WHERE DOES THE PROTON REALLY GET ITS SPIN?

Polarized scattering experiments reveal that quarks contribute surprisingly little to the proton's spin. This 'spin crisis' is doing much to clarify the subtle departures of the underlying field theory from the naive quark model.

Robert L. Jaffe

In 1987 the European Muon Collaboration, which had been scattering muons off polarized protons at CERN, shocked the particle physics community with the announcement[1] that little or none of the proton's spin can be attributed to the spins of its three constituent quarks—two "up" quarks and one "down" quark. That report precipitated what became known as "the spin crisis."

Now, after several further rounds of experiments by EMC and other groups at CERN and Stanford, the result has shifted somewhat: Quark spins appear to account for 20–30% of the spin of the proton or neutron. But the fact remains that much of the nucleon's spin lies elsewhere. A surprising corollary is that the "sea" of quark–antiquark pairs that reside with the three constituent (or "valence") quarks is strongly polarized in the direction *opposite* to the nucleon's net spin. Furthermore this sea turns out to contain a surprisingly large admixture of polarized "strange" quarks.[2]

Figure 1 is a recent photograph of the experimental complex of the Spin Muon Collaboration, the EMC group's successor in the spin-structure business at CERN.

The so-called spin crisis has had important effects beyond simply confronting theorists with a particularly sharp challenge to their incomplete understanding of quantum chromodynamics, the underlying field theory of quarks and the gluons that mediate their strong interactions. By validating the so-called Bjorken sum rule it has in fact given us a striking *confirmation* of QCD. The spin crisis has also added renewed urgency to the quest for an understanding of nucleon structure, and it has given new impetus to the use of high-energy leptonic probes (electrons, muons and neutrinos) of nucleon substructure. In its wake, a host of new experimental programs will supply us with a steady stream of high-precision data for the foreseeable future.

The story begins in the prehistory of QCD, when theorists struggling to piece together quark–gluon dynamics laid the phenomenological foundations of spin-dependent lepton–nucleon scattering. Beginning in about 1970, experiments designed to probe the nucleon's spin substructure were conceived, proposed and executed. The campaign came of age with the publication of the first EMC data in 1987. Only last year did further CERN data and discordant results from rival experiments finally arrive at something like a consensus. We theorists are still struggling to understand the implications of these experimental results.

Tribulations of quantum chromodynamics

When QCD emerged in the early 1970s, the full magnitude of the problem of nucleon structure began to be appreciated. The nucleon is a highly relativistic bound state of quarks and gluons. It cannot, even in principle, be separated into its components. Nearly massless quarks bind together by exchanging exactly massless gluons. QCD, much like quantum gravity, is inherently nonlinear: Gravitons gravitate and gluons attract one another with gluonic forces. The nonlinearities become so strong at long distances that quarks or gluons cannot be removed from the hadrons they inhabit. That makes it frustratingly difficult to calculate the observational consequences of the underlying theory. Even now, two decades after QCD was formulated, little is known from first principles about the structure of the nucleon and other hadrons made from the light (that is to say, the up, down and strange) quarks.

Yet the Lagrangian of QCD is remarkably simple and elegant. Apart from the quark masses, which have to be put in by hand, the QCD Lagrangian is completely determined by a natural generalization of electromagnetic gauge invariance to a set of noncommuting "charges," the three so-called colors originally introduced to evade the Pauli exclusion principle. The QCD Lagrangian,

$$L = \overline{q}\,(i\gamma{\cdot}D + m)\,q - \frac{1}{4}\,\mathrm{Tr}\,\mathbf{F}^{\mu\nu}\,\mathbf{F}_{\mu\nu}$$

can fit on a postage stamp, not to mention a T-shirt. I show it here just to display its simple elegance.

Moreover, hadron spectra and interactions show tantalizing regularities beyond those expected on the basis of symmetries alone. Tempted by these patterns, theorists have tried again and again to develop a quantitative understanding of the hadron as a bound state of quarks in QCD. At the same time, experimenters have extended their ability to probe the internal structure of hadrons, improving resolution, exploiting new degrees of freedom

