The Mystery of Nucleon Spin

A new generation of experiments promises to pin down more of the still uncertain internal structure of protons and neutrons

by Klaus Rith and Andreas Schäfer

Protons and neutrons were among the first subatomic particles discovered this century. They reside in the nuclei of atoms and are hence known as nucleons; they make up more than 99.9 percent of the matter in the everyday world around us, including this page and you yourself. (The other 0.1 percent is electrons.) Eighty years of experimental study and theoretical analysis have taught us much about the nucleons, yet certain of their fundamental properties still hold puzzles and surprises. For the past decade, physicists have labored to resolve a particular quandary known as the spin crisis.

This crisis emerged from the highly successful quark model of subatomic particles. Theorists developed this model as a neat, compact description of the myriad of new particles detected during the 1950s and 1960s, as well as of old familiars such as the proton and neutron. The properties and interactions of the particle zoo fell into patterns that could be explained by their being made of just three species of quark, called up, down and strange.

A proton consists of two up quarks and one down quark; a neutron has one up and two downs. Many of the nucleons' properties can be derived by combining properties of their constituent quarks in an elementary way. For example, the electric charge of a proton is exactly the sum of its quarks' fractional charges: $+1 = 2/3 + 2/3 - 1/3$. Attempts to observe individual quarks all failed, however, and many physicists considered quarks to be no more than a mathematical convenience—a bookkeeping system for describing interactions but not "real" objects that could be studied.

At the end of the 1960s, a collaboration of physicists from the Massachusetts Institute of Technology and the Stanford Linear Accelerator Center (SLAC) studied the inner structure of nucleons by passing a high-energy beam of electrons through liquid hydrogen. Because a hydrogen nucleus is a lone proton, this operation is almost as good as firing electrons at pure protons. From the details of the electrons' deflections, the structure of the proton is deduced.

Similar experiments had been carried out before, and all had revealed the proton to be essentially a spherical, "soft" blob of charge. To everyone's astonishment, at the higher energies made available by the new SLAC accelerator some of the electrons were scattered, as if they were striking tiny, hard points of charge within the protons. At first the experimenters thought that they had made a mistake or that some subtle effect was to blame. But the results were true: the first evidence of quarks as real objects.

Today we know that nucleons contain an incessant dance of evanescent particles flickering in and out of existence. Some of these are gluons, the particles that produce the strong force. The three main quarks that make up a nucleon—known as the valence quarks—exchange gluons back and forth, and the effect is like a strong, rubbery glue that holds them together [see "Glueballs," by Frank E. Close and Philip R. Page; Scientific American, November 1998]. Along with the three valence quarks and the gluons, short-lived "virtual" quarks and antiquarks materialize and vanish in pairs, contributing to the nucleon's properties [*see illustration on opposite page*].

A property of tremendous importance is spin, a form of innate angular momentum. All the particles that make up a nucleon have spin, and somehow the spins of all these whirling dervishes must add up to the observed total spin of a nucleon. At first glance, the three-quark model of a nucleon seems to account for its spin tidily: two of the quarks could have opposite spins, which cancel, and the spin of the remaining quark could produce precisely the observed spin of a nucleon. It is plausible that all the gluons and virtual quark-antiquark pairs should have spins that add up, on average, to zero. But reality is not that simple.

In the mid-1980s experimental results indicated that essentially *none* of a nucleon's spin was attributable to its quarks' spins. That surprise birthed the "spin crisis." An intense theoretical effort was launched to reconcile theory and experiment. Another surprise was that strange quarks, usually considered exiled to the domain of exotic, short-lived particles and high-energy interactions, seem to play a sizable role in the spin structure of the everyday nucleon.

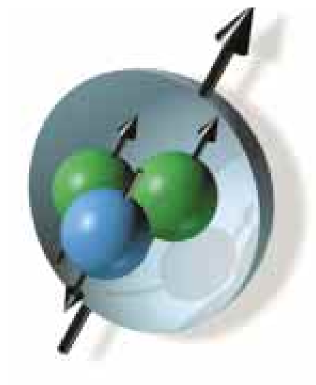
Today theorists believe they know how those features come about, and the experimental effort is entering a new era as laboratories in Europe and the U.S. probe the spin structure of nucleons with novel techniques and greater precision. It remains to be seen whether the results will confirm our understanding or generate fresh mysteries—and another "crisis."

