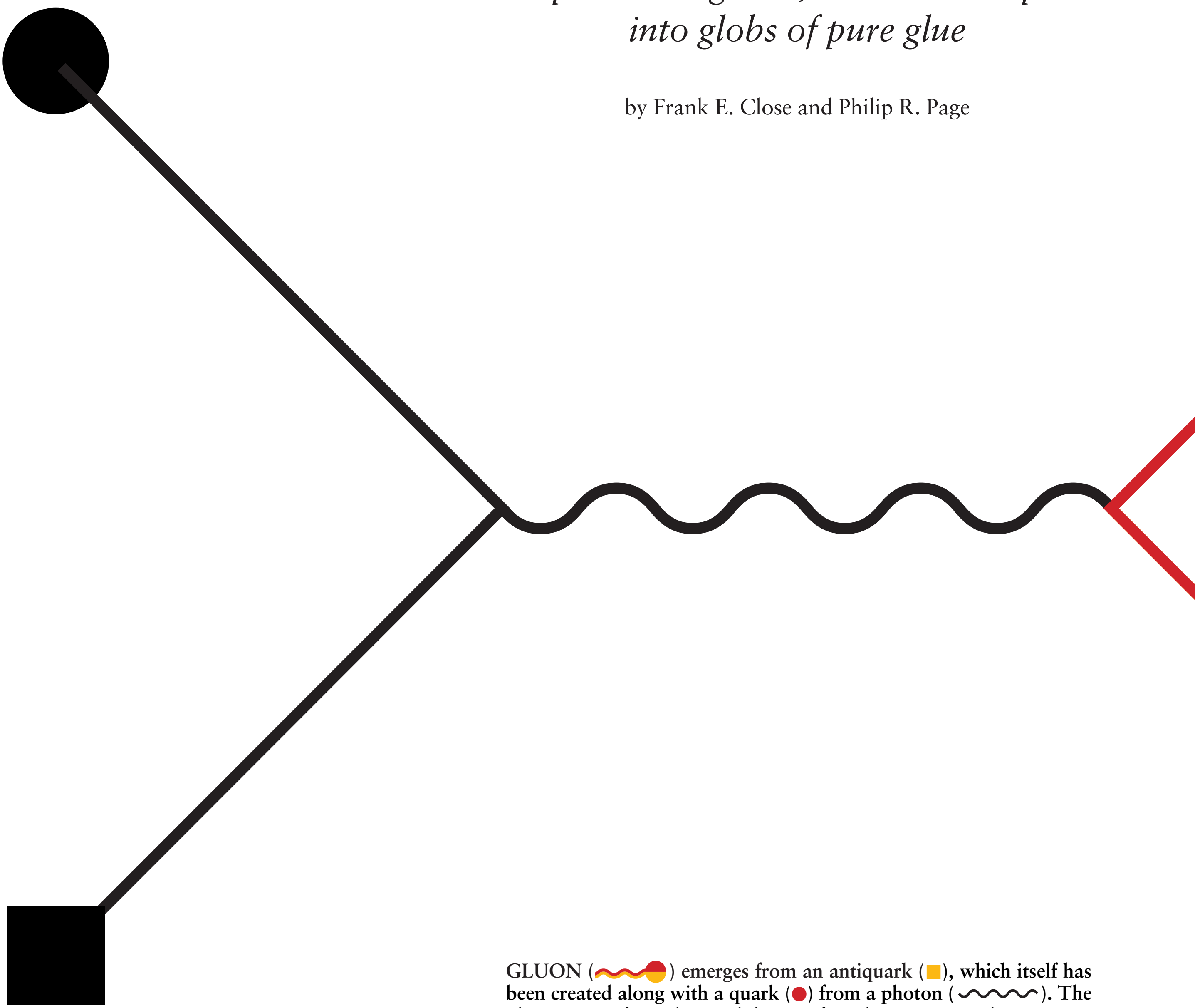
Glueballs

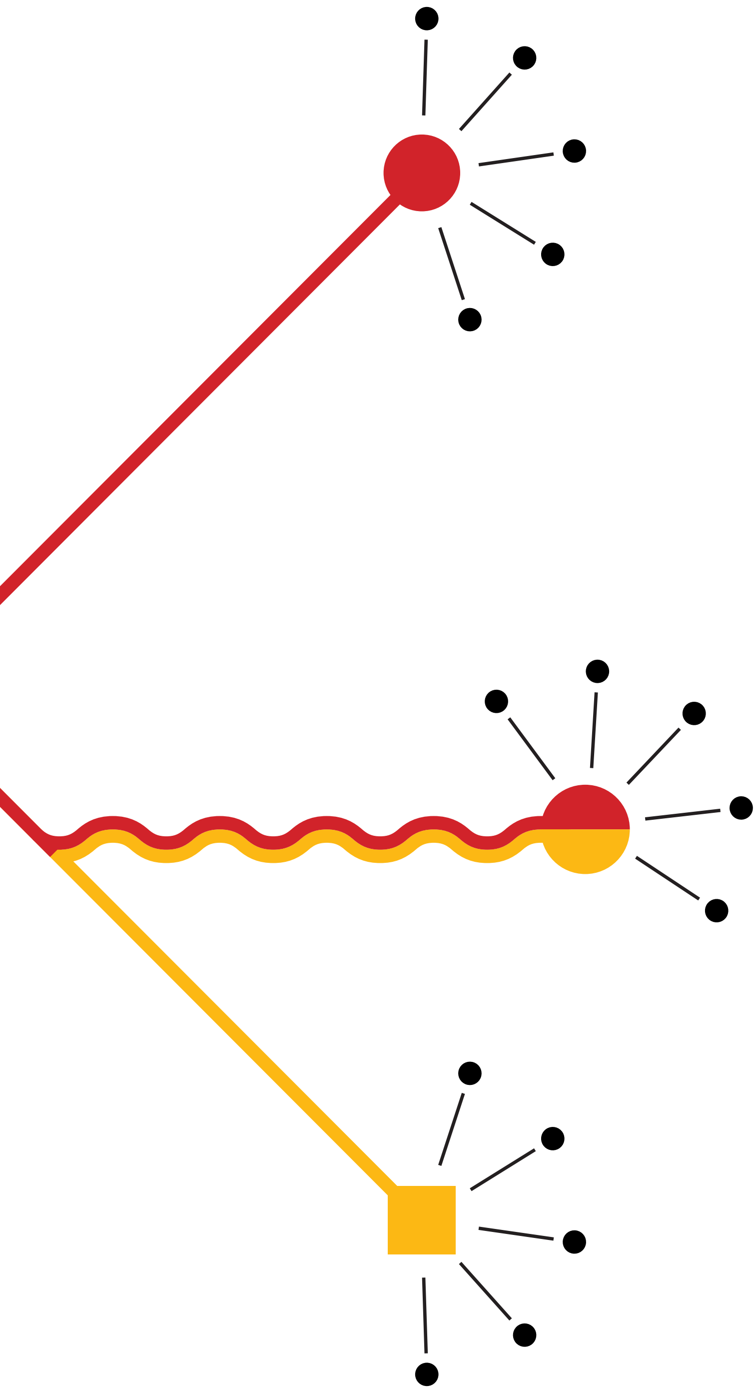
Gluons, which hold protons together, can also clump into globs of pure glue

by Frank E. Close and Philip R. Page



GLUON ( ) emerges from an antiquark (■), which itself has been created along with a quark (●) from a photon ( ). The photon came from the annihilation of an electron (●) with a positron (■). A quark, an antiquark and a gluon carry "color" charges that allow them to interact via the strong nuclear force. A color and its anticolor (or opposite) charge are depicted here by the same hue; the convention leads to every colored line being continuous. Because nature abhors color, the quark, the antiquark and the gluon combine with other particles to yield showers, or "jets" ( ), of colorless objects that are observed in experiments. The electron, the positron and the photon do not have color charge and are not subject to the strong force. Time flows from left to right in this Feynman diagram; such drawings were invented by Richard Feynman as an aid to calculation.

BRYAN CHRISTIE



There are no atoms of light. That is, photons do not attach to other photons, forming composite entities. But gluons, the particles that bind quarks—the basic units of matter—into objects such as protons, may indeed stick just to one another. Physicists call the resulting glob a glueball.

A glueball is thought to have a radius of 0.5×10^{-15} meter, less than that of a proton, and live for less time than light takes to cross a hydrogen atom. Ephemeral though these particles may seem, in the past year many physicists have become convinced that glueballs are showing up in experiments.

