/2$ . The energy of a collection of fermions is distributed according to Fermi-Dirac statistics.

The two kinds of statistics become important when a number of particles are considered as a single system, as the quarks are in a hadron. It is possible for all the bosons in such a system to share the same values of energy and spin. A group of fermions, on the other hand, must obey the fundamental principle of quantum mechanics called the exclusion principle, which was first stated by Wolfgang Pauli. The exclusion principle forbids any two fermions from sharing the same quantum-mechanical state, that is, the same values of energy, spin and other quantum numbers that identify the fermion. The exclusion principle is troublesome for the quark model because there are hadrons that can be ex-

plained only as a bound state of three identical quarks. The hadron designated omega minus, for example, is made up of three  $s$  quarks and all three quarks must have the same energy and spin. Two identical quarks could be accommodated by ensuring their spins point in

opposite directions, but in the omega minus two of the quarks must occupy the same state of energy and spin.

In order to resolve the impasse Moo-Young Han of Duke University, Yoichiro Nambu of the University of Chicago and Oscar W. Greenberg of the Univer-



**CONSTITUENTS OF GLUEBALLS** are the particles called gluons, whose role in the structure of matter is ordinarily to bind together quarks, which are the components of the proton, the neutron and many related particles. In a glueball the gluons are bound to one another in a composite structure without quarks. Each gluon has a property called color; indeed, a gluon can be represented as having both a color (shown here in the upper half of each circle) and an anticolor (lower half). The colors are arbitrary labels for mathematical properties and have no relation to ordinary colors. The gluons continually exchange additional colored gluons. Moreover, when a gluon has been emitted, it can emit still another gluon in turn. As a result a glueball initially made up of two gluons can become a bound state of three or more; the number of gluons in a glueball is not a well-defined quantity. Any combination of colors and anticolors can be exchanged among the gluons; the only constraint is that no net color can be generated. In this way the glueball as a whole remains "colorless," or neutral with respect to color.

sity of Maryland at College Park introduced the idea that quarks are distinguishable not only by flavor, spin and electric charge but also by the new attribute called color. If the three  $s$  quarks in the omega-minus particle are thought of as, say, red, blue and green, they do not occupy exactly the same quantum-mechanical state and so they do not violate the exclusion principle. (The term color and the color values red, blue and

green are arbitrary labels for distinctions that are essentially mathematical, and they have nothing to do with real colors.)

At first, postulating the existence of color seems to lead to more difficulties than it resolves. Color, like fractional charge, has not been detected in nature. All independent particles are colorless, and so the colors of the constituent quarks must somehow cancel one an-

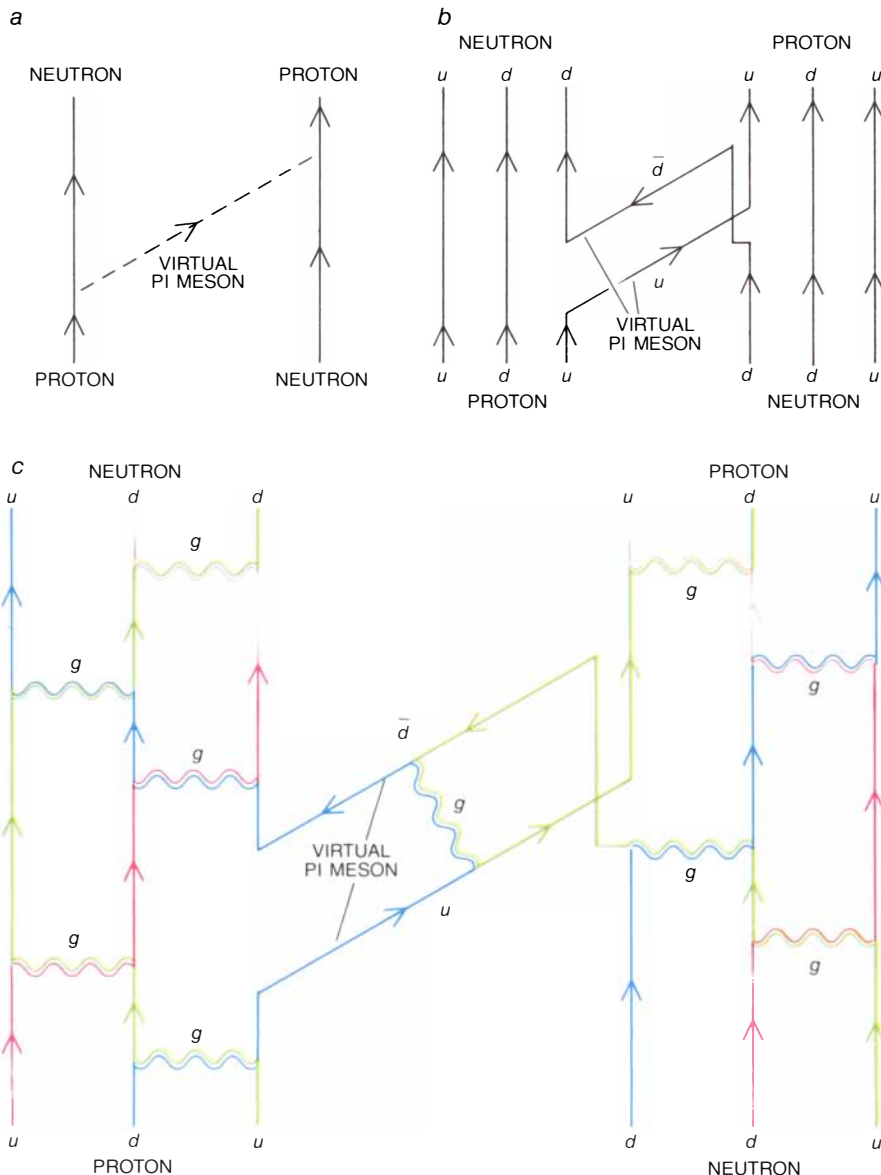
other. For the colors to cancel in a hadron made up of three quarks (such as the proton) there must be one quark in each of the colors red, blue and green. For hadrons made up of a quark and an anti-quark (such as the pi meson) the requirement that the particle be colorless is met if the constituents assume a color and its anticolor, say red and antired.

The apparent short range of the color force, the failure to detect fractional charge and the failure to detect color have not led to the abandonment of the quark hypothesis; it has been far too successful in explaining the properties of hadrons to be easily dismissed. Instead the three observations taken together suggest that quarks do exist but are permanently confined within hadrons. One of the major challenges for any theory of quark interactions, therefore, is to explain quark confinement.

Although the idea of color was first proposed in order to make the quark model consistent with the Pauli exclusion principle, color has since been given a central place in the model as the basis of the theory that describes the interactions of quarks. It is the color charges of quarks that give rise to forces acting between them, just as it is the electric charge of electrons and protons that generates the electromagnetic force in an atom. Indeed, the theory of the color force was constructed by direct analogy with the theory of the electromagnetic force.

The fundamental theory of the electromagnetic interactions of particles is quantum electrodynamics, or QED. It was developed over a 20-year period beginning in the late 1920's. The idea that the force between two electrically charged particles can be accounted for by an exchange of photons was introduced by QED. Only particles with an electric charge can take part in such an exchange; on the other hand, since the photon is electrically neutral, the exchange does not alter the charge of a particle that emits or absorbs a photon.