The Importance of Spin

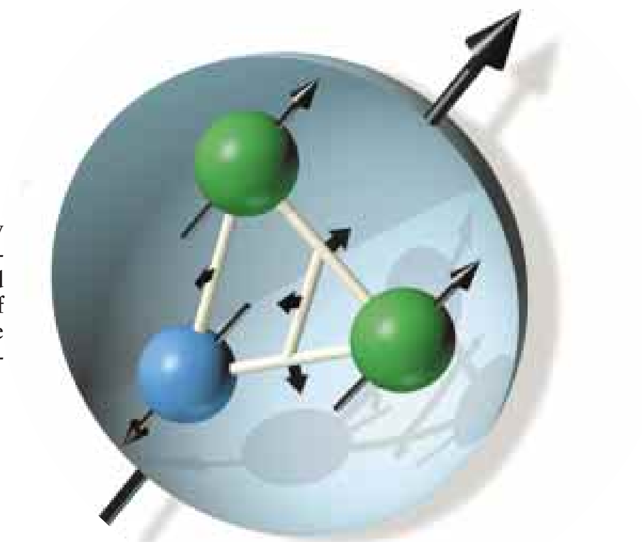
Anything that rotates or moves around a fixed point has angular momentum. The earth, for example, has orbital angular momentum from its yearly circuit around the sun and intrinsic angular momentum from its daily rotation on its axis. The spin of a fundamental particle corresponds to intrinsic angular momentum but has special quantum properties. Quantum mechanics requires spin to come only in multiples of a tiny fundamental quantity called

Four Views of a Proton

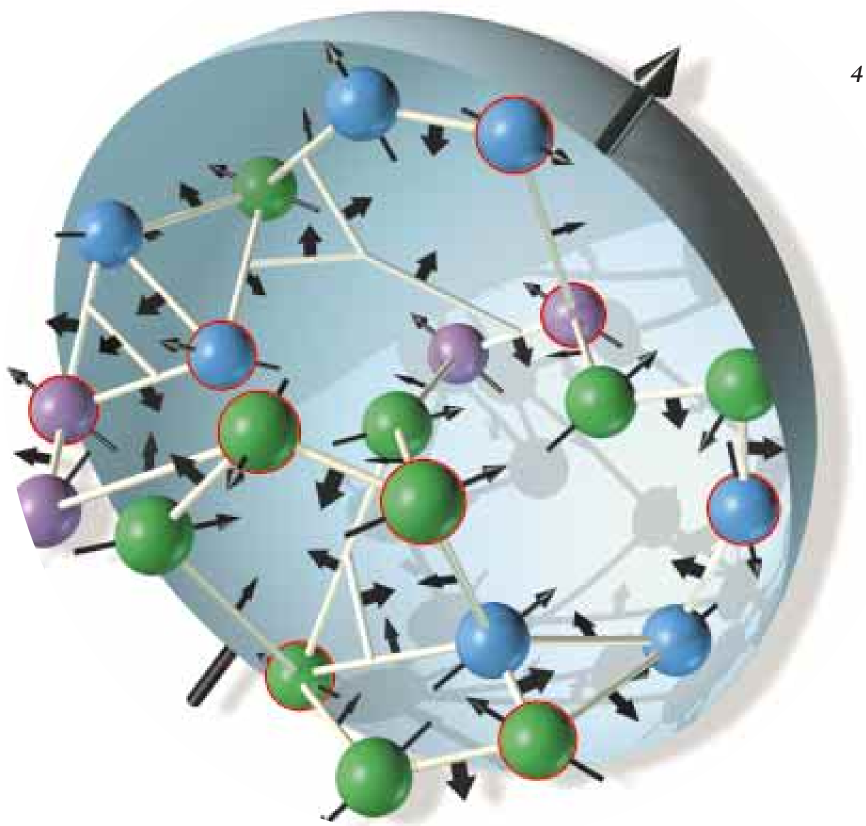
1 At low resolution the proton appears to be a "soft" blob (*gray*), about 2×10^{-15} meter in diameter, with a charge of +1 and an angular momentum, or spin, of ½ (*arrow*). For a spinning object, the arrow would point along the axis of rotation, so that the rotation would appear to be clockwise viewed along the arrow. Quantum particles have an innate spin of fixed magnitude that is distinct from the everyday notion of an object rotating.



