

the University of California in San Diego) and Kazumi Maki (University of Southern California) then constructed⁵ a continuum version of the same model that is exactly solvable. Although the seeds are there, none of the earlier models explicitly yields the prediction of fractional quantum numbers.

Su and Schrieffer recently extended⁶ their work to one-dimensional systems, where the charges associated with the soliton would be $\pm\frac{1}{3}$ and $\pm\frac{2}{3}$. Jeffrey Goldstone (MIT), when accepting his Heineman prize at the January APS meeting in New York, described similar investigations he had undertaken with Frank Wilczek (Institute for Theoretical Physics) to show how fractional quantum numbers emerge in various quantum field theories.

Solitons in linear molecules. A generic feature of any problem in which solitons arise is the presence of some strong non-linearity. In certain systems these nonlinearities lead to several distinct ground states of equal energy. Regions having different ground-state configurations are separated by localized interfaces of infinite energy called "solitons." One might picture solitons variously as domain walls in ferromagnetics, as phase boundaries in metal alloys, or as vortices in fluids.

In the model of a single polymeric chain of the isomer trans-polyacetylene proposed by Su, Schrieffer and Heeger, by Rice and by Takayama, Lin-Liu and Maki, the soliton becomes a kink in the bond alternation pattern of a linear molecule, interpolating between one end where the odd-numbered bonds are double and the other end, where the odd-numbered bonds are single. Thus the soliton in the phonon field arises because of the broken symmetry. The electronic states are modified by the soliton: The number of states per spin in the valence band and in the conduction band is reduced by $\frac{1}{2}$ and a singlet state appears in the gap between the two bands. The double degrees of freedom introduced by the electron spin obscure the fractional charge. Still, unusual spin-charge relationships result. The charged (+e) soliton has no spin. (The valence band is full, and all spins are paired.) The neutral soliton has spin of $\pm\frac{1}{2}$. (The isolated state is occupied by a single electron.)

The unusual spin-charge relationships predicted by the soliton model of polyacetylene provide the basis on which it can be experimentally tested. Researchers have been looking either for spin structures in undoped polyacetylene, which could correspond to neutral solitons, or for the absence of spin in doped polyacetylene. Additionally, spectroscopic measurements might detect a mid-gap energy level expected to be associated with soliton solutions, or infrared spectral studies might sense changes in lattice dynamics associated with soliton formation. Several experiments have

certainly provided evidence for such signatures, while others have yielded opposite results. Comparison of experimental results with one another and with the theoretical predictions is complicated by differences of sample preparation, by uncertainties over the morphology, and by the many possibilities for inhomogeneities. Furthermore, polyacetylene can exist in either of two isomeric forms, one of which cannot support solitons.

In an extension of their work on polyacetylene, Su and Schrieffer have studied one-dimensional systems with commensurability of three, that is, ones where the wavelength of a charge density wave equals three lattice spacings (one-third of an electron charge per site). A precursor to their work but in a different context was the analysis by Rice, Alan R. Bishop (Los Alamos), James A. Krumhansl (Cornell) and Steven E. Trullinger (USC), who pointed out that solitons might be current-carrying excitations in this class of one-dimensional systems. Because the solitons proposed by Su and Schrieffer would be associated with charges of $\pm\frac{1}{3}$, $\pm\frac{2}{3}$ or even $\pm\frac{4}{3}$, they would not be masked by the effect of the electron spin. Thus these systems may offer the possibility for the direct observation of fractional charges. The one-dimensional system TTF-TCNQ under pressure is one candidate for such experimentation.

Solitons in particle theory. Jackiw and Rebbi undertook their study as a formal mathematical investigation of various relativistic quantum field theories rather than as a vehicle to understand a particular physical phenomenon such as molecular structure. The one theory they studied that is analogous to the condensed-matter model involved a continuum rather than a lattice, and their fermions were spinless. Nevertheless, other features of their approach are very similar to that of the condensed-matter models. They both involved a fermion field coupled to a scalar field (the Bose field or the phonon field) with broken symmetry. The results in the particle theory were similar to those in the case of the linear molecule, except for the effect of the electron spin.

Have glueballs been seen?

