The Spin of the Proton
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If you have children in elementary school and they are learning science, what is the one page of paper that they are most likely going to be exposed to? The answer is probably.....yes.....the periodic table. This table page represents one of the greatest scientific achievements of mankind. It is an organized list of all the elements, and it obeys a pattern governed by quantum mechanics and, in particular, something called the Pauli Exclusion Principle. To construct the table, one simply counts the number of protons in a particular nucleus to get from one element to the next, and a new row is created whenever 'shells' are filled. The rules for filling a shell are relatively simple. At first glance the number of atoms per row is $2n^2$, where n is the row number. But, lamentably, this pattern breaks down quite quickly, and you will need some quantum mechanics background to make the next step.

The behavior of the elements or atoms is well described by quantum electrodynamics as a fundamental theory. And calculating the behavior of atoms is the main driving force of the field of physical chemistry. As a basic theory, it is quite well understood what forces describe the electron interactions between atoms. Among the understood questions in the field is why atoms bind to create molecules. We know why atoms stick together!

Let's assume for a moment that your child comes home one day and asks "Why does a proton stick to a proton?" Or for that matter, "why does a proton stick to a neutron?" Or "what is inside the proton? What is inside the neutron?" After you have recovered from the horrifying realization that the college expenses for this brain child are going to bury you for life, you will probably have to answer that you simply do not know and should consult a nuclear theorist (or perhaps a string theorist, ha!) for the answer. If you do this, you will find that the problem is well-defined. It has a name. And it is called 'confinement'. But with only a little more searching, you will realize that though it is well-defined, it is understood terribly!

Understanding the structure of the proton and the neutron is still one of the greatest challenges in physics. What do we know?

On the one hand, the proton is a very simple object. It has a definite mass and charge. It is incredibly stable. A limit on the decay of the proton tells that it has a lifetime that is many orders of magnitude older than the universe.

The neutron is the partner of the proton and also has simple and matching properties. The two main differences are, of course, that the neutron has no charge and it is heavier and can decay into a proton. In fact, a free neutron decays in approximately 15 minutes. However, when bound in a non-radioactive nucleus, the neutron is stable and like the proton does not decay. Table 1 summarizes the simple properties of the proton and neutron.

	Proton	Neutron
Mass	938 MeV	939.6 MeV
Charge	+1	0
Spin	1/2	1/2
Lifetime	$> 10^{25}$ years	887 seconds

Table 1. Proton and neutron properties

Given their basic nature and fundamental relation to matter as we know it, one could argue that the proton and neutron are fundamental particles. But using high energy scattering experiments performed now at many different accelerator laboratories, we have been able to see inside these two objects and what we find is complicated. Our present understanding is that the proton and neutron have extremely complex internal structures consisting of quarks of different flavors and gluons of different colors, all governed by QCD in a highly relativistic non-static model. Unraveling the simple external properties of the proton and neutron and relating them to the complicated internal structure remains one of the largest challenges in physics today.

Quarks	1st generation	2nd generation	3rd generation
Q= -1/3	down	strange	bottom
Q= +2/3	up	charm	top

Table 2. The six quarks

We do know something about the quarks inside the proton and neutron. Table 2 gives the six quarks that have been found in nature and their charge. The only known difference between quarks of the same charge and different generations are their mass. And for our particular study of the proton structure, it is actually the lightest quarks, up and down, that play the leading role.

In the most naive model of the proton, the proton consists of two up quarks and one down quark bound together. And to get a neutron, one simply interchanges one of the up quarks with one of the down quarks, yielding a zero charge object. From neutrino and electron scattering experiments, it is known that the structure of the proton is actually more complicated and also consists of sea quarks and sea anti-quarks (opposite charged quarks) and gluons that are the mediators of the strong interaction. In short, a proton today looks like this:

proton = u + u + d (valence quarks) + u $\overline{u}$, d $\overline{d}$, s $\overline{s}$ quarks + gluons

Disentangling the fraction of quarks and gluon contributions to the proton structure is one of the main goals of an enormous high energy collider program now being conducted at the DESY collider in Hamburg, Germany [1].

For this particular paper, the focus is narrowed down a step from studying the structure of the proton and neutron, which is an unbelievably broad topic. The focus here is to unravel what inside the proton accounts for its simple spin of $\frac{1}{2}$ [2,3]. We take as a postulate that the proton and neutron are made up of different quarks and gluons, and we are trying to find what fraction of the proton spin is carried by quarks and what fraction is carried by gluons. This field has generated quite a bit of excitement over the last decade, since the quarks were found in an initial experiment to only account for a very small fraction of the proton spin. This was terribly surprising, since most other macroscopic properties of the proton and neutron are well-described by the simple quark model. In short, we know that the following simple formula exists and we would like to know the numbers to plug in for the quark and gluon contributions:

Proton spin = 1/2 = "quarks" + "gluons" = Δq + ΔG

That Δq was found to be a small number generated a huge number of popular science articles [4-10].