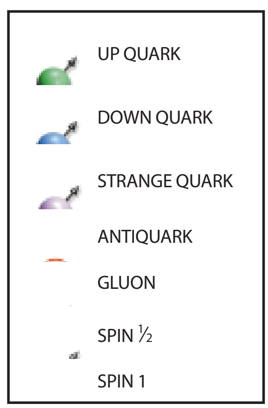
2 The quark model describes the proton as the sum of two up quarks (*green*) and one down quark (*blue*), whose individual charges and spins add up to the proton's properties. Each quark has a spin of ½, but the total spin will also be ½ if, for example, two of the quark spins cancel by being oppositely oriented.



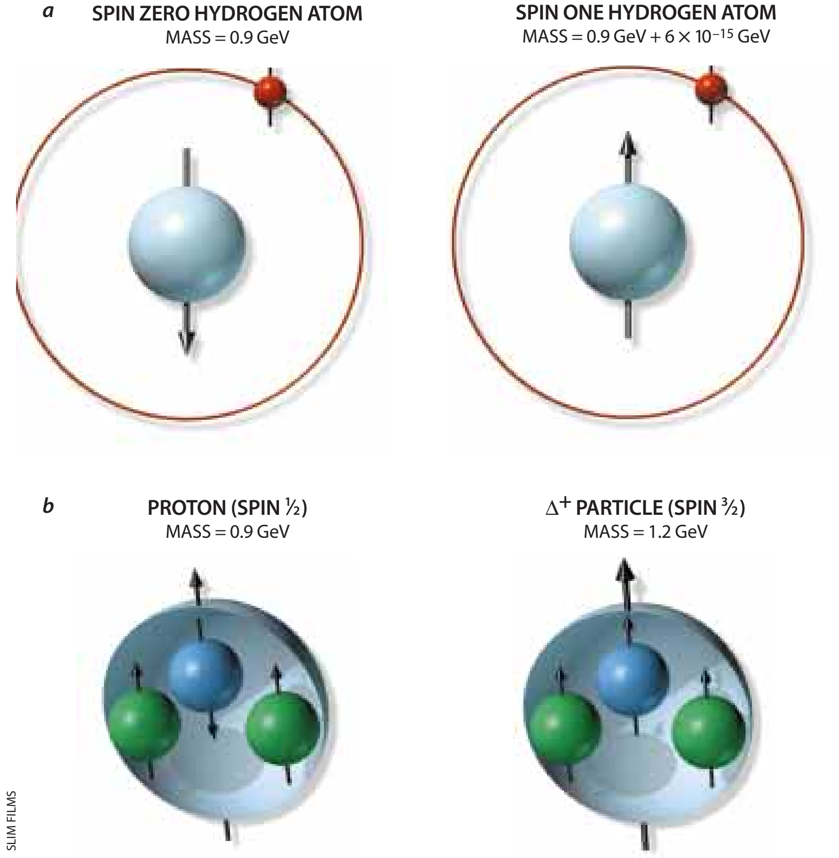
3 Experiments at the end of the 1960s revealed quarks to be essentially point particles within the proton, and the theory of quantum chromodynamics (QCD) described the force holding them together, illustrated here as a kind of elastic cord (*white*). The cord is a manifestation of particles (gluons) that each have a spin of one. The motion of the quarks and gluons within the proton can also contribute angular momentum to the proton spin.



4 The full quantum description of QCD adds a complicated, flickering dance of virtual quarks and antiquarks (*red outline*), including strange quarks (*purple*) not usually considered a part of ordinary matter. This snapshot of a single configuration only hints at the full quantum uncertainties and dynamic fluctuations. The details of how this dance produces the spin of the proton are still too difficult to be calculated reliably and are only gradually being revealed by experiment.



