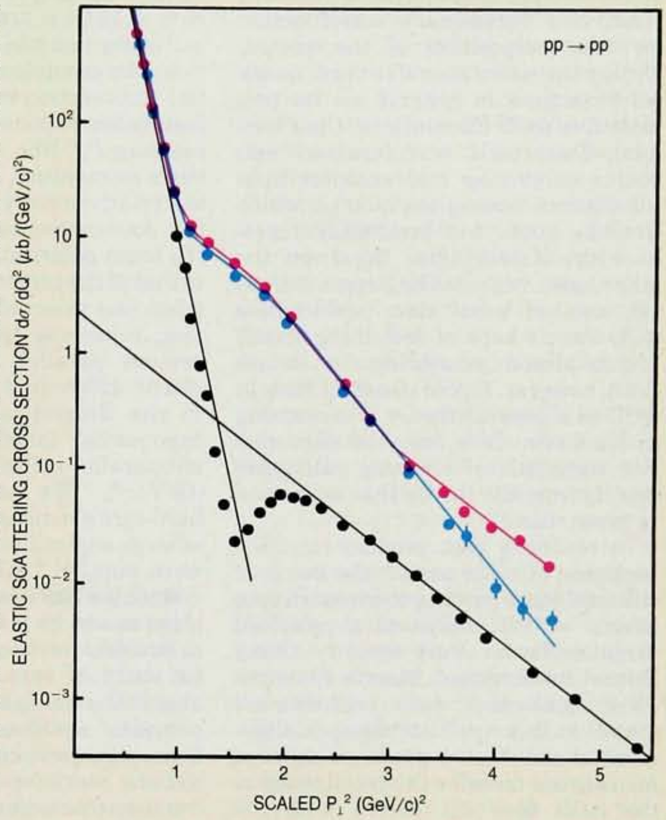
Polarized scattering data challenge quantum chromodynamics

It is a truism of elementary-particle theory that spin effects become negligible at high energy and large momentum transfer in collisions between protons—or any other spinning hadrons. But it doesn't appear to be true. For almost a decade now, Alan Krisch (University of Michigan) and his coworkers have been accumulating experimental evidence that spin–spin and spin–orbit interactions are far from negligible in large-angle proton–proton elastic scattering at high energies. Their most recent data[1] with an unpolarized 28-GeV proton beam hitting a polarized target at the Brookhaven Alternating Gradient Synchrotron indicate a quite spectacular and unanticipated growth of left–right asymmetry (a spin–orbit effect) as one looks at ever larger scattering angles. Two months ago[2] this Mighigan, Brookhaven, Notre Dame, Rice, Texas A&M, Zurich collaboration reported its first data taken with a polarized proton beam at the AGS—the first time a polarized beam has been achieved in a high-energy, strong-focusing proton synchrotron.



A polarized beam of protons scattered elastically off a polarized proton target manifests unexpectedly large spin–spin effects at large momentum transfer. The colored data points were taken with a vertically polarized 12-GeV proton beam at the ZGS. The abscissa gives the squared transverse momentum of either scattered proton, slightly scaled by a factor close to unity that suppresses dependence on beam energy. At large transverse momentum, the cross section is significantly larger when the two spins are parallel (red) than when they are antiparallel (blue). For comparison, we show *unpolarized* pp elastic scattering data from CERN at 10 times higher cm collision energy.

"We have absolutely no explanation for the Krisch data," confesses Stanford theorist Stanley Brodsky. Brodsky and Peter Lepage (Cornell) have achieved very considerable success in explaining and predicting a broad range of high-energy nonspin data in terms of quantum chromodynamics. QCD, as it is called, has become the widely accepted "standard theory" of the strong interactions. "These data may become our Achilles heel." In fact, spin-dependent effects have once before been decisive in killing a popular theory of the strong interactions. After Regge-pole theory had achieved spectacular success in describing a broad range of differential-cross-section data, a number of polarization measurements in the late 1960s and early 1970s dealt the theory a succession of embarrassments from which it never quite recovered.