The theory of the color force is called quantum chromodynamics, or QCD. The mathematical framework of the theory was developed in 1954 by C. N. Yang of the State University of New York at Stony Brook and Robert L. Mills of Ohio State University. It was first applied to the physics of strong interactions by Jun J. Sakurai of the University of Chicago. QCD states that one colored particle interacts with another by exchanging gluons. Because there are three kinds of color, however, QCD is substantially more complicated than QED. Furthermore, because the gluons themselves carry a color charge, the color of a particle that emits or absorbs a gluon can be changed. With three possible initial colors and three possible final colors, providing for all the color trans-



**STRONG FORCE** that binds the proton and the neutron in the nucleus of the atom can be understood at three increasingly fine-grained levels of explanation. At the first level the force can be thought of as acting through the exchange of a pi meson, which causes the proton and the neutron to exchange identities (a). At the second level the proton, the neutron and the pi meson are all regarded as being made up of the more elementary particles called quarks. In this scheme the pi meson in effect transfers an up, or  $u$ , quark from the proton to the neutron and transfers a down, or  $d$ , quark from the neutron to the proton (b). At the third level of explanation the strong binding force between the proton and the neutron is considered to be the net result of the action of the color force, which binds quarks together and is mediated by the exchange of gluons, the wavy lines designated  $g$  in the diagram (c). Because the gluons are colored their transfer can change the colors of the quarks. Although color is continually interchanged among the quarks that make up a free particle, the particle has no net color. The combination of red, blue and green and the combination of blue and antiblue both represent colorless states, just as the combination of ordinary light in such colors gives rise to white, or colorless, light.

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formations would seem to require nine kinds of gluon. Actually the three transformations that do not change the color of either the emitting or the absorbing particle can be accounted for by only two gluons. Hence there are eight kinds of gluon in all.

Each gluon is designated by the effect it has on the quark by which it is emitted. For example, when a red-to-blue gluon is emitted by a red quark, the red quark becomes blue. A blue quark that absorbs the red-to-blue gluon becomes a red quark. The colors of the gluon are such that when they are subtracted from those of the red quark, the red quark becomes blue, and when they are added to those of the blue quark, the blue quark becomes red.

If the color force is confined to a small region of space, the gluon may not be a directly observable aspect of QCD. Nevertheless, there is every reason to suppose the colors carried by the gluons enable them to form glueballs, or colorless bound states similar to the hadrons, the colorless bound states of quarks. The most direct way to observe the

properties of the gluons may be to study glueballs. The existence of the gluon and the glueball were predicted by Harald Fritzsch of the California Institute of Technology and by Gell-Mann.

**B**ecause gluons have no property comparable to the flavor of quarks, gluons can form fewer distinctive bound states than quarks can. Moreover, because a glueball must be colorless any bound state of the gluons that exhibits net color must be disallowed. With eight kinds of gluon it would seem that 64 kinds of glueball might be made by combining the gluons in pairs, but most of the combinations would have a net color. The only pairs of gluons that can form colorless glueballs are the eight pairs in which the colors cancel. For example, a red-antiblue gluon must be paired with a blue-antired one.

As it turns out, these eight pairs freely exchange their colors and form a so-called mixed state in which any one of them is equally likely to be found. Indeed, because the exchange of color amounts to the emission of a third gluon,

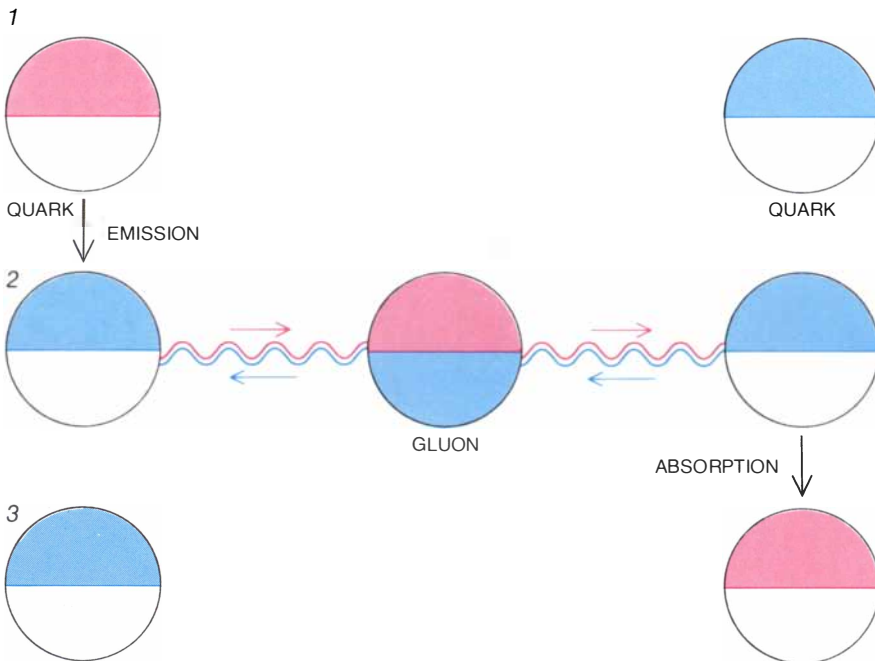
on, glueballs made up of three or more gluons can be generated as long as color neutrality is preserved. Glueballs made up of different numbers of gluons may not be experimentally distinguishable.

Even though there is only one basic kind of glueball it should exist in several states with different quantum numbers. In all the states the constituent gluons are the same, but they have different modes of motion. The quantum numbers most important for classifying the various states are the angular momentum, the parity and the charge-conjugation quantum numbers.

The total angular momentum of a glueball could in principle have any one of many possible values. One contribution to the total angular momentum is the intrinsic spin of one unit carried by each of the gluons. If the spins point in opposite directions, they cancel and the glueball has a total angular momentum equal to 0. If the spins point in the same direction, they add and the total angular momentum is equal to 2. There are other ways for the spins to combine, and in addition the glueball can have orbital angular momentum associated with the revolution of the gluons about their common center of mass; these refinements give rise to mixed spin states in which each possible value of the total angular momentum has some probability of being observed. The spin-0 and spin-2 states, however, are the ones most likely to be detected. It has become customary to refer to a spin-0 particle as either a scalar or a pseudoscalar particle; the one with a spin of 2 is called a tensor particle.

Both the parity and the charge-conjugation quantum numbers can be either positive or negative. The parity of a glueball is positive if in all its interactions the particle cannot be distinguished from its mirror reflection; otherwise the parity is negative. Similarly, the charge-conjugation number of a glueball is positive if the quantum-mechanical description of the particle is unchanged when every particle is replaced by the corresponding antiparticle. Among the spin-0 glueballs the scalar one has positive parity and the pseudoscalar one has negative parity. The tensor glueball can have either positive or negative parity. All three states can have either positive or negative charge conjugation.

