HUNTING THE PR

by EMLYN HUGHES

SLAC and CERN have led the search

for what carries the spin of the proton

and neutron.

ONE OF THE GREAT CHALLENGES in high energy physics is to understand the proton. On the one hand, the proton is a very simple, basic object. It has a definite mass and spin. It has a lifetime measured to be older than the Universe. Protons are abundant and are one of the most basic building blocks of matter. On the other hand, the proton has an extremely complicated internal structure. To the particle physicist it is so complicated that it cannot be regarded as a fundamental particle. The proton consists of quarks with different flavors and gluons of different colors, all moving inside it with mysterious dynamics. Quarks are confined to be inside the proton for reasons still not understood. In fact, the "confinement" problem is one of the great unsolved mysteries. In an attempt to understand how the proton works, physicists aim to connect the simple, fundamental properties of the proton to its complex, internal structure.

Many high energy physicists in two subfields study what the proton is made of and how it works. The first uses an enormous circular accelerator to excite electrons and protons to high energies and then collide them with one another. By breaking the proton at the highest energies possible, one can extract information on what is inside. The colliding protons at HERA at the DESY laboratory in Hamburg, Germany, have energies of 800 billion electron volts (800 GeV) whereas the energy of the electrons is 30 billion electron volts (30 GeV). This exciting new project began only a few years ago and was reviewed by Franz Eisele and Günter Wolf in a *Beam Line* article, "Looking Deeper Inside the Proton," in Vol. 24, No. 3, 1994.

A second major endeavor using high energy particle accelerators is directed at studying the proton's substructure in order to extract what is responsible for its spin of 1/2. This particular effort has become extremely exciting

since 1988 when it was found that the quarks inside the proton do not account for its spin. Before diving into this topic, it is worthwhile to review the spin of elementary particles.

Spin has played a unique role historically. It was first postulated by George Uhlenbeck and Samuel Goudsmit in 1925 in order to explain the hyperfine splitting in the atomic spectra of hydrogen. The mystery at the time was why the number of energy levels was twice as many as expected. Wolfgang Pauli postulated that the electron might have an additional quantum number that accounted for the splitting, whereas Goudsmit and Uhlenbeck postulated that the new quantum number should have a value of 1/2, and they named it "spin." Soon afterwards the proton and neutron themselves were found to have spin of 1/2 along with other atomic nuclei. This realization added fuel to the quantum mechanics revolution and created a field of study on the spin dependence of elementary particles. Today the spin of all elementary particles is regarded as a fundamental quantum number which takes on discrete values that are some multiple of 1/2, namely 0, 1/2, –1/2, 1, –1, 3/2, –3/2,….

Among all elementary particles, nature is further divided into two classes depending on spin. One class is those with half-integral spin called fermions (1/2, 3/2, 5/2, . . .) and the other is those with integral spin called bosons (0, 1, 2, . . .). These two classes have fundamentally different behaviors. For example, fermions obey the Pauli exclusion principle, which states that no two identical fermion particles can be in the same state. Bosons do not obey this rule. They can, in fact, clump together and form superatoms that exhibit bizarre behavior. Atomic cooling techniques have recently, for example, created such superatoms at temperatures on the order of 10 nanokelvin. In the study of particles and their interactions, most elementary particles used in the high energy laboratories are fermions, whereas the force carrying the interaction between these particles come from bosons. For example, we

accelerate protons, electrons, or muons (all spin 1/2) to high energies, and we study their interactions to learn about the strong or electroweak interaction via the exchange of photons, *W* bosons, or *Z* bosons (all spin 1).