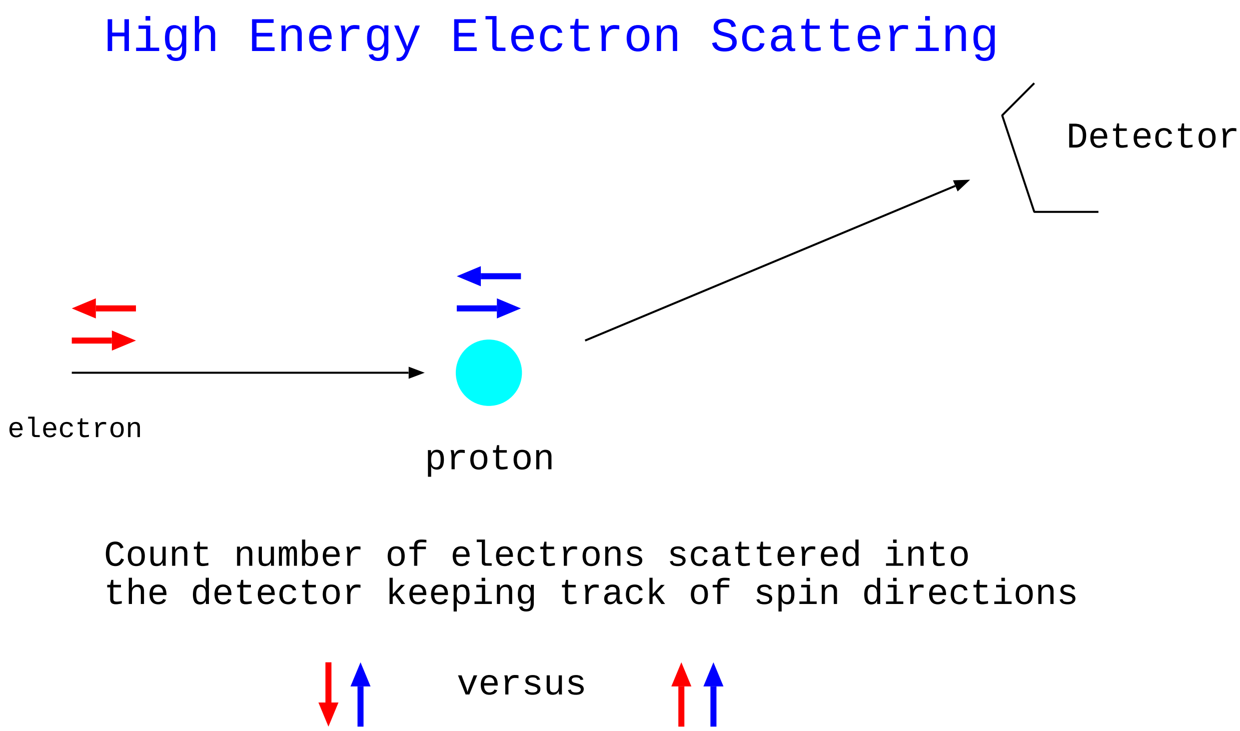

Figure 1. Schematic of a polarized electron polarized proton scattering experiment

How do we get information on the substructure of the proton? In order to 'see' inside, one needs a high energy machine. Figure 1 provides a schematic of one such device. To learn about the proton spin, one takes a beam of high energy electrons, controls the spin direction of the electrons and then scatters these electrons off a proton target, in which the spins of the protons are also controlled. One then simply counts the number of scattered electrons in a detector keeping track of the number of scattered electrons in which the spin of the beam and target are parallel versus anti-parallel to one another. If there is a force that depends on the spin directions of the proton and electron, then one will count a different number of electrons in the detector depending on the spin direction. Where does one find such a machine?

The first polarized electron scattering experiment was performed at the Stanford Linear Accelerator Center (SLAC) in Northern California. Soon afterwards, a muon (i.e. heavy electron) scattering experiment was performed at a laboratory in Geneva, Switzerland (CERN) and a second electron scattering experiment was eventually built in Hamburg, Germany (DESY laboratory).

In order to present and interpret results from these types of experiments, it is necessary to introduce a bit of the math and formalism and language used in this business. As stated above, we count electrons with different spin directions in a detector. More specifically, we perform an asymmetry measurement and extract an asymmetry, A_1, in which

$$A_1 = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

where $N^{\uparrow\downarrow}$ corresponds to the number of electrons counted in the detector with the beam and target spins aligned anti-parallel to one another and $N^{\uparrow\uparrow}$ corresponds to the same thing with the spins aligned parallel.

