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

It is 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 distance of the color force may indeed be infinite, but the 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 postulated: anti up (u), antidown (d) and antistrange (s). The positively charged pi meson is made up of a u quark and a d antiquark (uud), whereas the neutron is made up of a u quark and a d antiquark (uud).

One distinctive feature of the quark model is that each quark carries a fractional electric charge. The charge of the range of more than about 10⁻¹⁳ 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.
The charge of the proton 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 explained 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.
University 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 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 another. 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 antiquark (such as the pions) 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 with 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-

![Diagram of strong force between proton and neutron](image)

**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 π meson, which causes the proton and the neutron to exchange identities (a). At the second level the proton, the neutron and the π meson are all regarded as being made up of the more elementary particles called quarks. In this scheme the π 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 antibleue both represent colorless states, just as the combination of ordinary light in such colors gives rise to white, or colorless, light.
'83 Ford Bronco takes to the mountains with more torque than any 6-cylinder 4-wheeler. It's just one reason Bronco is the No. 1 seller in its class.† Inside, there's room and comfort for six with optional twin bench seats. Or go with standard bucket seats up front. Even underneath, Bronco's up on the competition. It's the only full-size, American-built sport utility with independent front suspension. Tough Ford Bronco. It's a beautiful way to go! Get it together — Buckle up.

†Based on R.L. Polk & Co. calendar year registrations as of May, 1982.

Optional Captain's Chairs shown

27 EST HWY 18 EPA EST MPG 4.9L Six and optional overdrive. Use for comparison. Your mileage may differ depending on speed, distance and weather. Actual highway mileage lower. California ratings may be less. See your Ford Dealer for the 1983 EPA Gas Mileage Guide.

FORD BRONCO
FORD DIVISION

AMERICA'S TRUCK TOUGH FORD BRONCO

© 1982 SCIENTIFIC AMERICAN, INC
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.

Because 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, 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 glue 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-

**Diagram:**

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 or 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).
STATE-OF-THE-ART

The Kodak Carousel 5600 projector

Slide viewing with a Kodak projector has never been as easy as it is now with the Kodak Carousel® 5600 projector. Because no other slide projector has all these features. Our exclusive Slide-Scan™ built-in screen, for example, can turn any room in the house into a screening room. And no matter what room you’re in, the illuminated control panel and built-in reading light eliminate fumbling around in the dark. There’s also a lamp that lasts up to 70 hours. Plus our auto-focus feature that helps make the slide you’re projecting look crisp and sharp. And, amazing but true, the projector even turns the lights off. The Kodak Carousel 5600 projector. It’s a gift anyone would love.

From Kodak
The Pro in Projectors

© Eastman Kodak Company, 1982
Physician, did you miss any of these significant developments in medical science?

• *Campylobacter fetus* subsp. *jejuni* is associated with a colitis that can clinically and sigmoidoscopically resemble acute idiopathic ulcerative colitis. Stool cultures are in order for *C. fetus* before beginning nonspecific anti-inflammatory therapy.

• Coumarin derivatives cross the placenta. A recent study shows that the consequences for the fetus can be severe. These include embryopathy, stillbirth, and premature delivery.

• Nonsteroidal anti-inflammatory drugs may produce a marked reduction in glomerular filtration rate; with termination of the drug, GFR returns to normal.

• The first documented incident of indigenous transmission of dengue in the continental United States since 1945 has been reported in Brownsville, Texas.

If these items are familiar you must be a prodigiously energetic or prodigiously lucky reader. With 2,000 or more journals published each year, information that significantly affects patient management all too easily slips by. Textbooks are out-of-date before they are published.

**SCIENTIFIC AMERICAN Medicine** is lucidly illustrated with drawings and photographs. Some examples are seen here and on the facing page.

**Trial Offer**
We invite you to try **SCIENTIFIC AMERICAN Medicine** — for two months at no cost. Send us the coupon and you will receive the two-volume text and two monthly updates. You may also take a CME test for credit. At the end of 60 days, if you decide to continue the subscription, we will bill you for $220 for the full 12 months (renewal is currently $170); otherwise return the two volumes.

Please mail the coupon today and let us take the hassle out of keeping up.
4. Gastroenterology
Gary M. Gray, M.D., Stanford University School of Medicine
Peter B. Gregory, M.D., Stanford University School of Medicine
John Austin Collins, M.D., Stanford University School of Medicine
Douglas Wilmore, M.D., Harvard Medical School and Brigham and Women’s Hospital

5. Hematology
Stanley L. Schrier, M.D., Stanford University School of Medicine

6. Immunology
John David, M.D., Harvard Medical School and Harvard School of Public Health

7. Infectious Disease
Thomas C. Merigan, M.D., Stanford University School of Medicine
Morton N. Swartz, M.D., F.A.C.P., Harvard Medical School and Massachusetts General Hospital
Cyrus C. Hopkins, M.D., Harvard Medical School and Massachusetts General Hospital
Adolf W. Karchmer, M.D., F.A.C.P., Harvard Medical School and Massachusetts General Hospital
Robert H. Rubin, M.D., F.A.C.P., Harvard Medical School and Massachusetts General Hospital
Harvey B. Simon, M.D., F.A.C.P., Harvard Medical School and Massachusetts General Hospital
Peter F. Weller, M.D., Harvard Medical School; Beth Israel Hospital, Boston; and Brigham and Women’s Hospital

8. Intensive and Emergency Care
Edward Rubenstein, M.D., F.A.C.P., Stanford University School of Medicine

9. Metabolism
George F. Cahill, Jr., M.D., Harvard Medical School, Howard Hughes Medical Institute; and Brigham and Women’s Hospital