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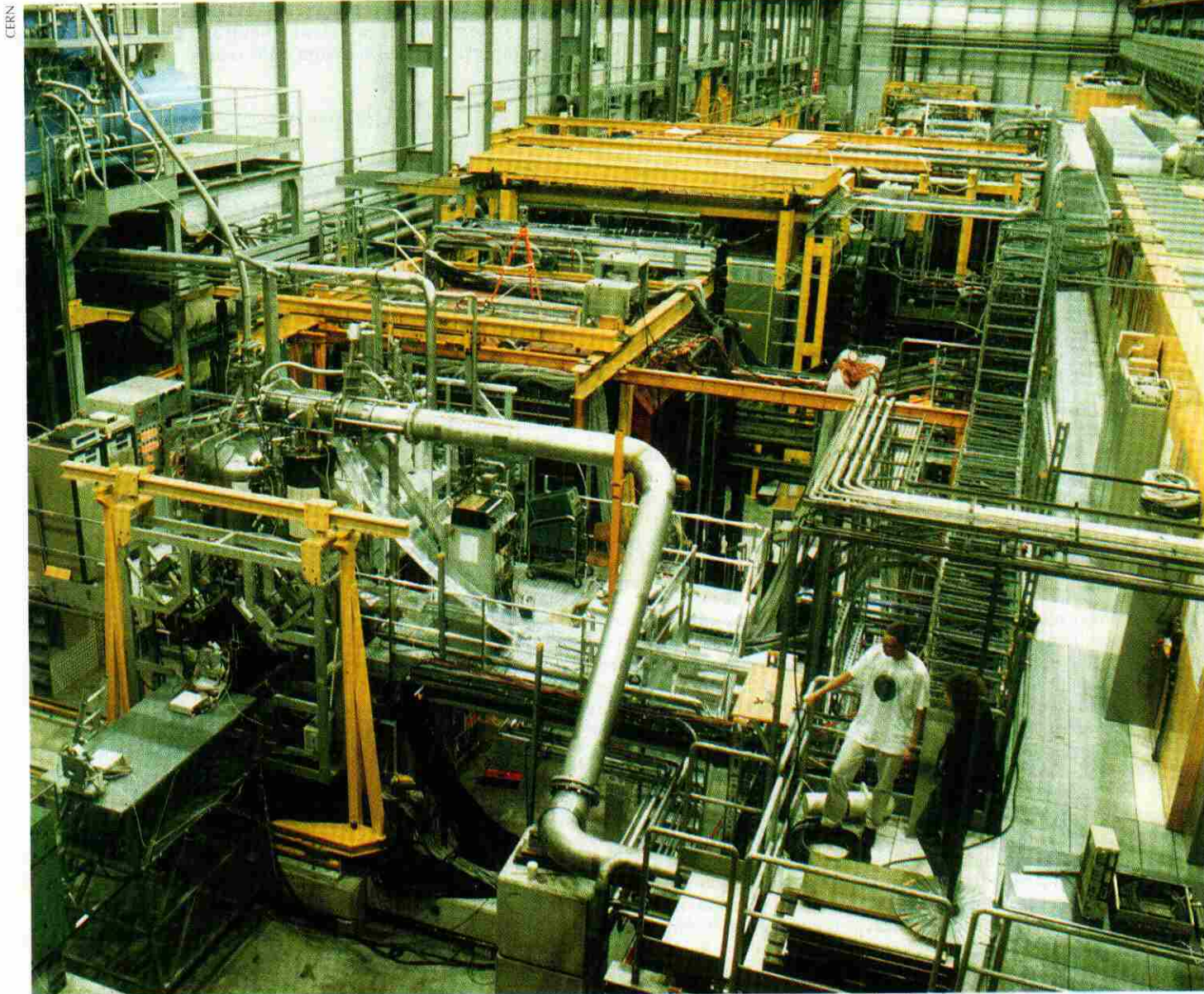
SPIN MUON COLLABORATION experiment at CERN's Super Proton Synchrotron examines the spin structure of protons and neutrons by scattering polarized, high-energy muons off polarized hydrogen and deuterium targets. This photo looks downstream along the muon beam, which comes from the lower left through open air. Twin targets of opposite polarization sit near the shiny cryostat tank visible at the left end of the prominent S-shaped helium pumping line. Immediately downstream of the targets is a large analyzing magnet, followed by scintillator hodoscopes and wire-chamber planes on both sides of a 3-meter-thick steel muon filter. FIGURE 1

such as polarization and learning to use our understanding of QCD at short distances to fashion new probes.

Typical of the questions that stymie theorists is, What carries the spin of the nucleon? Is it due primarily to the spins of the three valence quarks that compose the nucleon in the simplest models? If the nucleon were a nonrelativistic bound system, the spin of the ground state, in which all orbital angular momenta are zero, would be merely the spin of its constituents added up according to the time-honored rules of quantum mechanics. (That's why it's so much easier to calculate the bound states of the quarks with the heavy flavors: "charm" and "bottom.") But for relativistic systems like the nucleon, in which the constituent quark masses are small compared with the total mass, the answer is unclear. Orbital angular mo-

mentum, polarized quark–antiquark pairs and the spin-1 gluons can all contribute to the total angular momentum of the ground state.

Precise probes of the nucleon are few. Although hadronic phenomena are relatively accessible to experiment, most hadron–hadron interactions are difficult to relate to questions of structure. Richard Feynman once said that studying hadrons by scattering them off one another was like studying Swiss watches by throwing them at each other and examining the debris. It's even worse than that. You never see the constituent "gears," the quarks and gluons, among the debris—only more Swiss watches!