SLIM FILMS



SPIN STRUCTURE has a greater effect in subatomic particles than in atoms. In a hydrogen atom (*a*), aligning the spins of the proton (*gray*) and the electron (*red*) increases the atom's total spin from zero to one, but its mass by only a few millionths of an electron volt. The Δ^+ particle and the proton (*b*) each consist of two up quarks and one down quark and differ only in their spin, but this makes the Δ^+ 30 percent heavier than the proton.

Planck's quantum of action, $\hbar$ (pronounced "h-bar").

Only integer and half-integer multiples are allowed, and all the relatively familiar particles of matter—electrons, protons, neutrons and quarks—have the smallest possible nonzero quantity of spin, one half of $\hbar$. It is customary to say these particles have a spin of 1/2.

Spin is crucial in determining how a particle behaves. For example, if electrons had any spin other than 1/2, the way that they stack into orbitals around an atom would be radically altered. The periodic table of elements and all of chemistry would be mutated beyond recognition.

Calculating the spin of a composite particle by adding up the angular momenta of its components is not as simple as adding up electric charges, because each angular momentum has an orientation associated with it. The orientation of the earth's spin, for example, is represented by an arrow running along the earth's axis, pointing from south to north.

Nonetheless, computing such sums for an atom, even one with dozens of electrons, is well understood and is the kind of task physics students solve in quantum mechanics courses. Unfortunately, no one has succeeded with the analogous computations for the quarks and gluons that make up protons and neutrons.

The Trouble with QCD

The problem lies in the theory that describes the strong force, known as quantum chromodynamics, or QCD. Its equations have been known since the 1970s, but they have several features that make them devilishly hard to work with. Even today, with the most sophisticated mathematical techniques and the most powerful parallel computers, physicists cannot exactly solve the equations for a nucleon.

The strong force arises when quarks exchange gluons. The process is similar to the generation of the electromagnetic force when electrically charged particles swap photons. But two crucial differences make QCD far more mathematically intractable than electromagnetism. First, photons are electrically neutral and so do not "perceive" other photons directly, but gluons do interact with one another. Second, the strong interaction is about 100 times stronger than electromagnetism (hence its name). With a relatively feeble interaction such as electromagnetism, the simplest processes have the largest effects, and more complicated ones only need to be considered for higher precision. With the strong force, however, very complicated processes involving multiple interactions can make large contributions, and there is no easy way to deal with the resulting mathematics.

In fact, because gluons interact strongly with one another, QCD is a "nonlinear" theory: a small change in conditions can snowball into a large effect. Nonlinear dynamics is central to chaos theory, and the many studies of chaotic systems in recent years have shown how complex they can be. Moreover, QCD is a quantum field theory, implying that virtual quarks and gluons are constantly being created and annihilated; their individually brief but pervasive interactions must be taken into account. And if that were not enough, the uncertainty principle dictates that the quarks, which are confined within the tiny volume of a proton or neutron, must be in motion—at close to the speed of light.

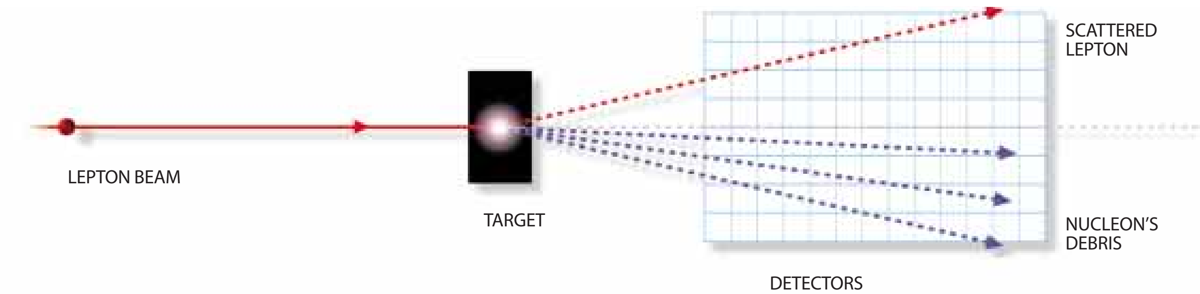
In some respects, spin is more important in QCD than in atomic physics. A hydrogen atom, for example, can have a total spin of zero or one, depending on whether the proton and the electron orbiting it have their spins parallel or antiparallel to each other [*see illustration on this page*]. But the difference in energy of these two alternatives is tiny. In contrast, consider the particle called Δ^+ (delta plus, the sign indicating its electric charge of +1). It is made of the same three quarks as a proton, but the spins add up to 3/2 instead of 1/2. The Δ^+ is 30 percent more massive than a proton, meaning that aligned spins require more energy.

