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NEW RESULTS ON NUCLEON SPIN STRUCTURE FUNCTIONS*

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ABSTRACT

The history, ancient and recent, of nucleon spin structure functions is reviewed. New first measurements of the neutron spin structure function are compared to past measurements of the proton spin structure function. The comparison sheds light on a fundamental QCD sum rule derived by Bjorken, and the results are used to interpret the spin of the nucleon in the Quark Parton Model.

The field of nucleon spin structure functions has existed for over twenty-five years. It has two goals: to study the internal spin structure of the proton and neutron and to test QCD. Over the years, experimental results from this field have generated a tremendous amount of theoretical activity. However, all the excitement over the past five years has come from just one proton spin structure function measurement. In this paper we report primarily on two new measurements of the neutron spin structure function.

It is important to place this year's results in the context of the past. First, we review the history of the field, focusing on the foundational theoretical work and then describe briefly the proton experiments and the implications of the results. Following that discussion, we move on to the new neutron spin structure function measurements and their implications. We then conclude with remarks on the future of the field. This paper should be viewed as a status report. We are by no means finished.

The field of nucleon spin structure functions began with the work of Bjorken. In 1966 [1] he derived what at the time was an obscure relationship between the spin dependent lepton nucleon scattering cross sections and the weak coupling constant from beta decay. Applying quark current algebra and taking the interaction at infinite four-momentum transfer (i.e., $Q^2 \to \infty$), he found that the difference between the integrals over the proton and neutron spin structure functions (g_1^p and g_1^n, respectively) is directly related to the weak coupling constant found in beta decay (g_A/g_V):

$$\int_0^1 g_1^p(x)dx - \int_0^1 g_1^n(x)dx = \frac{1}{6}\frac{g_A}{g_V}$$

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In 1969, Bjorken wrote a follow-up paper [2] in which he described explicitly the implications of this "sum rule." In it, he concluded that the sum rule implies large asymmetries in the scattering cross sections for deep inelastic scattering of polarized leptons off polarized targets with beam and target spins parallel versus anti-parallel.

In 1974, Ellis and Jaffe derived a sum rule [3] which gives independent predictions for the values of the proton and neutron spin structure function integrals. This sum rule assumed that the strange sea in the nucleon is unpolarized and that SU(3) symmetry between the up, down and strange quarks is valid. The sum rule related the individual proton and neutron spin structure function integrals to the F and D coupling constants [4] extracted from hyperon decay,

$$PROTON \qquad \int_0^1 g_1^p(x)dx = \frac{1}{18}[9F - D] \approx 0.17$$

$$NEUTRON \qquad \int_0^1 g_1^n(x)dx = \frac{1}{18}[6F - 4D] \approx -0.02$$

This result was exciting at the time, since it implied that the proton measurements should yield large asymmetries ($A_1 = g_1/F_1$). At the time polarized proton (as opposed to neutron) target technology was feasible.

Deep inelastic polarized lepton-nucleon scattering experiments now have a well established formalism. These experiments focus on measuring an asymmetry in the scattering cross section $d\sigma$ between conditions in which the target and beam spin directions are parallel ($\uparrow\uparrow$) versus anti-parallel ($\downarrow\downarrow$), namely

$$A = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}}$$

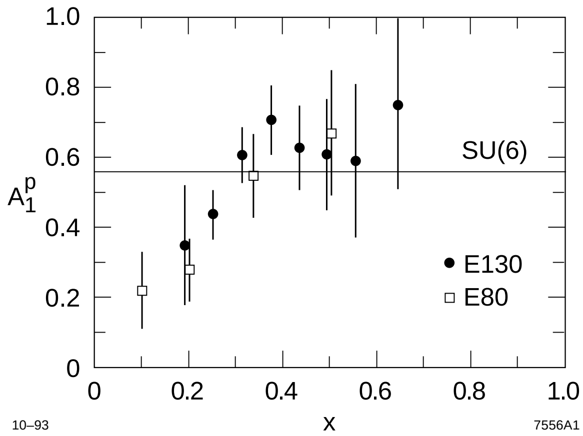

Figure 1: Results on the proton spin asymmetries A_1^p versus x for SLAC experiments E-80 and E-130. A naive QPM prediction SU(6) finds that this asymmetry should be 5/9 for the proton and 0 for the neutron.