This is our measurement. From this quantity, we find something called the proton or neutron spin structure function, g_1^p or g_1^n, where

$$g_1 \approx A_1 \cdot F_1$$

for a proton or a neutron. The function F_1 is a quantity that we find in scattering experiments in which we do not care in which direction the electron spin is pointed. The reason that we have to introduce this structure function g_1 is that it is the quantity that is directly related to the quark contribution to the proton and neutron spin.

In fact, g_1^p for the proton has the following relationship,

$$g_1^p = \frac{1}{2}[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s]$$

where Δu, Δd and Δs are, respectively, the individual up, down and strange quark contributions to the proton and neutron spin. More information is actually needed to extract the total quark contribution $\Delta q = \Delta u + \Delta d + \Delta s$. We know this extra information from rather reliable theoretical studies, but the crucial point is that one must measure g_1^p or g_1^n to nail down the final numbers.

A natural question to ask, just to get a feeling for what this field is all about, is what would one expect for the size of the measured asymmetries in one of these experiments? What do we think that A_1 will turn out to be?

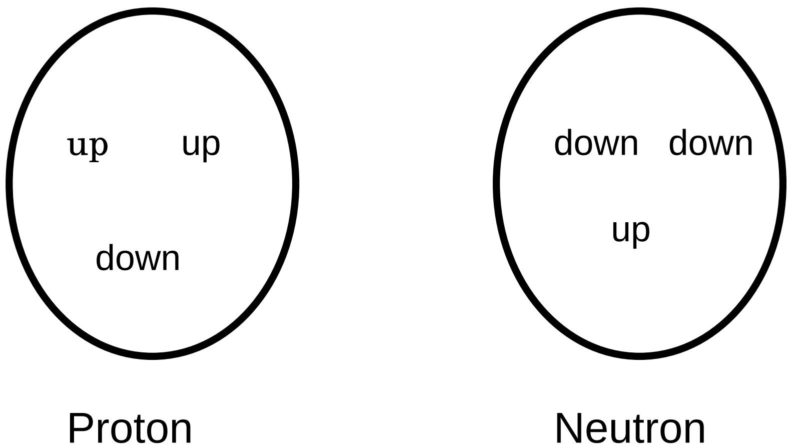

Figure 2. Simplest quark model of the proton and neutron

Let's assume for simplicity, that the proton is simply made up of two up quarks and one down quark and the neutron is made up of two down quarks and an up quark. And let's for the moment, ignore all sea quark and gluon contributions. Figure 2 presents the most naive model of the proton and neutron, just mentioned.

To extract the expected value of the spin-dependent asymmetry, A_1, we need to invoke some quantum mechanics. If one takes all combinations of three quark states, the polarized proton wave function can be written as:

$$|p^{\uparrow}> = \frac{1}{\sqrt{18}}(2|u^{\uparrow}u^{\uparrow}d^{\downarrow}> +2|u^{\uparrow}d^{\downarrow}u^{\uparrow}> +2|d^{\downarrow}u^{\uparrow}u^{\uparrow}> -|u^{\uparrow}u^{\downarrow}d^{\uparrow}> -|u^{\uparrow}d^{\uparrow}u^{\downarrow}> -|d^{\uparrow}u^{\uparrow}u^{\downarrow}> -|u^{\downarrow}u^{\uparrow}d^{\uparrow}> -|u^{\downarrow}d^{\uparrow}u^{\uparrow}> -|d^{\downarrow}u^{\uparrow}u^{\uparrow}>).$$

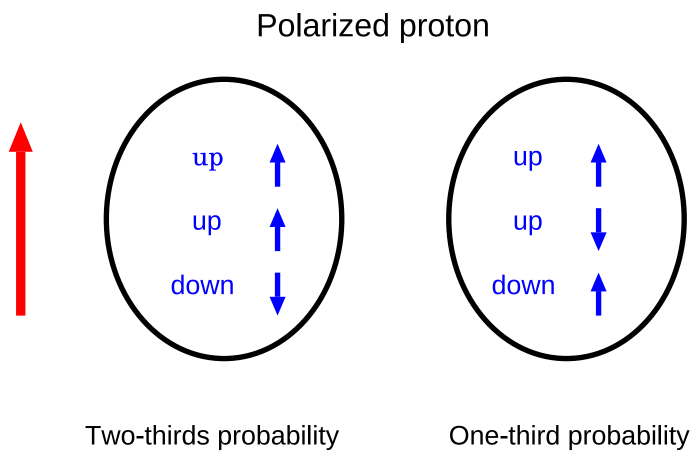

Figure 3. Simplest quark model of a *polarized* proton

If you have not had quantum mechanics before, just accept this statement and the next. If you have had quantum mechanics, then one should simply view the above result as a counting of all states possible and weighting them equally, taking into account how to count identical particles. To get a measurement from a quantum mechanics, one needs to square the wavefunction. If you do this, since each state is orthogonal, one gets the following result.