Matrix elements of electromagnetic and weak-current operators supply a small set of precise information about
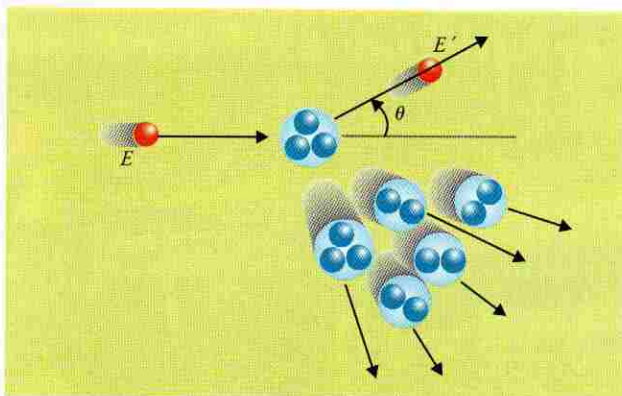
DEEP INELASTIC SCATTERING of a high-energy electron (or muon) off a stationary, quark-laden proton (or neutron) is described by two variables, Q^2 and ν. If an incident electron of energy E scatters through an angle θ off a nucleon of mass M, the Lorentz-invariant 4-momentum transfer squared Q^2 is given by $-4EE' \sin^2(\theta/2)$, where E' is the electron's final energy. The energy-transfer variable ν is defined as $E - E'$. The hadronic debris into which the nucleon breaks up is generally not measured. Polarizing the beam and target particles yields rich information about the spin structure of the nucleon. FIGURE 2

nucleons. We know the electric charges and magnetic moments of the proton and neutron, as well as their charge radii and the vector and axial "weak charges" measured in beta decay. But relativistic complications limit the usefulness of that kind of information. For example, the familiar connection between electron-scattering form factors and the Fourier transforms of charge and magnetization densities, well known from atomic and nuclear physics, fails for intrinsically relativistic systems like the proton.

In recent years our understanding of QCD at large momentum transfer (small distances) has provided a new set of experimental probes. It's somewhat like probing the electron distribution of an atom, which is really a problem in nonperturbative quantum electrodynamics, by using inelastic electron scattering in the *perturbative* Born approximation.

Bjorken's sum rule

Our spin crisis story begins at Stanford back in 1966 with theorist James Bjorken's speculations that the current operators mediating the weak and electromagnetic interactions might obey the same commutation relations as the free-field operators.[3] Among the consequences he derived from this supposition was a sum rule for the inelastic scattering of polarized electrons (or muons) off polarized protons and neutrons.

The inelastic process Bjorken considered is shown in figure 2. When Q^2, the square of the 4-momentum transferred from the incident charged lepton to the hadronic debris, is very large, this process is known as "deep" inelastic scattering. The polarization asymmetry, defined as the cross section measured with the spins of the incident lepton and target nucleon parallel (to each other and to the beam direction) minus the cross section with antiparallel spins, is proportional to a so-called structure function known as g_1. All the messy complexity of the composite proton or neutron target is summarized by four such phenomenological structure functions. Relativistic invariance tells us that they can be written as functions of Q^2 and ν, which is defined as the energy lost by the scattering lepton in the target rest frame. The structure functions should not depend on whether the probing

charged leptons are muons or electrons.

In terms of the proton and neutron structure functions g_1^{p} and g_1^{n}, the Bjorken sum rule reads

$$\int_0^\infty \frac{Q^2}{M\nu^2}\, d\nu \left(g_1^{\mathrm{p}}(Q^2,\nu) - g_1^{\mathrm{n}}(Q^2,\nu) \right) = \frac{g_A}{3} \tag{1}$$

The physical constant g_A is the weak axial charge (1.257 ± 0.003) measured in beta decay.

In 1966 Bjorken couldn't imagine an experimental test of this result. Having derived the sum rule, he wrote, "Something may be salvaged from this worthless equation by constructing an inequality." The remark illustrates nicely both Bjorken's modesty and the capacity of experimenters to surpass the expectations of theorists.

Back then the most striking feature of the sum rule was that the right-hand side of equation 1 is independent of Q^2. It was generally believed that the nucleon was a "soft" object incapable of absorbing a significant momentum transfer. Therefore, it was thought, the proton and neutron g_1 structure functions should fall exponentially with increasing Q^2. How then could the integral over ν yield a result independent of Q^2?

The first deep inelastic scattering experiments, carried out at the Stanford Linear Accelerator Center in the late 1960s, showed that cross sections did, in fact, remain large at large Q^2, just as Bjorken's sum rule implied they would. Furthermore, at large Q^2 the structure functions appeared to depend only on the dimensionless ratio $x = Q^2/2M\nu$, which became known as Bjorken's scaling variable.

Bjorken and others soon realized that this kind of scaling behavior reflected free-field dynamics at short distances inside the nucleon. That insight lent important support to the idea that the nucleon is composed of confined but weakly interacting pointlike quarks. (See Bjorken's reminiscence of Feynman's role in this realization in PHYSICS TODAY, February 1989, page 56.)

In the early 1970s, deep inelastic scattering became the principal "laboratory" for investigating QCD. Theorists predicted and experimenters observed logarithmic radiative corrections to the scaling behavior of the structure functions at high momentum transfer. Those radiative corrections have become the hallmark of QCD, and the Bjorken sum rule is widely regarded as a benchmark test of the theory.