There is general optimism among elementary-particle physicists that quantum chromodynamics will prove to be the correct theory of the strong interactions. Although QCD is constructed in close analogy to quantum electrodynamics, the uniquely successful gauge theory of the electromagnetic interactions, the multiplicity of QCD "color charges" make it considerably more elaborate than QED. Unlike the uncharged photon of QED, "gluons," the field quanta that mediate the strong interaction between quarks in

Jackiw commented to us that in relativistic field theory, one must postulate a broken symmetry; theorists don't yet understand how the symmetry in particle theories can be broken dynamically, as they are in the condensed-matter examples. The connection of solitons with broken symmetries is especially important because many current theories, most notably the unified field theories, postulate broken symmetries. These¹ broken symmetries then imply the presence of a soliton. Gerard 't Hooft (University of Utrecht) and Alexander Polyakov (Landau Institute in Moscow) have shown that solitons in three dimensions can be interpreted as magnetic monopoles. The possibility thus arises that magnetic monopoles may both exist and have fractional charges.

't Hooft warned against associating the fractionally charged solitons directly with quarks. The quark interacts too weakly and is too pointlike to be identified as a soliton. Nevertheless, the existence of solitons is important in theories of quark confinement.

Jackiw mentioned one other reason for excitement about the appearance of fractionally charged solitons. Whereas the fractional charges of quarks are now built into a theory in an *ad-hoc* manner, the solitons with their fractional quantum numbers emerge quite naturally in the soliton theories. In fact, several unconventional combinations of quantum numbers associated with solitons have already surfaced in other particle field theories. Other "unphysical" or unexpected quantum numbers may yet be encountered.

—BGL

References

1. R. Jackiw, C. Rebbi, Phys. Rev. **D13**, 3398 (1976).
2. R. Jackiw, J. R. Schrieffer, to be published in Nuclear Physics B.
3. W. P. Su, J. R. Schrieffer, A. J. Heeger, Phys. Rev. **B22**, 2099 (1980).
4. M. J. Rice, Phys. Lett. **71A**, 152 (1979).
5. H. Takayama, Y. R. Lin-Liu, K. Maki, Phys. Rev. **B21**, 2388 (1980).
6. W. P. Su, J. R. Schrieffer, Phys. Rev. Lett. **46**, 738 (1981).

QCD, are themselves bearers of the color charges.

Thus, in addition to the quark bound states that appear to account for all the well-known mesons and baryons, QCD leads us to expect a new class of elementary particles—quarkless bound states of the gluons themselves. Finding such "glueballs" (some prefer the name "gluonium") would constitute an important verification of QCD. Specific model calculations within the framework of QCD have in fact predicted a number of two-

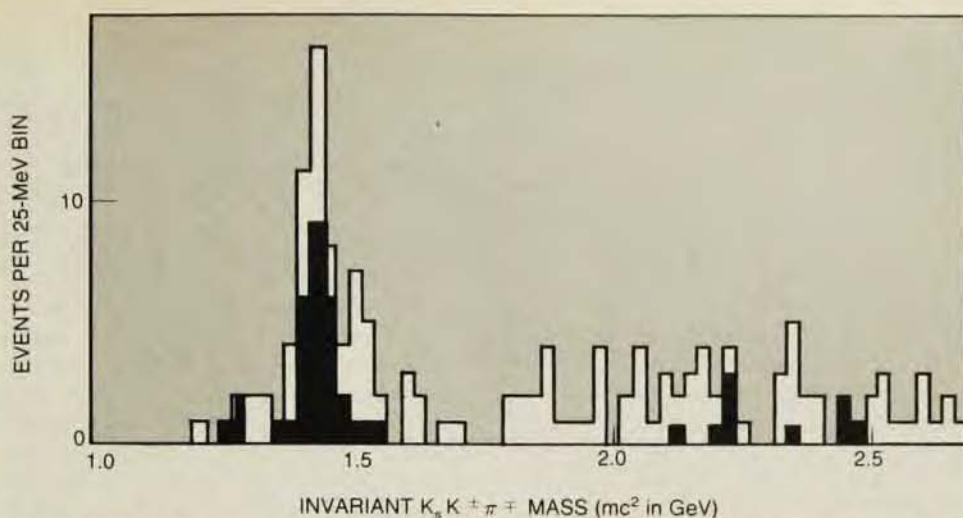
and three-gluon bound states in the meson-rich mass range between 1 and 2 GeV.

Two recent papers argue that we may already have seen our first glueball. Calculating the spectrum of low-lying glueball states from the "MIT bag model," John Donoghue (University of Massachusetts), Kenneth Johnson (MIT) and Bing An Li (SLAC) conclude¹ that the prominent resonance near 1.4 GeV recently seen at SLAC^{2,3} as a product of the radiative decay of the famous J/ψ charmonium state is "most likely" to be a glueball. Michael Chanowitz (Lawrence Berkeley Lab) reaches much the same conclusion⁴ from an extensive survey of the apparent contradictions between different experiments that have seen similar resonances near this mass.