Lepton "Microscopes"

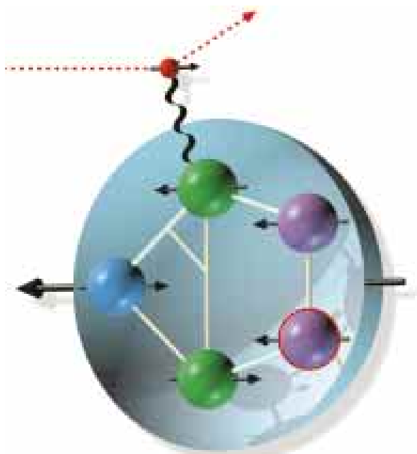
Experimenters investigate the structure of nucleons typically by bombarding a target of them with beams of energetic particles, such as electrons or muons. (The muon is a heavier, unstable cousin of the electron.) These particles, called leptons, are oblivious to the strong

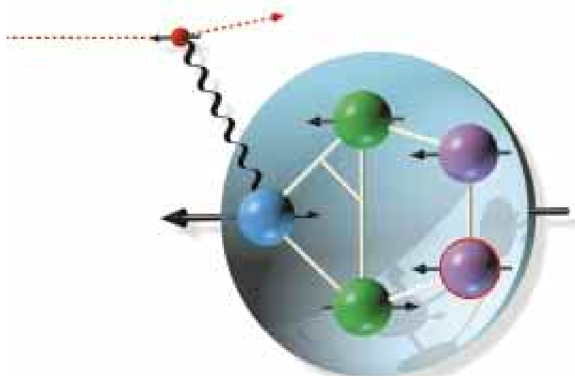
Revealing a Nucleon's Spin Structure

An accelerator directs a beam of polarized electrons or muons ("leptons") at a target of polarized nucleons. Detectors measure the resulting deflections and energy losses of the leptons. Recent experiments also analyze the debris from the nucleons for clues about what type of quark was struck to produce each deflection.

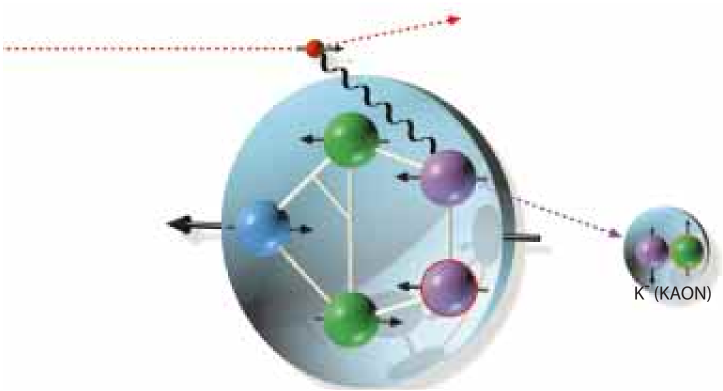


A lepton is deflected when it exchanges a photon with one of the quarks in the nucleon. Leptons with their spins aligned along the beam interact almost exclusively with quarks that have the opposite spin alignment (*below left*). When the beam polarization (or the nucleon polarization) is reversed (*below right*), the leptons interact with different quarks, changing the pattern of scattering angles and energy losses that are seen. The difference reveals the asymmetry of the quark spins in the nucleon.