Finding a glueball would be a thrilling culmination to a colorful story. By the 1960s scientists had realized that some of the particles they observed in experiments are compounds of smaller objects called quarks. Along with electric charge, quarks have other, odder attributes. One kind—called flavor—comes in six varieties whimsically named up, down, charm, strange, top and bottom. Another kind of property is called "color" charge. An up quark, for instance, comes in three basic colors: red, yellow or blue.

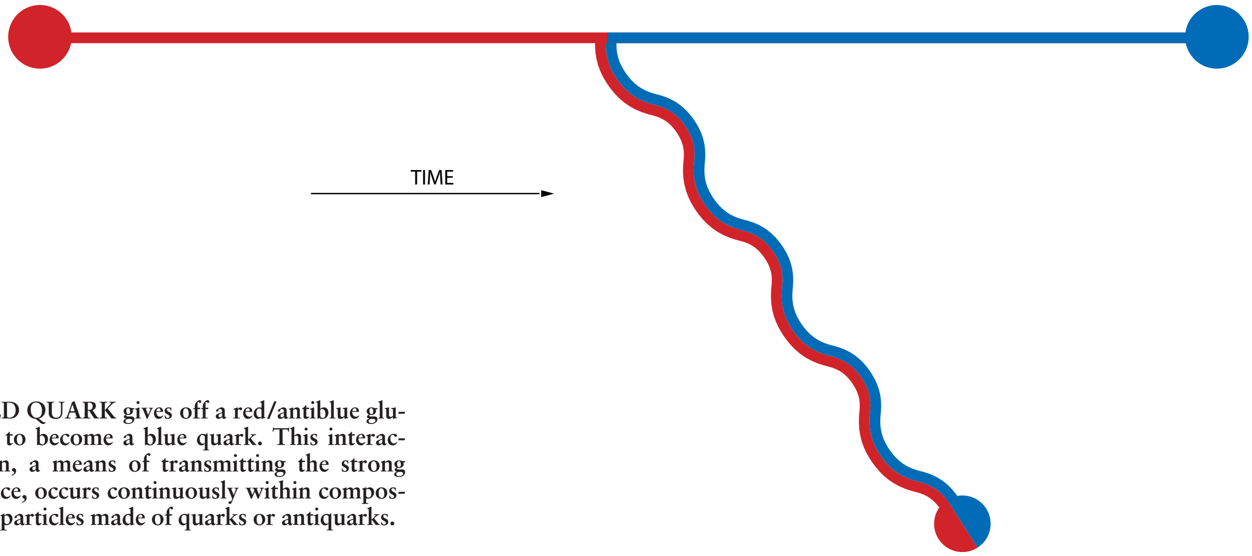
A blue quark will bind with a red quark and a yellow quark, forming a "white" object that has no color charge. The result may be a proton, a neutron or any one of innumerable three-quark composites called baryons. (Physicists call these charges "color" because all three of them add up to zero, just as the three primary colors add up to white.) The attraction between different colors is in fact the so-called strong nuclear force, which binds quarks into these larger, stable objects.

Quarks may also attach to antiquarks, particles that have opposite charges to the quarks. An antiquark comes in anticolors—antired, antiyellow or antiblue. (An anticolor is mathematically denoted by negative color. Antired, for instance, is a "minus red.") Opposite colors attract. A red quark, for instance, will bind with an antired antiquark to form a white object called a meson. The most common meson is a pion, often observed in nuclear reactions.

Electric and color charges are analogous in other ways. The theory of electromagnetism describes the attraction between opposite electric charges. In the 1940s physicists merged electromagnetism with relativity and quantum theory, creating a branch of fundamental physics termed quantum electrodynamics, or QED. This theory—the most successful known to physics—holds that the electromagnetic force is transmitted by massless objects called photons. These quanta of light banish the classical idea of action at a distance: they bounce, say, between an electron and its antiparticle, the positron, in such a manner as to draw the two together.

The equivalent theory of color charges, which communicate via the strong force, is called quantum chromodynamics, or QCD. Gluons, the massless quanta of the strong force, transmit this interaction.