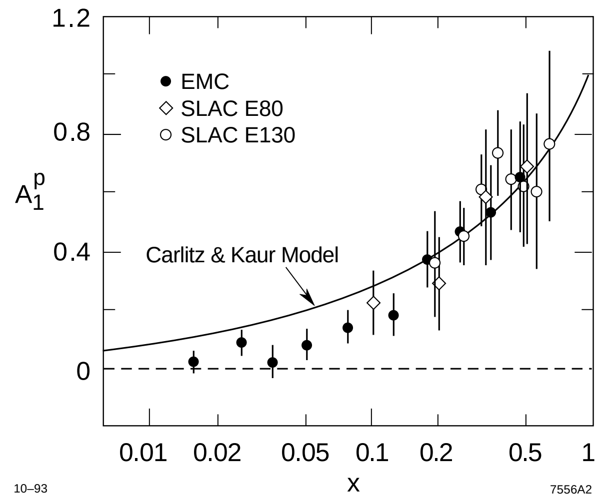

Figure 2: Results on A_1^p versus x for the EMC experiment compared to a theoretical quark parton model developed by Carlitz and Kaur. This model preserves the Ellis-Jaffe sum rule prediction. Data from SLAC experiments E-80 and E-130 are presented for comparison.

The philosophy of the asymmetry measurement allows one to neglect multiplicative effects which to first order cancel between the numerator and denominator of the asymmetry, such as the detector acceptance and deadtime and the absolute beam intensity and energy.

From the measured asymmetries and the known unpolarized structure functions, the spin dependent structure function g_1 is found,

$$g_1(x, Q^2) \approx \frac{A(x, Q^2) \cdot F_2(x, Q^2)}{2xD[1 + R(x, Q^2)]}$$

Here $R(x, Q^2)$ is the ratio of the longitudinal to transverse structure functions, $F_2(x, Q^2)$ is the spin-averaged structure function of the proton and neutron, and D is a purely kinematic factor which characterizes the polarization of the virtual photon.

The first experiment to measure the proton spin structure function was performed at SLAC (E-80) [5]. This experiment pioneered the technology of producing polarized electrons [6] and used this development to scatter polarized electrons at 10 and 16 GeV off a polarized butanol target in End Station A at SLAC. The experiment measured the proton spin structure function over the range of x from 0.1 to 0.5 at an average Q^2 of 2 GeV^2. A remeasurement of the proton spin structure function at SLAC (E-130) [7] with a beam energy of 16 and 23 GeV increased the statistical precision and covered the x range from 0.2 to 0.65 at a higher average Q^2 of 6 GeV^2. Results on the large asymmetries measured are presented in Figure 1 compared to a naive Quark Parton Model (QPM) prediction. These results were interpreted as a strong confirmation of the QPM. The resulting integral for the proton from SLAC was $\int g_1^p(x)dx = 0.17 \pm 0.05$. This was in good agreement with the Ellis Jaffe sum rule, where the large uncertainty on the measured proton integral came from the fact that there was no data on g_1^p at x below 0.1.

At this point in time, the studies moved to CERN. In 1988 the EMC collaboration at CERN [8] reported on scattering 200 GeV polarized muons off a polarized ammonia target in order to measure the proton spin asymmetries down to low values of x (Figure 2). The results agreed with the earlier SLAC measurements for the common x range, namely $x > 0.1$. However, there was a great surprise from the data on the proton spin asymmetries at low x (i.e., $0.01 < x < 0.1$). Here all the values of the asymmetry came in lower than expected as shown in Figure 2. Included is a QPM prediction by Carlitz and Kaur [9]. The low values of the asymmetries at low x implied low values for the proton spin structure function g_1^p which implied an overall low value for the integral over the proton spin structure function. The result for the proton integral from the EMC measurement was $\int g_1^p(x)dx = 0.126 \pm 0.010\ (stat.) \pm 0.015\ (syst.)$. This result had twice the precision in the determination of the proton integral compared to the old SLAC measurements and disagreed with the Ellis Jaffe sum rule prediction $\int g_1^p(x)dx = 0.189 \pm 0.005$ (using the F and D constants available in 1988) by ~ 3.5 standard deviations. The violation had large implications for the QPM. The EMC result implied that the **strange sea was highly polarized**,

Table 1: Comparison of the CERN SMC muon scattering experiment to the SLAC E142 electron scattering experiment.