In the particular case covered in this article, the study of the proton's spin is taking place using high energy electrons and muons scattering off proton and neutron targets. The boson responsible for this interaction is the photon, the particle that gives us light. There are several basic questions relevant to the internal spin structure of the proton: What is carrying the spin of the proton? Does the present theory of strong interactions, named for the sake of simplicity "quantum chromodynamics," or QCD for short, account for the behavior of the proton? Can we understand what inside the proton gives it spin and why? This is where the proton spin story begins.
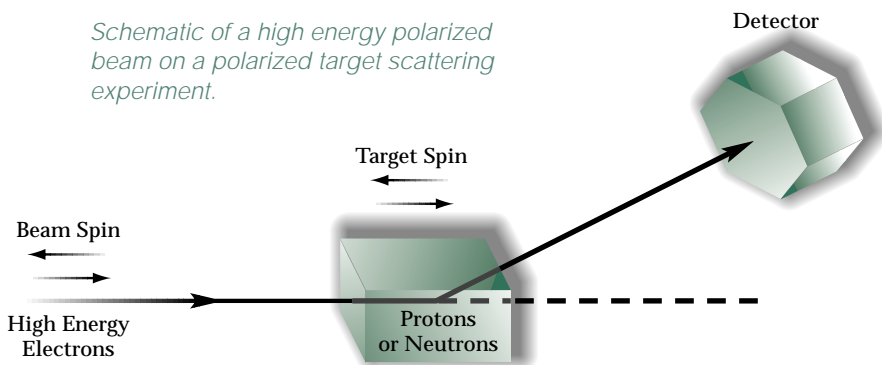
THE EMC SPIN EXPERIMENT

As a graduate student working at CERN, the European particle physics laboratory in Geneva, Switzerland, I spent a few nights rambling through the Old Town pubs. Joining me on the excursions was my friend and fellow graduate student, Vassili

Papavassiliou. Vassili was a student at Yale working with my father, so our overlap had some humorous aspects. Although we discussed on a superficial level what he was doing, I confess that I did not absorb his enthusiasm for his thesis topic.

At the time I was performing one of the "hot" high energy fixed-target particle physics experiments. My thesis experiment used a high energy neutrino beam to measure the mixing between the weak and electromagnetic interactions. The measurement was performed immediately following the 1983 discovery at CERN of the *W* and *Z* bosons. The electroweak theory was established, soon to win CERN its first Nobel Prize in physics, and my experiment was going to be one of the first experimental tests of the radiative corrections to the electroweak theory. In retrospect, the result came out as expected—solid, but little excitement—not exactly a Nobel candidate.

In contrast, Vassili was pursuing the measurement of something called the proton spin structure function, using a high energy muon beam scattering off an enormous ultra-cold liquid ammonia target. Vassili was remeasuring some structure function that had first been extracted at the Stanford Linear Accelerator Center (SLAC) ten years earlier (E80,E130). To me, characterizing some complicated internal behavior of the proton and reconfirming its quark parton model predictions seemed on the dull side. I could not have been more wrong. The fallout from Vassili's thesis experiment, the measurement of the proton spin structure function, is still felt today, a decade later.

Schematic of a high energy polarized beam on a polarized target scattering experiment.

Detector

Target Spin

Beam Spin

High Energy Electrons

Protons or Neutrons

The EMC experiment (mentioned above) took a high energy muon beam produced by colliding high energy protons off a solid target at the CERN accelerator and selected the muon energies in such a way that the spin of the muon pointed along its momentum. There is some magic here. The muon spin will point in a particular direction when the muon originates from the decay of heavier particles called pions and kaons, and then a particular momentum of the muons is selected. The magic comes from the violation of parity in the weak interaction decay of the pions and kaons. But this is a story in itself—grounded in Nobel Prize winning work by T. D. Lee and C. N. Yang at Columbia in 1956.

The muon beam is directed onto a polarized ammonia target in which the protons in the ammonia have their own spins aligned either parallel or anti-parallel to the muon beam direction. In the experiment one records the outgoing scattered muons from the beam-target interaction. It is worth thinking of this as just a gigantic Rutherford scattering experiment, except one that is now keeping track of the relative spin directions of the beam and target (see diagram on the left). After one year of collecting data, the EMC experimentalists analyzed a few million events and extracted the proton spin structure function in a new kinematic region probing deeper inside the proton with this 200 billion electron volt (200 GeV) muon beam.

Why did the EMC result generate so much excitement? It was found at SLAC in the late 1970s and early 1980s that the number of scattered beam particles was larger when the beam

and target spins are anti-parallel, compared to parallel. This was expected from the quark parton model and essentially followed the fact that the quarks inside the proton themselves line up in the direction of the proton's spin. A simplistic view of the proton is shown on the right. It was thought that when the muons interacted and transferred a large energy to the proton, the proton would break up and the fraction of spin carried by the broken pieces would be less than by the entire proton. So the spin dependence would get smaller at higher energies. What was surprising was that the EMC experiment found that the loss of spin dependence appeared to be happening faster than anticipated. The illustration on the right shows the asymmetries from the proton scattering experiment, comparing a standard quark parton model prediction with the EMC results. At low x (high energy transfer), the data fall consistently below the quark parton model prediction. This subtle effect had enormous consequences.

