SLAC POLARIZED DEEP INELASTIC SCATTERING EXPERIMENTS

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1 Introduction

Over the past decade, the SLAC fixed target program has focused on studying the question of what carries the spin of the proton and neutron. This program, however, is now coming to an end. There will be one more round of data collection in the winter of 1999 after which the plan is to embark on a fixed target program devoted to performing precision electroweak studies. The latest data from SLAC still is being analysed. Here we present preliminary results from this analysis as well as results published since the last spin conference. Overall, the SLAC fixed target program has produced a huge data set of experimental measurements of the nucleon spin structure functions at a variety of energies. Before presenting the SLAC data, we briefly review the field.

The question being asked is to what extent the quarks in the proton account for its spin of 1/2. The simplest presentation of 'how things add up' is given in the formula below,

$$\mathrm{Proton's\ \ Spin} = \frac{1}{2} = \frac{1}{2}\Delta\mathrm{q} + \Delta\mathrm{G} + \mathrm{L_q} + \mathrm{L_G}$$

where Δq is the quark contribution to the proton's spin, ΔG is the gluon contribution and L_q and L_G are the orbital angular momentum contributions coming from the quarks and gluons, respectively. Accepting the caveat that one needs to define a particular renormalization scheme, the measurements from the SLAC experiments provide a value for Δq as well as give a $\sim 10\%$ test of perturbative QCD.

The excitement in this field was a result of a measurement from the EMC collaboration at CERN in 1988 which found that Δq was surprisingly small and close to zero. If quarks did not account for the spin of the proton, one could imagine that the entire quark model's description of the proton's structure was suspect. The consequence of these developments resulted in the creation of a rather large experimental nuclear and high energy physics community directed at performing a first test of the fundamental Bjorken sum rule [1]. This sum rule relates the integral over the proton and neutron spin structure functions and is given below

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

where $\frac{g_A}{g_V}$ is the ratio of the weak coupling constants that one extracts from neutron beta decay.

Over the past several years, a large bank of experimental data on these two structure functions has been created and reported in the popular press [2-8].

Before discussing the results from the SLAC experiments, in particular, it is useful to define the measured quantities. All polarized deep inelastic lepton scattering experiments involve the production of a polarized lepton beam scattering off a polarized target and the detection of the scattered leptons in a magnetic spectrometer. The energies of the initial and final scattered lepton are found and the kinematics of a scattering event are extracted from the energies and scattering angles defining the x and Q^2 of the event. In these experiments an asymmetry is measured

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

where $d\sigma^{\uparrow\downarrow(\uparrow\uparrow)}$ is the scattering cross section for the beam and target spins anti-parallel (parallel) to one another. From the measurement of A_1, one can extract the nucleon spin structure function which is closely related to the unpolarized structure function F_1,

$$g_1(x,Q^2) \approx A_1(x,Q^2) \cdot F_1(x,Q^2)$$

The spin structure function g_1 is extracted for a proton and a neutron separately using different polarized targets.

With the measurements of g_1, one can test the Bjorken sum rule, given above. And one can glean information on the quark's contribution to the nucleon's spin. Within the boundaries of various theoretical assumptions (e.g. SU(3) flavor symmetry), one can use the measurements to test, for example, the Ellis-Jaffe sum rules [9] given below

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

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

These sum rules imply a $\sim 60\%$ contribution of the quarks to the nucleon's spin, and the proton sum rule was found to be violated in the measurement performed by the EMC collaboration in 1987. It is worth noting that the violation of the Ellis-Jaffe sum rule and the fact that the quarks do not carry a large amount of the proton's spin are equivalent.

2 Recent SLAC Experiments and Results

Over the past several years the fixed target program at SLAC has provided high energy polarized electrons scattering from polarized targets in order to extract the nucleon spin structure functions g_1^p and g_1^n. The polarization of the electron beam is high using new technology from strained GaAs cathodes.

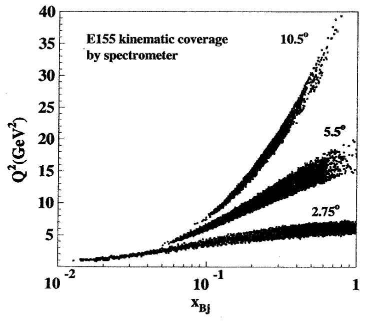

Figure 1: Scatter plot defining data collection regions in x and Q^2 for the SLAC 50 GeV experiments.