Comparison of CERN SMC to SLAC E-142		
	SMC	E-142
Beam particle	Muons	Electrons
Beam Energy	100 GeV	19 to 26 GeV
Beam polarization	82 %	39 %
Target material	Deuterated Butanol	^{3}He
Target polarization	35 %	35 %
Fraction polarization nucleons	0.19	0.11
Number of events	3 million	300 million
x range	$0.006<x<0.6$	$0.03<x<0.6$
Q^2 range	$1<Q^2<30$ GeV^2	$1<Q^2<6$ GeV^2

$\Delta s = -20\%$ and the **total quark contribution to the proton spin was near zero.** Thus began a crisis in the field, resulting in hundreds of theoretical papers. If the proton has a problem, what does the neutron have to say?

This year brings the first measurements of the neutron spin structure function from CERN and SLAC. The CERN SMC (Spin Muon Collaboration) experiment [10] scattered 100 GeV polarized muons off a polarized deuterated butanol target and detected $\sim$ 3 million scattered muons in an upgraded version of the EMC spectrometer. Table 1 presents various parameters and goals achieved in the SMC experiment and compares them to the SLAC experiment described below. The primary advantage of the SMC experiment over the SLAC experiments is the high beam energy (similar to the EMC experiment) which enables a measurement of the spin structure function at low x. The price that is paid in the experiment is that the muon flux is low ($\sim$ 3 x 10^6 particles per second), and the statistical error bars are quite large. Technical improvements in the SMC experiment compared to the EMC experiment include more rapid reversal of the target spins ($\sim$ every 8 hours) and a measurement of the muon beam polarization via muon decay [11]. The SMC experiment determined the deuteron structure function down to $x = 0.006$. The deuteron in the butanol target gives direct information on the sum of the proton and neutron spin structure functions.

A concurrent measurement from SLAC (Experiment E-142) [12] determined the neutron spin structure function using 23 GeV polarized electrons scattering off a polarized ^{3}He gas target. Polarized ^{3}He is a good model for a polarized neutron, since to a large extent the two proton spins in the ^{3}He nucleus are anti-parallel due to the Pauli exclusion principle. Experiment E-142 involved scattering electrons at high intensity ($\sim$ 2

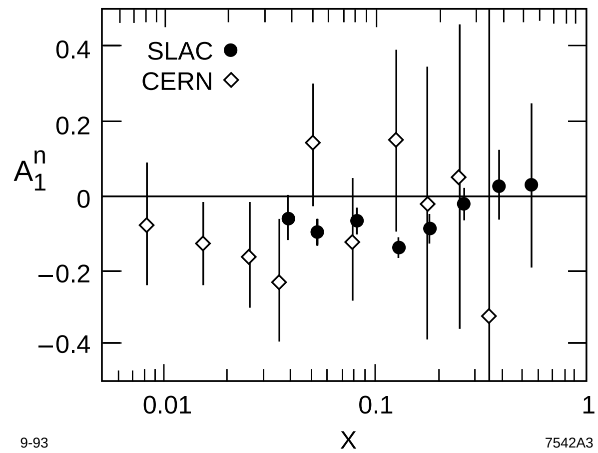

Figure 3: A comparison of A_1^n versus x extracted from the SLAC E-142 experiment and from the difference of the SMC deuteron measurements and the EMC proton measurements.

x 10^{13} electrons/second) and detecting the scattered electrons in two single arm spectrometers set up at small angles (4.5° and 7°). Approximately 300 million scattered electron events were recorded yielding small statistical error bars but over a more limited x range ($x > 0.03$) due to the lower beam energy than CERN. Table 1 also presents various conditions pertaining to the E-142 experiment. A comparison of the neutron asymmetries extracted from SLAC (Experiment E-142) and CERN (subtracting EMC proton results from SMC deuteron results) is given in Figure 3. The higher statistical precision from the SLAC E-142 data and the lower x measurements from the CERN EMC/SMC data are evident.

