A Review of Nucleon Spin Structure Experiments

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Abstract

I present a review, from an experimenter's perspective, of nucleon spin structure measurements. Several recent experiments combined with theoretical input and interpretations have clouded and cleared the picture we have of nucleon spin strucure in the quark–parton model. Recently, high precision measurements (*i.e.* better than 10%) and the use of polarized ^{3}He and ^{2}H targets has provided experimenters with increased confidence by way of the consistency of results extracted from different experiments. Some conclusions drawn from the accomplishments of completed experiments at SLAC and CERN (EMC/SMC) combined with theory and models are that the quark spin component of the nucleon spin is about 1/3, the sea quarks have a significant negative polarization, and the Q^2 dependence of the structure functions is very interesting. Imminent experiments plan to enhance the precision, extend the range of kinematic parameters over which the data are extracted and to look at new exclusive channels with the hope of tagging the flavor of the scattered quark.

I. Introduction

The modern view of nucleon structure is based on the parton picture of quarks and gluons interacting via the strong interaction and is in principle descibed completely by QCD. The role of spin of the quarks (spin 1/2) and gluons (spin 1) is well known in terms of the Pauli principle, the spectrum of hadrons, and color as a degree of freedom and the carier of the strong "charge." The quark-parton model seems successful in describing static properties of the hadrons, and though QCD is currently useful in calculations in certain limits, the dynamic properties of quarks and gluons are currently considered observables, *i.e.* they are not practically derived from first principles. The measurement of the spin dependent and spin independent quark momentum distributions therefore provides data crucial to parameterizing nucleon structure and can be used to estimate certain sum rules that reveal fundamental featues of the nucleons described by QCD. Deep inelastic scattering of polarized electrons and muons from polarized nucleons is sensitive to the spin dependence of the quark momentum distributions. These spin-dependent structure functions provide crucial information on the dynamics of quarks and gluons in the nucleons. Also important are the structure functions in the limit of high and low x, that is in the perturbative regime and in the quark-sea dominated regime, and what is the Q^2 dependence.

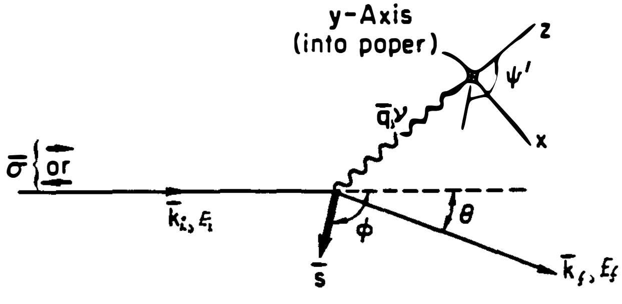

Figure 1. Deep Inelastic Scattering Kinematics

In figure 1 we illustrate deep inelastic scattering of polarized leptons from a polarized nucleon. Spin dependence leads to cross sections that depend on the relative orientation of electron and nucleon spin. We express the cross sections for electron and nucleon spin projections parallel to (↑) and opposite (↓) the electron momentum in terms of spin averaged (W_1 and W_2) and spin dependent (G_1 and G_2) structure functions:

$$\frac{d^2\sigma^{\uparrow\downarrow}}{dQ^2 d\nu} + \frac{d^2\sigma^{\uparrow\uparrow}}{dQ^2 d\nu} = \frac{4\pi\alpha^2}{Q^4}\frac{E'}{E}[2W_1(Q^2,\nu)\sin^2\frac{\theta}{2} + W_2(Q^2,\nu)\cos^2\frac{\theta}{2}].$$

$$\frac{d^2\sigma^{\uparrow\downarrow}}{dQ^2 d\nu} - \frac{d^2\sigma^{\uparrow\uparrow}}{dQ^2 d\nu} = \frac{4\pi\alpha^2}{Q^2}\frac{E'}{E}[M_p D G_1(Q^2,\nu)(E + E'\cos\theta) - Q^2 D' G_2(Q^2,\nu)]. \tag{1}$$