Armed with the experimental result from EMC, theorists were able to calculate the total spin content of the proton carried by the quarks. The result was close to zero! Quarks were not carrying the spin of the proton. What did? Was the measurement wrong? Was the theory of the strong interactions incomplete? Hundreds of theoretical papers were written. The field exploded and the famous "proton spin crisis" was born.

Here was a wonderful example relating the macroscopic property of the proton, its spin of 1/2, with its substructure, the quark content of the proton. But… it was not working!
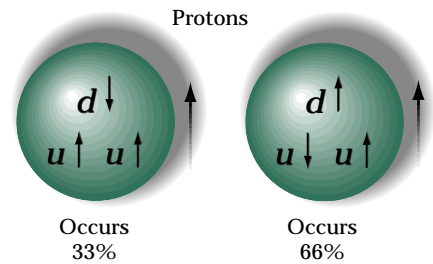
Naive model of the quark spin direction inside the proton.
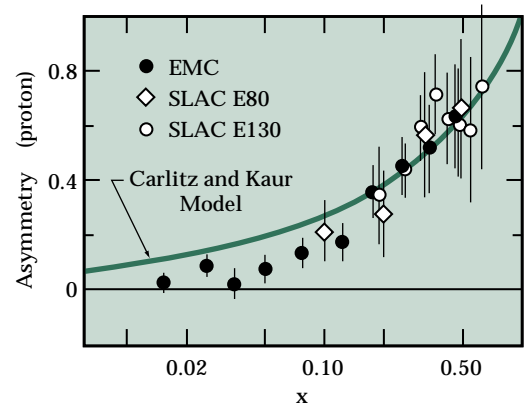
Early results on the proton spin asymmetry measurements compared to a quark parton model prediction. Notice that for small x the data fall below the prediction.

SLAC SPIN PHYSICS PROGRAM

The news of the CERN EMC experiment broke to the international community in the summer of 1987. SLAC reentered the business in 1989.

If the proton's internal structure was giving unexpected answers, then the next question was "what about the neutron?" Besides charge, the neutron is essentially the brother of the proton. In any quark model description, the proton consists of two "up" valence quarks (each with charge +2/3) and one "down" valence quark (with charge −1/3) plus sea quarks and gluons which give no total net charge. The total charge of the proton, naturally, works out to be +1. By a respected principle, called isospin invariance, the neutron is regarded as being identical to the proton except that one interchanges one up quark with one down quark to create a neutron. Therefore, the neutron has two down quarks and one up quark for a total neutron charge of zero.

To address the issue of the proton spin crisis, SLAC first sought to measure the neutron spin structure function. The experiment, E142, required reopening the fixed-target facility that had not operated at high energies since the early 1980s. E142 required a 23-GeV polarized electron beam using the entire accelerator to achieve the full energy. Luckily, the polarized beam facility already existed and worked reliably owing to the enormous effort invested in polarizing the electron beam for the Linear Collider project, the flagship at the time. The beam was directed into End Station A where it scattered off a polarized ^{3}He target. The scattered electrons were then detected in a spectrometer that determined the scattered electron's energy after the interaction (see diagram on the bottom left).

Why use polarized ^{3}He? It turns out that it is virtually impossible to create a neutron target. Free neutrons live only about ten minutes, and they are hard to contain. In fact, the highest density of neutrons to date comes from those contained in a bottle at ultra-cold temperatures next to a nuclear reactor. In addition, the density is tiny, not enough to perform a high energy physics scattering experiment. Since we cannot produce a free neutron target, we have to use nuclear targets and then infer the contribution coming from the neutrons inside.

