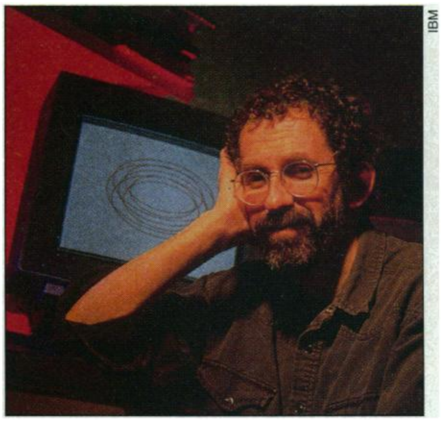
Mastering Nature's Strong Force

Physicists have demonstrated their grasp of the force that binds the atomic nucleus by learning how to identify the exotic particles it spawns, called glueballs

"Quark" is fanciful, "electron" is classical, but in the lexicon of elementary particle physics, "glueball" is as descriptive as it gets. Glueballs, if they really exist, are made entirely of sticky stuff—of gluons, particles that carry the strong force that binds quarks together to make up protons and neutrons. Glueballs also live up to their name by being, in the words of Princeton University theorist David Gross, "nasty objects"—short-lived, elusive, and easy to confuse with more mundane particles. Worse still, the theory that predicts glueballs, called quantum chromodynamics (QCD), "is a theory where you can write down the fundamental equations," says University of Chicago theorist Jonathan Rosner, "but then you have one hell of a time trying to solve them." As a result, theorists have had only the vaguest idea what a glueball should look like.

Yet physicists may finally have caught glimpses of these recalcitrant objects, thanks to the convergence of two lines of work. One is a 20-year quest to extract accurate predictions from QCD by so-called lattice calculations, which have at last given glueball hunters a picture of their quarry. The other is a quarter century of accelerator experiments that have observed hundreds of short-lived particles known as resonances, which can now be compared with the theoretical predictions to identify any glueballs lurking among them.

In the 18 December *Physical Review Letters*, for example, IBM physicist Don Weingarten and collaborators James Sexton and Alessandro Vaccarino present lattice QCD predictions of glueball mass, lifetime, and decay properties that seem to match the properties of a resonance first spotted more than a decade ago at the Stanford Linear Accelerator Center (SLAC). Joining the IBM candidate are two others, from an experiment at the European center for particle physics (CERN) and from the Institute of High-Energy Physics in Beijing. "There's finally a convergence," says Frank Close, head of theoretical physics at the U.K.'s

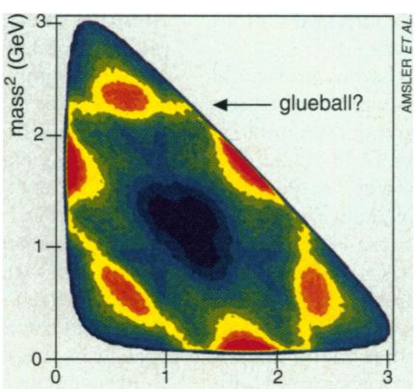


A glueball and its champion. IBM's Don Weingarten and a schematic of the strong-force field inside a glueball.

Rutherford-Appleton Laboratory. "It's sensible to start taking seriously that [glueballs] really do exist."

If so, physicists will have done more than add a new and particularly elusive particle to their menagerie. Theorists will also have the first confirmation that they truly understand QCD and the strong interactions—that they can make meaningful predictions about the quagmire of quarks and gluons inside the atomic nucleus. Says physicist and Nobel laureate Kenneth Wilson of Ohio State University, "Part of establishing that we really understand what's going on in QCD, and that what we see in nature is described by QCD, is to establish what's happening in the glueball sector."

QCD has always been the most troublesome of the theories that make up the Standard Model of high-energy physics. It grew out of the quark model of the 1960s, which proposed that indivisible particles—quarks—are the fundamental building blocks of matter. While the quark model could account for many accelerator results, it did not manage to explain what actually holds quarks together to make protons and neutrons. Nor could it say why, try as they might, investigators could never dislodge a single "free" quark and observe it.



It could be a contender. A plot of data from CERN's Crystal Barrel experiment shows short-lived "resonances" that form when proton-antiproton combinations decay into three pions. Among them is a state *(arrow)* that may be a glueball.

QCD, which was born in 1973, "was the underlying theory that made [the quark model] respectable," says Rosner. In QCD, quarks are held together by their interaction with a "chromoelectric" field carried by gluons, just as the electromagnetic field is carried by photons. QCD implies, however, that unlike any other force, the force carried by the gluons is very weak when the quarks are close together, but gets increasingly stronger at larger distances. That's why free quarks are never seen, only jets of particles assumed to originate in a quark when it is on the verge of being knocked free in a collision. "If you try to pull a quark free of a proton," explains Weingarten, "the charge gets bigger and bigger; the amount of energy in the field gets bigger and bigger; eventually the energy in the field is so big that it spontaneously produces a quark-antiquark pair. Instead of getting a free quark, you get two hadrons [particles made of two or more quarks] instead of one."