Pictorially, the polarized proton with spin pointed up will look like one of two objects (Figure 3) with the left object occurring 2/3 of the time and the right object occurring 1/3 of the time. In another words, if one scatters an electron off a polarized proton, 2/3 of the time, the electron will see the left object and 1/3 of the time it will see the right object. And to calculate final results, one has to weight the two situations.

If one now asks what is the probability that the electron will scatter off an up quark with spin up, then one has to count the probability of hitting the left or right object times the probability that the electron will scatter off an up quark with spin up. The answer is

$$\mathrm{P}(\mathrm{u}^{\uparrow}) = 2/3 \cdot 2/3 + 1/3 \cdot 1/3 = 5/9$$

The first 2/3 comes from hitting the left object, the second 2/3 comes from the probability of hitting an up quark with spin up in the left object, the next 1/3 comes from the probability of hitting the right object and the last 1/3 comes from the probability of hitting an up quark with spin up in the right object.

One can calculate the probability of finding each type of polarized quark and the results are:

$P(u^{\uparrow}) = 5/9 \qquad P(u^{\downarrow}) = 1/9$

$P(d^{\uparrow}) = 1/9 \qquad P(d^{\downarrow}) = 2/9$

Notice that you have to scatter off some quark somewhere. So the sum of all the above probabilities is one, as expected.

The last step is to calculate the asymmetry A_1. For scattering off a proton, the formula is to multiply the charge squared of the quark times the probability of the quark being spin up minus spin down and then divide by the sum of the quark probabilities. And one has to add together the different quark flavors. It simpler to see this in a formula:

$$A_1^p = \frac{\frac{4}{9}[P(u^{\uparrow})-P(u^{\downarrow})]+\frac{1}{9}[P(d^{\uparrow})-P(d^{\downarrow})]}{\frac{4}{9}[P(u^{\uparrow})+P(u^{\downarrow})]+\frac{1}{9}[P(d^{\uparrow})+P(d^{\downarrow})]}$$

If you plug in the numbers, one finds that $A_1^p = 5/9$, which is a large asymmetry! In another words, one should see large non-zero spin asymmetries in such a scattering experiment.

If one wants to calculate the same quantity for the neutron, it is just necessary to interchange an up quark probability with a down quark probability. In another words, take the result of P(u) and interchange it with P(d). If you go through the same calculation, you find that for the neutron A_1^n=0.

This is an important result. In the early days, it was expected that the neutron asymmetry would be small and not observable. So the first experiments were designed to go after the measurement of the proton asymmetry A_1^p.