Not everyone agrees. Paul Fishbane (University of Virginia), Sydney Meshkov (National Bureau of Standards) and their collaborators argue⁵ that the SLAC data do not contradict the more conventional interpretation of the 1.4-GeV resonance as a bound state of two quarks. Furthermore, they conclude from a perturbation-theoretic QCD calculation that such a glueball resonance would have to be much narrower than the enhancement seen at SLAC. For those who don't like the glueball interpretation, a prediction by Harry Lipkin and Isaac Cohen⁶ (Weizmann Institute) provides a possible alternative. They calculate that one of the ordinary spin-zero mesons should have a radially excited state of mass and width close to those of the SLAC resonance.

Radiative decay of the J/ψ is just about the best place to look for glueballs. This was pointed out two years ago by James Bjorken (Fermilab) and K. Ishikawa (DESY, Hamburg). The extraordinary narrowness of the J/ψ resonant width is attributed to the absence of any decay process in which quarks persist without flavor change from the initial to the final state. Being the lowest-lying bound state of the charmed quark and its antiquark, the J/ψ is too light to decay into charmed mesons. All of its decays into hadrons must therefore pass through a purely gluonic intermediate state. The semi-empirical rule telling us that such intermediate states strongly suppress any reaction is called the "OZI rule"—after Susumu Okubo (University of Rochester), George Zweig (Caltech) and Jugoro Iizuka (Kanazawa University, Japan), who first pointed it out in the mid-1960s.

When the J/ψ decays into a purely hadronic state, QCD tells us that the predominant intermediate state consists of three gluons. One would not see a three-gluon resonance in such a decay, because the energy of the three-gluon system is fixed at the J/ψ mass (3.1 GeV). A glueball search requires that one be able to look over a continuous range of masses. Any two of these three gluons would of course have a continuously variable energy, but they would not constitute a



A prominent enhancement near 1.44 GeV appears in the $K_s K^\pm \pi^\mp$ invariant-mass distribution from radiative decays of the J/ψ charmonium state. These data, taken at the SLAC Mark II detector, come from decay events identified as $J/\psi \rightarrow K_s K^\pm \pi^\mp \gamma$. It is speculated that this resonance is a bound state of two gluons. Shaded events have KK mass close to the δ resonance.

colorless SU(3) "color singlet." QCD requires that all observable hadrons—including glueballs—must have no net color charge; in the language of the SU(3) color symmetry of the theory, they must be color singlets. The purely hadronic decays of the J/ψ therefore would not be a variable-mass source of glueballs.

The radiative J/ψ decay, on the other hand, should do the trick. In these decays, where the final state consists of hadrons plus a single energetic photon, one of the three gluons in the dominant QCD Feynman diagram is replaced by a photon. Because the J/ψ and the photon are both colorless and flavorless, the two remaining gluons are guaranteed to constitute a color and flavor singlet—just what's needed for a glueball. (Gluons do not carry any of the quark flavors, such as charm or strangeness.) Furthermore, the mass of the gluon pair is "tunable," simply by looking for photons of different energies coming directly from the J/ψ decay.

Two experiments at SLAC have been looking at the radiative decay of the J/ψ . Before its recent transfer from the older SPEAR e^+e^- storage ring to the newer PEP ring, the Mark II detector, operated by a SLAC-LBL collaboration, had looked at about a million J/ψ decays over a two-year period. About 5% of all J/ψ decays produce a photon sufficiently energetic to indicate an unambiguous radiative decay. With its array of 16 drift-chamber layers in a strong magnetic field, time-of-flight scintillation counters and liquid-argon calorimeters, the general-purpose Mark II detector can identify and measure the momenta and directions of charged particles and photons coming from a J/ψ decay.

Searching for possible glueball resonances among the identifiable decay states in the accumulated Mark II data, Daniel Scharre² (SLAC) and his colleagues have discovered a prominent peak centered at (1440 ± 15) MeV in the $K \bar{K} \pi$

mass distributions from the radiative decay processes $J/\psi \rightarrow \gamma K_s K^\pm \pi^\mp$, where K_s is the short-lived neutral K meson. The only known quark-antiquark state of similar mass and resonant width (about 50 MeV) with a prominent $K \bar{K} \pi$ decay mode is the relatively obscure E meson at (1420 ± 10) MeV, seen mostly in $\pi^- p$ scattering experiments.