Parton distributions

The standard physical model for deep inelastic scattering in QCD is the quark "parton" model, in which Bjorken's x is the fraction of the target proton's momentum (as viewed in a frame in which the proton has very high momentum) attributed to the quark about to be struck by the incident lepton. Thus the structure functions become probability distributions in x for the quarks inside the nucleon.

These quark probability distributions play a key role in the description of all high-momentum-transfer processes. The structure functions are sums of individual probability distributions, each labeled by the flavor and spin direction of the quarks in question. (Quarks, like nucleons and leptons, are spin-$\frac{1}{2}$ fermions.) Isotopic symmetry relates the quark distributions in the neutron and proton. It dictates, for example, that the momentum distribution of up-flavored quarks (not to be confused with spin directions) in the proton must equal the distribution of down-flavored quarks in the neutron.

The parton formalism was generalized to scattering of polarized electrons off polarized targets by Julius Kuti

and colleagues in 1970.[4] The spin-dependent proton g_1 structure function, for example, is given by $g_1^p(x) =$

$$\frac{4}{9}\Delta u(x) + \frac{4}{9}\Delta\overline{u}(x) + \frac{1}{9}\Delta d(x) + \frac{1}{9}\Delta\overline{d}(x) + \frac{1}{9}\Delta s(x) + \frac{1}{9}\Delta\overline{s}(x) \quad (2)$$

Here $\Delta u(x)$ is shorthand for the *difference* between up-quark x distributions for quark spins parallel and anti-parallel to the spin of the host proton. The other terms refer in the same way to down-quark, strange-quark and corresponding antiquark contributions to g_1^p. Because this is electromagnetic scattering, each contributing term in equation 2 is proportional to the square of that flavor's electric charge. (The charge of the up quark, for example, is $+\frac{2}{3}e$.) For convenience, only the x dependence of the structure functions is displayed in this notation. But one should bear in mind the nonscaling $\log Q^2$ dependence at high momentum transfer introduced by QCD radiative corrections.

The integral of $\Delta u(x) + \Delta\overline{u}(x)$ over all x (from 0 to 1), which we denote by Δu, is the fraction of the proton's spin, in the parton model, carried by up and anti-up quarks. Defining the analogous contributions of down and strange quarks to the proton spin and generalizing Bjorken's sum rule, we get

$$\int_0^1 g_1^p(x)\,dx = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right) \quad (3)$$

To determine the right-hand side of equation 3, theorists turned once again to beta-decay data.[5] The invariant matrix elements F and D measured in the beta decay of strange cousins of the nucleon can be related to $\Delta u - \Delta s$ and $\Delta u - \Delta d$ by the approximate SU(3) flavor symmetry of the strong interactions. That still doesn't give us the sum $\Delta u + \Delta d + \Delta s$, which is the fraction of the proton's spin carried by all the light quarks and antiquarks. Calling that sum Σ, we can rewrite equation 3 as

$$18\int_0^1 g_1^p(x)\,dx = 3F + D + 2\Sigma \quad (4)$$

with a similar expression for the integral of the neutron structure function $g_1^n(x)$.

In 1973 John Ellis and I suggested that the strange quarks in the nucleon might not be polarized.[6] In the simplest models, the nucleon contains only the valence up and down quarks. In more sophisticated models relativistic effects generate a sea of quark–antiquark pairs. Perhaps, we conjectured, those virtual pairs would not be highly correlated with the total spin. Furthermore, the greater mass of the strange quark suggested to us that strange–antistrange pairs would be much less abundant in the sea than up–antiup and down–antidown quark pairs. Thus we proposed to evaluate equation 4 with the Δs contribution taken to be zero. Doing that, one gets the so-called Ellis–Jaffe sum rules. With current values of F and D and the inclusion of QCD radiative corrections, the Ellis–Jaffe sum rule for the proton structure function nowadays reads

$$\int_0^\infty g_1^p(x, Q^2)\,dx = 0.176 \pm 0.006 \quad (5)$$

for Q^2 around 10 GeV^2. The corresponding integral for the neutron structure function comes out to -0.002 ± 0.005, consistent with zero.

The study of QCD corrections to these sum rules has advanced dramatically in recent years. They include gluon radiative corrections proportional to α_s, the QCD coupling-strength parameter, which decreases logarithmically with Q^2; "higher-twist corrections" for multiparticle correlations, which vanish at large momentum transfer like powers of $1/Q^2$; and kinematic target-mass corrections proportional to powers of M^2/Q^2.

