Polarized Deep Inelastic Lepton-Nucleon Scattering: Inclusive Results

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This paper reviews the world results on polarized deep inelastic lepton nucleon scattering and their implications on our understanding of the spin structure of the proton and neutron. Results on the tests of the Bjorken and Ellis-Jaffe sum rules are presented as well as a discussion of the Next-to-Leading Order analyses of the nucleon spin structure functions.

1. INTRODUCTION

For nearly four decades now, physicists have tried to draw a relationship between the simple spin one-half of the proton (and neutron) and its internal structure. More specifically, the goal has been to determine the values for the quantities identified in the following decomposition [1]:

$$\text{Proton}'\text{s spin} = \frac{1}{2} = \frac{1}{2}\Delta q + L_q + \Delta G + L_G \quad (1)$$

where Δq is the polarized quark contribution to the proton's spin, ΔG is the polarized gluon contribution, L_q is the quark angular momentum contribution and L_G is the gluon angular momentum contribution. Unfortunately, it has been difficult to connect these four quantities with experimental measurements. Today, we have some information on Δq (assuming a factorization scheme), a rough look at ΔG and virtually no experimental information on L_q and L_G. For an up-to-date review of theoretical work on this topic, we refer to the paper presented by Robert Jaffe in this conference.

The primary method for studying the proton's internal spin structure has been high energy polarized deep inelastic lepton scattering from various fixed target experiments at laboratories around the world. In these experiments one detects the outgoing scattering lepton (inclusive scattering) and measures an asymmetry,

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

where $\sigma^{\uparrow\downarrow}(\sigma^{\uparrow\uparrow})$ corresponds to the scattering cross section with the beam and target spins anti-parallel (parallel) to one another. From these asymmetries and unpolarized structure function measurements, it is straightforward to extract the proton and neutron spin structure functions, g_1^p and g_1^n. Figure 1 presents published results [2] on these measurements from polarized electron experiments at SLAC and DESY and polarized muon experiments at CERN. All measurements are in excellent agreement.

What does one do with these results? Two answers.

First, the integrals over x of the nucleon spin structure functions, $\int_0^1 g_1(x)dx$, can be used to test Quark Parton Model (QPM) and QCD sum rules. The two important sum rules in the study of nucleon spin structure are the Bjorken sum rule [3],

$$\int_0^1 g_1^p(x)dx - \int_0^1 g_1^n(x)dx = \frac{1}{6}\frac{g_A}{g_V} \quad (2)$$

and the Ellis-Jaffe Sum Rule [4], which, for the proton, is

$$\Gamma_1^p = \int_0^1 g_1^p(x)dx = \frac{1}{18}(9F - D) \approx 0.17 \quad (3)$$

and for the neutron

$$\Gamma_1^n = \int_0^1 g_1^n(x)dx = \frac{1}{18}(4F - 5D) \approx -0.02 \quad (4)$$

Here F and D are the weak coupling constants describing hyperon decay, and $\frac{g_A}{g_V} = F + D$. The