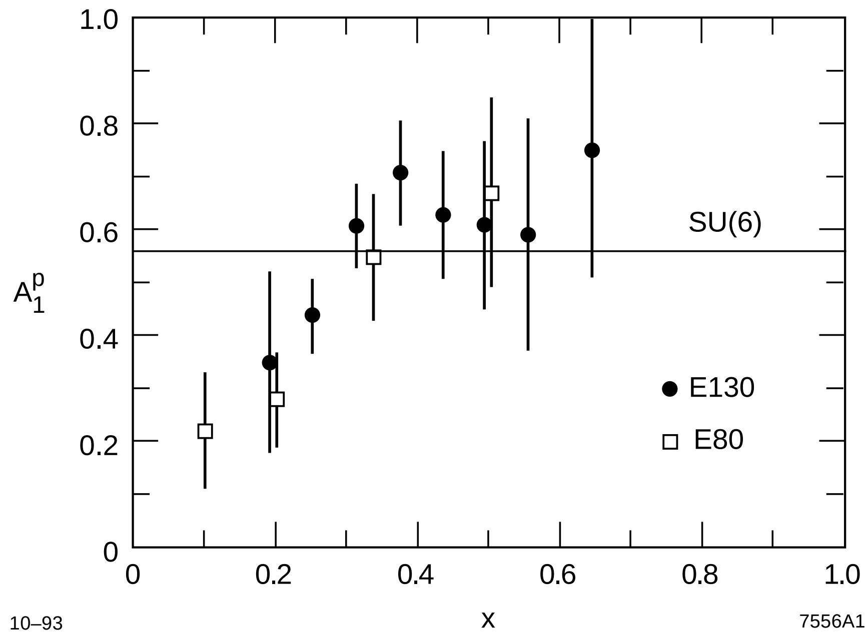

Figure 4. Early SLAC polarized scattering results

The first Yale-SLAC polarized electron polarized proton experiments were performed in the late 1970s and early 1980s, under the leadership of my father, Vernon Hughes. These experiments involved scattering high energy polarized electrons with energies up to 23 billion electron volts off a polarized butanol target ($C_6O_4H_8$). Only the hydrogen in the target contributes to the polarization-dependent scattering, since carbon and oxygen are spin 0 nuclei. One expected to see large asymmetries A_1^p and that was indeed what was found as shown in Figure 4. (Note that the asymmetries A_1^p are plotted against a variable called 'x'. This term is a kinematic variable which depends on the beam energies and scattering angles and is related to the momentum of the struck quark. For this paper, just know that it is the variable against which all these functions are normally plotted in this field of research.) The measurements were consistent with the A_1^p =5/9 prediction. In fact, the results were such a good confirmation of the quark parton model, that SLAC discontinued the program as being low in future discovery potential.

At this point, the laboratory in Geneva (CERN) picked up the ball.

In the mid 1980's CERN ran a follow-up polarized proton experiment scattering instead of electrons, muons in a remeasurement of the proton spin structure function. The one large difference between the early SLAC and new CERN experiment was that the beam energy was higher at CERN by an order of magnitude, 200 billion electron volts. From this measurement, enough new data existed in a new kinematic region to be able to extract a first complete measurement of the quark contribution to the proton spin, namely Δq. The result was that the fraction of quark contribution was found to be

$$\Delta \mathrm{q} = 12\% \pm 16\%$$

This result was low and in disagreement with the predictions from the standard quark parton models at the time. That the quarks did not appear to be carrying the proton's spin raised a great interest in the field and was dubbed by the theoretical community 'The Proton Spin Crisis'. That it was called a 'crisis' was perhaps an overdramatic reaction, but the interest in the field became large. Figure 5 presents the asymmetry results from the CERN experiment (called EMC). One sees that asymmetries are measured over a larger range in x, and some interesting features appear. First, the new CERN results were consistent with the old SLAC results over the same kinematic range. But the new CERN results come in low compared to a quark parton model prediction at low values of x. The quark parton model prediction shown would have yielded a 75% contribution to the spin coming from the quarks. But that all the measurements came in low yielded a central value of 12% for the quark contribution to the proton spin.

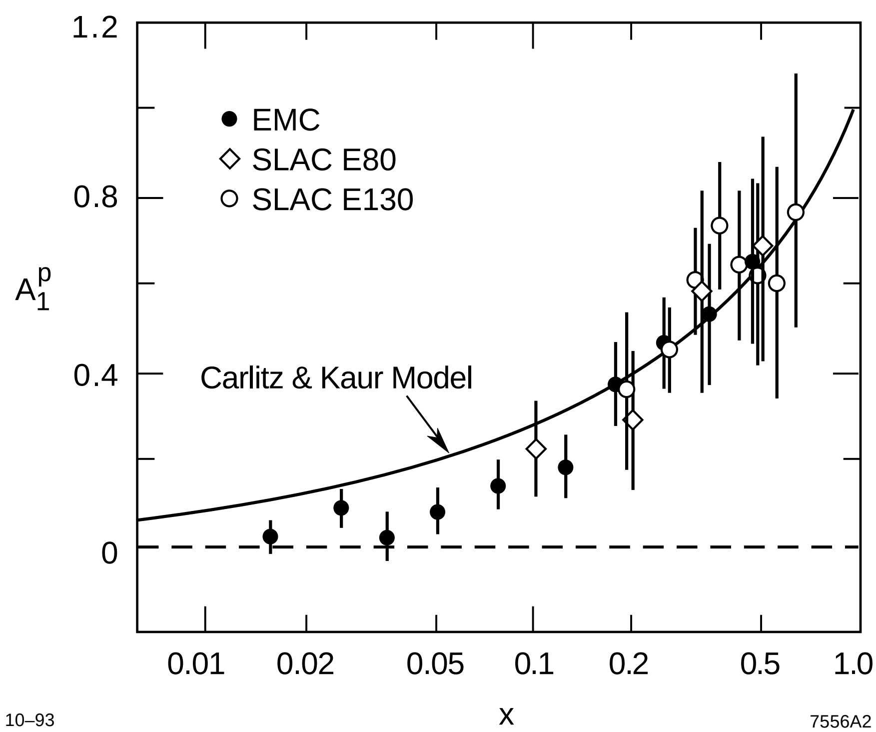

Figure 5. CERN EMC measurements of A_1^p compared to the old SLAC results

Initially, this surprising result called into question the entire quark model for the proton's substructure. And experimentally, this situation gave birth to a race to go out and measure the neutron spin structure function for the first time. The neutron race began almost concurrently in 1990 at SLAC, CERN and DESY in response to the 1988 EMC result.