Requiring no such assumptions beyond QCD and the charge independence of the strong interactions, Bjorken's sum rule is more fundamental than ours. But the separate Ellis–Jaffe sum rules for the neutron and proton have attracted great interest, because they involve Σ, the quark-spin contribution to the nucleon spin. In 1974 Lalit Sehgal pointed out[7] that equation 4 could be rewritten in terms of known quantities and the Σ one would like to know. He noted that choosing Δs to be zero gave a Σ of about 0.6. His paper was not widely noticed, but it presaged future developments: With accepted beta-decay parameters and the seemingly benign assumption that Δs vanishes, he found that a significant fraction of the spin of the nucleon is *not* accounted for by the intrinsic spins of
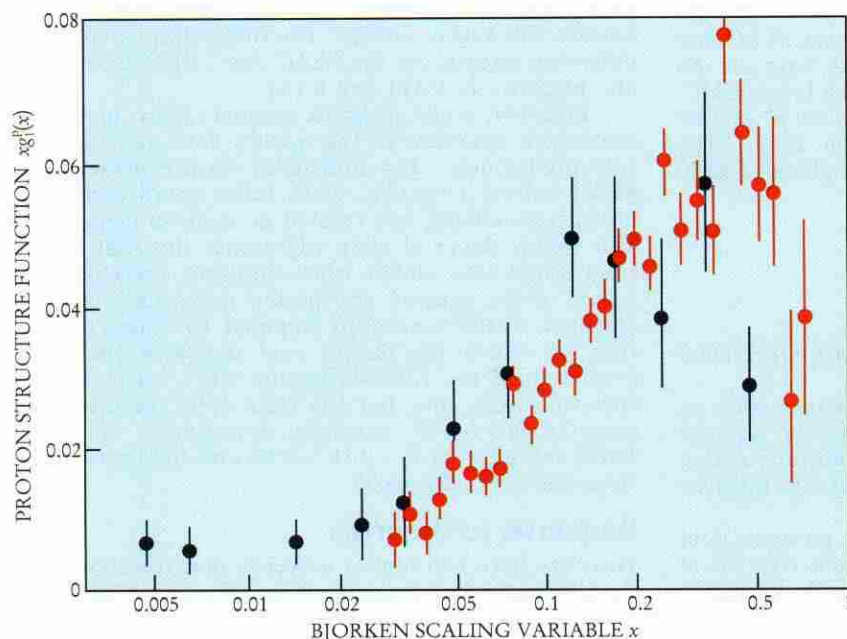
SPIN-DEPENDENT PROTON STRUCTURE FUNCTION $xg_1^p(x)$ measured with electrons at SLAC (red data points) and muons at CERN (black data points), plotted against Bjorken's scaling variable x. The two measurements are now reasonably consistent with each other. The CERN data have the larger error bars, but they extend to smaller x. (Adapted from refs. 13 and 14.) FIGURE 3

the quarks. Indeed, simple nonrelativistic quark models predict that the weak axial charge g_A should be $5/3$, rather than the 1.257 observed in beta decay. By contrast, the relativistic models that got g_A right invariably distributed the nucleon's spin over both the spins and the *orbital* angular momenta the quarks. Thus astute observers knew as early as 1974 that the nucleon's spin structure must be more complex than the simple quark models indicated.

An experimental science

The first, pioneering measurements of deep inelastic spin asymmetries were published[2] just over ten years after the appearance of Bjorken's 1966 paper.[3] The experiment was carried out at the Stanford Linear Accelerator Center by a collaboration led by Vernon Hughes (Yale) and David Coward (SLAC). Already in the late 1960s Hughes recognized the promise of polarized electron–nucleon scattering, and he has led experimenters and coaxed theorists to study polarized deep inelastic phenomena ever since.[8] The early SLAC polarized-proton data[9] provided a crude test of Bjorken scaling, but they had neither sufficient precision nor x range to test the sum rules for g_1^p.

By the late 1970s Hughes and collaborators had mounted a considerably more ambitious experiment at SLAC. In 1983 they published the first evaluation of the proton sum-rule integral.[10] They obtained $\int g_1^p(x)\, dx = 0.17 \pm 0.05$, in good agreement with the theory, assuming $\Delta s = 0$.

These groundbreaking experiments at SLAC were limited by both statistics and kinematics. The relatively low electron-beam energy at SLAC kept Q^2 well below the asymptotic regime, especially for x less than 0.1. Therefore the evaluation of the sum rule depended on a speculative extrapolation of g_1^p to $x = 0$. The low-x behavior of the structure functions remains a matter of some controversy even to this day.

Next the experimental focus shifted to the Super Proton Synchrotron at CERN, where the European Muon Collaboration, already famous for its work on deep inelastic muon scattering off unpolarized targets, now mounted a major effort to measure g_1^p. From the decay of pions at SPS energies one could make a muon beam with energies up to 200 GeV and a natural longitudinal polarization of about 80%. At such high energy, the EMC collaboration was able to reach much higher Q^2 and lower x than the SLAC experiments had attained. In any case, SLAC had now shifted its attention to its linear-collider program. So Hughes and his Yale group crossed the ocean to join EMC.

The EMC collaboration reported its first g_1^p results informally at several conferences early in 1987. The results were entirely unexpected: The combined CERN and SLAC data gave

$$\int_0^\infty g_1^p\, dx = 0.126 \pm 0.018$$

compared with a theoretical expectation of 0.176 ± 0.006 based on $\Delta s = 0$.