A corresponding relationship exists for scattering of longitudinally polarized electrons from a transversely polarized target. The kinematic quantities are defined as follows:

$$x = \frac{\mathrm{Q}^2}{2\mathrm{M_p}\nu}; \quad Q^2 = \nu^2 - |\vec{q}|^2; \quad \nu = E_i - E_f \tag{2}$$

and D is the polarization of the virtual photon

$$D = \frac{y(2-y)}{y^2 + 2(1-y)(1+R)}, \tag{3}$$

where $y = \frac{\nu}{E}$ and $R = \frac{\sigma_L}{\sigma_T}$, and D' depends on kinematics.

In the scaling limit (ν, Q^2 large) these structure functions are predicted to depend only on x and are identified with the momentum (or x) distributions of the quarks within the nucleons:

$$\begin{aligned} M_p^2 \nu W_1(\nu, Q^2) &\rightarrow F_1(x) \\ M_p \nu^2 W_2(\nu, Q^2) &\rightarrow F_2(x) \\ M_p \nu^2 G_2(\nu, Q^2) &\rightarrow g_2(x) \\ M_p^2 \nu G_1(\nu, Q^2) &\rightarrow g_1(x) \end{aligned} \tag{4}$$

For experiments at finite Q^2, appropriate corrections must be made, as discussed later.

II. Spin Dependent Structure Functions

The structure functions are interpreted as a measure of the probabilities for scattering from a parton in the nucleon with 4-momentum xP where P is the nucleon momentum in the infinite momentum frame where $E = p$ for both the electron and nucleon. The spin dependent structure function is the difference of the probabilities for parton spin parallel and anitparallel to the nucleon. Thus

$$g_1^N(\mathrm{x}) = \frac{1}{2}\sum_f e_f^2[q_f^{\uparrow}(x) - q_f^{\downarrow}(x)] \tag{5}$$

where e_f is the charge of the parton of flavor f and $q_f^{\uparrow}$ and $q_f^{\downarrow}$ are the structure functions for parton spin parallel and antiparallel to the nucleon spin.

Of particular interest is the integral over all momenta, *i.e.* over all x which gives the parton or quark polarization in the polarized nucleon weighted by the square of the quark charges. In the limit of $SU_f(3)$ symmetry, *i.e.* neglecting heavy quarks

$$\Gamma_1^N = \int_0^1 g_1^N(x)\mathrm{d}x = \frac{4}{9}\Delta \mathrm{u}^N + \frac{1}{9}\Delta \mathrm{d}^N + \frac{1}{9}\Delta \mathrm{s}^N \tag{6}$$

where $\Delta \mathrm{u}^N = \int_0^1 [q_u^\uparrow(x) - q_u^\downarrow(x)]dx$ is the difference of probability for spin parallel and anit-parallel up-quarks with obvious notation labeling the down-quarks and strange-quarks. Theoretical predictions for this integral (sum rules) begin with the naive quark model for which

$$\Delta \mathrm{u}^p = \Delta \mathrm{d}^n = \frac{4}{3} \quad \text{and} \quad \Delta \mathrm{d}^p = \Delta \mathrm{u}^n = -\frac{1}{3} \tag{7}$$

which must then be corrected for QCD effects. These corrections are inherent in the Gamow-Teller decays of octet baryons, that is in the quantities g_A/g_V for neutron and hyperon decay. Within the context of $SU_f(3)$ symmetry (*i.e.* the Cabibbo model) these can be expressed in terms of two numbers, $F = 0.47 \pm 0.04$ and $D = 0.81 \pm 0.03$ (see for example reference [1].

$$g_A(n \to pe\bar{\nu}) \propto \Delta u - \Delta d = F + D = 1.28 \pm 0.05$$

$$g_A(\Sigma^- \to nl\bar{\nu}) \propto \Delta d - \Delta s = F - D = -0.34 \pm 0.05 \tag{8}$$

Isospin symmetry combined with the first expression yields the Bjorken Sum Rule [2] which constrains the difference of the neutron and proton integrals of $g_1(x)$. Ellis and Jaffe [3] have taken the approach of assuming $\Delta s = 0$ to predict sum rules for the proton and neutron seperately. The predictions of these sum rules are discussed along with experimental results in section 4.