To get a neutron requires a bit more work than a proton. A neutron experiment can not be performed on a free neutron, since a free neutron is not stable. So, one must perform the experiment with nuclear targets. The two possibilities are a polarized deuteron (one polarized neutron bound to one polarized proton) or a polarized helium-3 (one polarized neutron bound to two, on average, unpolarized protons). The deuteron is a simpler object than helium-3, but to get a neutron result requires a large subtraction from the polarized proton contribution. Polarized helium-3, on the other hand, largely corrects itself, since the two proton spins line up anti-parallel to one another due to the Pauli Exclusion Principle (the same rule that gives us the periodic table).

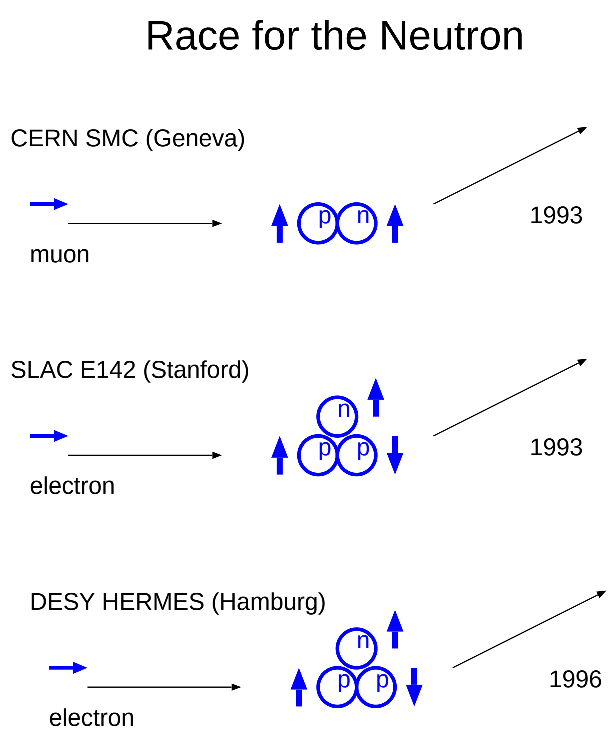

Figure 6. First polarized neutron experiments

Figure 6 presents a schematic of the first experiments to go after the neutron. The muon experiment at CERN used polarized muons scattering off a polarized deuteron. And the

SLAC and DESY experiments used polarized electrons scattering off polarized helium-3. SLAC and DESY later have gone on to perform deuteron measurements.

The first results came out in 1993 from CERN and SLAC. DESY, due to technical beam related issues, only came out with its first result in 1996. Figure 7 presents the first round of results on the neutron spin structure function measurement performed by 1995 at CERN and SLAC. One sees an interesting result. The neutron appears to be small and negative, which is exactly what is predicted by the quark models correcting for the sea quark contribution. One also sees the advantage and disadvantage of electron scattering versus muon scattering experiments. Muons are at higher energy, so they provide measurements over a large kinematic range. However, electron experiments have a higher intensity, so the error bars are smaller in the range that they access. The two measurements have served important complementary roles in unraveling what we know today.

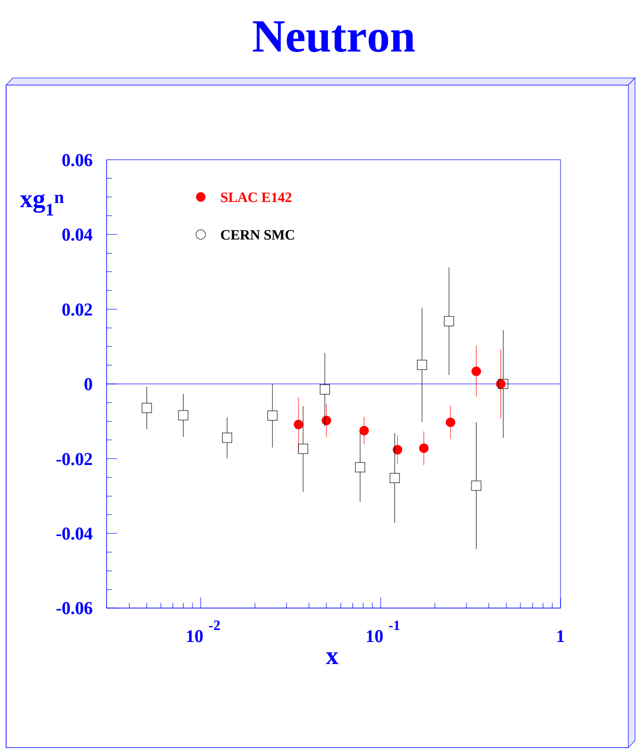

Figure 7. First measurements of the neutron spin structure function g_1^n

Following 1995, a long list of new experiments at CERN, SLAC and DESY have been performed yielding a large world data sample on the proton and neutron spin structure functions. Figure 8 presents the published data as of approximately one year ago coming from the three programs. More data has been produced and the final compilation of results will converge within the next year. However, it is already evident that each experiments appears to confirm the results of the original EMC experiment performed over 10 years ago.