This rather surprising result corresponds to $\Sigma = 0.120 \pm 0.16$. Within errors, in other words, the new CERN data were consistent with the astonishing notion that *none* of the proton's spin is attributable to the intrinsic spins of its up, down or strange quarks.

Equivalently, the EMC data yielded a nonzero Δs of -0.190 ± 0.056, indicating that a significant fraction of the proton spin is carried by strange quark–antiquark pairs. Although the EMC results were statistically consistent with the previous SLAC results and less than three standard deviations away from the theoretical expectation, they nonetheless ignited a wildfire among theorists and stimulated other experimental groups to extend these measurements.

The first order of business of the Spin Muon Collaboration, EMC's successor in the late 1980s, was to measure the neutron structure function with a polarized deuterium target. At the same time a new collaboration at SLAC undertook a program of high-intensity studies of polarized-electron scattering from polarized proton, deuteron and helium-3 targets. The goal was to disentangle neutron and proton spin asymmetries.

Father and son

The spokesman for the new SLAC experiment was Emlyn Hughes, Vernon's son. Vernon was the SMC spokesman, and the two experiments, for some time, appeared to be finding conflicting results. Thus father and son found themselves in a friendly rivalry in pursuit of the nucleon's spin structure. The two rival collaborations announced their first data on g_1^n and the neutron-spin sum rule early in 1993, almost simultaneously. For $\int g_1^n\, dx$, the CERN experiment obtained -0.08 ± 0.04 with its deuterium target,[11] and the SLAC helium-3 target[12] yielded -0.022 ± 0.011. The best theoretical expectation for the neutron integral, assuming Δs vanishes, is -0.002 ± 0.005. The SLAC result claims better precision because the ^{3}He nucleus, with its paired proton spins, is a very good approximation to a neutron target for spin-structure studies. (See PHYSICS TODAY, June, page 17.)

The most recent proton measurements from SLAC[13] and SMC[14] have brought the two groups into fairly good agreement. (See figure 3.) These new results have made possible the first accurate tests of Bjorken's sum rule. For the difference integral

$$\int_0^1 (g_1^p - g_1^n)\, dx$$

which is $1/2$ the left side of equation 1, the SLAC collaboration reports a measured value of 0.149 ± 0.014 and SMC reports 0.204 ± 0.029. Both experimental values are in fact quite consistent with theoretical expectations, because the QCD calculation has a slight Q^2 dependence at finite momentum transfer and the CERN experiment is at considerably higher energy. The theoretical values of the difference integral for the SLAC and CERN experiments are, respectively, 0.171 and 0.185.

Figure 4, a plot of $\int g_1^p\, dx$ against $\int g_1^n\, dx$, provides a convenient overview of the world's data and the sum-rule predictions. The horizontal strip represents the SLAC helium-3 results, which (after small corrections for nuclear effects) are treated as neutron-target data. The yellow diagonal strip represents the SMC deuterium-target data, which (when similarly corrected) yield a sum of the neutron and proton integrals. The blue diagonal is the constraint imposed by Bjorken's sum rule, on which the darker spot indicates the $\Delta s = 0$ prediction of the Ellis–Jaffe sum rules. The Bjorken sum rule looks fine, but the Ellis–Jaffe conjecture appears to fail by $2\frac{1}{2}$ standard deviations. The latest world value for Δs is -0.10 ± 0.03, and the best current value for Σ is 0.27 ± 0.05.

Responses to the crisis

Theorists have had almost a decade now to ruminate on the implications of the spin crisis. No simple "gee whiz" explanation accounts for how little of the nucleon's spin is carried by quark spin. Real insight probably awaits a
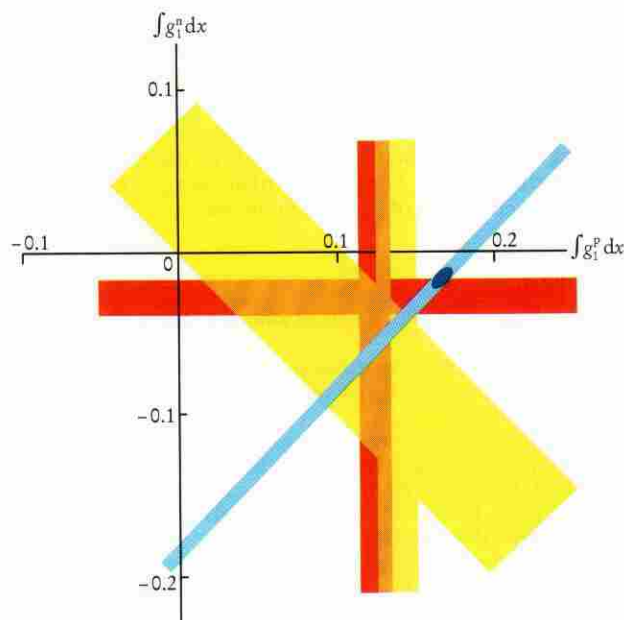
STRUCTURE FUNCTION INTEGRALS $\int g_1^n dx$ and $\int g_1^p dx$, plotted against each other, summarize the current experimental status of the theoretical sum rules at $Q^2 = 5$ GeV². Bjorken's sum rule and its uncertainty are represented by the blue diagonal strip, with the dark blue spot indicating the prediction of the more restrictive Ellis–Jaffe sum rules. Vertical bars show the SLAC (red) and CERN (yellow) proton-target data and their uncertainties. The horizontal bar shows the result from the SLAC ³He-target experiment, and the yellow diagonal shows the CERN deuterium-target result. **FIGURE 4**