The description of a hadron or a glueball as a composite of two colored particles that occasionally exchange a third colored particle is not entirely adequate. In QCD the vacuum in which the particles exist is itself an active contributor to their properties. Surrounding every quark and every gluon is a cloud of particles that are briefly materialized from the vacuum. They are called virtual particles because they cannot be detected directly; they owe their ephemeral ex-



**GLUON EXCHANGE** between two quarks can result in the transfer of color from one quark to the other. The colors are arbitrarily designated red and antired, blue and antiblue and green and antigreen. The color of a quark or a gluon is represented by the color of the upper half of each circle, whereas the anticolor of the particle is represented by the color of the lower half of the circle. The anticolors can be thought of as negative colors: thus a red-antiblue gluon has the red color value +1 and the blue color value -1. The absence of a color or an anticolor indicates that the numerical value of the color is 0. A gluon emitted by a quark carries away a discrete quantity of each color. The colors that remain on the quark after the emission of the gluon are obtained by subtracting the numerical value of each color carried by the gluon from the corresponding value of the color of the original quark. The color red of a red quark is reduced from 1 to 0 by the emission of a gluon that carries away a red color of 1 (that is, 1 minus 1 is equal to 0); the color blue, which has the value 0 in the red quark, becomes 1 when a gluon carries away a blue color of -1 (that is, 0 minus -1 is equal to 1). Similarly, when a quark absorbs a gluon, the color values of the gluon are added to the corresponding color values of the quark. The color blue of the blue quark is reduced to 0 when a gluon that carries a blue color of -1 is absorbed (that is, 1 plus -1 is equal to 0); the color red, which has the value 0 in the blue quark, becomes 1 when a gluon that carries a red color of 1 is absorbed (that is, 0 plus 1 is equal to 1).



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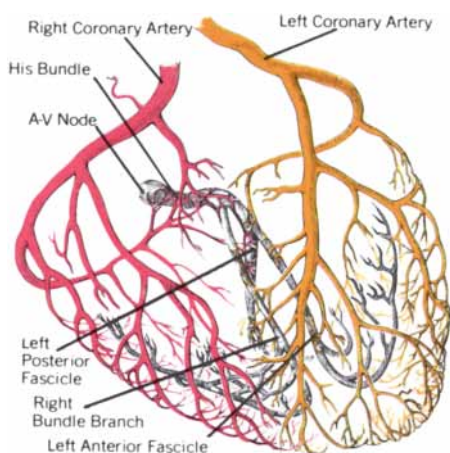
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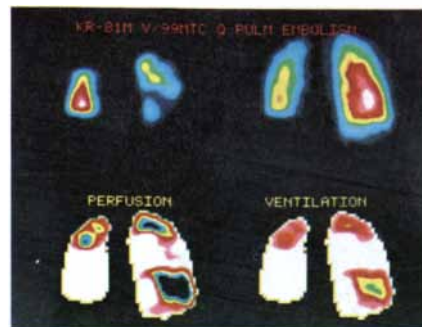
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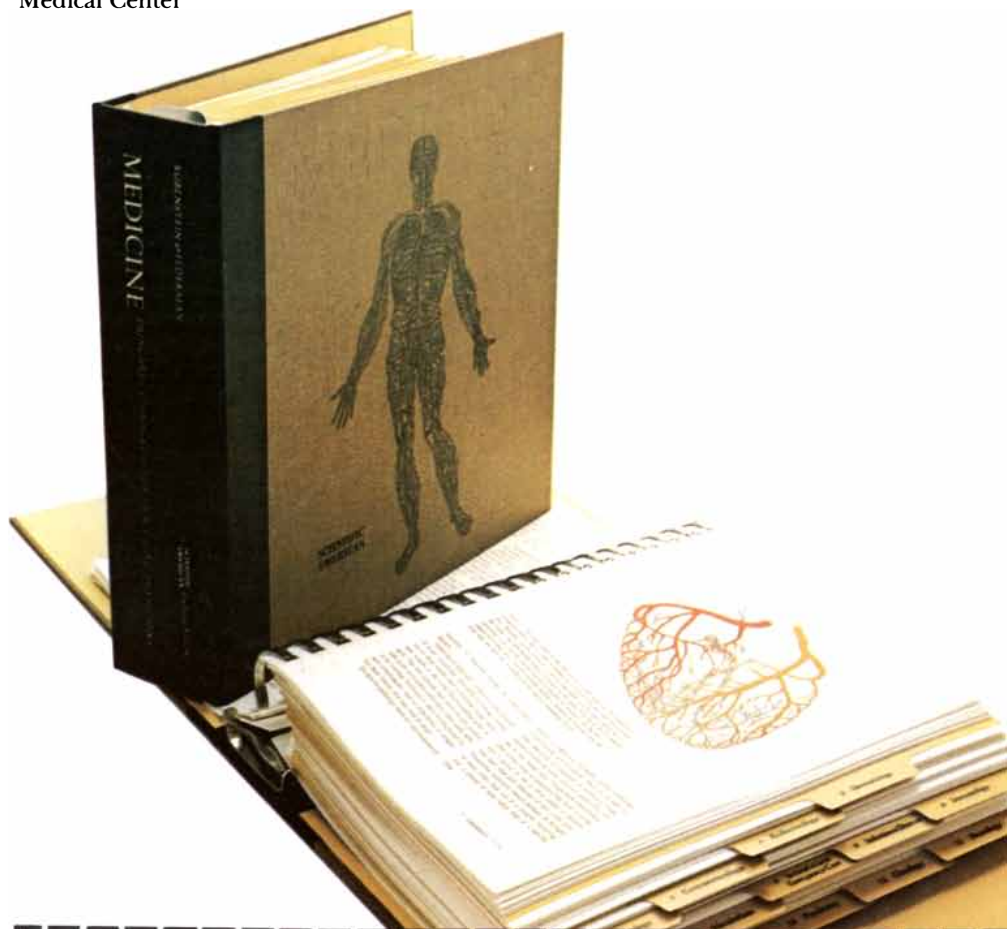
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istence to the uncertainty principle of Werner Heisenberg.

According to the uncertainty principle, the law of conservation of energy can seemingly be violated if the violation is brief enough to go "unnoticed." The energy needed to create virtual particles can be "borrowed" from the vacuum surrounding the quark or the gluon because there is some uncertainty about the average energy level of the vacuum over any interval of time. The shorter the interval, the more uncertain the energy, and so more energy becomes available for materializing virtual particles. The spontaneous creation and subsequent annihilation of virtual particles in the vacuum is called the fluctuation of the quantum field. The virtual particles of importance to the color force are gluons and quark-antiquark pairs. The only constraint on their creation is that the sum of the three colors remain constant throughout the interaction.

One consequence of quantum fluctuations is a substantial reduction in the magnitude of the color force at close