While QCD theorists do not believe that the Krisch data place the standard theory in mortal danger, the polarized-proton data have underscored a lively dispute regarding the applicability of *perturbative* QCD methods at finite values of momentum transfer. As its name suggests, QCD is formulated in close analogy to quantum electrodynamics, the uniquely successful theory of the interaction of photons with electrons. But because the "strong coupling constant" α_s of QCD is of order unity, one cannot unquestioningly use the perturbation-series expansion methods that work so well in QED, where the coupling constant is the fine-structure constant, $1/137$. That is to say, while the exchange of two virtual photons between electrons is $(1/137)^2$ less likely than the exchange of a single photon, the analogous exchange of two gluons between quarks in QCD is (at least at low momentum transfer) no less probable than the exchange of a single gluon. Higher powers of a large coupling constant do not render higher-order Feynman diagrams negligible.

Thus one has a theory with which one can do explicit calculations only under restricted circumstances. The question now being hotly debated is: How restricted are these circumstances? At the Washington APS meeting in April, the champions of the two opposing schools of thought confronted one another. Following a talk in which Brodsky argued that perturbative QCD should be applicable in most cases where momentum transfer exceeds a few GeV/c, Nathan Isgur (University of Toronto) made an emphatic case for the uselessness of perturbation methods for "exclusive" reactions (where all outgoing particles are specified) at any value of momentum transfer accessible to experimenters now or in the forseeable future. "If he's right, it's very sad," says Brodsky wistfully. "We would lose much of the theory's predictive power and testability." Isgur agrees. They agree on very little else.

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Spin effects are extremely difficult to calculate, even in perturbative QCD. At first glance, the theory appears to support the conventional wisdom that spin effects must vanish at large momentum transfer—basically because the QCD Lagrangian specifies that sufficiently hard collisions between quarks preserve helicity (the projection of a particle's spin on its direction of motion). But Brodsky points with optimism to the recent spectacular success of V. L. Chernyak and A. R. Zhitnitskii at Novosibirsk in deriving a realistic, relativistic three-quark wavefunction for the composition of the proton. Unlike the naive nonrelativistic quark wavefunctions in general use for perturbative QCD calculations, the Chernyak–Zhitnitskii wavefunction embodies surprising and complex spin correlations among the quarks, which Brodsky hopes will eventually reproduce the Krisch data. Isgur, on the other hand, regards the Krisch data as yet another proof that perturbative QCD has no hope of describing elastic proton–proton scattering in detail. Both, however, repose steadfast faith in QCD as a general theory of the strong interactions. It is only the perturbative technique of wresting calculable results from the theory that is at issue between them.

In reactions that produce unstable particles, one can exploit the decay of the final-state particle to measure spin effects without resort to a polarized target or beam. Very recently, Gerry Bunce (Brookhaven), Marvin Marshak (Wisconsin) and their collaborators found[3] in this way that the spin alignment of rho mesons produced at large momentum transfer in πp collisions at the AGS does not accord with the straightforward expectations of perturbative QCD. A similar challenge to QCD is posed by the ten-year-old Fermilab data of Bunce, Lee Pondrom (Wisconsin) and company, which demonstrated the persistence of strong polarization in hyperons produced at high energy and large momentum transfer.

Polarized targets and beams, if one has both, allow one to compare, for example, proton–proton scattering cross sections for different spin states of the two-proton system. Just such an experimental setup was available to Krisch and his collaborators at the Argonne National Laboratory's Zero Gradient Synchrotron until the ZGS was shut down in 1979. With a polarized proton beam capable of energies up to 12 GeV and a polarized proton target, the Michigan–Argonne collaboration observed differences in total cross sections and elastic-scattering differential cross sections between different polarization states of the colliding protons. At beam energies of a few GeV, differences in total cross section between parallel and antiparallel two-spin configurations in proton–proton collisions present no fundamental problem for high-energy theory. Low-energy scattering mechanisms (resonances, threshold effects and the like) are expected to depend on whether the two protons form a spin singlet or triplet.