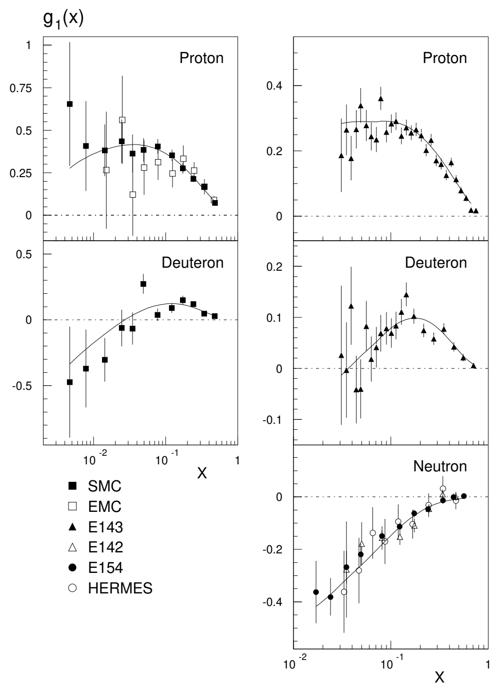

Figure 1. *World results on the nucleon spin structure function g_1.*

Bjorken sum rule evaluated at a finite energies (i.e. finite Q^2) is a fundamental prediction of perturbative QCD. The Ellis-Jaffe sum rule is a less rigorous relationship coming from a QPM picture in which the strange sea polarization is assumed to be negligible and the quark contribution to the proton spin is expected to be approximately 75%. Figure 2 presents a comparison of the neutron versus the proton integrals compared to the sum rule predictions. Every combination of a proton, neutron and deuteron measurement is in agreement with the Bjorken sum rule prediction (which is a line in this figure). The world average value and the confidence level is drawn in and intersects the Bjorken Sum rule line to within one standard deviation. However, all integral measurements are off from the Ellis-Jaffe sum rule prediction. One should note that, in particular, all deuteron measurements are many standard deviations away from the Ellis-Jaffe sum rule prediction. The violation of the Ellis-Jaffe sum rule

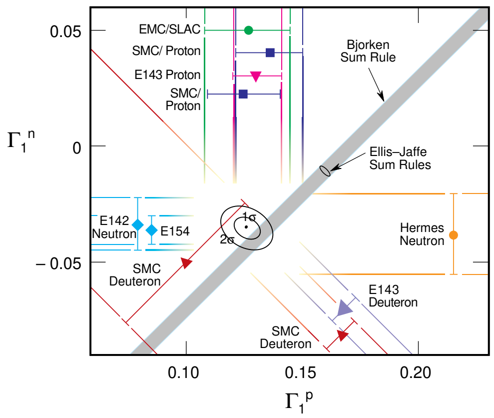

Figure 2. *Neutron, Γ_1^n, versus Proton, Γ_1^p, integral results from various experiments compared to the Bjorken and Ellis-Jaffe sum rule predictions.*

can be translated into a prediction for the quark contribution to the nucleon's spin, Δq, as being approximately 20%.

Second, the nucleon spin structure function measurements can be used along with a Next-to-Leading Order (NLO) perturbative QCD analysis to extract the polarized quark contributions to the nucleon's spin. By studying scaling violations of the spin structure functions and their shapes with x and Q^2, one can extract quark parton model predictions of polarized quark and gluon contributions. Numerous analyses have been done [2,5–9], all with somewhat different initial assumptions. However, all the results give essentially the same basic conclusions.

Figure 3 and Figure 4 show one set of fits to the proton and neutron spin structure functions [9]. From these fits, one can extract the valence versus sea and gluon contributions to the spin structure functions. Figure 5 provides a prediction for the