A balky theory

QCD had no rival as an explanation for the strong interactions, says Weingarten. But it was short on detailed predictions, because its equations could not be solved, or at least not for ordinary matter. The problem is the quantum mechanical uncertainty principle, which implies that any QCD calculation has to deal not only with the interacting particles themselves but also with clouds of "virtual" gluons and quark-antiquark pairs that appear unpredictably from the vacuum and vanish again.

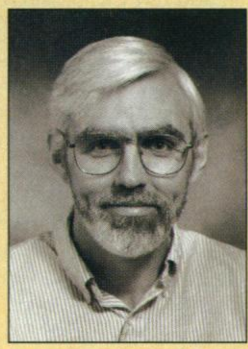
Because the number of possible interactions among the real and phantom particles is infinite, physicists have to rely on approximation schemes, known as perturbation expansions, which provide solutions to the equations of a quantum theory when the forces between particles are weak. In QCD, the interactions are weak at high energies, above several billion electron volts, and perturbation expansions have been used to predict the existence of phenomena seen in high-energy collisions, such as gluon jets—spurts of hadrons analogous to quark jets. At lower energies, where the strong interactions are indeed strong, perturbation theory fails.

It's at these energies, points out University of Texas theorist and Nobel Prize–winner Steven Weinberg, where some of the biggest questions in particle physics lie: why

Catching the Strong Force in a Coarser Net

By the standards of particle physics, making a glueball—a clump of the force particles called gluons—is easy. It requires nothing more than a modest-sized accelerator. But knowing how to recognize this hypothetical particle is another matter: It takes years of supercomputer calculations of the behavior of the strong force, which binds the atomic nucleus (see main text). That's not how physicists pictured such calculations when the underlying strategy, called lattice QCD (quantum chromodynamics), was invented 20 years ago. "The dream was you could just use the computer as an experimental device to learn about how QCD works," making quick calculations and then comparing them with experiment, says Princeton University physicist David Gross. That dream may now be taking a step closer to reality.

A handful of QCD theorists, led by Peter Lepage of Cornell University, Paul Mackenzie of the Fermi National Accelerator Laboratory, and Peter Hasenfratz of the University of Bern in Switzerland, have come up with ways to vastly reduce the computing time needed to get a meaningful result about the strong force. "This is a revolutionary development," says Lepage. "Strong interactions and QCD will never look the same again, if we're right." Physicists who have studied the work agree. Nobelist Kenneth Wilson of Ohio State University, who invented lattice QCD in 1974, calls it "a major advance." Another Nobelist, Steven Weinberg of the University of Texas, Austin, says it "appears to be a real breakthrough."


CORNELL UNIV.

Quickening QCD. Cornell's Peter Lepage.

The key development, Lepage explains, is a way to calculate QCD equations on a four-dimensional lattice using grid spacings "much larger" than ever before required without losing accuracy. The computing power needed to run a lattice QCD calculation goes up as the sixth power of the grid density, says Lepage. Conversely, "if you can figure out a way to double or triple the lattice spacing without affecting your accuracy, you can get huge reductions in computational cost."

The trick is extending the reach of the technique that QCD theorists use to fill in the grid. The grid excludes all physics that occurs on a scale smaller than the lattice spacing itself. Because in physics smaller scales correspond to higher energies, the grid also excludes all higher energy physics from the calculations. Lattice QCD architects have traditionally dealt with the loss by using perturbation theory—a method for getting approximate solutions to quantum equations—to analyze the short-distance, high-energy behavior of their equations. The lower the energy at which perturbation theory can be used, the larger the grid spacing can be without losing accuracy.

Unfortunately, as Lepage explains, when it came to lattice QCD, perturbation theory only worked at very high energies, meaning a fine grid. "In lattice QCD," says Lepage, "a lot of studies seemed to indicate that you didn't get good results from perturbation theory even at energies of 10 or 20 or 30 GeV [billion electron volts]." That was a puzzle, he notes, because when perturbation methods were applied to the raw QCD equations, known as "continuum" QCD, results could be had at energies as low as 1 GeV—at the cost, however, of physics at still lower energies, which the lattice technique can explore.

The discrepancy, however, turned out to be fruitful. In 1990, Lepage and Mackenzie decided to see whether they could close the gap by some mathematical tinkering—rearranging the perturbation series used in lattice calculations. The result, says Lepage, is an algorithm that appears to work with a lattice spacing four to eight times larger than the spacing in current lattice QCD algorithms. "Raise that to the sixth power," he says, "and you get numbers like 4000 and 300,000, and that's the kind of computational advantage you might expect."