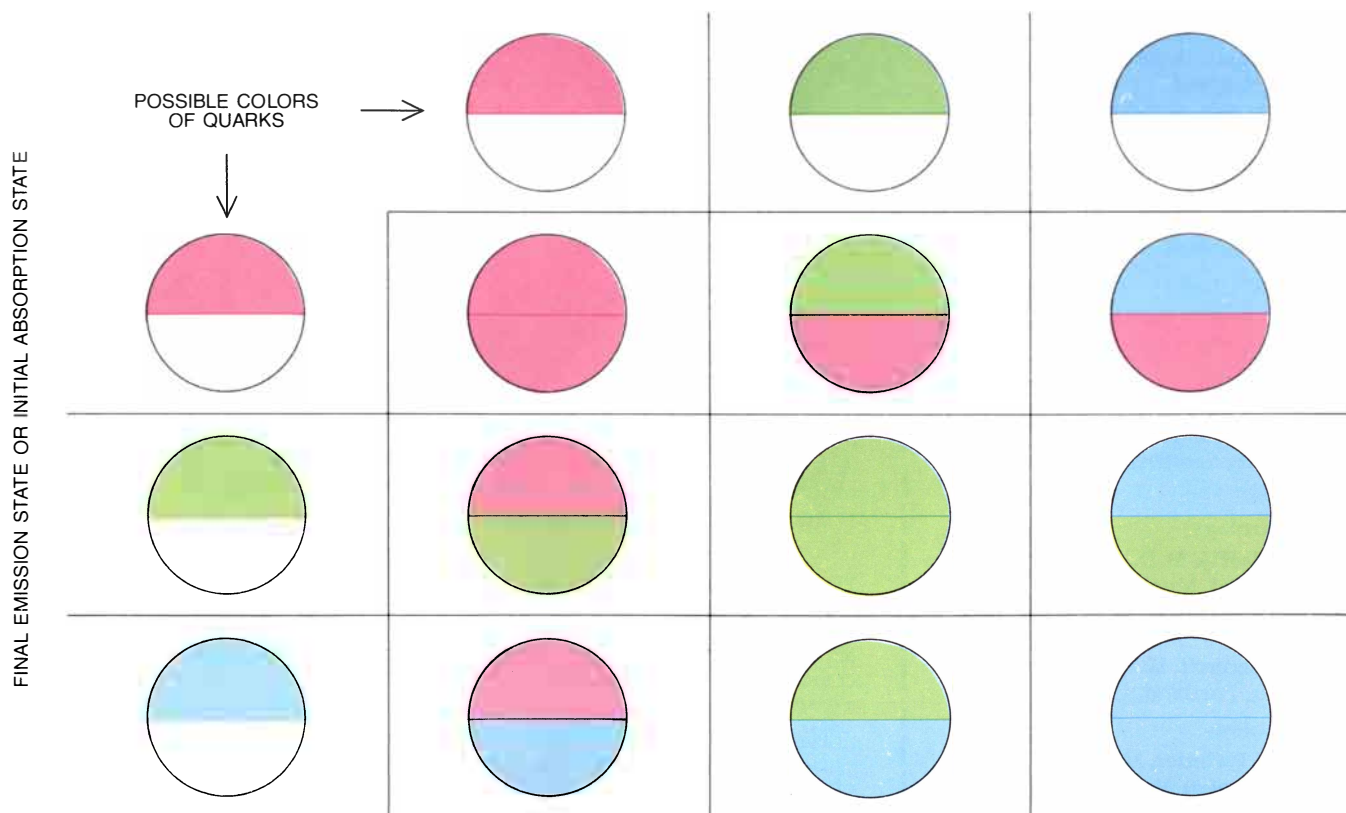
range. The virtual colored particles surrounding a quark or a gluon account for a large part of the color force that is "felt" by a test particle outside the cloud of virtual particles. As the test particle is moved inside the cloud, however, the effective color force diminishes. At a range of about  $10^{-13}$  centimeter, which corresponds roughly to the diameter of a hadron or a glueball, quarks and gluons can move about almost freely in one another's presence. This loosening of the bonds between colored particles at close range is called asymptotic freedom; it was first discussed by Kurt Symanzik of the Deutsches Elektronen-Synchrotron (DESY) in Hamburg and was later shown to follow from QCD by Gerard 't Hooft of the University of Utrecht, H. David Politzer of Harvard University and David Gross and Frank Wilczek of Princeton University.

One of the most important early successes of QCD was a prediction of the experimental consequences of asymptotic freedom. When an electron

and a positron are made to collide head on at high energy, a focused jet or shower of hadrons with relatively coherent flight paths is frequently observed in the products of the collision. Both double and triple jets have been seen; the puzzle is why the hadrons should be bunched in the jets rather than distributed more uniformly. When asymptotic freedom was shown to be a consequence of QCD, the jet events could be explained.

The positron is the antiparticle of the electron, and so when the two particles collide, they annihilate each other. When the particle and the antiparticle have been accelerated to a high energy, all that energy as well as the energy equivalent of their mass is released in a small volume. If the energy density is sufficient, a quark and an antiquark materialize in the small volume. Because momentum must be conserved the momentum of the center of mass of the quark-antiquark pair must be the same as the momentum of the center of mass of the colliding positron and electron, namely zero. Hence the quark and the

INITIAL EMISSION STATE OR FINAL ABSORPTION STATE



**CLASSIFICATION OF GLUONS** is based on their effects on the colors of the quarks that emit or absorb them. Because the effects of the emission of a colored gluon are the reverse of the effects of absorption, the table can be read two ways. If the circles colored red, green and blue across the top row represent the possible color states of a quark before it emits a gluon, the circles in the left column represent the color states of the same quark after the emission. The colors of the emitted gluon are diagrammed at the intersection of the column and the row corresponding to the initial and the final colors of the emitting quark. (The colors and anticolors are represented as

they are in the illustration on page 146.) If one of the colored circles in the left column represents the initial color state of an absorbing quark, one of the circles in the top row represents the same quark's color state after the absorption of a gluon. The gluon that takes part in the interaction lies at the intersection of the row and the column to which the initial and the final absorption states belong. The three solid-colored gluons along the main diagonal of the table can be expressed mathematically as combinations of two independent matrices that can each be associated with a gluon. Hence there are generally considered to be eight distinct gluons instead of nine.

antiquark begin to move apart in opposite directions.

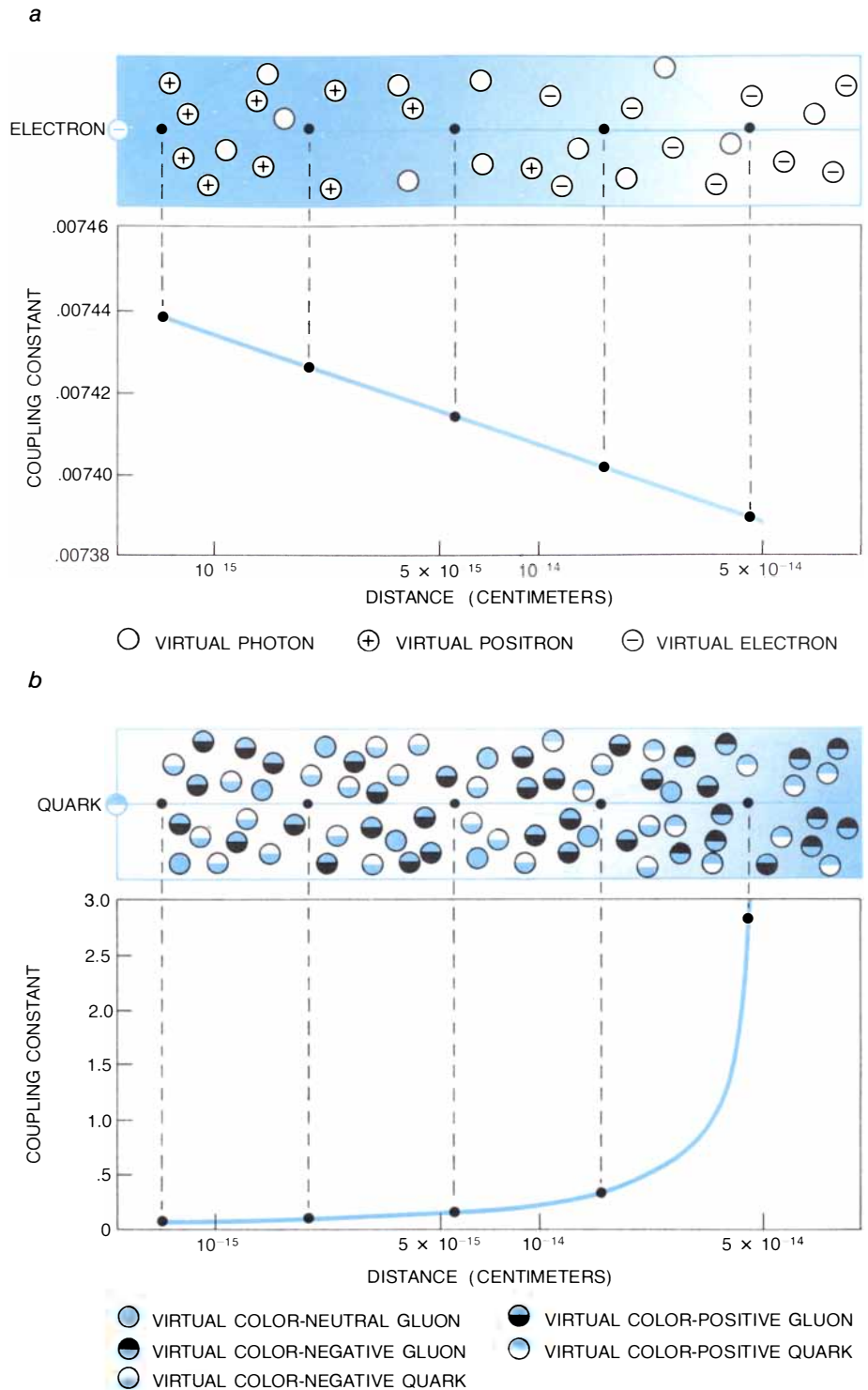
As long as the two particles remain within about  $10^{-13}$  centimeter of each other their trajectories do not come under the influence of the color force because of asymptotic freedom. When the quark and the antiquark begin to feel the color force, however, the energy of the interaction causes new quarks and antiquarks to materialize and subsequently to combine with the initial quark and antiquark to form hadrons. Many of the hadrons are unstable, but they decay into longer-lived hadrons that can be detected. The net result is a double jet of hadrons that retains the signature of the freely divergent motion of the initial quark and antiquark.