In 1995 the energy of the electron beam was raised to 50 GeV with the construction of a new beamline. Two recent experiments have used this new beam to scatter the electrons off a polarized ^{3}He target in 1996 (SLAC Experiment E154) and off a polarized ammonia and LiD target in 1997 (SLAC Experiment E155). Each of the experiments collected a total of a few hundred million events using the new 50 GeV electron beam running with a $\sim 80\%$ polarization.

With the higher beam energy the kinematic range covered by the data is large. One obtains measurements at high values of Q^2 and low values of x, allowing for detailed studies of the Q^2 evolution of the spin structure functions and of the convergence of these structure functions as x approaches zero, an important feature in trying to extract the nucleon integrals. Figure 1 gives the x and Q^2 range covered by the most recent E155 experiment. A new spectrometer built at 10.5° was installed for the E155 experiment to cover data to a higher values of Q^2. The new 10.5° spectrometer was not available for the E154 experiment.

Before presenting the results on the spin structure function measurements, it is useful to discuss some properties of the beam and target used in the experiments.

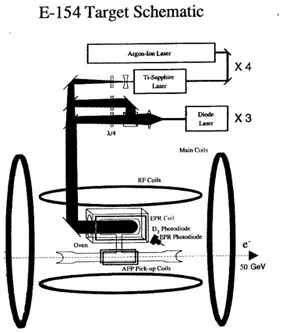

Figure 2: Schematic of polarized helium-3 target used in the E154 experiment.

The SLAC electron beam is a pulsed beam running at 120 Hz with helicity reversal of the electron spins performed randomly on a pulse-by-pulse basis. SLAC can produce from 10^9 up to a few 10^{11} electrons per pulse, resulting in an average current as high as several μAmps. Each pulse lasts for a few 100 ns. Therefore, the pulses are short and have a high peak current. The result of such beam conditions is that the experiments can only analyze inclusive electron scattering. The duty cycle is too short for performing semi-inclusive studies. However, the high electron current does provide for a high statistics measurement of g_1^p and g_1^n.

For the E154 experiment a high current beam is directed onto a polarized ^{3}He target in order to extract the neutron spin structure function g_1^n. Polarized ^{3}He can be modelled as one polarized neutron bound to two unpolarized protons. This model is to a large degree true, since the proton spins pair off due to the Pauli Exclusion Principle. A schematic of the polarized target is shown in Figure 2. The target consists of a double glass cell filled with polarized ^{3}He and rubidium vapor. The ^{3}He is polarized in the top cell in a two step process. First, polarized rubidium is produced via optical pumping. And second, the polarized rubidium atom transfers its polarization to the ^{3}He nucleus via spin exchange collisions. The polarized ^{3}He then diffuses to the bottom cell through which the electron beam passes. An enormous investment in laser power is needed to polarize a sufficient amount of rubidium to maintain the polarized ^{3}He. For the SLAC target, approximately 60 watts of laser power at 795 nm was used for the optical pumping. Measurement of the ^{3}He polarization was accomplished using NMR and frequency shift techniques. The resulting target ran at an average of about 35% polarization and achieved values as high as 50%.

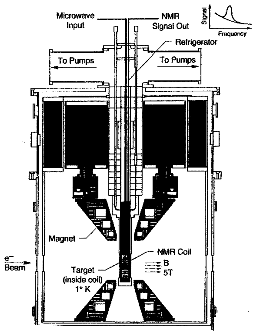

Figure 3: Schematic of polarized ammonia and LiD target used in the E155 experiment.

The target for the E155 experiment uses a completely different technique. In the E155 experiment ammonia (NH_3) and ^{6}LiD are used to extract the proton and deuteron spin structure functions, respectively. The ^{6}LiD nucleus itself is modelled as a helium-4 bound to a deuteron. Thus, ^{6}LiD corresponds effectively to two polarized deuterons and one unpolarized helium-4. Both the ammonia and LiD targets are cooled to $\sim$1 degree Kelvin and placed in a 5 Tesla magnetic field shown in Figure 3. The samples are polarized with rf excitation using the method of dynamic nuclear polarization. Measurement of the polarization of the targets are performed using NMR techniques. The E155 target collected data with a similar luminosity to E154, but the electron beam current was substantially lower and the solid target substantially thicker. In the end, the E155 proton target achieved an average polarization of approximately 80% and the deuteron target ran with $\sim$25% polarization.

Electrons scattered from the polarized targets were detected in one of three spectrometer arms located at 2.75, 5.5, and 10.5 degrees, respectively (Figure 4). The electrons were directed through a series of bend magnetics where they are momentum selected. A pair of Cerenkov counters were used to identify the electrons. A series of hodoscopes were used for tracking and momentum determination, and in the rear was a lead glass shower counter which determined the energy of the electron from the shower deposition. During the experiment, approximately one scattered electron event occured per pulse in the 2.75 degree spectrometer arm and substantially lower rates in the other two arms.