But the persistence, and even growth, of spin-dependent effects in pp elastic scattering as one goes to higher energies at large scattering angles begins to be a major theoretical challenge. Looking at elastic scattering with a 12-GeV proton beam polarized vertically (normal to the beam direction), the group found that the differential cross section exhibited a relatively featureless exponential falloff with increasing $P_\perp^2$ (the square of the transverse momentum, roughly equal to Q^2, the relativistically invariant square of the four-momentum transfer), when the beam polarization was *antiparallel* to that of the target. The surprise came when one reversed the beam polarization, rendering the spins of the two protons parallel. In that case the elastic differential cross section began to rise dramatically away from the exponential falloff exhibited by the antiparallel collisions at $P_\perp^2$ above 3 $(\mathrm{GeV}/c)^2$. "We seemed to be seeing a hard-core elastic scattering component at large angles, but only when the spins were parallel," Krisch recalls.

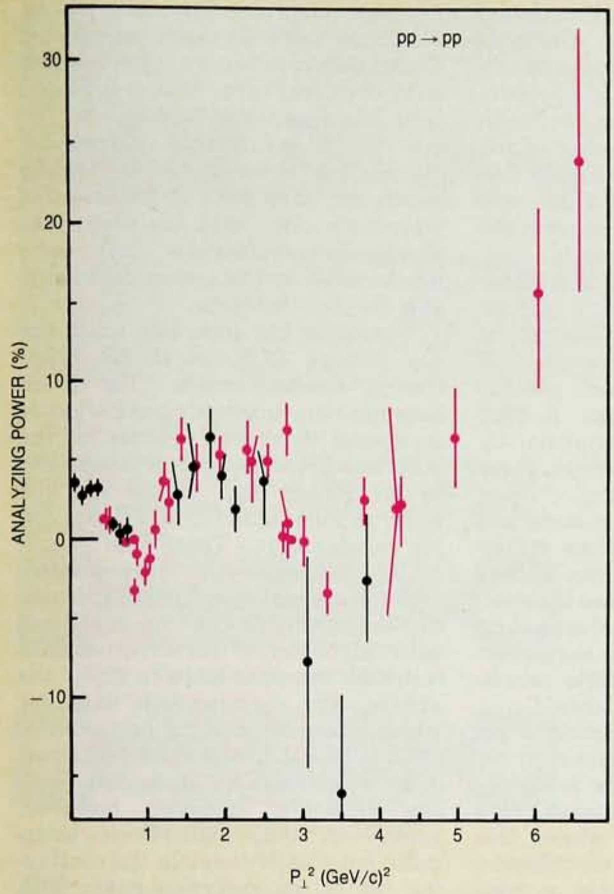
When the ZGS was retired, the collaboration moved its polarized proton target to Brookhaven to continue its systematic study of spin effects in large $P_\perp$ elastic scattering at the AGS. The AGS provides significantly higher proton beam energies—up to 28 GeV—than did the weak-focusing Argonne ZGS, but the achievement of polarized beams at a strong-focusing proton synchrotron has been a prodigious technological challenge. Before last summer, the collaboration took its data at Brookhaven only with an unpolarized proton beam.

To achieve a polarized beam in a proton synchrotron, one begins with a polarized ion source. But the spin orientation of the protons must be maintained over a circulating journey of several hundred thousand miles through bending and focusing magnets during the acceleration cycle. In a zero-gradient (weak-focusing) synchrotron, where the beam sees very little horizontal magnetic field strength, this is not a great difficulty. But the strong-focusing design of machines such as the AGS, which facilitates the accommodation of higher-energy beams, requires quadrupole focusing magnets spaced around the ring. The strong horizontal fields of these quadrupoles tend to flip the spin of vertically polarized beam protons. A vertically polarized proton will precess about the vertical fields of the accelerator ring's bending magnets. If this precession frequency is in resonance with the frequency of the proton's repeated encounters with the horizontal quadrupole fields, the beam quickly loses its polarization. To circumvent the numerous depolarizing resonances the proton beam would encounter during the AGS acceleration cycle, special ultrafast "resonance-jumping" quadrupole magnets have been placed strategically around the ring. They are required to come up to 20 megawatts of power on time scales of a microsecond, permitting the beam to jump through successive resonances on the way to full energy. "The development of these ultrafast, high-power quadrupoles, by Larry Ratner (Brookhaven) and other members of the collaboration, is a significant technological achievement," Krisch told us. A similar undertaking at CERN, to provide polarized beams at the Proton Synchrotron, a machine very much like the AGS, was dropped some years ago, partly because of doubts that the resonance-jumping scheme would work, and partly because of theoretical skepticism as to the existence of interesting spin physics at those energies.