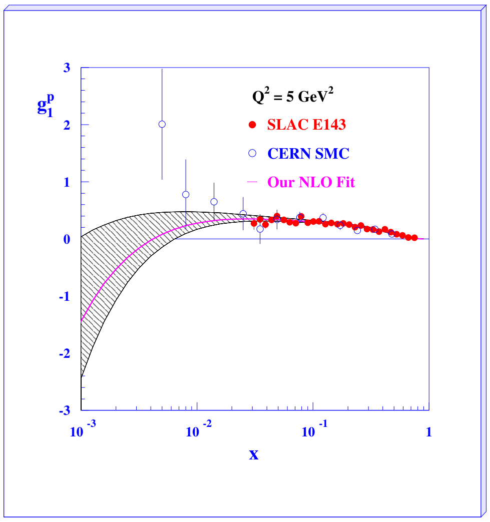

Figure 3. *Proton spin structure function results compared to a NLO QCD fit.*

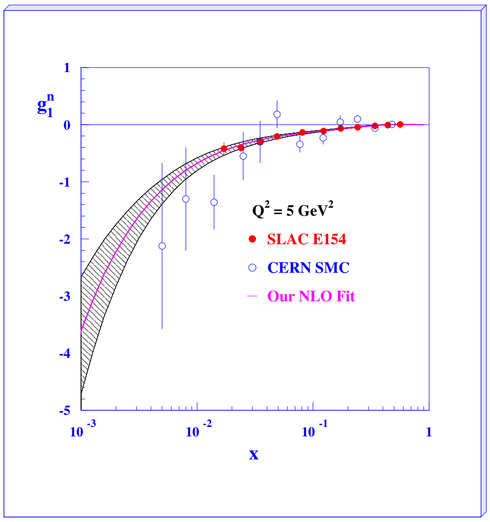

Figure 4. *Neutron spin structure function results compared to a NLO QCD fit.*

contributions to the neutron spin structure function, for example. Note that the valence versus sea contributions appear to be rougly equal at x values near 10^{-3}, and the sea and gluons begin to dominate at lower x values. The uncertainty in the valence, sea and gluon contributions also grows rapidly at low values of x, where no data exists. To improve this picture substantially, more data at lower x would be needed.

Armed with these predictions, it is also straightforward to extract the individual quark and gluon contributions to the nucleon's spin. Table 1 presents a summary of results coming from the SLAC analysis [9]. The gluon contribution appears to be positive and is established at the level of approximately two standard deviations. It is important to point out that all these conclusions depend on defining some factorization scheme. For the present results, we have taken the $\overline{MS}$ scheme.

Recent results on the measurement of the proton spin structure function from the HERMES collaboration have been published [10]. Figure 6 shows a comparison of these results with the SLAC E143 collaboration and the SMC collaboration. The agreement is excellent.

Results on the proton and neutron spin structure function from SLAC Experiment E155, which collected data in the winter of 1997, are still not finalized, but have been released as preliminary. Figure 7 and Figure 8 presents the results and a comparison to previous experiments. The overlap with the published results is impressive. As these measurements are released, a final world analysis of the polarized inclusive scattering data can be performed. It is unlikely that the final analysis will change the interpretations, since the fits are limited mostly by systematic and theoretical uncertainties, and the measurements are in excellent agreement with what has already been published.

A final round of data collection aimed at measuring with precision the spin structure function g_2 for the proton and neutron is presently taking place. The experiment (SLAC Experiment E155x) uses a longitudinally polarized beam scat-

Table 1
Results on the quark and gluon distributions in the $\overline{MS}$ scheme from the SLAC NLO analysis.

	Value	Stat.	Syst.	Theory
Δu_V	0.69	± 0.03	± 0.03	± 0.14
Δd_V	-0.40	± 0.03	± 0.03	± 0.07
$\Delta \overline{Q}$	-0.02	± 0.02	± 0.01	± 0.03
ΔQ	0.20	± 0.06	± 0.05	± 0.01
ΔG	1.8	± 0.7	± 0.5	± 0.6

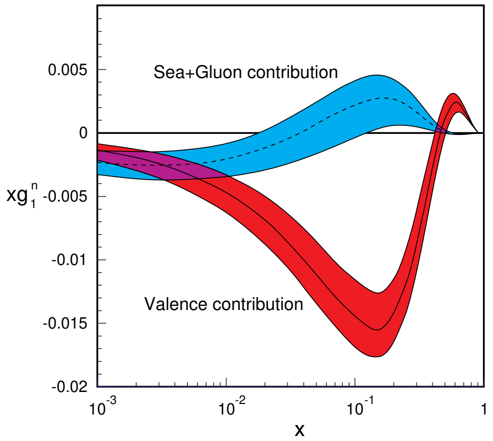

Figure 5. *Contribution of valence quarks versus sea quarks and gluons to the neutron spin structure function g_1^n versus x.*

tering off a transversely polarized target. The experiment will improve substantially on the measurement of this structure function and is expected to make a g_2 measurement comparable in precision to the g_1 results from SLAC.