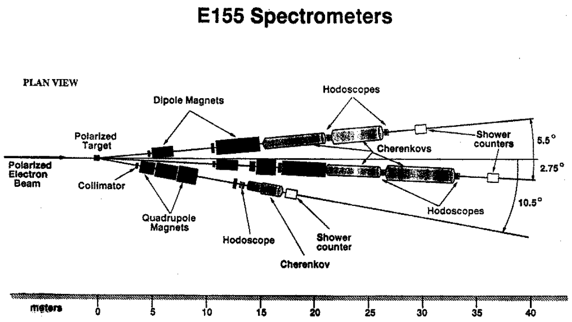

Figure 4: Spectrometer setup for the E155 experiment.

Experiment E154 collected data in the fall of 1995 and the data were published July of 1997 in three articles [10-12]. The success of the experiment is evident in the high statistical precision of the g_1^n data. Figure 5 presents g_1^n versus x for the E154 experiment compared to an earlier measurement in 1992 using the same target. The higher beam polarization in E154 coupled with the higher energy beam at 50 GeV provide high precision data down to quite low values of x near 0.01.

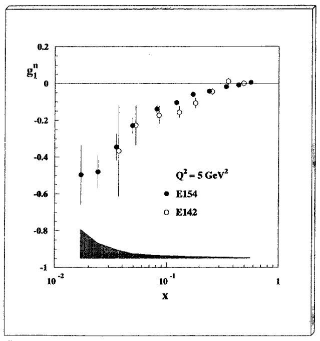

Figure 5: Results on g_1^n from SLAC Experiment E154 compared to an earlier experiment (SLAC Experiment E142).

From this new data and a previous precision measurement of the proton

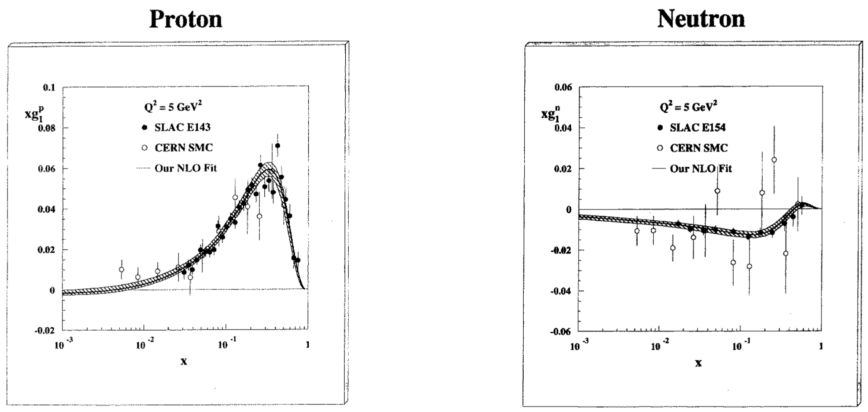

Figure 6: Results on xg_1^p (left) and xg_1^n (right) versus x from SLAC and CERN experiments compared to a global NLO fit.

spin structure function, the spin structure function data can be used to perform Next-to-Leading Order (NLO) fits using the DGLAP evolution equations [13]. Figure 6 presents the results of a set of such fits. The fits are driven heavily by the SLAC data and the SLAC neutron data, in particular, completely dominate the function form of the fits. With the parameterizations used in the fits, one can extract the spin-dependent quark distributions. Figure 7 shows the contributions of the gluons, sea and valence quarks to the neutron spin structure function at various x values. At high values of x, the structure function is well described by the valence contribution, whereas the sea and gluon contribution is predicted to come into full force only at quite low values of x, near x = 0.01. From these fits, one can also extract a first look at the spin dependent gluon distribution, ΔG. Figure 7 shows ΔG as a function of x resulting from the fits to g_1^p and g_1^n. One sees a positive contribution, but the result is only two standard deviations above zero. A major goal for the future is to extract some more direct measurement information on ΔG. With the parameterizations of the spin dependent quark distributions, one can extract values for the integrals over the various quark distributions. From such fits, we find Δq = 0.20 $\pm$ 0.06 and ΔG = 1.8 $\pm$ 0.9 in the $\overline{MS}$ scheme. The strange sea contribution, Δs, is unconstrained.