In some instances one of the quarks formed after a collision emits a gluon, which moves along a free trajectory as long as it stays within the range of asymptotic freedom. As the gluon moves away from this region, however, it too begins to feel the influence of the color force; the gluon's energy is thereby converted into pairs of quarks and antiquarks and ultimately into a third jet of hadrons. Three-jet events have been observed in several detectors at DESY.

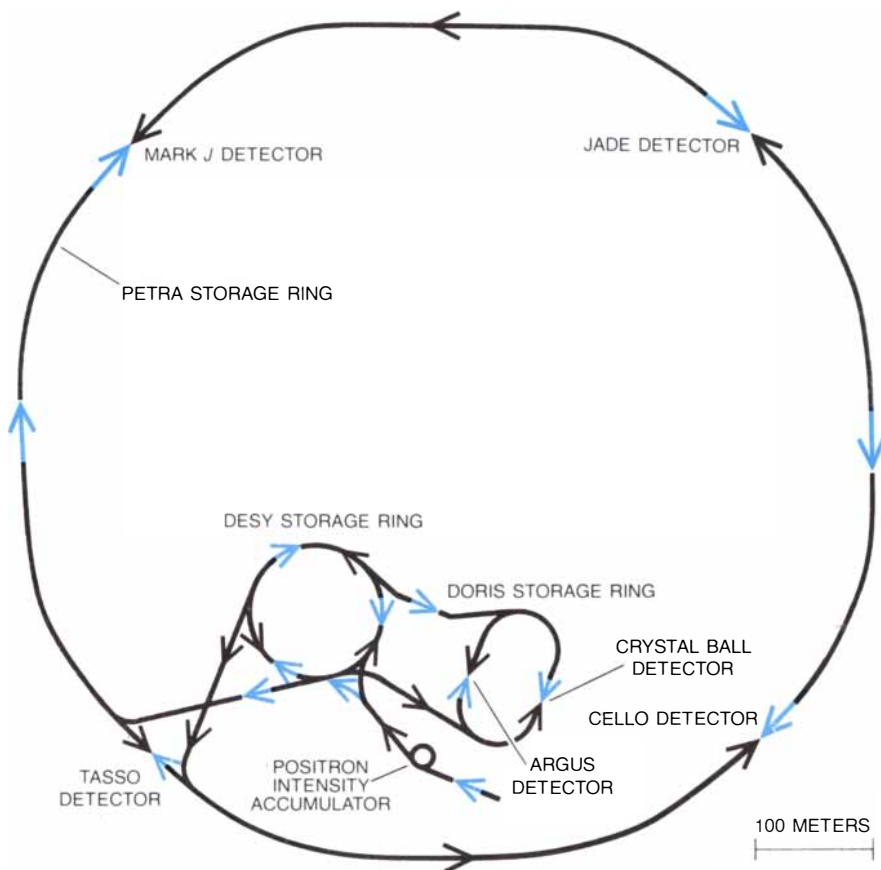
In spite of the success of QCD in explaining the negligible strength of the color force over short distances, theoretical prediction of the effects of the force over longer distances has presented formidable difficulties. Indeed, a demonstration that the permanent confinement of quarks and colors is a consequence of QCD has not yet been forthcoming. A number of phenomenological models have therefore been suggested that simplify the calculations and still predict the confinement of quarks. Within the models it is possible to calculate the energy of bound quarks and gluons in the various states of excitation allowed by quantum mechanics. The calculations are analogous in principle to the determination of the energy states of the electron orbitals in an atom, and they yield predictions of the mass of particles that correspond to the various energy states of the bound quarks and gluons.

In one such model, called the string model, the quarks that make up a hadron are attached to one another by a string that has a fixed energy (or mass) per unit length. When the quarks are close together, the string is slack, and so the quarks move about freely. If the distance between the quarks is increased, however, the string must elongate and the energy of the system must increase proportionally. In the string model a single free quark corresponds to a quark at the end of an infinitely long string, and so the quark must acquire infinite energy in order to exist as a free particle.

The string model can also be applied to the glueball simply by substituting



**CLOUD OF VIRTUAL PARTICLES** envelops a charged particle and causes the intrinsic strength of the force associated with the charge to vary with distance at extremely short range. The intrinsic strength of the force is defined by a coupling constant. In quantum electrodynamics (QED), the theory that describes the electromagnetic force, an electron is surrounded by virtual photons and by virtual electrons and positrons. The virtual photons are electrically neutral, and so they do not affect the electromagnetic force. The positively charged virtual positrons, however, are attracted to the negatively charged real electron, whereas the negatively charged virtual electrons are repelled. The net effect is that at distances greater than about  $10^{-13}$  centimeter the intrinsic strength of the force generated by the real electron is screened by the cloud of virtual positrons. At distances of less than  $10^{-13}$  centimeter the effect of the screen of charge diminishes and the coupling constant becomes larger, perhaps indefinitely large (a). In quantum chromodynamics (QCD), the theory that describes the color force, the effects of the virtual particles that surround a quark are reversed. The colors of the virtual quark and antiquark pairs screen the real color charge much as the virtual electrons and positrons screen the real electron charge. The virtual gluons, however, act differently: they tend to cluster around a real quark that has a like color, and so the color is spread out in space. The ultimate result is that the coupling constant associated with the color force diminishes with distance (b).