The Crystal Ball detector, sitting on the other side of SPEAR, is run by a Caltech, Harvard, Princeton, SLAC, Stanford collaboration. This spherical array of 730 NaI crystals has by now looked at two million J/ψ decays. With the radiative decays from half this sample already analyzed, the Crystal Ball has found the same 1440-MeV enhancement³, in the decay state $\gamma K^+ K^- \pi^0$. The extraordinary spatial and energy resolution of the NaI array for photon detection, covering 90% of the total 4π solid angle, compensates for the absence of an analyzing magnetic field in the Crystal Ball. The energy resolution of the Crystal Ball is so good that one can see the 1440-MeV enhancement simply by looking at the "inclusive" photon spectrum, without considering the other decay products.

How do we recognize a glueball when we see one? Why not simply identify the SLAC resonance with the prosaic E(1420) meson, which has a secure niche in the SU(3) nonet of axial-vector (spin one, even parity) quark-antiquark states? Chanowitz details a number of arguments for concluding that the E(1420) produced in πp collisions is not the same object as the resonance seen in the J/ψ radiative decay, which he gives the new name G(1440). He further concludes, but somewhat less strongly, that the G is a pseudoscalar (spin zero, odd parity) bound state of two gluons.

► In $\pi^- p$ collision processes where we have no particular reason to anticipate glueballs, the E is seen as a relatively weak $K \bar{K} \pi$ enhancement, invariably accom-

panied by a stronger signal from the D meson at 1285 MeV. This is exactly what's expected from the standard SU(3) assignment of the E and D(1285) as partners in the nonet of axial-vector mesons. In the J/ψ radiative decay, on the other hand, where QCD tells us that a two-gluon intermediate state dominates, the G(1440) is quite prominent, but the D(1285) is not seen. If the G is in fact the axial-vector E, one would have to explain the absence of the D in the SLAC experiments. Chanowitz argues that the simplest such explanation, namely a pure flavor-singlet E, is implausible but not excluded.

► In πp experiments, the E is clearly seen to be a spin-one object. Thirty years ago, Chen-Ning Yang showed that a spin-one state cannot couple to two massless vector particles. QCD assumes that gluons are just such massless vector particles. The Yang theorem would thus appear to forbid the coupling of the axial-vector E meson to the two-gluon intermediate state dominating the J/ψ decay.

► In J/ψ radiative decay and πp collisions the $K\bar{K}\pi$ enhancements near 1.4 GeV emerge in quite different configurations. In the radiative decay, the two kaons tend to form a δ resonance, whereas the E is seen predominantly in a $\bar{K}^*K$ configuration.

► If the radiative decay resonance is a glueball decaying by way of $\delta\pi$, Chanowitz concludes from QCD perturbation theory that it must be a pseudoscalar. The SLAC data are still insufficient to permit a spin determination of the G(1440). But there is yet another $K\bar{K}\pi$ resonance near 1.4 GeV that appears to be pseudoscalar. If this enhancement, seen in $\bar{p}p$ annihilations at rest, does have a different spin from that produced in πp collisions, the two resonances cannot be the same state. Chanowitz seizes upon the absence of an accompanying D and the prominence of the $\delta\pi$ configuration in the resonance seen in the $\bar{p}p$ experiment to identify it with the SLAC G(1440). Although at first glance nothing prevents the E and D from appearing strongly in $\bar{p}p$ annihilations, Chanowitz calculates that these spin-one states should be strongly suppressed in annihilations at rest by a centrifugal barrier to which the spin-zero G would be immune.

► If the G is a conventional quark-antiquark state rather than a glueball, there appears to be no room for it in the established scheme of quark-antiquark nonets—unless it be a radial excitation of the pseudoscalar η' . But then, Chanowitz asks, why don't we see the other isoscalar member of the radially excited pseudoscalar nonet in the J/ψ decay? (Once again, this absence would be understood if the η' radial excitation were a very pure flavor singlet. But Chanowitz contends that this is inconsistent with the experiment that discovered the radial excitation of the η at Argonne.)

Theoretical predictions. Chanowitz argues that the ability of QCD to calculate the details of the glueball spectrum is still too unreliable to provide much guidance in the search for glueballs. "We must take our lead from the experiments," he contends. While invoking many of the same experimental arguments Chanowitz makes, Donoghue, Johnson and Li have taken their lead from the MIT bag model, a specific realization of QCD in which quarks and gluons are imagined to reside in confining "bubbles" they have drilled out of the surrounding vacuum. The bag model, introduced by Johnson, Allen Chodos, Robert Jaffe, Charles Thorn and Victor Weisskopf at MIT in 1974, has had considerable success in explaining quark confinement and the properties of the hadrons. This model offers a natural explanation of why the low-lying glueball states should be heavier than the corresponding conventional mesons.