10. Nephrology
Roy H. Maffly, M.D., Stanford University School of Medicine and Palo Alto Veterans Administration Medical Center
William Bennett, M.D., Health Sciences University, Portland, Oregon

11. Neurology
Robert W. P. Cutler, M.D., Stanford University School of Medicine

12. Oncology
Saul A. Rosenberg, M.D., F.A.C.P., Stanford University School of Medicine

13. Psychiatry
Ned H. Cassem, M.D., Harvard Medical School and Massachusetts General Hospital

14. Respiratory Medicine
Eugene D. Robin, M.D., F.A.C.P., Stanford University School of Medicine

15. Rheumatology
Stephen M. Krane, M.D., Harvard Medical School and Massachusetts General Hospital
Dwight R. Robinson, M.D., Harvard Medical School and Massachusetts General Hospital
Andrei Calin, M.D., M.A., M.R.C.P., Stanford University School of Medicine and Palo Alto Veterans Administration Medical Center

Order by Phone
You can order SCIENTIFIC AMERICAN Medicine by telephone. Please call this toll-free number: 1-800-345-8112 (in Pennsylvania, call 1-800-662-2444); you will be billed after your subscription begins. Toll-free calls are acceptable only for orders placed in the continental United States.

Please enroll me as a subscriber to SCIENTIFIC AMERICAN Medicine. On receipt of this coupon you will send me the advanced two-volume text described in your announcement and update it regularly by sending me new monthly subsections. I understand that the price of $220 for first year of service is tax deductible, as is current renewal at $170. If I am not entirely satisfied, I may cancel at any time during the first 60 days, returning all materials for a complete refund.

- Please enter my subscription for SCIENTIFIC AMERICAN Medicine
- I shall also enroll in the CME program
- I enclose a check made out to SCIENTIFIC AMERICAN Medicine for $220*
- Bill me ________ Account Number

Expiration Date ____________

*Please add sales tax for California, Illinois, Massachusetts, Michigan, and New York

Name __________________________
MD Specialty __________________________
Address __________________________
City __________________________ State ________ Zip ________

Signature __________________________

Please allow six to eight weeks for delivery. All payments must be in U.S. dollars. CME is available outside the U.S. and its possessions for an additional $65. Surface routes used unless airmail delivery is prepaid.

© 1982 SCIENTIFIC AMERICAN, INC
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 colliding positron and electron, namely zero. Hence the quark and the

---

**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

![Diagram of virtual particles and their effects on electron charge](image)

**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 $10^{-14}$ 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).
The problem is not only 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-

 approximations 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 theory was based on the group $SU(2)$,

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.

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.
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 numbers, 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 K bar 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 K bar 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-
HOW TO BEAT TODAY'S HARDCOVER PRICES

You don't judge a book by its cover, so why pay for the cover? QPB books are softcover editions in hardcover sizes, durably bound and printed on fine paper. But they cost up to 65% less than their hardcover counterparts.

Now you know how to beat today's prices: Join QPB.

Let's try each other for 6 months. Quality Paperback Book Club, Inc., Middletown, Pa. 17057. Please enroll me in QPBand send the 3 choices I've listed below. Bill me $3, plus shipping and handling charges. I understand that I am not required to buy another book. You will send me QPB Review is delayed and you receive your monthly QPB Review.

<table>
<thead>
<tr>
<th>Hardcover</th>
<th>QPB Softcover</th>
<th>QPB Ed</th>
<th>Hardcover</th>
<th>QPB</th>
<th>Hardcover</th>
</tr>
</thead>
<tbody>
<tr>
<td>$15.50</td>
<td>$7.95</td>
<td></td>
<td>$15.50</td>
<td>$7.95</td>
<td>$15.50</td>
</tr>
<tr>
<td>$15.50</td>
<td>$7.95</td>
<td></td>
<td>$15.50</td>
<td>$7.95</td>
<td>$15.50</td>
</tr>
<tr>
<td>$15.50</td>
<td>$7.95</td>
<td></td>
<td>$15.50</td>
<td>$7.95</td>
<td>$15.50</td>
</tr>
</tbody>
</table>

Please call (484) 368-9500.

Join now. Pick any 3 books or sets for $1 each—with no obligation to buy another book.

596. The Solar Age Resource Book Editors of 'Solar Age' magazine QPB: $7.95

267. The Timelines of History Bernard Grun Hardcover: $29.95 QPB: $11.95


182. Ah, But Your Land Is Beautiful Alan Paton Hardcover: $12.95 QPB: $6.95

414. The Life and Times of Joe McCarthy. Thomas C. Reeves Hardcover: $19.95 QPB: $9.95

421. Life on Earth: A Natural History. David Attenborough Hardcover: $22.50 QPB: $9.95

574. The Foundation Trilogy (3 Vols.) Isaac Asimov QPB: $6.95


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 stable particles that can be detected are indicated by the colored regions in the table. Blank channel, makes it possible to identify certain decay products as signals of glueball candidates.

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 University of California at Berkeley and I suggested it was the pseudoscalar glueball.

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.

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.
W is for Eagle Wagon. And for wherever. Because Eagle is the only automobile in the world that lets you go from 2-wheel drive to full-time 4-wheel drive at the flick of a switch. 2-wheel drive for high mileage on the highway. 4-wheel drive for worry-free traction and security when the roads weave, the weather worsens, or when you just want to wander where there is no road.

And Eagle’s well-appointed interior makes the going all the more wonderful. Why not see the 1983 Eagle Wagon today. Wherever you’re going, whatever the weather, it’ll fit you to a W.

The 2-wheel/4-wheel drive EAGLE
FROM AMERICAN MOTORS

*Optional 5-speed stick. Use these figures for comparison. Your results may differ due to driving speed, weather conditions and trip length. Highway and California figures lower.