Gluons are fundamentally different from photons. Even though photons allow particles of opposite electric charge to attract, they themselves do not have charge. So one photon cannot push or pull on another. Gluons, however, are themselves colored. A red quark, for instance, can turn into a blue quark by radiating a red/antiblue gluon. Basically, a gluon can attract another gluon.



RED QUARK gives off a red/antiblue gluon to become a blue quark. This interaction, a means of transmitting the strong force, occurs continuously within composite particles made of quarks or antiquarks.

This behavior makes gluons peculiar compared with their electromagnetic cousins. Photons surround an electron uniformly, forming a shell with spherical symmetry. Moreover, the density of photons falls off with distance, so that the attraction between an electron and positron diminishes with the inverse square of the distance between them. Gluons are not so uniformly distributed. Instead they clump together into a tube linking a quark and an antiquark. The color originating in the quark can be thought to "flow" through the gluon tube to the antiquark, where it becomes absorbed.

A Tube of Glue

When the tube is stretched out, it pulls back with a constant force, whatever its length. An infinite amount of energy would be required to stretch the tube to infinite length—that is, to pull apart a quark and an antiquark. As a result, free quarks never occur: nature abhors color. But a gluon tube holding a meson together may break into two pieces. The colored ends of the new tubes correspond to quarks (or antiquarks), so that one meson breaks into two [*see illustration on opposite page*].

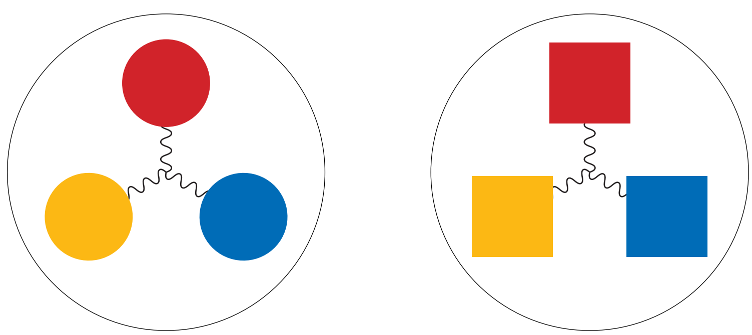
Gluons acting in this way, at least in theory, do fit the observations. But are they real? The clearest evidence for gluons comes from the annihilation of an electron with a positron. The energy released when these particles combine is often reborn as a quark and an antiquark that initially fly in opposite directions. The tube between them breaks up into a shower of mesons and baryons. So an experimenter sees jets of the composite particles emerging back to back.

Sometimes, however, the quark or antiquark may emit a gluon, giving rise to a total of three jets [*see illustration on preceding page*]. Researchers at DESY (German Electron Synchrotron) in Hamburg first observed these triads in 1979. Happily, they had just the properties that QCD theorists had predicted. Such experiments have also confirmed that gluons can emit other gluons.

Other investigations at DESY, in which high-energy electrons penetrate protons to survey their internal structure, have discerned the presence of gluons. The particles reveal themselves in other ways as well. For instance, mesons made of heavy quarks or antiquarks have the masses expected if the quantum of color force has an intrinsic angular momentum of 1—as a gluon does.

But gluons may in fact manifest themselves directly. In 1972 Harald Fritzsch and Murray Gell-Mann, both then at the California Institute of Technology, predicted that two or more gluons—say, a red/antiblue and a blue/antired—can combine into a strongly bound, neutral-colored particle of pure glue. This hypothetical object is called a glueball. The theorists also argued that a gluon can bind with a meson to form a hybrid. For instance, a red quark and an antiblue antiquark can conceivably bind with a blue/antired gluon, forming a white combination.

It was an elegant idea. Quantum chromodynamics is, however, a rather messy theory: the peculiar, sticky character of the strong force makes it impossible for physicists to carry out exact calculations. Almost everything known about color and glue comes not from direct calculation but from massive computer simulations known as lattice QCD [see "Quarks by Computer," by Donald H. Weingarten; SCIENTIFIC AMERICAN, February 1996]. This approach regards space-time as a grid, called a lattice. A quark might sit at one point of the lat-



BARYON (*left*) is overall neutral in color, or "white." The most common baryon is the proton or the neutron. The quarks within a proton interact with one another by exchanging gluons and perpetually altering their color. An antibaryon (*right*), such as an antiproton, contains an antired, an antiblue and an antiyellow antiquark.

tice, being connected by a line with an antiquark at another point. In such computations, an entity made of pure glue does turn up: a gluon line that closes in on itself like a snake eating its own tail. This loop is a crude representation of a glueball.