deeper understanding of the nucleon as a bound state of confined quarks—as elusive as ever. Some theorists have considered other potential carriers of spin inside the nucleon and developed ingenious insights along the way. Others have reexamined the role of spin in deep inelastic processes, discovering or refining new probes of hadron substructure and spawning a new generation of experiments now in various stages of development.

Even attempts to account for the discrepancy in rather trivial ways have proven quite fruitful. Here are some of the more popular ways of explaining away the spin crisis with "trivial" considerations:

▷ SU(3) flavor-symmetry violation may have made the estimate of $\Delta u - \Delta s$ inaccurate.

▷ Unexpected phenomena at very small x may have been overlooked.

▷ Subasymptotic Q^2 corrections may have contaminated either theory or experiment.

At present we have no indication of low-x peculiarities or significant SU(3) violation in the beta-decay data. An *elastic* neutrino–proton scattering experiment[15] under way at the Los Alamos proton accelerator will yield a direct measurement of $\Delta u - \Delta d - \Delta s$. Comparison of this LAMPF measurement with deep inelastic data could rule out SU(3) violation as the culprit.

Interest in subasymptotic corrections peaked in the summer of 1993, when the SLAC and SMC measurements of g_1^n appeared to differ significantly. Theorists reevaluated corrections of order $1/Q^2$ to the theory and found them to be inconsequential.[16] The disagreement between the two experimental groups no longer seems very significant, but the exercise has left the theorists with a much better understanding of these corrections. In fact they now advocate looking for correction effects as a way of

measuring spin correlations—an interesting but difficult prospect.

Whatever fraction of the nucleon's spin is not accounted for by quark spin must be made up by quark orbital angular momentum (L_q), gluon orbital angular momentum (L_G) and gluon spin (ΔG). Gluons, like photons and the weak gauge bosons, have spin 1. Because the spin of the nucleon is ½, we get

$$\frac{\Sigma}{2} + L_q + L_G + \Delta G = \frac{1}{2} \qquad (6)$$

The sum Σ includes the contribution of quark–antiquark pairs. Because strange quarks in the nucleon would appear only in pairs, the nonvanishing of Δs is *prima facie* evidence that virtual quark–antiquark pairs carry a significant fraction of its spin.

The importance of quark orbital angular momentum, which one might have taken to vanish in the ground state, has been evident since the work of Sehgal. In the so-called Skyrme model, where the nucleon is a soliton in the pion field, Σ is very small, so that nearly all of the nucleon's spin comes from quark orbital motion within pions.[17] But because the Skyrme model has many problems with more traditional hadronic phenomenology, no one takes it very seriously as a way out of the spin crisis.[18]

Of the various components of the nucleon spin in equation 6, only Σ has been measured. No one knows how to measure the orbital terms. ΔG can be measured in deep inelastic scattering experiments in which gluon–gluon or gluon–quark scattering dominates. One of the most interesting suggestions to come out of the spin crisis is that ΔG may contribute significantly to the nucleon spin.[19]

Deep theorems about nonrenormalization of conserved charges ensure that *differences* of quark spin fractions, such as $\Delta u - \Delta d$, must be quite independent of Q^2. The same is not true for the sum Σ. The famous triangle anomaly spoils the conservation of the flavor-independent axial current in QCD, thus allowing Σ to depend on the momentum transfer. The theory lets us calculate this dependence at large Q^2 but not when Q^2 is small. Physically, as the resolution of one's probe becomes finer with increasing Q^2, a spin-up quark, let us say, resolves into a quark and a cloud of gluons, including a component in which the quark has spin down. Because all quarks suffer this sort of "anomalous depolarization" equally, the effect cancels from differences but persists in the sum Σ.

The momentum-transfer dependence of each quark spin fraction is associated with the gluon spin distribution. The up-quark contribution Δu, for example, is given by

$$\Delta u(Q^2) = \Delta u_0 - \alpha_s(Q^2) \, \Delta G(Q^2)/2\pi$$

where Δu_0 is the Q^2-*independent* component of the up-quark spin fraction. Some have proposed that Δu_0, Δd_0 and Δs_0 should be identified with the values from the naive quark model, with Δs_0 taken to be zero. Then the anomalously small experimental value of Σ could be explained by a large (positive) gluon spin contribution ΔG. Unfortunately this proposal has technical problems. It turns out that such a decomposition is inherently ambiguous: The Q^2-independent spin-fraction components cannot be independently measured. But the possibility that gluons carry a significant fraction of the nucleon spin is an interesting one that can be tested experimentally.