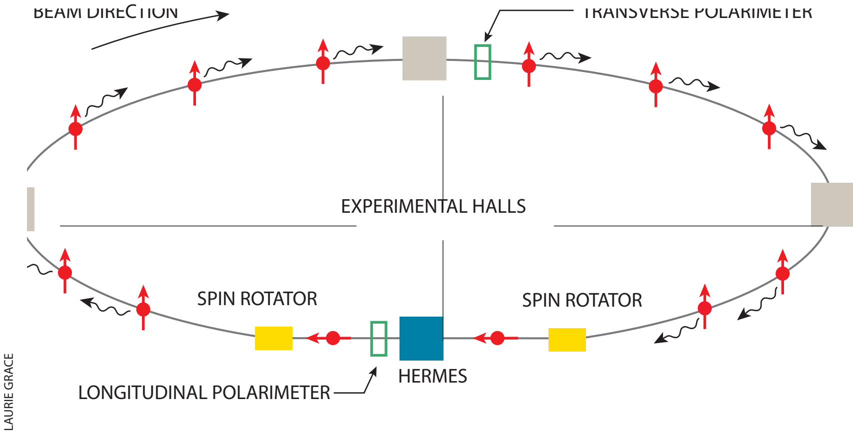




If a negative kaon is knocked out of the nucleon with large energy (*below left*), the photon probably has struck one of its constituents—a strange quark or an up antiquark. By counting the corresponding lepton deflections, physicists determine the polarization of those quarks. In the HERMES experiment (*photograph*), the electron beam travels in the large gray pipe toward the spectrometer magnet (*blue*). The target and some small detectors are installed in front of the magnet; the main particle detectors are behind the magnet.



SLIM FILMS; HEIKE THUM-SCHMIELAU *DESY (photograph)*



HERA COLLIDER accelerates electrons in a 6.3-kilometer- (3.9-mile-) circumference storage ring. The electrons (*red*) circulate about 47,000 times per second, continuously emitting hard x-rays called synchrotron radiation (*black*). Gradually, over about 30 minutes, the synchrotron radiation polarizes the electron spins (*red arrows*) at right angles to the beam path (100 percent polarization is depicted, but 60 percent is typical in practice). The HERMES target and detectors (*blue*) occupy the eastern experimental hall; three other experiments (*brown*) share the HERA beam. Special magnets (*yellow*) rotate the polarization to lie along the beam path before the HERMES collision point and then rotate it back to transverse afterward. Polarimeters monitor the polarization.

force, so the resulting collisions are governed by electromagnetism. Also, leptons seem to behave like perfect dimensionless points. The mathematics of how they interact with nucleons is thus greatly simplified and very well understood; the complications lie in the structure of the nucleon itself, not in the probe being used.

When an electron or muon passes near a nucleon in the target, it feels a force from the electric charges that make up the nucleon. In the language of quantum field theory, the lepton and the nucleon exchange a photon, transferring energy from one to the other and deflecting the lepton [*see illustration on preceding page*]. By careful measurements of the leptons' deflections and energy losses in the collisions, researchers build up a picture of how electric charges—such as those carried by quarks—are distributed within the nucleon.

The accelerator (which speeds up the leptons) and the detector (which catches the ones deflected from the target) act together like a gigantic microscope. As the momentum of the transferred photon is increased, this microscope examines the nucleon structure in finer detail. Typically a lepton needs an energy of about 100 giga-electron volts (GeV) to resolve details down to a few percent of the nucleon size. (One GeV is the usual energy unit used in QCD physics; it is approximately equivalent to the mass of a proton or a neutron at rest.)

For studies of the spin structure of nucleons, the spins of the particles in both the beam and the target must be polarized—that is, aligned. The basic interaction between the lepton and the target quark is still the exchange of a photon, but if the spin axis of the lepton beam points along the beam, the leptons will primarily exchange photons with quarks having the opposite spin. Thus, from the deflections of the leptons, experimenters learn how quarks with a specific orientation of spin are distributed in the nucleon. In particular, measurements made first with one polarization and then with the beam (or target) polarization reversed reveal the asymmetry of the quark spins—the imbalance of parallel and antiparallel spins.