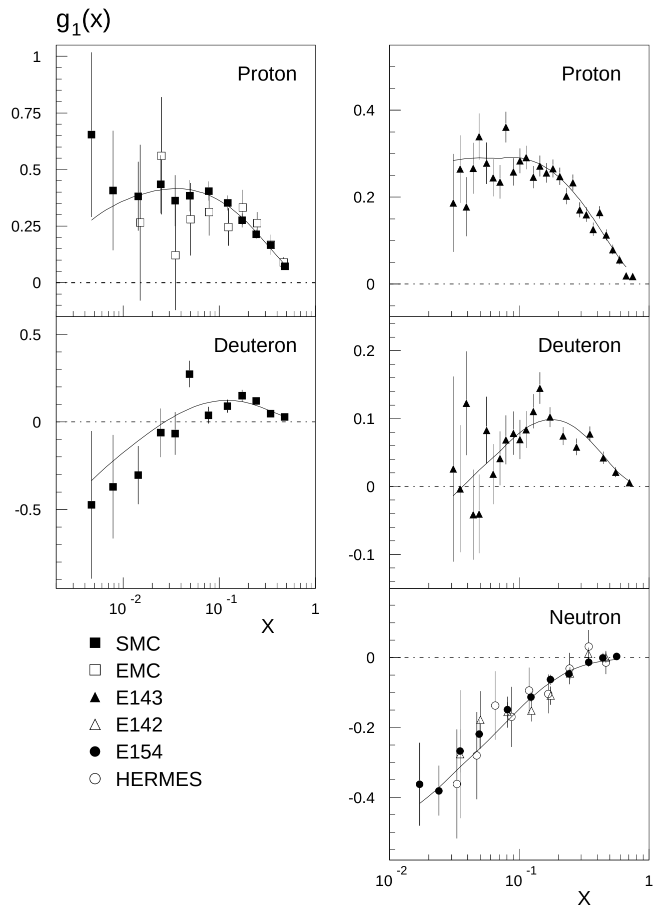

Figure 8. World data on the spin structure functions

Along with the experimental progress has been significant theoretical work. This paper does not discuss in detail how one extracts the quark contribution Δq and the gluon contribution ΔG to the proton spin. To perform a world fit to all the data takes calculations on what are called 'Next-to-Leading Order Perturbative QCD' corrections. It is not in the scope of this review to discuss how these work. One needs to start with a graduate level training in theoretical QCD physics to understand this stuff! What became apparent over the past five years is that these calculations were necessary to give a reasonable and consistent picture of the proton and neutron spin substructure. For this review, I will simple quote the results and their uncertainty. The results for Δq and ΔG are:

$$\Delta q = 0.2 \pm 0.1$$

$$\Delta G = 1.8 \pm 1.0$$

One sees that with a decade of work beyond the original EMC experiment, the result of a small value for Δq remains essentially intact, though the uncertainty has been reduced significantly. (It should be noted that there are caveats to this result such as choosing a correct factorization scheme, but I am dropping this 'expert' point.) Also, one sees that the experiments have now provided enough information to get a first glance at the value of ΔG, the polarized gluon contribution. ΔG appears to be positive, but the uncertainty is large. The future of this field of study is now directed at hunting the value of ΔG. One would like to extract a value of ΔG to a precision similar to Δq, namely an order of magnitude better! Another interesting way of presenting the ΔG result is to see how the result depends on x; this is demonstrated in Figure 9. This result comes from a recent fit to today's world data.