Preliminary results on the proton and neutron spin structure functions from the 50 GeV experiment E155 are presented in Figure 8. The neutron results come from measuring the deuteron spin structure function with the LiD

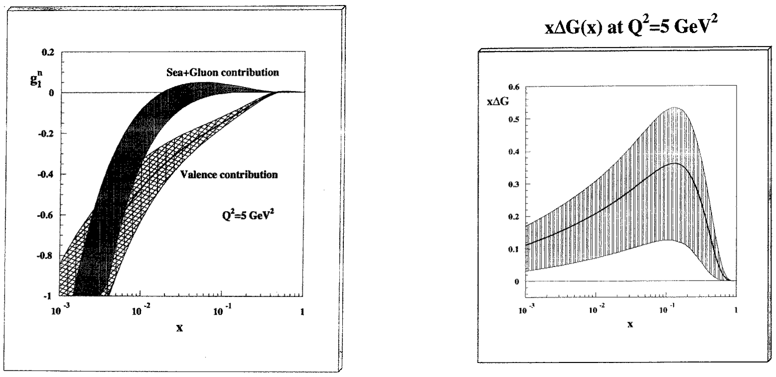

Figure 7: NLO fit results on the contribution from the valence, sea and gluons to g_1^n (left). NLO fit prediction of the gluon contribution to the proton's spin (right).

target and then subtracting out the proton results. The new data on the proton is in fine agreement with previous measurements with a significant improvement in the statistical precision. The E155 neutron data is comparable, but has slightly larger uncertainties than those of E154. In any case, the neutron results from E154 and E155 are in good agreement and provide no evidence that a neutron extracted from a deuteron compared to one extracted from a helium-3 nucleus are different within the observed precision. Final publication of the results from E155 are expected to be submitted for publication in winter 1999.

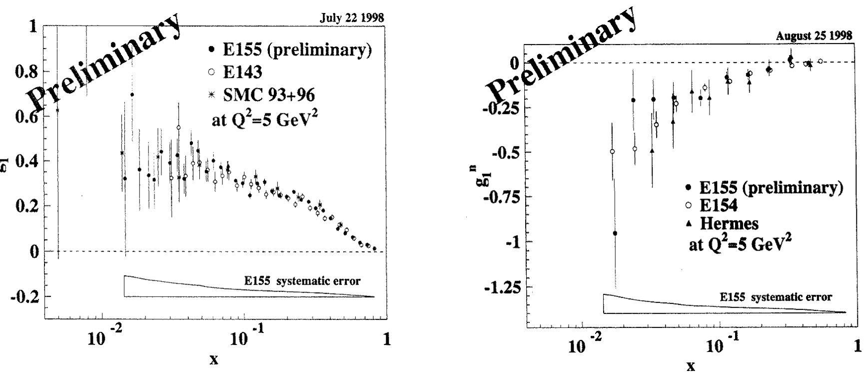

Figure 8: Preliminary results on g_1^p (left) and g_1^n (right) from SLAC Experiment E155.

In winter of 1999, one last experiment directed at studying nucleon spin structure will be performed. In this last run called E155x, a longitudinally polarized electron beam will scatter off a transversely polarized ammonia and LiD target in order to extract a twist-3 related structure function g_2 given by

$$g_2(x,Q^2) = g_2^{ww}(x,Q^2) - \int_x^1 \frac{\partial}{\partial y}\left(\frac{m}{M}h_T(y,Q^2) + \eta(y,Q^2)\right)\frac{dy}{y}$$

The first term in this expression g_2^{ww} [14] is a twist-2 dependent term that depends on g_1. The second term in the expression is also twist-2, but small since it is weighted down by the mass of the quarks. And the final term is twist-3. It is expected that this last term gives new information on the spin-dependent quark distributions in the proton. E155x will be a dedicated run to try to distinguish the difference between g_2^{ww} and g_2=0. Previous data on g_2 have not come close to being sensitive to g_2^{ww} (see Figure 9). Only a minimal amount of beamtime was devoted to this measurement. And so one sees that the g_2^n structure function is highly statistics limited. Figure 9 presents an estimation of how well g_2 should be measured for the proton and neutron from a dedicated two month run. One sees that the data represents a dramatic improvement in the measurement of g_2 compared to what exists now. In addition, this data should be able to distinguish for the first time between the case that g_2=g_2^{ww} and the case that $g_2 = 0$.