The three experiments (EMC, SMC, E-142) presently provide the world's data sample on the nucleon spin structure functions. Figure 4 gives results for the asymmetry measurements from the proton (EMC), the deuteron (SMC) and the neutron (E-142). In general, the proton asymmetries are large and positive, the neutron asymmetries are small and negative and the deuteron asymmetries are the average of the two. The present world results for the integrals over g_1 are

EMC Proton

$$\int_0^1 g_1^p(x)dx = 0.126 \pm 0.010\ (stat.) \pm 0.015\ (syst.)$$

SMC Deuteron

$$\int_0^1 g_1^d(x)dx = 0.023 \pm 0.020\ (stat.) \pm 0.015\ (syst.)$$

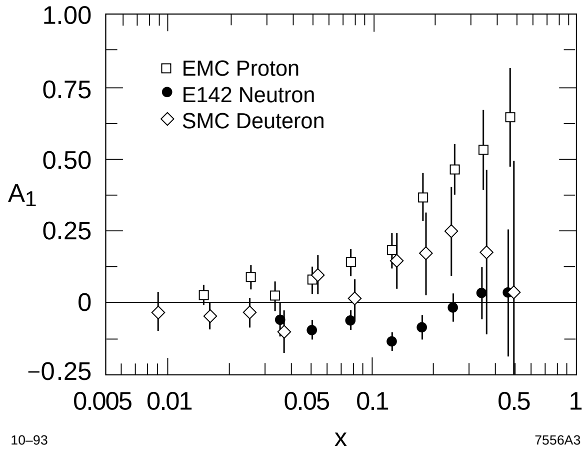

Figure 4: Results on A_1 versus x for the EMC proton data, SMC deuteron data and E-142 neutron data.

E-142 Neutron

$$\int_0^1 g_1^n(x)dx = -0.022 \pm 0.007\ (stat.) \pm 0.009\ (syst.)$$

Here the deuteron is defined by convention as $d = 1/2(p+n)$.

The primary motivation for these experiments is to test QCD by probing the Bjorken sum rule. Each pair of integrals can be used to test the sum rule. Figure 5 presents two standard deviation bands for the integral results extracted from the proton, neutron and deuteron measurements. A band for the Bjorken sum rule prediction using only first order Perturbative QCD (PQCD) corrections is shown. Within two standard deviations, all pairs of integrals agree with the Bjorken sum rule prediction evaluated to first order in PQCD. The Ellis Jaffe sum rule represents a point on this diagram and is shown using modern F and D constants [4]. The CERN results are each more than two standard deviations from the updated Ellis-Jaffe sum rule prediction, whereas the neutron results from SLAC are in agreement with the Ellis-Jaffe sum rule prediction.

Higher order PQCD corrections [13] bring the agreement between the experiments and the Bjorken sum rule even closer. Figure 6 demonstrates how the higher order PQCD corrections affect the Bjorken sum rule and give a comparison of the sum rule prediction to the measured pairs of integrals. In comparing integrals from different experiments, it is assumed that the asymmetry measurements per bin in x are independent of Q^2, and the unpolarized structure function F_1 is evolved to the appropriate Q^2.