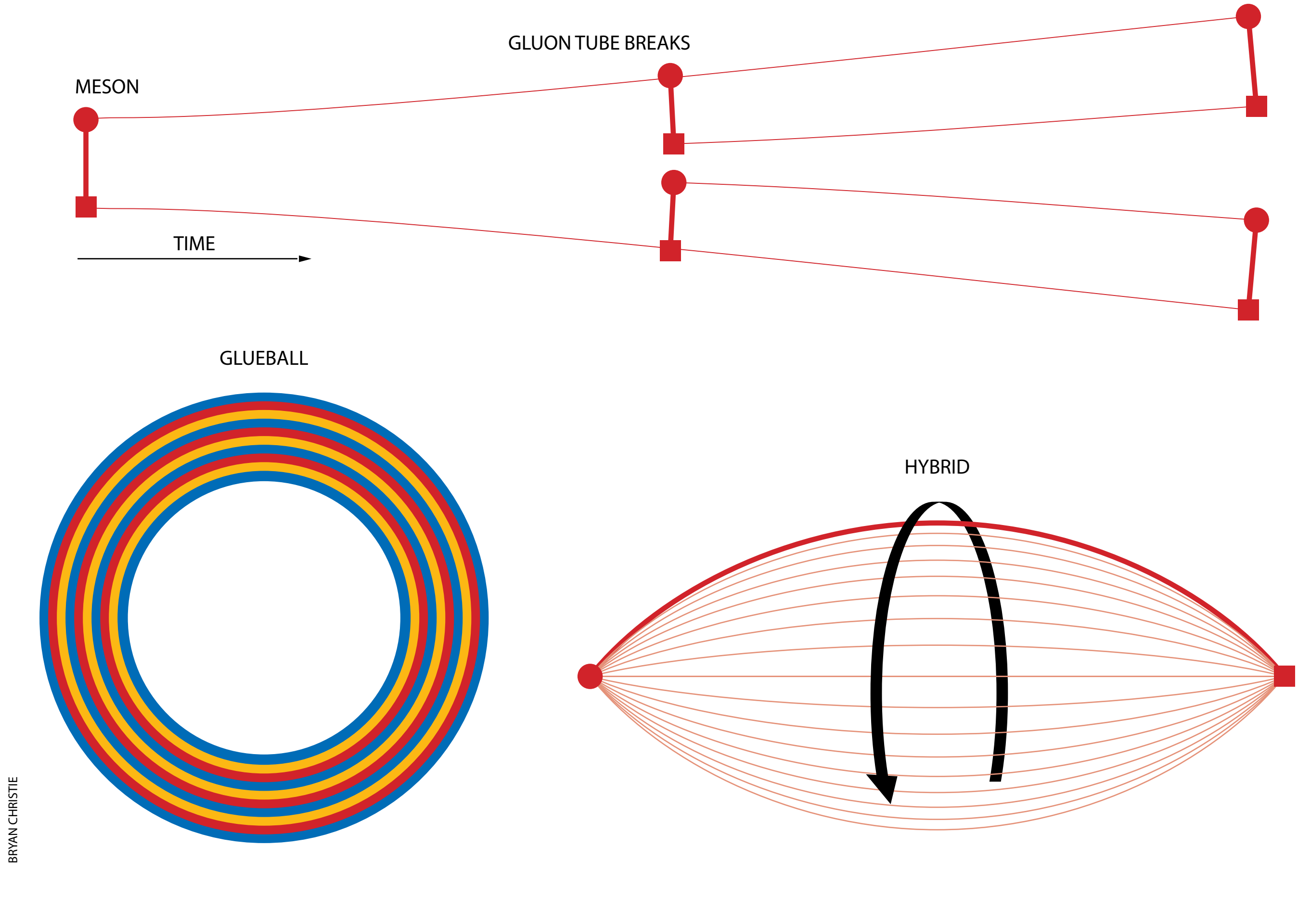
The lightest glueball allowed by theory corresponds to a circular tube of glue and has no angular momentum. According to quantum mechanics, an object without angular momentum must have the symmetry of a sphere. And in fact the glue ring can be oriented in any direction, so that the wave function describing it ultimately corresponds to a spherical shell. Glueballs of other, elongated shapes have nonspherical wave functions. They therefore have angular momenta and larger masses.