Before the polarized beam became available at the AGS last summer, the collaboration was able to plague the theorists with intriguing new spin-effect data, using only a polarized proton target. Proton–proton collisions are, of course, parity conserving. But if the target protons are polarized perpendicular to the beam, it is not a violation of parity to find a left–right asymmetry of scattered particles in the beam plane normal to the polarization direction. The fractional left–right asymmetry observed in such scattering (divided by the percentage polarization of the target, which is always less than 100%) is referred to as the "analyzing power" of the scattering system.

From 1982 through 1984, Krisch and his collaborators at Brookhaven were able to measure the analyzing power of 28-GeV pp elastic scattering at ever-higher values of $P_\perp$. The experimental task becomes increasingly arduous as one goes to higher and higher $P_\perp$—corresponding, at fixed beam energy, to ever-larger scattering angles—because the differential cross section falls very steeply with increasing $P_\perp$. To get usable counting rates at $P_\perp^2$ above a few $(\mathrm{GeV}/c)^2$, one needs to bombard the polarized target with a very intense proton beam. This has two serious adverse consequences for the polarized target: It creates crystal damage centers in the target pellets, and it subjects the cryogenic target to a severe heat load.

Both these problems have been overcome in the last two years by modifying the traditional polarized target oper-



The analyzing power of pp elastic scattering, as measured with vertically polarized proton targets at Brookhaven (28 GeV, color) and CERN (24 GeV, black). The high-transverse-momentum points measured in the last two years by Krisch and collaborators indicate a quite unexpected growth of the analyzing power (the fractional left–right scattering asymmetry, a spin–orbit effect) with increasing momentum transfer.

ation, providing now target polarization levels of 60% with incident beam intensities exceeding 3×10^{10} protons per second. The protons to be polarized in these target pellets are hydrogen nuclei in some hydrogen-rich compound—antifreeze or ammonia. The brute-force approach to polarization—very low temperature and high magnetic field—is frustrated by the very small magnetic moment of the proton. The trick in use since the early 1960s is to take advantage of the fact that electrons, being much lighter, have a 660-times larger magnetic moment than protons.

Somehow one introduces unpaired electrons into the target pellet, polarizes them by brute force, and then transfers the spin polarization to the nearby hydrogen nuclei by microwave induction of an appropriate transfer transition. The traditional method has been to dope the target pellets with chromium compounds that have unpaired inner-shell electrons—"a difficult, black art," Krisch told us. But the cumulative radiation damage due to intense proton bombardment quickly renders these chemically doped target pellets ineffective. The new technique is to make a virtue of radiation damage. Subjecting the undoped target pellets to prolonged bombardment by an electron linac, it turns out, somehow provides a high and persistent level of unpaired, polarizable electrons without any chromium doping.

The second problem, carrying away the heat load imposed by the intense proton beam, has now been dealt with by adding some liquid He^4 to the traditional He^3 refrigerant. He^3 gets one down to the necessary 0.5-kelvin temperature (in a field of 25 kilogauss), but its heat capacity is rather limited. Adding some He^4 turns out to improve greatly the heat-removal capacity of the cryogenic system. Being a superfluid, He^4 "crawls all over everything," and besides, its heat capacity is much larger than that of He^3.

Surprise. As the collaboration has made its way laboriously to ever-larger $P_\perp{}^2$ in 28-GeV pp elastic scattering, its findings fly ever more disturbingly in the face of conventional wisdom. Below 4 $(\mathrm{GeV}/c)^2$ the measured analyzing power oscillates around zero, but then it takes off. At 6 $(\mathrm{GeV}/c)^2$ it exceeds 15%, and last summer the group reported a preliminary measurement of $51 \pm 17\%$ at 6.5 $(\mathrm{GeV}/c)^2$, setting off a flurry of astonishment. With increasing statistics, that number has now come down to a somewhat less spectacular $24 \pm 8\%$. But the theorists are nonetheless taking note. No one expected to find such large and growing spin-orbit effects at such high values of momentum transfer.

"Theorists are adept at arguing away unpleasant differential-cross-section data by fiddling with form factors," Krisch suggests. "But spin data are harder to fiddle with. You see a change when the experimenter does nothing more than flip a spin direction. That can't be accounted for by modifying the presumed shape of the particle.