The second motivation for performing spin structure function measurements is to test models of nucleon spin

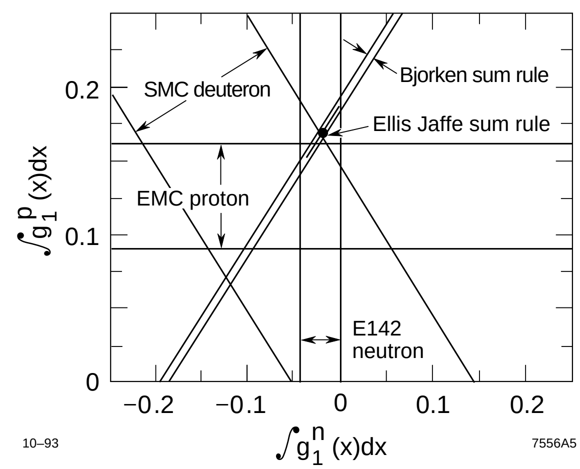

Figure 5: Allowed regions for the integrals $\int_0^1 g_1^p(x)dx$ and $\int_0^1 g_1^n(x)dx$ extracted from the EMC proton, SMC deuteron and E-142 neutron results. Bands represent regions within $\pm 2\sigma$ of the central value. The Bjorken sum rule evaluated at Q^2 of 10 GeV^2 is shown as a band on this diagram. The Ellis Jaffe sum rule represents a point in this diagram.

structure and the QPM. Each of the integrals can be used independently to extract the quark spin flavor contribution to the nucleon spin. The language used to interpret the spin of the nucleon is given in terms of three parameters which characterize the up, down and strange sea contribution to the proton spin in the QPM,

$$\Delta u = \int [u^{\uparrow}(x) - u^{\downarrow}(x)]dx$$

$$\Delta d = \int [d^{\uparrow}(x) - d^{\downarrow}(x)]dx$$

$$\Delta s = \int [s^{\uparrow}(x) - s^{\downarrow}(x)]dx$$

and $\Delta q = \Delta u + \Delta d + \Delta s$, which represents the total quark contribution to the spin of the nucleon. Here $u^{\uparrow}$(x) ($u^{\downarrow}$(x)) represent the up quark distribution with quark spin parallel (anti-parallel) to the nucleon spin. To solve for the three parameters requires three equations. Two of these equations come from SU(3) symmetry between the up, down and strange sea quarks.

From beta decay,

$$\Delta u - \Delta d = F + D \quad (1)$$

From hyperon decay,

$$\Delta s - \Delta d = D - F \quad (2)$$

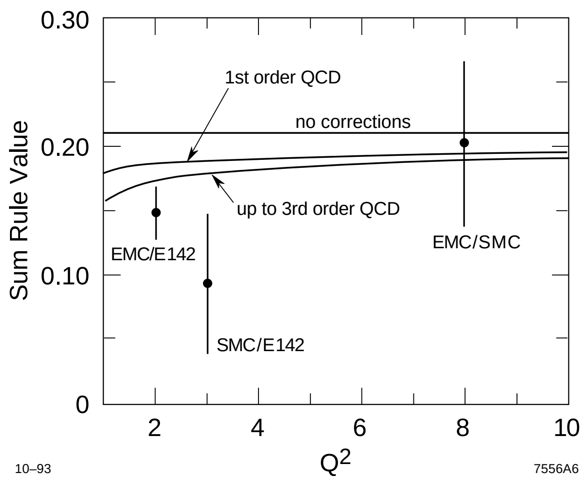

Figure 6: Results on the value of the Bjorken sum rule taking pairs of measured integral results from the EMC, SMC, and E-142 experiments. Results are compared by propagating all structure functions to the same Q^2 values, and by assuming the measured asymmetries $A_1(x)$ are independent of Q^2. Bjorken sum rule predictions using only first order PQCD and using up to third order PQCD are also given.