In summary, the inclusive polarized deep inelastic scattering programs around the world have provided a major new data bank of information on the nucleon spin structure functions. The NLO perturbative QCD analyses of this data yield values for the total quark and gluon contribution to the proton's spin to be approximately,

$$\Delta q \approx 20 \pm 10\%$$

and

$$\Delta G \approx 1.8 \pm 1.$$

The determination of Δq is approximately an order of magnitude more precise than the extraction of ΔG. This can be understood quite simply in that one can only extract information on the polarized gluon contribution from the shape dependence of the spin structure functions, whereas information on the quark contribution comes from the total proton and neutron integrals, as described in the discussion on testing sum rules.

The most important future goal of the field is to improve substantially on the determination of ΔG. Programs at CERN (the COMPASS experiment) at DESY (HERMES and perhaps a polarized proton beam in HERA) and at Brookhaven (RHIC Spin) also discussed at this conference will be aimed specifically at extracting ΔG with an order of magnitude better precision. For a discussion of a possible future polarized proton program at HERA, for example, see the talk of Vernon Hughes in these proceedings.

Although tremendous progress has been made on understanding the spin structure of the proton, we are still a long way from obtaining a complete picture of the proton's spin and how it is decomposed (i.e. Equation 1).

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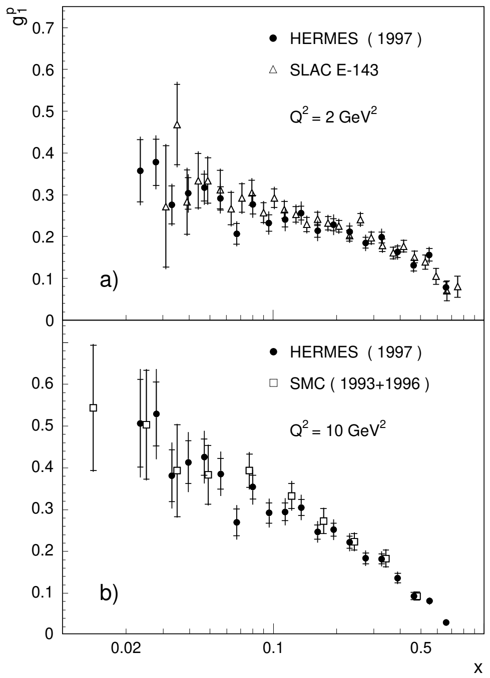

Figure 6. *Results on the proton spin structure function from HERMES compared to the SLAC E143 collaboration and SMC experiments.*

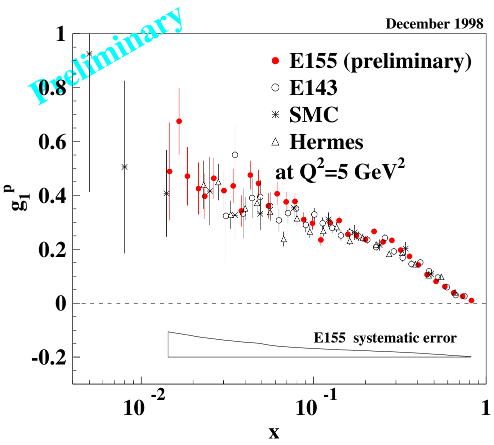

Figure 7. *Preliminary results on the proton spin structure function from the SLAC E155 collaboration compared to SMC, E143 and HERMES.*

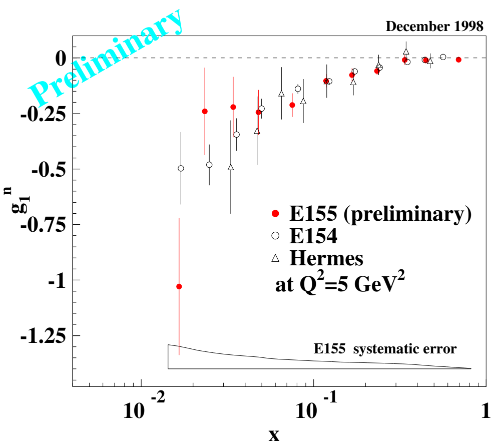

Figure 8. *Preliminary results on the neutron spin structure function from the E155 Collaboration compared to other electron scattering measurements using polarized ^{3}He targets.*

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