Sometimes the stringlike tube of glue connecting a quark-antiquark pair is slack, so that it does not lie along the axis connecting the pair but hangs off it. It may then spin about this axis like a jump rope. Such configurations can be thought of as containing an extra gluon, corresponding to the aforementioned hybrids. Because the rotation requires considerable energy, the total internal energy or mass of a hybrid will be larger than that of a meson alone.

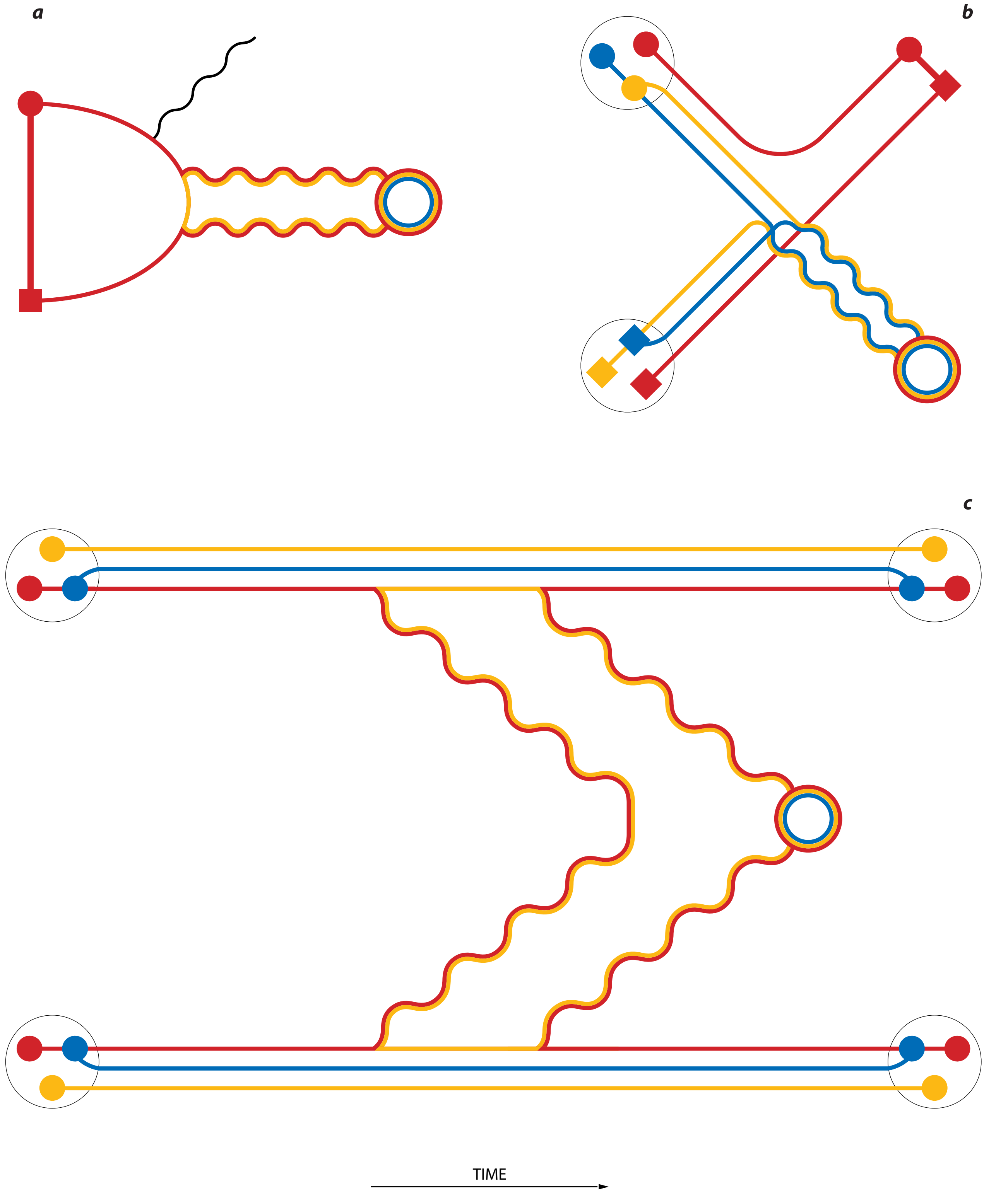
An ordinary meson (one not linked to an extra gluon) can also rotate, but it does so about the axis perpendicular to the line joining the quark and the antiquark that this particle contains. The mesons of lowest energy have no such rotation and are described as S-wave. Typically an S-wave meson (such as the commonplace pion) will decay into two S-wave mesons. A hybrid rarely decays in this manner, however, because the angular momentum it possesses by virtue of its peculiar rotation must be conserved. Instead hybrids are predicted to decay into one S-wave meson and another short-lived meson that does have some internal angular momentum. The latter then breaks up into two S-wave mesons. In sum, the hybrid should announce its presence by yielding at least three S-wave mesons.