**PLAN OF THE STORAGE RINGS** at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg shows the paths along which electrons and positrons can be accelerated in opposite directions and made to collide; it is in the aftermath of such collisions that possible evidence of glueballs has been detected. A beam of electrons (colored arrows) can meet a beam of positrons (black arrows) at any of several detecting stations. When the particles collide, they annihilate one another and their kinetic energy as well as the energy associated with their mass becomes available for the creation of new particles. The detectors labeled in the diagram are constructed to be highly sensitive to various kinds of signals given off when the newly created particles decay. The electrons and positrons can be accelerated to a wide spectrum of energies.

gluons for quarks at the ends of the string. In the case of the glueball the entire mass of the particle is embodied in the mass of the string, since the gluons themselves are massless. The model predicts that the least energetic glueballs should have masses of between 1 and 2 GeV. (A GeV is a billion electron volts, the energy acquired by an electron that is accelerated through a potential difference of a billion volts.)

Kenneth G. Wilson of Cornell University has developed a method of calculating the mass of hadrons and glueballs that does not depend on phenomenological models but relies instead on successive numerical approximations. The method is called the lattice gauge theory, and it is particularly well suited to simulating the effects of the color force by means of a digital computer. A grid or lattice of points is imposed throughout the space and time occupied by the particles, and the values of the variables needed for describing the motions of the particles are calculated only at the lattice points. The numerical ap-

proximations of continuous space and time can be improved by making the mesh of the lattice progressively finer. Michael J. Creutz of the Brookhaven National Laboratory recently showed that both quark confinement and asymptotic freedom are predicted by the lattice gauge theory.

In the past year my colleagues and I have calculated the mass of several possible glueball states and have suggested several experimental contexts in which they might be observed. The masses can be calculated in two independent ways, depending on what underlying mathematical assumptions are made to describe the interactions. Asao Sato of the University of Tokyo, Gerrit Schierholz of the University of Hamburg, Michael J. Teper of DESY and I have calculated the mass of three of the glueball states, assuming that the mathematical group that represents the gluons is either the one called  $SU(2)$  or the one called  $SU(3)$ . Mathematical groups enter the theory of elementary particles as a way

of describing the possible transformations among particles. The group  $SU(2)$  applies to particles that have two kinds of charge and whose transformations can therefore be classified in a two-by-two matrix. Of course, colored particles have three kinds of color charge, and so QCD is based on the group  $SU(3)$ . Nevertheless, the results we obtained by assuming that the theory was based on the group  $SU(2)$  were almost the same as they were in  $SU(3)$ . The  $SU(2)$  calculations can usually be employed for pilot studies, and they are considerably less time-consuming.

We found that the mass of the scalar glueball (the one with a spin of zero and positive parity) is about 1 GeV, whereas the mass of the pseudoscalar (spin-0, negative-parity) glueball is about 1.5 GeV; the mass of the tensor (spin-2) glueball that has both positive parity and positive charge conjugation is between 1.5 and 2 GeV. The values are consistent with the ones determined through phenomenological models such as the string model. They also agree quite closely with the masses calculated by two other groups of investigators: Giorgio Parisi and his collaborators at the University of Rome and Bernd Berg of the European Organization for Nuclear Research (CERN), Alain Billoire of the Saclay Nuclear Research Center and Claudio Rebbi of the Brookhaven National Laboratory.

Schierholz, Teper and I have also investigated the spatial structure of the scalar and the tensor glueballs. We have found that the gluons in the scalar glueball tend to distribute themselves evenly in a sphere surrounding the center of the glueball. In the tensor glueball they tend to cluster in a toroidal region and only rarely occupy the center.

In order to identify glueballs when they are generated, their properties, their mode of production and their most likely channels for decaying into more-stable particles must be clearly understood. The problem is not only one of finding a few glueball signatures in a welter of background noise; it is also one of determining exactly how to distinguish the glueball signatures from the signatures of hadrons that have not yet been assigned a classification in the quark model.

It is not possible to generate glueballs alone. In the method of generating particles that is most suitable for observing glueballs a beam of electrons and a beam of positrons are accelerated in opposite directions and allowed to collide at a controlled energy. The lifetime of a glueball produced in the collision is extremely short: on the order of  $10^{-25}$  second. Hence it is not possible to observe glueballs directly; one can only infer their short-term existence from the properties of the daughter particles into which they decay. The signature or sig-

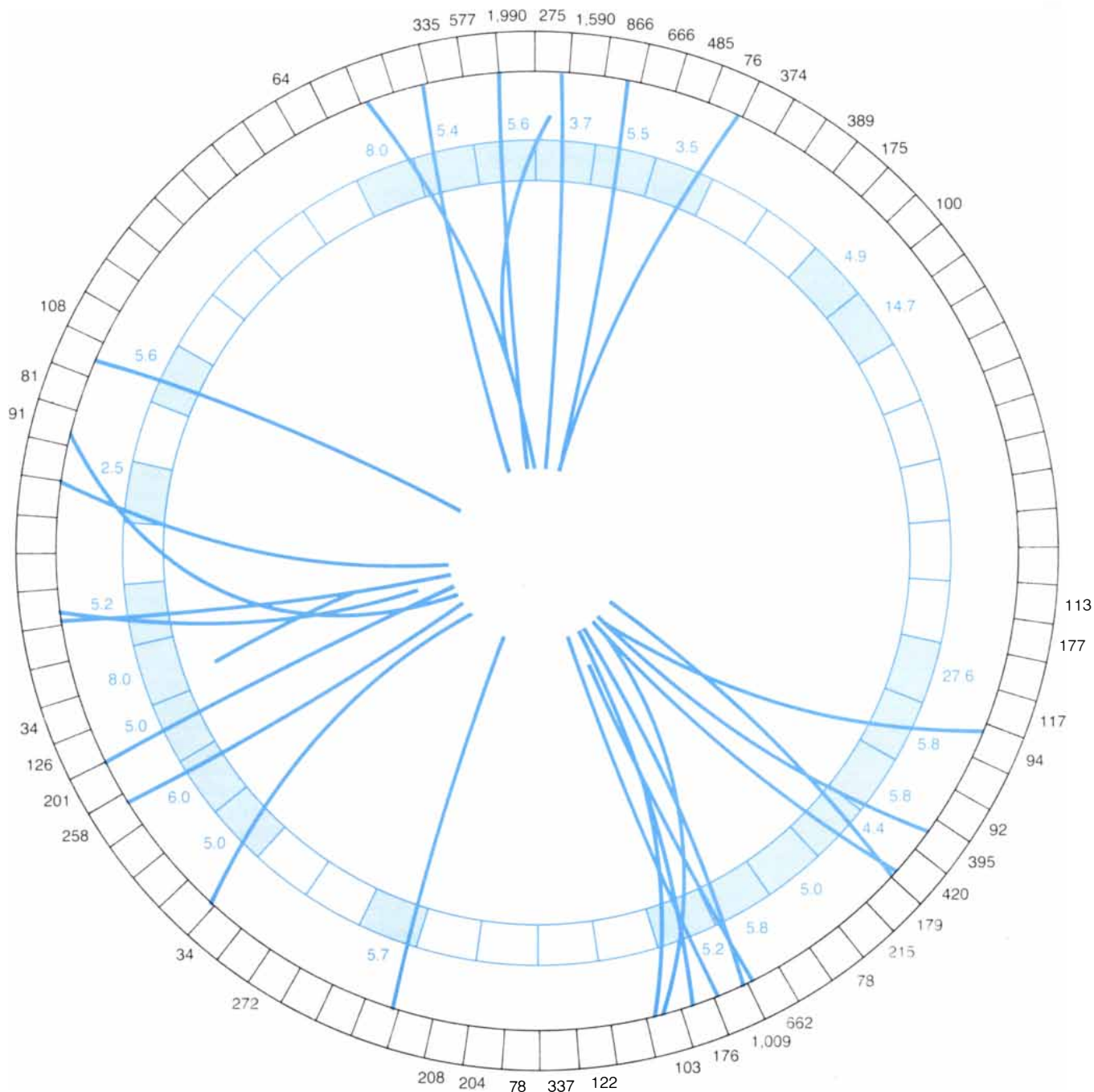
nal of a glueball is observed as a resonance: a peak in the number of hadrons detected when the energy of the colliding particles is adjusted to match the mass of the glueball.