The polarized ^{3}He nucleus is an elegant approximation to a polarized neutron. The nucleus of ^{3}He consists of two protons and one neutron. When one polarizes the ^{3}He nucleus, the neutron spin aligns itself in the same direction as the ^{3}He nuclear spin, whereas the two proton spins line up anti-parallel to one another according to the Pauli exclusion principle (see the top figure on the right). Therefore, scattering off a polarized ^{3}He nucleus is equivalent to scattering off a polarized neutron plus

Set-up of the SLAC E142 experiment.
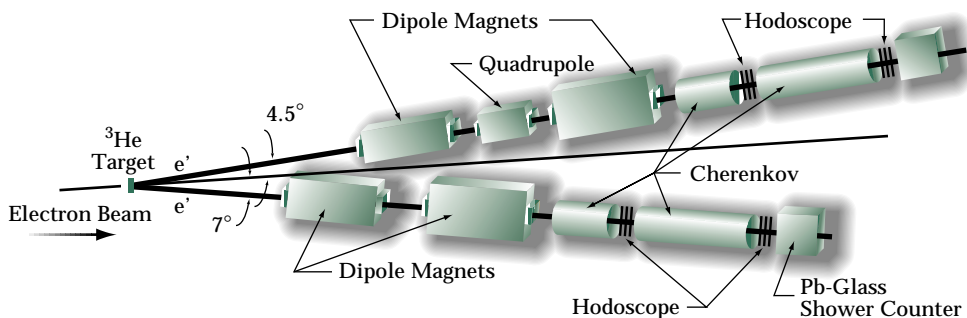
two unpolarized protons on average. Any effect in the experiment that depends on target spin will be largely a result of scattering from the polarized neutron in ^{3}He itself.

Armed with a high density polarized ^{3}He gas target, E142 measured for the first time with relatively high precision the neutron spin structure function. The results were interesting and at first somewhat controversial. The results on proton spin crisis implied that the neutron spin structure results should give large negative asymmetries. However, E142 found small negative results. The difference between expectation and experimental measurement generated controversy in the field. But in parallel, theoretical work on strong interaction corrections was being developed. With these new corrections, the proton and neutron results appeared to be reconciled. Here was a case where the interaction between new experimental results and advances in theoretical work pointed towards a coherent description of the proton and its spin.

A year later in 1993, SLAC ran an incredibly high precision measurement of the proton and deuteron spin structure function in experiment E143 using the facility built for E142. The experiment confirmed both the 1988 EMC proton measurement and the E142 neutron result. The deuteron consists of one polarized proton and one polarized neutron. If one scatters electrons off the deuteron and subtracts the proton result, one gets an independent neutron result. The results from the E143 proton measurement are compared to the EMC result in the bottom right illustration.

The statistically precise data set from SLAC provided by the E142 and E143 experiments represented a major advance in the field. Theoretical corrections became an important ingredient for interpreting the results and developing a consistent picture of the quark contribution to the proton's spin. In parallel with the SLAC program, CERN continued collecting data with an upgraded version of the EMC experiment called SMC (Spin Muon Collaboration). The CERN experiments had a deeper view into the nucleon coming from the 200-GeV beam, but the SLAC experiments had the higher statistical precision. Today the world data sample with modern theoretical corrections appear to give a 30 percent contribution to the proton's spin coming from the quarks. The psychology of the community has evolved since 1988. With an initial result of a quark contribution between 0 and 20 percent, a change to a 30 percent result appears to be viewed as more palatable. Still, where is the rest of the proton's spin?