In the past year, Lepage, Mackenzie, and their collaborators demonstrated the potential of their techniques by calculating the mass spectrum and quantum properties of particles made of heavy quarks—all on PC-sized computers, says Lepage. Independently, Hasenfratz and Ferenc Niedermayer, at the University of Bern, and their collaborators have had similar successes using closely related techniques.

How far the new algorithms will take QCD is still an open question. The theorists have yet to work light quarks into the algorithms, which will be key to generating accurate predictions about the particles making up ordinary matter. Still, says Lepage, if all goes well within the next couple of years, the new algorithms should make it possible for supercomputers to run problems that are untouchable on present machines. At the same time, the kinds of problems now being on done on supercomputers should be doable on workstations, if not PCs.

"For the past year," says Lepage, "I've been going around giving talks at just about every university. ... The people I really get a kick out of are the young guys from small universities who come up and say, 'Gee, I've been working on the edges of this subject. If this stuff you're saying is really true, I can really compete. I don't have to be part of a collaboration or have an enormous computer to do it.' "

–G.T.

the mass of a proton is what it is, for instance, or why quarks interact the way they do. It's also at these energies that glueballs should manifest themselves, if they exist.

The existence of glueballs is one of the key predictions of QCD, and because it is independent of the quark model, it's a good test of whether theorists have sufficient command of the theory to find answers to these other questions. Like quarks, gluons can never exist as free particles. Instead, they should clump together, forming "coherent superpositions, like a little smoke ring made of the chromoelectric field," as Weingarten puts it. Indeed, a whole spectrum of glueballs should exist, depending, for example, on the number of gluons they contain.

While experimentalists have looked for glueballs for 20 years, the results have been ambiguous at best. One problem is distinguishing a potential glueball from the hundreds of other short-lived resonances observed in accelerator experiments, which tend to be unstable combinations of quarks and antiquarks. "A very large number of these states ... are fairly clearly quark-antiquark," says Carnegie Mellon University theorist Fred Gilman, "but up to this point no one has found an absolutely gold-plated unambiguous thing that is not."

The problem is knowing what to look for, explains Rosner. All that will distinguish glueballs from more mundane hadrons is their various quantum charges, all of which have to be zero—"they have to be neutral, flavorless, colorless" says Rosner, "and I used to joke tasteless also"—and their mass and decay properties. The latter have to be predicted accurately from the equations of QCD, however, which is where lattice QCD comes in.

Developed in 1974 by Ken Wilson, lattice QCD replaces the continuous space and time of the QCD equations with a four-dimensional grid and then tries to solve the theory at each discrete point on the lattice. The approach reduces the problem from an infinite one to a finite, albeit enormous one. Over the last 15 years, perhaps a half-dozen collaborations have built special-purpose massively parallel supercomputers to work out QCD calculations, while theorists have developed ways to simplify lattice QCD and cut the required computing expense without sacrificing accuracy.

An early success in this game came in 1993, when, after a year and a half of supercomputer calculations, Weingarten and collaborators predicted the masses of a dozen hadrons, including the proton, to within 6% of their measured values (*Science*, 21 May 1993, p. 1077). That same year Weingarten, Sexton, and Vaccarino offered their first mass prediction for the lightest possible glueball: 1740 million electron volts (MeV), plus or minus 70—a little less than twice the mass of the proton.

The candidates multiply

This prediction coincided with a 1710 MeV particle known as the theta, which was first observed back in 1981 at SLAC's SPEAR electron-positron collider in the decay of J/Psi particles. These are particles composed of a charm quark and its antiquark, and their decay products were already under suspicion as potential glueballs, explains Close. Researchers speculated that after the quark and the antiquark annihilate each other in the course of the decay, the gluons that held the two quarks together would linger for a moment. "People had proposed that [the theta] might be a glueball," says Weingarten, "but not with very much conviction."

Weingarten thinks he has now eliminated most doubts. After two more years of calculations, he says, "we found that the [theta's] lifetime is long enough that for sure it should be observable in experiments. And then we calculated individually its decay rates, and those agree with the observed numbers within statistical uncertainties." Weingarten believes his new results clinch the issue—the 1710 MeV theta is a glueball. His colleagues are impressed, although slightly less confident. Says Michael Creutz, a QCD theorist at Brookhaven, "It looks good to me. It is fairly convincing."