Solving for the normal modes of two- and three-gluon fields under the confining boundary conditions of the MIT bag, Donoghue and his colleagues are led to predict the existence of pseudoscalar and spin-two bound states of two gluons with masses near 1.3 GeV and widths of about 50 MeV. They associate the pseudoscalar glueball with the G(1440) seen at SLAC. They imagine the spin-two glueball to be hiding under the wide f quark-antiquark resonance centered at 1.27 GeV. The spectrum of three-gluon bound states, they calculate, begins at somewhat higher masses, where the proliferation of wide $q\bar{q}$ mesons will make them difficult to find.

Fishbane, Meshkov, Joseph Coyne (NBS), Carl Carlson and Franz Gross (both at William and Mary) have arrived at a somewhat different glueball spectrum by way of a non-relativistic potential model. Because such a model gives effective masses to the bound gluons, they argue that Yang's theorem need not apply, permitting spin-one states of two gluons that are excluded in the bag model. In particular, they would expect to see a spin-one glueball state, odd under parity inversion and even under charge conjugation. They label this state an "oddball," because such a combination of quantum numbers is impossible for a quark-antiquark system. They suggest that looking for oddballs is a very good way to search out glueballs.

The opposition of Fishbane and his colleagues to the designation of the SLAC $K\bar{K}\pi$ resonance as a pseudoscalar glueball is threefold. "The hallmark of our model," Meshkov told us, "is that low-spin glueball resonances should be extremely narrow," much narrower than the 50-MeV width observed at SLAC. They also argue that the Mark II data simply do not make a convincing case. In particular, they dispute the contention that the decay pattern of the SLAC enhancement differs significantly from the $\bar{K}^*K$ pattern seen in the πp experiments. Finally,

Meshkov and his colleagues conclude from a gluon-fusion-model calculation that a 50-MeV-wide pseudoscalar glueball at 1.4 GeV would show up in high-energy π^+p collisions with a signal fifty times stronger than the E enhancement seen in a recent π^+p experiment at Fermilab.

In the immediate future, the experimental picture should become clearer. Scharre told us that when the second half of the Crystal Ball data sample is analyzed this summer, the group hopes to have a reliable determination of the spin of the G(1440). If it is found to be a pseudoscalar, the glueball conjecture of Chanowitz and the bag theorists will be much strengthened.

Sam Lindenbaum's Brookhaven-CCNY group believes that their $\pi^+p \rightarrow \phi\phi n$ data from the Brookhaven Multiparticle Spectrometer offer strong indirect evidence for the existence of one or more glueball resonances. Because the ϕ meson pairs (consisting entirely of strange quarks) must be formed out of a purely gluonic intermediate state, one expects this reaction to suffer strong OZI suppression. The complete absence of this anticipated suppression, Lindenbaum argues, points strongly to resonance formation among the intermediate gluons. The new Multiparticle Spectrometer II will soon provide the group with an order of magnitude more data. If prominent resonances show up in the $\phi\phi$ mass distribution, as Lindenbaum expects from the absence of OZI suppression, they would be strong glueball candidates, especially if they are oddballs.

To deal with the suggestion of Cohen and Lipkin, that the G(1440) is not a glueball but a radially excited η' , one will have to look more closely for its excited η companion in J/ψ decay, and for a pseudoscalar hiding under the spin-one E(1420) in πp experiments. Lipkin points out that it is difficult to predict production rates for these radially excited states because of their mixing with the ground-state pseudoscalar mesons. He is further troubled by the fact that the G(1440) seems to prefer to decay into strange mesons (kaons). A characteristic signature of glueballs, he argues, would be their flavor blindness; they should have no preference for strangeness. —BMS

References

1. J. F. Donoghue, K. Johnson, Bing Am Li, Phys. Lett. **99B**, 416 (1981).
2. D. L. Scharre *et al.*, Phys. Lett. **97B**, 329 (1980).
3. D. G. Aschman, to be published in Proceedings of 15th Rencontre de Moriond, Les Arc, France (1980).
4. M. Chanowitz, Phys. Rev. Lett. **46**, 981 (1981).
5. C. Carlson, J. Coyne, P. Fishbane, F. Gross, S. Meshkov, Phys. Lett. **98B**, 110 (1981).
6. I. Cohen, H. Lipkin, Nucl. Phys. **B151**, 16 (1979). □