But the quark story was not over. The experiments at SLAC in 1992 and 1993 suffered from one significant weakness. They were performed at relatively low energies—20 to 30 GeV. Remeasuring the spin structure functions with the high precision and a higher energy beam would help solidify the results and check their interpretations. Theoretical corrections are very energy dependent and become large at low energies. Testing that one gets the same answer with smaller theoretical corrections at high energies was well motivated. In response, SLAC upgraded the beam energy for the fixed-target program to 50 GeV. Although this energy is
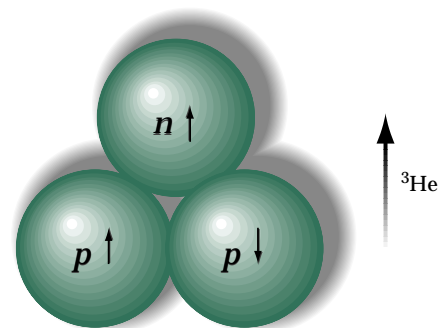
Spin directions of the protons and neutron in polarized ^{3}He.
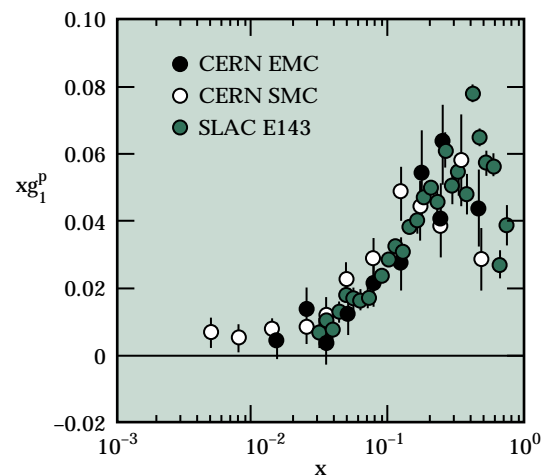
World data on the proton spin structure function versus x.
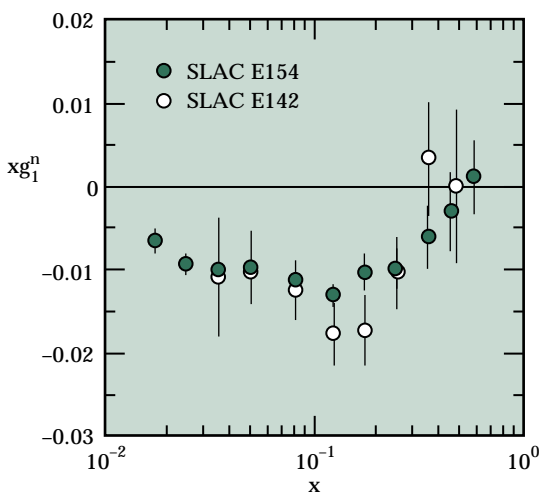
Neutron spin structure function data versus x from SLAC Experiment 142 (1992) and Experiment 154 (1995).

Energies of the electron-proton collider program at DESY in Germany.

only twice that of the previous experiments and still a factor of four lower than the CERN muon beam, the corrections get smaller rapidly as the energy increases—in particular changing from 20 GeV to 50 GeV.

In the fall of 1995 SLAC ran the first 50-GeV fixed-target experiment. The experiment, E154, collected about 100 million electron scattering events in a two-month running period with an 80 percent polarized beam scattering off a new thin-windowed high density ^{3}He target with up to 50 percent polarization for the ^{3}He nuclei. The experiment was a roller-coaster ride, since numerous target cells exploded in the beam. Without giving exact numbers, enough targets vented that there were, indeed, some interesting meetings between the SLAC directorate and the experimentalists during the experiment. Target replacements were especially painful, since it took a full day to repolarize the new target up to reasonable polarization values. But by the end, the story was a success. Enough high quality data were eventually logged to tape—especially in the last week—that the proposal specifications were actually met. The high statistical precision of E154 experiment set a new standard for measurements of the neutron spin structure function. The top left figure shows a comparison of the result from E154 with those from the 1992 experiment E142.

Presently E155, the twin of E143, is collecting data. The experiment is remeasuring the proton and deuteron spin structure functions with high precision using the new 50-GeV beam facility. The final set of data over the five year period from the End Station A fixed-target program represents a powerful compilation of spin structure function results for the proton and neutron. It is difficult to envision any future experiments outdoing the precision of these SLAC experiments in this energy range.

THE FUTURE

Where is the field heading? Are we done? Are the last measurements just clean-up? The quarks carry about 30 percent of the spin, today's best guess. Now what? What is left?

There is a missing 70 percent to our puzzle. There is high expectation that much of this contribution is coming from the gluons in the nucleon. The gluons have spin 1 and they can conspire to add up and give a contribution to the proton's spin. But there is little experimental evidence for the existence of the gluon's influence on the proton's spin. The future of the field is to hunt down the gluons.