But the theta has a rival as the lightest glueball. Since 1993 Close and Claude Amsler of the University of Zurich in Switzerland have mounted their own glueball search. Guiding it was a mass prediction from UK QCD, a collaboration of seven British universities, which has its own massively parallel supercomputer for lattice QCD calculations and has predicted a glueball mass of 1550 MeV, plus or minus 100. Close and Amsler went hunting in the data generated by Amsler's experiment, known as the Crystal Barrel, at the Low-Energy Antiproton Ring (LEAR) at CERN. The experiment, says Close, has been running for 5 years, accumulating millions of events in which neutral hadrons are created and then decay into photons and perhaps glueballs. When Close and Amsler searched the Crystal Barrel data, one decay product, a particle with a mass of 1500 MeV, seemed to fit the requirements, as Close and Amsler reported in June in *Physics Letters B*.

While Weingarten and Amsler have doubts about each other's glueball candidate, Close suggests that both might be the same light glueball in two different guises, with slightly different masses. "What's possible," he explains, "is that the Crystal Barrel state and the theta are two complementary mixed states of glueball and conventional quark states."

The next heaviest glueball should weigh in at roughly 2200 MeV, according to both Weingarten and UK QCD, and it may have been sighted in the early 1980s at SLAC. Labeled the ξ, the particle appeared briefly along the path by which a J/Psi decays into a photon and two hadrons. However, since the SLAC sighting it had not reappeared.

This past August, however, a collaboration known as BES at the Institute of High-Energy Physics in Beijing reported at the International Symposium on Lepton-Photon physics in Beijing that it, too, had observed the ξ, at exactly the same energy SLAC had reported. Moreover, says Walter Toki of Colorado State University, a member of the collaboration, their candidate apparently decays as QCD suggests a glueball should: into a pair of pions (quark-antiquark pairs) as well as into proton and antiproton pairs. Carnegie Mellon's Gilman agrees: "It's a very good candidate to be a glueball."

What's needed to confirm these candidates as glueballs, everybody agrees, is more experimental data and even finer QCD calculations. Amsler's Crystal Barrel experiment will close up shop at the end of 1996, when CERN shuts off LEAR to begin building its Large Hadron Collider, but the BES collaboration is finishing a major upgrade of both the detector and the experiment, says Toki, and will go back on-line next spring. Meanwhile, three collaborations—one Japanese, one Italian, and one U.S.—are in the process of developing QCD-friendly supercomputers that will be up to 100 times faster than the current generation. And recently a handful of theorists have derived new schemes that may speed up the calculations by another factor of 1000 or more (see box).

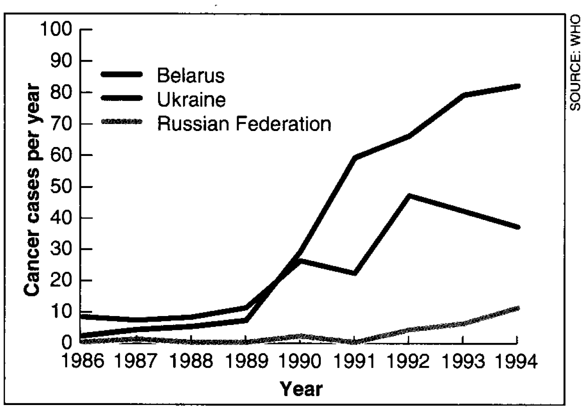
In the end, lattice QCD theorists hope that the accuracy of their predictions will rival that of the other Standard Model theories. At that point, having mastered the theory, they'll be able to look for holes in it—discrepancies between its predictions and observations that might point to new physics, beyond the Standard Model, says Wilson. "I have to remind people from time to time that general relativity, for instance, showed up in the *n*th decimal place of the orbit of Mercury—a very small correction. But that was the first indication that something was wrong" with Newtonian mechanics.

–**Gary Taubes**

RADIATION BIOLOGY

Chernobyl's Thyroid Cancer Toll

GENEVA—Last month, at an international meeting of some 600 radiation scientists,* an expert panel put its imprimatur on a scientific conclusion that has recently gained increasing acceptance: The explosive increase in childhood thyroid cancer in Belarus, the Ukraine, and the Russian Federation—the countries most contaminated by the 1986 Chernobyl nuclear accident—can be directly linked to the released radiation, and most likely to contamination by radioactive iodine isotopes.



Sharp increase. Childhoood thyroid cancer is rising in the three republics most affected by Chernobyl.

And the toll could be high. Keith Baverstock, coordinator of the World Health Organization's (WHO's) International Thyroid Project, says that the most conservative mathematical model for estimating risk predicts that "a few percent" of the approximately one million children exposed to radiation in Belarus could eventually contract the disease. And Dillwyn Williams, a thyroid expert at Cambridge University in the United Kingdom, told the meeting that for very young children in the most heavily exposed areas, this figure could rise as high as 10%.

But even though radiation is the main suspect in this thyroid