The first such polarized experiments were carried out in the late 1970s at SLAC with an electron beam and a cryogenic target of butanol (C_4H_9OH). The SLAC results, published in the early 1980s, agreed with expectations that about 60 percent of the proton's spin comes from its quarks and that strange quarks make very little contribution to this. The data were limited, however, by the relatively low energy of the SLAC electron beam (10 to 20 GeV), and the conclusions depended on a plausible extrapolation to higher energies.

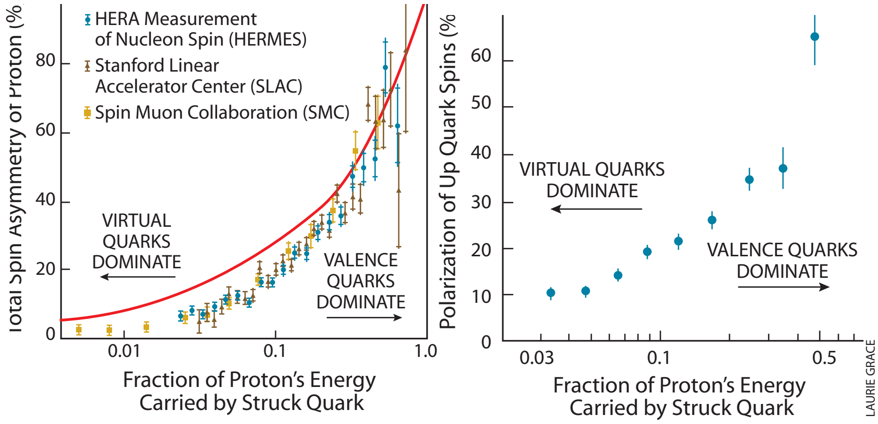
In the mid-1980s a group of physicists called the European Muon Collaboration (EMC) began experiments at CERN, the European laboratory for particle physics near Geneva, with a 200-GeV muon beam and a polarized solid ammonia (NH_3) target. A beam of protons from the accelerator first makes a beam of high-energy pions, which decay naturally in flight to muons that are 80 to 90 percent polarized. But the resulting muon beam intensity is only about a millionth of that of the polarized electron beam at SLAC. To cope with this paucity, the EMC's cryogenic targets were made 72 centimeters (28 inches) long. With a shorter target, too few of the muons would interact with a polarized proton while they passed through the ammonia to produce accurate measurements.

By exploring the proton spin structure at higher energies, the CERN group made the startling discovery that the quark spins contribute very little of the spin of the proton. In addition, it appeared likely that virtual strange quarks within a proton are quite polarized and make an unexpectedly large contribution to the total spin: about 10 percent but aligned the wrong way!

A few years later extraordinary technological advances in achieving highly polarized beams and targets led to a new generation of experiments with much greater precision. As well as technological ingenuity, all involved large-scale organization of manpower and resources. The Spin Muon Collaboration (SMC) took over the earlier apparatus at CERN, substituting a 1.2-meter target (the longest ever built) made with deuterium (hydrogen with a neutron added to the nucleus). New experiments began at SLAC as well, using target materials containing hydrogen or deuterium and also a helium 3 target. Helium 3 has one neutron and two protons with opposite spins that cancel. Experiments with deuterium and helium 3 provide important data on the neutron's spin structure, which should be very closely related to that of the proton.

HERMES and Beyond

In 1988 an international collaboration (including one of us, Rith) proposed adapting for nucleon spin measurements an electron-proton collider called HERA at the German Electron Synchrotron (DESY, pronounced "daisy") in Hamburg. It came to be known as the HERMES (HERa MEasurement of nucleon Spin) collaboration. Electrons circulate around HERA's ring about 47,000 times per second, producing an average beam 10,000 times more in-



SPIN POLARIZATION of the proton is measured by many experiments. The total spin asymmetry from recent measurements by SLAC, SMC and HERMES (*left*) shows that quark spins contribute only a small portion of proton spin. Data following the curve would have indicated a larger contribution, as was expected in the early 1980s. The spin polarization of just the up quarks and antiquarks (*right*) was measured recently by HERMES.

tense than the one at SLAC [*see illustration on opposite page*]. This intense beam can be used with low-density gaseous targets of pure atomic hydrogen, deuterium or helium 3. Such targets avoid the spin "dilution" that occurs with targets of butanol and ammonia that have many unpolarized proton and neutron pairs in their carbon, nitrogen and oxygen atoms.