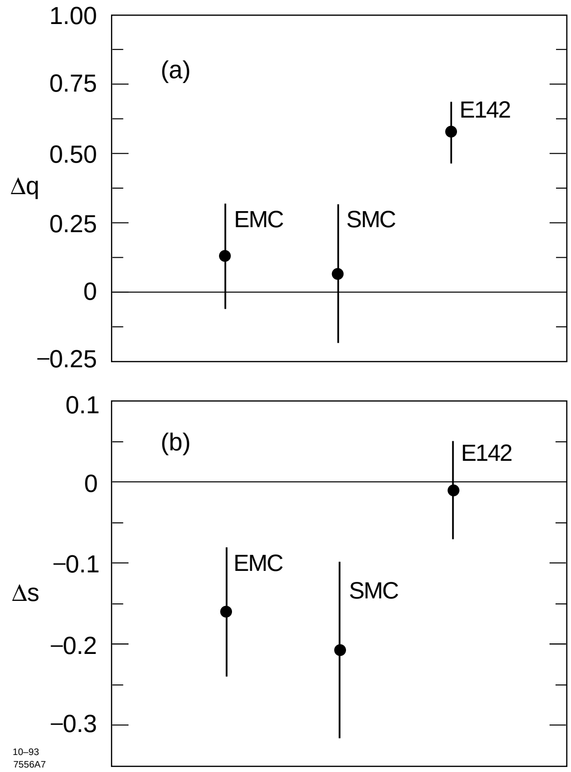

Figure 7: The amount of (a) polarized strange sea Δs and (b) the total quark contribution to the nucleon spin Δq extracted from the three experiments (EMC, SMC and E-142).

The third equation (3) comes from the QPM definition of the spin structure function g_1 of **either** the proton, neutron or deuteron, namely

$$PROTON \int g_1^p(x)dx = \frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s$$

or

$$NEUTRON \int g_1^n(x)dx = \frac{4}{9}\Delta d + \frac{1}{9}\Delta u + \frac{1}{9}\Delta s$$

or

$$DEUTERON \int g_1^d(x)dx = \frac{5}{18}\Delta u + \frac{5}{18}\Delta d + \frac{1}{9}\Delta s$$

Notice that isospin invariance has been invoked (i.e., Δu of a proton is equivalent to Δd of a neutron). With three experiments providing one of the above integrals, and from the values of $F = 0.47 \pm 0.04$ and $D = 0.81 \pm 0.03$ [4] extracted from the hyperon decay data, one can solve for the individual quark flavor contributions to the proton spin. Figure 7 presents the contribution of the strange sea Δs and total quark content Δq extracted from the different experiments. A world with CERN only results would conclude that the quarks do not carry the spin of the nucleon, on average, and the strange sea polarization is large and negative. A SLAC only view would reach the opposite conclusion, that quarks carry half the nucleon spin and the strange sea polarization is consistent with zero (i.e., Ellis Jaffe sum rule prediction). If one splits the difference, all measurements are in agreement with the world average to within about one standard deviation. Which view is correct still requires further study with higher precision data at high Q^2, where theoretical corrections are small. In summary, the jury is not out on whether or not the quarks carry the nucleon spin.

For the immediate future, a new round of precision measurements of the proton is being carried out in 1993 and should be published in 1994. The SMC experiment is presently remeasuring the proton spin structure function using a polarized butanol target. The butanol target, as stated earlier, allows for more rapid spin reversals than the EMC ammonia target. This feature is important, since the largest systematic uncertainty in the EMC experiment came from the infrequent reversal of the target spins. Changes in the detector acceptance between reversals could result in a false asymmetry contribution to the measured asymmetry. SMC will also improve the muon beam polarization determination compared to EMC (which used only a Monte Carlo simulation of the muon beam production from pion decay), using the existing muon decay polarimeter and a new muon-electron scattering polarimeter.

The E-143 experiment at SLAC will run in November 1993 until February. This experiment will scatter 30 GeV electrons with high polarization (i.e., $> 80\%$) off polarized ammonia and deuterated ammonia targets and use the existing E-142 spectrometer. This experiment will measure both the proton and deuteron spin structure functions with a high statistical precision (similar if not better than E-142), down to values of x near 0.02. The big issue to be addressed immediately by these two experiments is whether the EMC proton spin structure function measurement at low x is confirmed.

Future measurements with 50 GeV beams (higher Q^2) at SLAC [14], higher statistical precision at CERN [15], and pure hydrogen, deuteron and ^{3}He internal gas targets with 30 GeV electron beams at HERA (HERMES collaboration) [16] should be able to pin down the fundamental question of the origin of the nucleon spin.

Historically, nucleon spin structure functions have produced a result approximately every five years. Recently the activity in the field has expanded to multiple results appearing each year. By 1997 there should be a large tabulation of nucleon spin structure function data over a wide range of x and Q^2, hopefully revealing a consistent picture.

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