Strangeness in the nucleon

Several new programs have emerged from studies motivated by the spin crisis. Two of them deserve special mention: the search for strangeness in the nucleon and the study of *transverse* deep inelastic spin effects. The

presence of strange-quark pairs in the nucleon challenges a venerable piece of QCD folklore known as the Okubo–Zweig–Iizuki rule. The OZI rule would have us believe that the only "important" quarks in a hadron are the valence quarks required to produce its quantum numbers. Small violations of the OZI rule have been known for a long time. Deep inelastic data available since the early 1970s require that strange–antistrange quark pairs carry $2.6 \pm 0.6\%$ of the nucleon's linear momentum, a small but nonzero amount. But we now know that $\Delta s = -0.190 \pm 0.056$, which makes $\bar{s}s$ pairs much more important contributors to the nucleon's intrinsic *angular* momentum.

These numbers can be related to the expectation values of strange-quark operators in the nucleon state. Expectation values of other strange-quark operators, such as the strangeness radius and the strangeness magnetic moment of the proton and neutron, generate very small parity-violating asymmetries in low-energy *elastic* electron scattering. High-precision experiments to measure these strange components of the nucleon wavefunction are under way at MIT's Bates Electron Accelerator and in preparation at the new CEBAF high-intensity electron accelerator, in Newport News, Virginia.

We've learned so much from the study of deep inelastic scattering of longitudinally polarized leptons and hadrons. So what about transverse polarization? It has been known since the early 1970s that transverse and longitudinal spin effects in deep inelastic lepton scattering differ from each other only by corrections that vanish like $1/\sqrt{Q^2}$. These differences are summarized by a structure function denoted by $g_2(x, Q^2)$, measured by scattering longitudinally polarized electrons from a target polarized transverse to the beam. We now understand enough about QCD at short distances to be very interested in g_2. The so-called Burkhardt–Cuttingham sum rule predicts that its integral over all x must vanish. In general, g_2 probes spin-dependent quark–gluon correlations in the nucleon. It should provide detailed guidance for theorists building sophisticated models of hadron structure and benchmarks for those who try to compute hadron properties on supercomputers. The first g_2 measurements should be announced by experimenters at CERN and SLAC this year. More-precise values will become available when the HERMES experiment, employing polarized internal gas targets in the electron storage ring at HERA in Hamburg, gets under way later this decade.[20] (See PHYSICS TODAY, November 1994, page 19.)

Remarkably, the dominant transverse spin effects in QCD were missed by early workers. First recognized by John Ralston and David Soper at the University of Oregon in 1979,[21] they are summarized by another structure function, now known as h_1, which measures the distribution of quarks polarized along or against the spin of a nucleon polarized transverse to its momentum. This structure function does not couple to electron scattering, but it dominates transverse spin effects in deep inelastic processes with purely hadronic initial states, for example, the production of wide-angle muon pairs in high-energy pp collisions. It remained obscure until it was rediscovered by theorists working on the spin crisis.[22] If h_1 can be measured, it will provide a contrast with g_1. In nonrelativistic systems they are identical. Therefore h_1 tells us just how relativistic the quarks in the nucleon are. That's a question of some controversy among theorists. Proposals to measure h_1 include muon-pair production in polarized pp collisions in the Relativistic Heavy Ion Collider under construction at Brookhaven[23] and pion production in polarized electron–proton collisions at HERMES.

This cursory survey cannot do justice to the rich array of experimental programs that have developed in response to the spin crisis. It is not unfair to say that several fields of hadron physics, such as deep inelastic high-energy scattering and precision low-energy elastic scattering, have been reinvigorated by the attempt to understand the spin structure of the nucleon. Theorists, however, are still playing catch-up, hoping to build a more robust and sophisticated model of nucleon substructure that can predict the rich array of spin phenomena now accessible to experiment.

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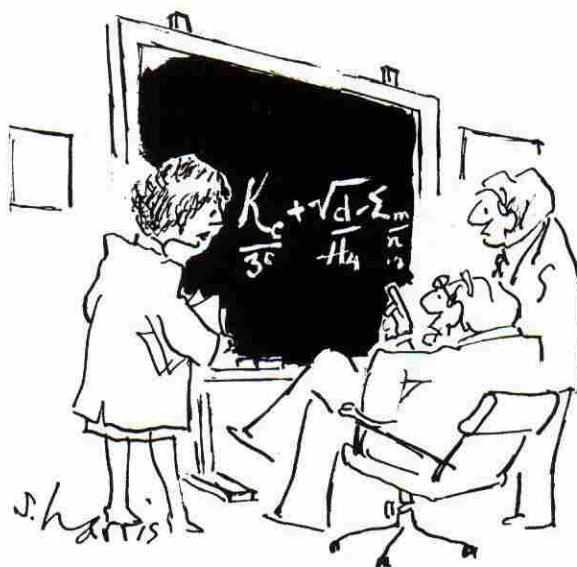
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