Serious technical concerns had to be overcome. It took four years of effort for the DESY accelerator experts and members of the HERMES collaboration to demonstrate and then routinely attain high polarization. At that point, HERMES received its final approval, and the detectors were built and installed. HERMES began taking data in the summer of 1995.

The results of all the second-generation experiments agree nicely with one another [*see illustration above, at left*] and confirm that only about 30 percent of a proton's spin is produced by its quark's spins. Moreover, experiments are now beginning to pin down the contribution of each kind of quark by studying the nucleon debris from each collision. The illustration at the right shows recent HERMES results for the polarized up-quark distribution. HERMES will also provide the first *direct* measurements of the strange quark polarizations by singling out those collisions that produce a negative kaon (which consists of a strange quark and an up antiquark).

The missing 70 percent of the spin no longer constitutes a "crisis." It can come from gluon spins (each gluon has a spin of one) and from the orbital angular momentum from the motion of all the quarks and gluons within the nucleon. Indeed, present-day theoretical models of spin structure can match the experimental data provided that the total gluon contribution is about one to two quantum units of spin. An orbital angular momentum (from the motion of all the particles in a nucleon) of about –1 is also required.

That such large quantities are present within a nucleon of total spin of ½ is quite counterintuitive. Can we verify these surprising gluon and orbital contributions independently? At present, no one has proposed a practical way to measure the orbital contribution. Data from HERMES indicate that gluons do contribute to the nucleon's spin, but the extent of the contribution cannot be assessed yet. Studies that collide polarized protons together at high energy should also directly determine the spin from gluons. Such experiments will begin next year at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory [see "A Little Big Bang," by Madhusree Mukerjee; SCIENTIFIC AMERICAN, March]. The next-generation experiment at CERN—COMPASS—will also measure the gluon contribution. If the measured contribution turns out to be too small, we will face a far more drastic "spin crisis" than ever before.

Clarifying the internal structure of the nucleons will also have significance in other realms of particle physics. The spin contributions are intimately related to mathematical structures that appear not only in QCD but also in, for example, weak interactions (which cause some nuclei to decay and help to power the sun). In particular, the Bjorken sum rule, first derived by James Bjorken of SLAC in 1966, relates the scattering of polarized electrons off polarized nucleons (an electromagnetic process) to the decay of a neutron (a weak process).

The spin experiments are verifying the Bjorken sum rule with increasing precision and are thus verifying elements of the basic mathematical structure of QCD and the Standard Model. In this way, scientists are learning more about the fundamental properties of our universe even as they work toward a complete answer to the seemingly simple but remarkably difficult question: What produces the spin of a nucleon?

The Authors

KLAUS RITH and ANDREAS SCHÄFER are both members of the HERMES collaboration. Rith has worked on lepton-nucleon scattering since his 1974 Ph.D., which was on the design and construction of a detector for use with an electron synchrotron at the University of Bonn. He has worked on the muon-nucleon experiments at CERN near Geneva, and he was spokesman for the HERMES collaboration for several years. Rith is a professor of particle physics at the University of Erlangen-Nürnberg in Germany. Schäfer became active in nucleon spin theory during his first postdoc, as a Toleman Prize Fellow at the California Institute of Technology in 1987. The "spin crisis" was just blossoming, and he learned that a group in the same building developing a polarized target "needed a theoretician to help them keep up with the enormous number of theory papers being generated." Schäfer is a professor at the University of Regensburg in Germany, where he leads a high-energy theory and quantum chromodynamics group.

Further Reading

COLLISIONS BETWEEN SPINNING PROTONS. Alan D. Krisch in *Scientific American,* Vol. 257, No. 2, pages 42–50; August 1987.

THE PARTICLE EXPLOSION. F. E. Close, M. Marten and C. Sutton. Oxford University Press, 1987.

WHERE DOES THE PROTON REALLY GET ITS SPIN? Robert L. Jaffe in *Physics Today,* Vol. 48, No. 9, pages 24–30; September 1995.