Isgur and Llewellyn Smith. Proton–proton elastic scattering is an example of what one calls, in the trade, an exclusive reaction. One has specified all the particles in the final state. "Deep inelastic" electron–proton scattering, by contrast, is an "inclusive" reaction; one specifies only the outgoing electron, its four-momentum transfer squared (Q^2) and its energy loss in the collision. One ignores all the other particles in the final state, except for insisting that the collision was inelastic—the struck proton has been broken up into a system of two or more hadrons, which one doesn't measure. Deep inelastic lepton–proton scattering represents an undisputed triumph of perturbative QCD. The triumphs claimed for the perturbative theory by Brodsky and like-minded theorists in exclusive reactions, Isgur tells us, are illusory.

Isgur and Christopher Llewellyn Smith (Oxford) last year undertook[4] to define the limits of applicability of perturbative QCD. If the strong coupling constant were truly a constant of order unity, one could never hope to apply a perturbation series in powers of α_s with any hope of convergence. But because, unlike QED, QCD is a non-Abelian theory whose quanta (gluons) carry the charge (color) of the theory, the effective coupling constant varies with the momentum a quark transfers to the gluon it emits. At small Q^2 the coupling constant is indeed about 1. As Q^2 goes to infinity, however, the effective coupling vanishes. This is often described as "infrared slavery and asymptotic freedom." The momentum transfer is the Fourier conjugate of the distance between interacting quarks; large Q^2 corresponds to close encounters, and small Q^2 implies large distances. The color force between quarks becomes infinitely strong at large distances, explaining their rigorous confinement in hadrons. When probed at small distances inside a hadron, on the other hand, quarks behave almost as if they were free.

For Q^2 between a few $(\mathrm{GeV}/c)^2$ and a few hundred $(\mathrm{GeV}/c)^2$, the effective strong coupling constant is of order 0.1. This is the regime in which theorists have traditionally labored to explain and predict experimental scattering data with perturbative QCD. In such large-momentum-transfer processes, two mechanisms are operative: the "hard" gluon exchanges that describe the violent close encounters between individual quarks, and the longer-range "soft" processes that ensure quark confinement. The former, involving large Q^2 and hence a small effective coupling constant, are amenable to perturbative treatment; the latter are not.

In exclusive reactions, Isgur and Llewellyn Smith argue, the perturbative hard-scattering mechanism is always in competition with the nonperturbative confinement processes required to nudge the quarks neatly into the specified final-state hadrons. QCD tells us that the nonperturbative component falls by at least a factor of Q^2 faster with increasing momentum transfer than does the perturbative component. Thus, the conventional wisdom has it, for Q^2 larger than a few $(\mathrm{GeV}/c)^2$, the perturbative component will dominate and the process is calculable. For inclusive reactions, where the final state is left largely unspecified, the confinement mechanisms offer no such competition.

But Isgur and Llewellyn Smith contend that this conventional picture ignores an additional cost imposed by each hard gluon exchange. Every large-Q^2 gluon exchange required by the perturbative mechanism of a given reaction suppresses the perturbative amplitude by a factor of α_s—which at large Q^2 means an order of magnitude. The factors of α_s involved in the confinement component, by contrast, are of order unity; they produce no such suppression. Thus, in an exclusive reaction requiring the exchange of n hard gluons, the requirement for perturbative dominance becomes: $(\alpha_s)^n Q^2$, or equivalently $10^{-n} Q^2$, must be larger than a few $(\mathrm{GeV}/c)^2$. With this new rule of thumb, "Asymptopia is simply out of reach in any present or forseeable exclusive experiment," Isgur told his Washington audience. At the largest accessible momentum transfers, the nonperturbative confinement component will remain dominant.

Higher beam energies won't solve the problem, Isgur told us; one is limited by counting rate. If one measures pp elastic scattering at fixed large angle as one increases the beam energy, for example, the differential cross section falls like Q^{20}. Doubling the center-of-mass collision energy would quadruple Q^2 at 90°, but that would suppress the counting rate by a factor of a trillion!