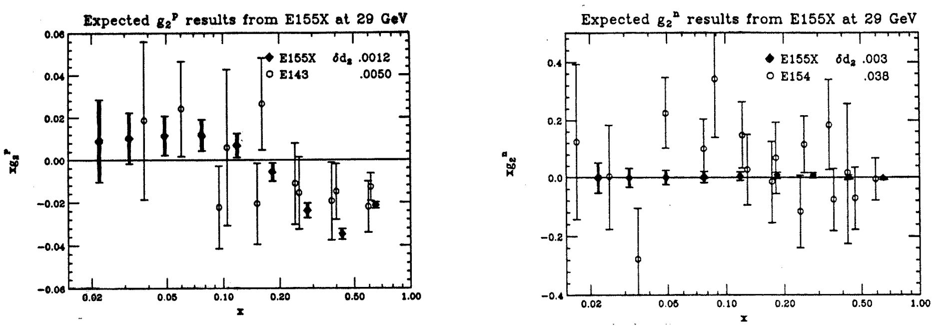

Figure 9: Estimation of the statistical precision achievable on xg_2^p and xg_2^n compared to the past coming from the winter 1999 run of Experiment E155x.

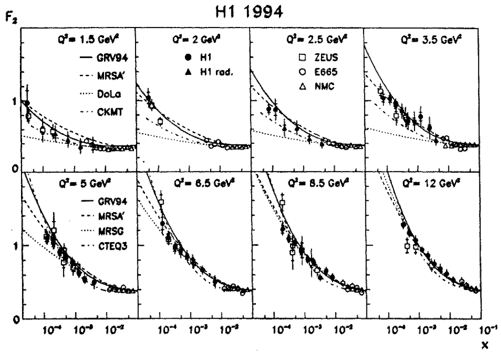

Figure 10: Unpolarized proton structure function measurements of F_2^p from the H1 experiment at DESY.

3 FUTURE

The fixed target program at SLAC will continue to scatter polarized electron beams off targets; however, the next several years of the experimental program will be used to perform precision tests of the electroweak theory. For the foreseeable future the E155x experiment will be the last in a decade's worth of work to study the spin structure of the nucleon. Simply stated, the future of polarized electron−polarized nucleon scattering will move elsewhere. And, at present, the most interesting possibility in polarized lepton-nucleon scattering is to continue these studies at the DESY collider in Hamburg, Germany. The idea is to polarize the protons in the HERA ring and collide them with the already polarized electron beam.

This idea is covered in the plenary talk of Albert de Roeck in these conference proceedings, so we will only discuss it briefly here. The main idea is the following: if one can polarize the proton beam at HERA, one could measure structure functions and analyze jet studies that ultimately access g_1^p and ΔG values down to x near 10^{-4}. Unpolarized structure function measurements have already been done by H1 [15] and ZEUS [16], an example of which is shown in Figure 10. From the evolution equations, one can extract the gluon contribution to the proton structure, shown in Figure 11. The large rise in gluons at low x suggests that low x is a natural hunting grounds for polarized gluon information. Therefore, repeating structure function studies at low x with polarized beams would be a valuable input into nucleon spin structure studies. A comparison of the region accessed for a measurement of ΔG by

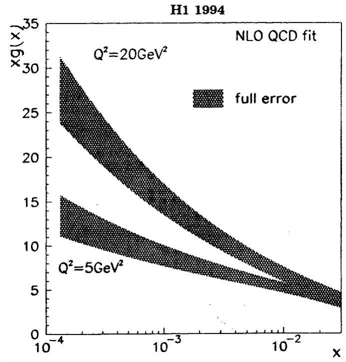

Figure 11: Results on the gluon contribution coming from unpolarized results in the H1 experiment at DESY.

RHIC spin at Brookhaven, a polarized HERA and the COMPASS experiment at CERN is presented in Figure 12. One sees that a polarized proton beam at HERA allows one to access extremely low values of x, beyond what could be envisioned at any other experimental program. It is interesting to note that with such programs around the world, one could extract $\int_{0.001}^{0.6} \Delta G \, dx$ to a precision of ± 0.2 [17].

In summary, between 1992 and 1998, SLAC has produced a huge data sample of precision measurements of g_1^p and g_1^n for x greater than 0.01. From this data, one can extract a 10%-ish measurement of the quark distributions (once the renormalization scheme is defined). In 1999, SLAC will run a dedicated precision measurement of the structure functions g_2^p and g_2^n for its last round of nucleon spin studies. With the SLAC program ramping down, the future will be aimed at hunting ΔG at numerous high energy physics laboratories around the world.

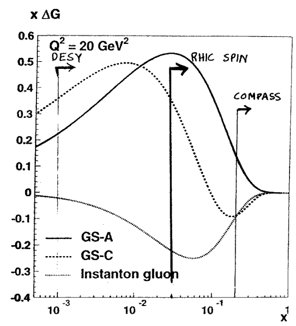

Figure 12: Comparison of the kinematic range in Bjorken x available in the extraction of the polarized gluon distribution from different experimental programs.

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