There are presently two methods to go out and to trap the gluon's spin. One is to continue running mercilessly the deep inelastic scattering spin experiments and to exploit them at ever increasing energies. A natural, ambitious continuation is to take the HERA collider program discussed in the beginning of this article and polarize the electron and proton beams. The electron beam at HERA is actually already polarized for a fixed-target program called HERMES. Polarizing the proton beam would allow for a truly high energy measurement of the proton spin structure function (bottom figure on the left). As one accesses higher and higher energies in proton or neutron
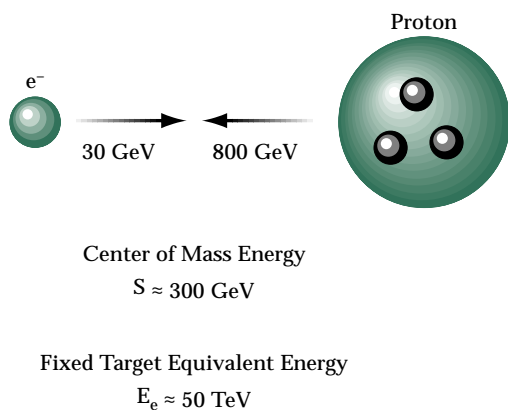
scattering, one sees the structure functions at lower and lower *x*. Gluon effects are expected to show up at low *x*. So studying the shape of the spin structure functions at high energies may be one of the best windows on the gluons and their impact on the proton spin. Another idea in such a program would be to inject polarized ^{3}He into the HERA proton ring. This would, of course, allow for a high energy measurement of the neutron spin structure function to match the proton measurement.

A second endeavor to learn about the gluons—perhaps more directly— is to study jet production from proton collisions at high energies. When some probe interacts with the proton (either an electron, a muon, or another proton), one can break up the proton and identify the final-state particles. Some of these particles have a production that depends heavily on the existence of gluons. By studying these particles and their spin dependence, one can infer the gluon effects. There is a program approved to collect data at CERN called COMPASS that will use an upgraded muon beam line in a new fixed-target program to try to identify these final state effects. Possibly the most promising program in the near future, however, will come from high energy polarized proton-proton collisions produced at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory. Observing a clear gluon spin signature is rapidly becoming the target for the field.

I am often asked why it is interesting to continue studying the proton's spin and characterizing what contributes to the spin. The question has different answers depending on the physics problems being addressed.

To the atomic physicist, the proton is a fundamental piece of the hydrogen atom. The interaction of the proton with an electron represents more-or-less the birth of atomic physics. Effects due to spin-dependent interactions are known to affect high precision atomic spectroscopy. The splitting of the hyperfine interaction in hydrogen, for example, actually has a term that depends on the proton spin structure function.

To the nuclear physicist, confinement and how a proton is bound to a neutron (in the deuteron) is probably the most fundamental question in the field. Since the proton and neutron are complicated, understanding this complexity is critical to understanding binding between each other and within nuclei, in general. No longer can one think of the proton and neutron as individual particles. One needs to understand what is inside to understand why they are bound together and how the strong interaction works.

To the particle physicist, the proton is the most promising tool for studying high energy interactions and searching for new forces. The largest high energy accelerator project in the world, called the Large Hadron Collider, now being constructed at CERN, will search for new particles coming from the interaction between two colliding high energy (7 trillion electron-volts) protons. Backgrounds from proton-proton collisions coming from the internal structure must be understood in order to detect new interactions. The backgrounds depend on understanding the proton structure.

The discovery of the top quark (see "The Discovery of the Top Quark," by Bill Carithers and Paul Grannis, in the Fall 1995 *Beam Line*, Vol. 25, No. 3) was a detailed study of extracting a signal above large strong interaction backgrounds.

All three fields of physics mentioned above are needed to run the spin structure function experiments successfully.

Finally, there is spin as a quantum number and its importance to physics in general. The most studied, but unconfirmed, theory today is called supersymmetry (refer to "Whatever Happened to the Theory of Everything?" by Lance Dixon in the Summer 1994 *Beam Line*, Vol. 24, No. 2). Supersymmetry is mathematically elegant. It gives mass to the various particles that we observe. It is a strong basis for the most popular unified theoretical studies today (superstrings). And it unifies the fermions and bosons. Spin is critical to the theory as it is to quantum mechanics. The present article discusses spin as it applies to the proton's structure. This is only one facet of spin's effect on fundamental particles and nuclei. We still do not understand the origin of spin. Lurking in the background of all spin studies is this global question. And although there is no well-defined program that directly attacks the mystery of the origin of spin, it is an unavoidable player in much of modern-day physics. If one were to look back from the twenty-first century and judge the greatest physics advances in the previous century, it would be delightful to claim to have cracked the mystery of the origin of mass and spin in our Universe.