Defending the faith. Brodsky points to the many successful predictions perturbative QCD has already claimed for exclusive-reaction data. The proton's magnetic form factor, for example, as measured in elastic electron–proton scattering, falls like Q^{-4}, just as predicted by perturbative QCD. (Electron–proton scattering is of course electromagnetic, but the form factor describing the distribution of hard quark scatterers in the proton is governed by hadronic interactions.) Isgur counters that this success is illusory. The measured proton form factor *looks* nearly flat when multiplied by Q^4, he concedes; but this, he and Llewellyn Smith calculate, is a transient feature of the competition between perturbative and confinement mechanisms, which will go away when higher-momentum-transfer data become available.

Brodsky also invokes new SLAC data on $\gamma\gamma \to \pi^+\pi^-$ and K^+K^-. (These "two-photon" interactions are not, of course, collisions between real photons, but rather between virtual photons emitted in e^+e^- collisions.) A 1981 perturbative QCD calculation by Brodsky and Lepage describes these new data extraordinarily well. "These data probe the meson form factors, and they test the entire formalism of perturbative QCD." The Brodsky–Lepage calculation not only predicted the energy-dependence of the two-photon data correctly. "We also got the normalization right, with no adjustable parameters, which is far from trivial."

The Isgur–Llewellyn Smith argument about coupling-constant suppression in exclusive reactions is simply misconceived, Brodsky contends. "It's difficult to understand where this dominance of the soft contribution would come from. There are no mass scales in QCD that could postpone the onset of the perturbative regime. It's an outrageous idea that exclusive reactions are so different."

Brodsky attributes the "apparent" success of Isgur and Llewelyn Smith in fitting the proton form-factor data with a dominant nonperturbative component to their use of a conventional, excessively naive, nonrelativistic three-quark wavefunction for the proton. This wavefunction has the three constituent quarks sharing the proton's momentum symmetrically among themselves. The important new result[6] of Chernyak and Zhitnitskii, Brodsky told us, shows that the quarks, in fact, play very asymmetric roles in the relativistic domain. Fully two-thirds of the momentum is carried by the one "up" quark (charge $+\frac{2}{3}$) whose spin is parallel to the proton's momentum. In contrast to the rigorously relativistic wavefunction derived by Chernyak and Zhitnitskii, Brodsky contends, that of Isgur and Llewellyn Smith is "made up *ad hoc*" to achieve the desired result.

The Chernyak–Zhitnitskii wavefunction, with a far more complex quark spin structure than previously imagined, Brodsky suggests, might well conspire with other mechanisms to yield the surprising spin effects observed by Krisch and his collaborators. No one has as yet undertaken to calculate pp elastic scattering with the new relativistic wavefunction. "It involves more than a hundred thousand Feynman diagrams," Brodsky told us. The most difficult such calculation undertaken to date is $\gamma\gamma \to p\bar{p}$, calculated by Glennys Farrar (Rutgers), Filippo Neri (Maryland) and Ezio Maina (Torino). When they used the symmetrical, nonrelativistic wavefunction, Brodsky points out, they were off by orders of magnitude. But with the Chernyak–Zhitniksii wavefunction they came much closer to the sparse data available for this reaction.

"I suppose the spin data could one day defrock QCD, as it did Regge theory," Brodsky muses. "The Krisch data are very interesting, with lots of intriguing structure." Farrar, on the other hand, sees nothing very surprising in the Krisch data or the rho and hyperon polarization data of Bunce and his collaborators. These spin effects, which measure the interference between helicity-conserving and non-conserving amplitudes "are consistent with 'higher-twist' perturbative QCD terms on the order of 10 to 20%," she argues. The deep-inelastic data, for which everyone expects perturbative QCD to be valid, also indicate higher-order amplitudes at about this level, she contends. Brodsky, however, points out that higher-twist terms could not possibly explain the continuing *rise* of the analyzing power with increasing $P_\perp$ in the figure on page 19. It comes down to whether one believes that this trend indicated by the recent Krisch data is real.

"These are exciting times," says Brodsky. "If Chernyak and Zhitnitskii are right, we've had our first look at the real three-quark wavefunction inside the proton." He professes to "love the debate" with Isgur and Llewellyn Smith. "It focuses attention on a very important issue in QCD. We're beginning to be able to use QCD in a predictive way, and it's useful to have such critics looking over our shoulders and asking 'Are you sure?'" —BMS

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