Since a glueball has no internal quantum number corresponding to the flavor of quarks, every glueball candidate

must be a flavorless particle. The absence of flavor is not a sufficient condition for identifying a glueball, however; there are ordinary hadrons, such as the eta-prime meson, that have no flavor either. Moreover, glueballs can assume every possible value of the spin, parity and charge-conjugation quantum num-

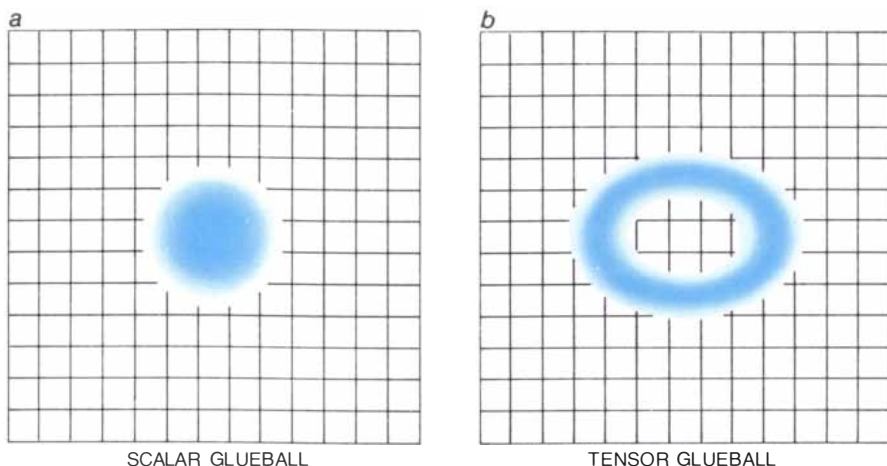
bers, so that any glueball whose set of quantum numbers is shared by a hadron is difficult to identify unambiguously.

On the other hand, there are a few predicted glueball states whose quantum numbers do not match those of any hadron. Sato, Schierholz, Teper and I have recently calculated the masses of



**THREE-JET EVENT** demonstrates the existence of the gluon and confirms the weakening of the color force at close range. Both the gluon and the weakening effect, which is called asymptotic freedom, are predicted by QCD. When an electron and a positron collide head on, they annihilate each other. The kinetic energy as well as the energy associated with the mass of the particle is converted by the collision into a high-energy photon, and a quark and an antiquark materialize from the energy of the photon. Because the electron and the positron move in opposite directions just before the collision, their total momentum is zero. In order to conserve momentum after the collision the quark and the antiquark begin to move away from each other in opposite directions. A gluon emitted by one of the quarks moves

off in a third direction. The trajectory of each particle is a straight line during the initial stages of flight because of asymptotic freedom; the color force does not appreciably influence the motion of the particles at a range of less than about  $10^{-13}$  centimeter. As the particles decay each gives rise to a shower of daughter particles. The initial divergence of the three particles is therefore reflected in the observed divergence of the jets. Each number in colored type gives the time of flight in nanoseconds of the detected particle to which the number corresponds. The time is measured from the moment of the electron-positron collision to the moment of the detection. Each number in black type gives the energy, in megaelectron volts (MeV), of the particle. The event shown was recorded by the JADE detector at DESY.



**DYNAMIC STRUCTURE** of a glueball can be pictured much as the structure of the electrons in an atom can, namely by plotting the wave function of the gluons that make up the glueball. In the diagram are plotted the wave functions of two glueball states that have been tentatively identified among the by-products of electron-positron annihilations: the scalar, or spin-0, glueball (a) and the tensor, or spin-2, glueball (b). The density of the shading at every point corresponds to the amplitude of the wave function at that point. The square of the amplitude of the wave function is the probability that a gluon will be found in a small region of space.

two such states. We found the masses to be about 1.5 to 2 GeV, low enough to be produced in the decay of the  $J/\psi$  meson, the hadron made up of the charm quark and the anticharm antiquark, which is readily generated in an electron-positron storage ring. (Recall that charm, like up, down and strange, is a quark flavor.) If particles having such masses and quantum numbers are ever

detected, they could be unambiguously identified as glueballs.

Because of the similarity of many glueball states to ordinary hadrons it is good experimental strategy to focus attention on processes that are thought to give rise to significant numbers of glueballs. One likely process is the creation of a quark and the corresponding antiquark that subsequently annihilate

each other; the products of the annihilation can take many forms, including two gluons with opposite color charges. In many reactions quark-antiquark pairs are formed, but relatively few pairs annihilate each other. The empirical rule of thumb that suppresses the annihilation is called the OZI rule, after Susumu Okubo of the University of Rochester, Zweig and Jugoro Iizuka of Nagoya University. When the OZI rule is violated, gluons are emitted copiously and glueballs are likely to form. A violation of the OZI rule can also give rise to the time-reversed reaction: the decay of a glueball can lead to the formation of new quark-antiquark pairs.

One reaction that violates the OZI rule is the decay of the  $J/\psi$  meson. Another reaction is the formation of the phi meson, a hadron made up of a strange quark and an antistrange antiquark. Phi mesons are emitted when pi mesons bombard a fixed target of protons. In both reactions signals have been detected that may indicate the presence of glueballs.

When a glueball is created, there are several ways it can decay to yield detectable particles. For example, the pseudoscalar glueball, which has zero spin and negative parity, can decay into an eta meson and two pi mesons or into a  $K$  meson, a  $\bar{K}$  meson and a pi meson. The former mode, however, can be observed in great quantities from the decay of other particles, and so the signal from the glueball is almost completely washed out. The latter signal, however, in which the  $K$  and  $\bar{K}$  mesons are present, is known to be favored by the pseudoscalar glueball; even a few such detected events could be discerned.

One decay channel in which a glueball could be distinguished from hadrons with identical quantum numbers is the decay into two photons. Because quarks are electrically charged and gluons are electrically neutral it turns out that particles made up of quarks are more likely to decay into photons than glueballs are. Accordingly I have estimated that there should be fewer instances in which a glueball emits two photons than there are in which a hadron does.

Of all the reactions that might give rise to glueballs the ones most likely to lead to an unambiguous glueball candidate are the decays of the  $J/\psi$  meson that include photons among the detected products. A survey of events of this kind was made at the Stanford Linear Accelerator Center (SLAC) and two glueball candidates emerged. One candidate was a particle observed two years ago by experimenters working with the Mark II detector; its mass was 1.44 GeV, but at the time of its detection its spin and parity were not determined. Because the resonance was discovered in a reaction that closely matched the reac-

SPIN	PARITY	CHARGE CONJUGATION	TWO-GLUON STATE	MANY-GLUON STATE	QUARK AND ANTIQUARK
0	+	+	.72 GeV		
0	+	-			
0	-	+	$1.37 \pm .35$ GeV $- .26$		
0	-	-		$1.4 \pm .6$ GeV $- .4$	
1	+	+			
1	+	-	$3.22 \pm .16$ GeV		
1	-	+		$2.36 \pm .217$ GeV $- .21$	
1	-	-			
2	+	+	$1.6 \pm .085$ GeV		
2	+	-			
2	-	+			
2	-	-		$3.6 \pm .03$ GeV $- .02$	

**POSSIBLE QUANTUM NUMBERS** of glueball states and states of ordinary mesons (in which a quark and an antiquark are bound together) can be calculated theoretically and compared with values determined experimentally. Colored squares in the table indicate the states, or particles, for which certain combinations of the three quantum numbers spin, parity and charge conjugation are theoretically possible. Many combinations are possible for both glueballs and ordinary mesons, and so the determination that a particle has such quantum numbers would still leave the identity of the particle in doubt. For the combinations of quantum numbers that are possible only in the glueball state the experimental determination of the quantum numbers would be unambiguous evidence for the existence of a glueball. The theoretical energy values of the glueball states listed were calculated recently by the author and his co-workers.