For many years, the two of us could only paraphrase Mark Twain: "Everybody talks about hybrids, but nobody does anything about them." Experimenters find it difficult to detect all three mesons emitted in a decay and thus rarely have sought to observe them.

In December 1994 we finished a calculation of all possible decays of hybrids, using a model in which the glue tube is made up of a chain of balls representing gluons. The model yields results similar to those of lattice calculations, but it can



MESON, GLUEBALL AND HYBRID are three composites involving a tube of gluons. A commonly observed type of particle, a meson consists of a quark and an antiquark connected by a gluon tube. Color can be thought to originate in the quark and "flow" to the antiquark. If the tube should break at some point, the colored ends serve as a quark and an antiquark, giving rise to two mesons. A glueball appears in calculations as a ring of pure glue. Because the colors of the gluons cancel one another, in theory a glueball should be quite stable. A hybrid, another hypothetical particle, is essentially a meson in which the gluon tube rotates about a line connecting the quark and the antiquark. It can be thought of as a meson allied with an extra gluon.



BRYAN CHRISTIE

PROCESSES RICH IN GLUE are promising places to seek glueballs. A ψ meson may decay by giving off two gluons, which join into a glueball (*a*). Or a proton might crash into an antiproton, so that the quarks of the former interact with the antiquarks of the latter, emitting two gluons and a meson (*b*). The gluons may combine into a glueball. Moreover, when two protons collide head-on, their constituent quarks communicate by interchanging gluons (*c*). Two of these gluons could merge into a glueball. The glueball may itself decay in diverse ways, yielding two pions or other mesons (*not shown*).

illuminate more situations. (Lattice calculations cannot as yet describe the decays of hybrids, but they should be able to do so quite soon.) To our excitement, we realized that a hybrid might have been discovered earlier that year.

In the summer of 1994 experimenters based at the Institute for High Energy Physics in Protvino, Russia, had reported an object called π(1800) emerging from collisions of pions with protons. (The number in parentheses denotes the mass in million electron volts, or MeV.) This particle has the quantum characteristics and pattern of decay expected for a hybrid.

Exotics

Unfortunately, the identity of π(1800) still remains uncertain. But recent evidence has emerged for the existence of special hybrids called exotics. Mesons are characterized by several quantum numbers: their internal angular momentum (J), their appearance when reflected through their center (parity, or P) and their identity when particles are interchanged with antiparticles (charge conjugation, or C). Exotics have combinations of these three quantum numbers that are forbidden for mesons. The simplest exotic has J = 1, P = –1 and C = +1. (The commonplace meson with J = 1 has P = –1 and C = –1.)

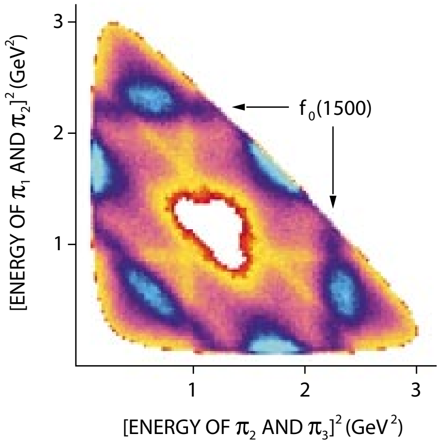
In 1997 experimenters at Brookhaven National Laboratory, also working with pion beams and proton targets, reported possible evidence for this exotic. Soon after, the Crystal Barrel collaboration at CERN, the European laboratory for particle physics near Geneva, also announced signs of the same exotic. These objects were, however, not observed by their breakup into three S-wave mesons. Instead the experimenters searched for two S-wave mesons, the η (eta) and the π (pion). (These are not the most abundant products of an exotic's decay but are simply those that can be more readily detected.) Most recently, the Brookhaven group has reported evidence for an exotic of a different mass. Whether or not these objects are actually exotics remains a matter of much argumentation.