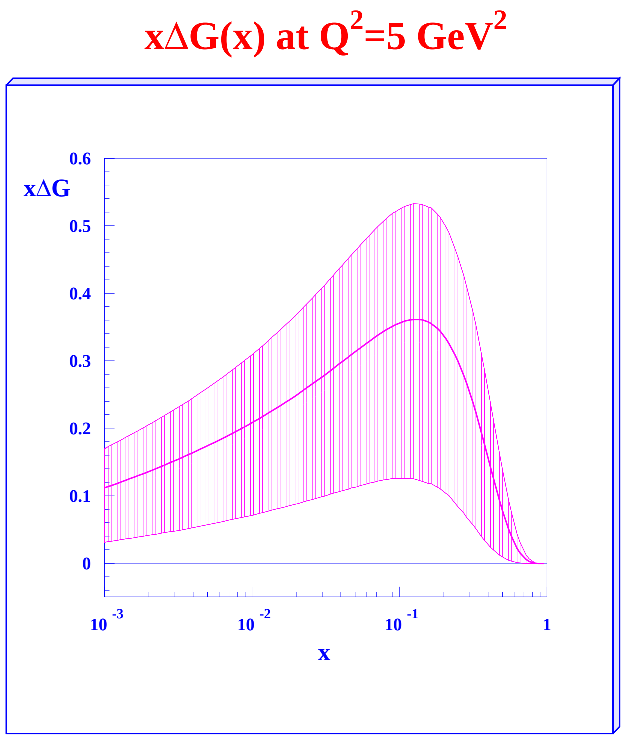

Figure 9. Polarized gluon contribution to the proton spin structure function

This brings me to the future. The future experiments are geared at finding out about ΔG. What are the most promising future programs? There are four. To extract ΔG, it would be useful to proceed to even higher energy experiments, since gluon contributions are dominant at low values of x, which require high energies.

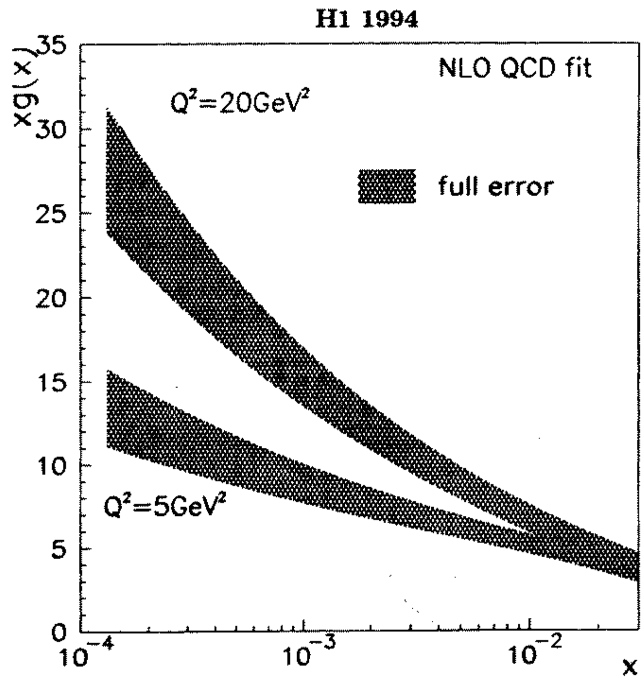

Figure 10. Unpolarized gluon contribution to the proton structure

The best way to get a high energy electron scattering off a high energy proton is to collide these two objects head on. If one takes, for example, a 30 billion electron volt electron and crashes it head on into a 800 billion electron volt proton, one attains energies 1000 times greater than the SLAC electron scattering experiments. Such a machine already exists at the DESY laboratory in Hamburg. What is missing is that the proton beam spin is not yet controllable. The electron spin in this machine is...which is how one obtains the HERMES fixed target results. It is conceivable that DESY lab may upgrade their proton beam control to be able to embark in a spin program after the year 2005. This decision is currently under review. To give an idea of the handle of such a program, Figure 10 shows existing results on G(x), the spin-independent gluon contribution to the proton extracted from the DESY collider program. Making a similar measurement on ΔG would be the goal of a new collider with the proton spin under control. No existing program proposed could do as clean a job at studying this quantity as the DESY collider proposal.

However, one other collider program that is not as clean theoretically, but far along as a project is to collide polarized protons off polarized protons in the RHIC Spin program at Brookhaven. This program will not access as large a kinematic range as DESY and it must contend with larger theoretical uncertainties, since now one is colliding two protons instead of a proton with an electron. But, much is known from the lower energy experiments to calibrate the RHIC Spin program to extract ΔG. This program will begin running in the next few years and is well placed to take the first dedicated look at ΔG. The hope here is to extract ΔG with a precision near 0.1 for values of x greater than 0.03.

The last program that I will mention is a new fixed target program at CERN, called COMPASS. The idea of this study is to extract ΔG by increasing the statistics and detector efficiency for final state interactions in an upgraded dedicated muon experiment. COMPASS will also only measure ΔG in a large x range greater than 0.1, but it is also an approved project on a reasonable time scale, beginning in the next few years. The HERMES program at DESY is also embarking on a similar program that more or less directly competes with the CERN COMPASS experiment.

In short, there is still a large experimental community out there directed at studying what carries the spin of the proton. This effort is focused at the leading experimental high energy laboratories around the world and is likely to continue over the next decade. It has, indeed, taken years to answer what appear to be simple questions on the proton's structure. We have learned lots, but there is still a long way to go before the mysterious internal workings of the proton become as familiar to us as a Swiss watch.

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