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0	+	+							
0	-	+							
2	+	+							

**POSSIBLE CHANNELS** for the decay of a glueball in any of three energy states into more stable particles that can be detected are indicated by the colored regions in the table. Blank regions indicate decay channels that can be ruled out on theoretical grounds. The relative abundance of the particles detected after the collisions of electrons and positrons in a storage ring, together with theoretical predictions of the probability that the decay will follow a given channel, makes it possible to identify certain decay products as signals of glueball candidates.

tion one would expect from a glueball, several of my colleagues and I suggested it was the pseudoscalar glueball.

A number of other investigators, however, were disinclined to accept the glueball interpretation. The same reaction can also signal the decay of a hadron

called the *E* meson, whose mass is 1.42 GeV. The resolution of the resonance peak, they argued, was not sharp enough to distinguish two particles whose masses are so nearly equal.

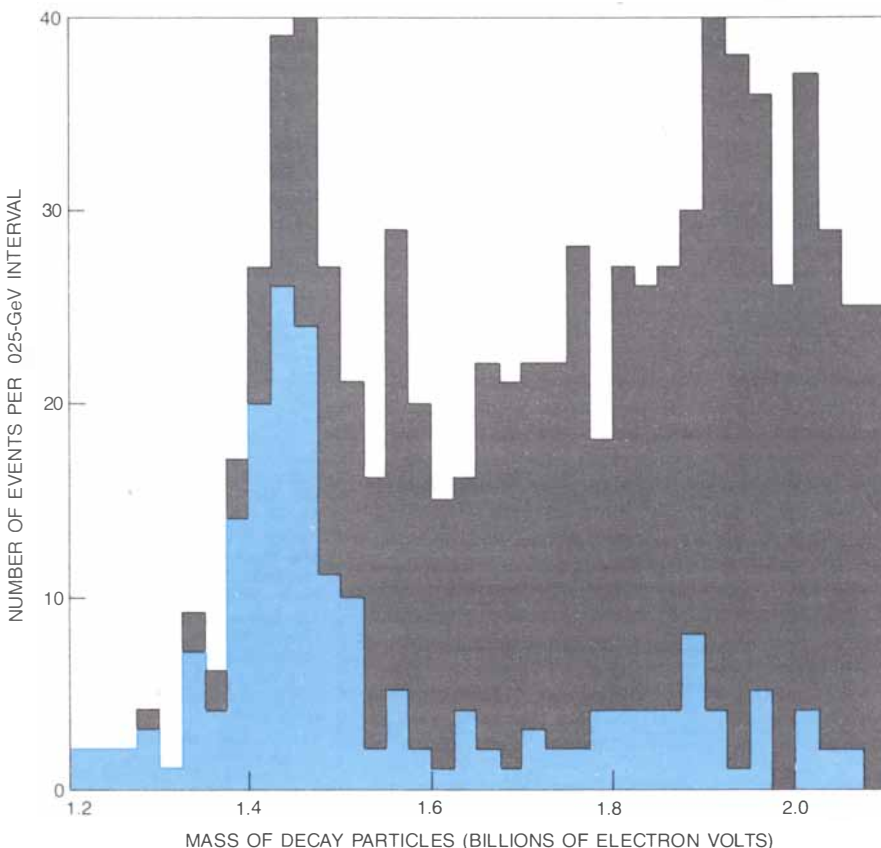
To ascertain the identity of the particle Michael S. Chanowitz of the Univer-

sity of California at Berkeley and I suggested that the spin and the parity of the new resonance be measured; I noted that the rate at which pairs of photons were released by the decay might be measured also. About a year later a detector then at SLAC called the Crystal Ball measured the photon production in the reaction with great sensitivity. The particle having a mass of 1.44 GeV was found to have zero spin and negative parity; in other words, it is a pseudoscalar particle. The *E* meson, on the other hand, is a spin-1 particle with positive parity. The spin-0 particle is therefore likely to be the first confirmed glueball.

The second glueball candidate was also observed at SLAC by workers using the Crystal Ball detector. It has a mass of 1.67 GeV and a spin of 2, so that it may be a tensor glueball. The particle decays to yield two eta mesons, which then decay to yield four photons. Its mass is in agreement with the mass predicted for the tensor glueball by the lattice gauge theory, but the number of photon quadruplets that are detected is much smaller than the theory requires.

A tensor glueball emitted during the decay of the *J/psi* meson is expected to have another possible mode of decay: in some instances it should yield two neutral rho mesons. The number of rho mesons recently observed by the Mark II detector is in agreement with the theoretical production rate of rho mesons in the decay of the tensor glueball. The evidence therefore slightly favors the existence of the tensor glueball, but more data are needed before the identification of the particle can be secure.

The lattice gauge theory also predicts the existence of a scalar glueball, which should be the least massive one of all. Most low-mass particles are relatively stable, and so the resolution of a resonance in their decay products is clear. The scalar glueball, however, has not yet been seen. My guess is that the particle exists, but that its unusual properties give rise to a wide but low resonance that is quite difficult to detect.



**EVIDENCE FOR A GLUEBALL** is the sharp resonance, or peak, found when the number of detected events of a certain kind is plotted against the energy released by the collision of an electron and a positron. The resonance indicates that the energy of the collision is momentarily bound up in the mass of a particle just after the collision, instead of being distributed throughout a range of energy values. Although the original particle decays spontaneously into longer-lived particles and energetic photons, the energy of the decay products can still be determined. In the experiment from which the data in the graph were taken the total energy of every decay that created a  $K^+$  meson, a  $K^-$  meson, a neutral pi meson and a photon was determined. The number of such events in each energy interval was then plotted (gray region). A second graph was constructed (colored region) including only those events in which the mass of the  $K^+$  and the  $K^-$  mesons did not exceed 1.125 billion electron volts (GeV). The added constraint served as a noise filter; a resonance at 1.44 GeV stands out clearly. Because the resonance agrees with the predicted mass of the glueball and because the predicted low-energy states of bound systems of quarks have already been accounted for by other particles, the data strongly suggest that glueballs are actually being materialized. The data were obtained from the Crystal Ball detector while the detector was installed at the Stanford Linear Accelerator Center (SLAC).

The discovery of a glueball, like the discovery of any new particle, is a remarkable event in its own right. For the theory of strong interactions, however, the glueball is a find of special significance. Its positive identification would confirm one of the most important distinctions between quantum chromodynamics and its parent theory, quantum electrodynamics, namely the nature of the relation between the charge associated with an interaction and the particle that mediates the interaction. The tentative identification of the pseudoscalar glueball is a success of QCD that is not directly inherited from QED. Our work for the near future will surely be to consolidate the success and continue the search for new glueballs.

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