Glueballs are proving even harder to find, because most experiments check for final products made up of quarks and antiquarks. In 1993 a collaboration based at the University of Edinburgh predicted a mass of 1,550 MeV for glueballs using lattice theory. Soon after, Donald Weingarten of the IBM Thomas J. Watson Research Center and his co-workers calculated a mass of 1,740 MeV. Later they predicted that glueballs should live for 10^{-24} second. This minuscule amount of time is actually long enough for glueballs to be detected.

In conferences of the time, one of us (Close) emphasized that intensive experimental effort should be devoted to searching for glueballs of mass in the range 1,500 to 1,800 MeV—without knowledge that the Crystal Barrel collaboration was starting to uncover a short-lived object known as $f_0(1500)$. Its angular momentum (denoted by the subscript) is 0, whereas its mass is within the predicted realm. This object could be the lightest glueball.

Or maybe not. For more than a decade, experimenters have had evidence of an object called $f_J(1710)$, whose angular momentum J is still undetermined. If J turns out to be 0, this object will be a rival candidate for a glueball.

As if this ambiguity were not confusing enough, the situation is worsened by quantum mechanics, which dictates that two objects of identical quantum numbers and similar masses can mix with each other. Calculations predict two mesons of the same quantum numbers as the glueball in the same region of mass. The glueball should combine with these mesons to produce three final objects that are partially glue. Indeed, the $f_0(1500)$ and $f_J(1710)$ do seem to share features that would incriminate them as being about half glueball. Unfortunately, the evidence remains inconclusive.



SOURCE: CRYSTAL BARREL COLLABORATION, CERN

DALITZ PLOT of a collision between a proton and an antiproton may encode evidence of a glueball. The reaction yields three pions, two of which may have come from the breakup of a glueball. Each axis plots the square of the combined energy of two of the three pions taken together. A region of enhanced intensity (*blues*) indicates a short-lived particle that produced pions of a specific energy. The dark blue bands at 2.2 GeV^2 correspond to a particle dubbed $f_0(1500)$, which is possibly a glueball (1 GeV = 10^9 electron volts).

In early 1999 accelerators that produce reams of *B* mesons will start taking data in the U.S. and in Japan [see "The Asymmetry between Matter and Antimatter," by Helen R. Quinn and Michael S. Witherell; SCIENTIFIC AMERICAN, October]. Among their other uses, these mesons offer a promising new avenue for generating glueballs and hybrids.

Precision experiments dedicated to the search will also begin next year at Thomas Jefferson National Accelerator Facility in Newport News, Va. And in 2001 researchers at CERN will join in. One of these experiments will, we fondly hope, upturn unambiguous evidence of unadulterated glue. SA

The Authors

FRANK E. CLOSE and PHILIP R. PAGE began collaborating on gluon excitations in 1992 at the University of Oxford, where Close was Page's thesis supervisor. Close is currently head of theoretical particle physics at Rutherford Appleton Laboratory near Oxford and visiting professor at the University of Birmingham in England. He is also vice president of the British Association for the Advancement of Science. Page spent a year at Thomas Jefferson National Accelerator Facility in Newport News, Va., before moving to Los Alamos National Laboratory, where he is a staff scientist.

Further Reading

THE QUARK STRUCTURE OF MATTER. Frank Close in *The New Physics*. Edited by Paul Davies. Cambridge University Press, 1989.

GLUEBALLS AND HYBRIDS: NEW STATES OF MATTER. F. E. Close in *Contemporary Physics,* Vol. 38, No. 1, pages 1–12; January 1997.

PARTICLE PHYSICS: EXOTIC MESON PLAYS HARD-TO-GET. F. E. Close in *Nature,* Vol. 389, pages 230–231; September 18, 1997.