3. The Experiments

The first experiments took place at SLAC in the 1970's, where polarized electrons were scattered from targets of frozen Butanol in which protons were dynamically polarized (E80 [4] and E130 [5]). The data for assymetries measured in E130 are shown in figure 2. These first experiments were statistically limited in precision and also limited in the range of x and Q^2. Extrapolation to low x and high x, essential to extract the proton integral Γ_1^p is model dependent. It has been the practice to assume that $g_1 \to 0$ by a power law (Regge Trajectory) [6] as $x \to 0$ and that the asymmetry $A_1 \to 1$ as $x \to 1$. The sum rules derived with E80 and E130 data are consistent with the Ellis Jaffe sum rule and the Bjorken sum rule when the neutron integral Γ_1^n, vanishes. The dominant uncertainties in the integrals are due to extrapolation to low x, and the next generation of experiments was designed to greatly extend the data range at low x. These experiments were undertaken at CERN with polarized muons by the EMC/SMC collaborations [7]. Muons produced in pion decay are polarized in the pion rest frame due to parity violation and the CERN beam provides muon energies up to 100 GeV allowing much greater energy loss (ν) and therefore lower x for $Q^2 > 1$ GeV, the customary cut for Deep Inelastic Scattering.

The EMC experiment used a large, 1 meter long dynamically polarized NH_3 target with two halves oppisitely polarized and vertex reconstruction of the muon scattering events to identify the target half and therefore the target polarization. Data from EMC, also shown in figure 2, greatly extended the low x range and therefore reduced the systematic uncertainty due to low x extrapolation. The proton integral from EMC combined with the analysis outlined in section 1 produced an unexpected violation of the Ellis-Jaffe sum rule and the conclusions that the sea quarks had a large negative polarization and that the total quark spin contribution to the proton spin was very small and consistent with 0. Though this result was surprising, it should be empahsized that it did not disagree with QCD and the quark-parton model; recall that the spin structure functions are observables. The validity of the **model dependent** extrapolations to low and high x are most important in these interpretations of the measurements. The EMC results for Δq are given in table 1.

The EMC result for the proton integral combined with the Bjorken sum rule predicted the neutron integral. Alternatively, a measurement of the neutron spin structure function combined with the proton data could provide a test of the Bjorken sum rule. Polarized neutrons are available only in targets of polarized nuclei ^{2}H and ^{3}He. Both have been used, ^{2}H in dynamically polarized targets at CERN [8] and SLAC [9] and a spin exchange pumped polarized ^{3}He target at SLAC [10]. The nuclear physics issues of extracting neutron information from measurments with nuclei seem to be well under control in both cases and do not dominate the systematic uncertainties at this point.

The neutron data for g_1^n extracted from the SLAC proton/deuteron (E143) and ^{3}He (E142) experiments are shown in figure 3. Figure 3 shows data for experiments with very different targets, and with the two nuclei, and figure 3 shows that the results are completely consistent over the commonly measured ranges. This is a remarkable concurrence that bolsters confidence in the esperiments' results and the assigned systematic errors. In order to understand what goes into extracting the results, we briefly describe the analysis proceedures for the example of ^{3}He.

Several steps of analysis proceed from the electron counting rates to $g_1^n(x)$. g_1 for ^{3}He is derived from the asymmetry A_1 extracted from measurement of electron scattering rates for parallel and antiparallel target and electron spin. (Effects due to the orthogonal structure function g_2 have been shown to be negligible for E-142 and E143 and are neglected in this analysis.)

$$A_1(x,Q^2) = \frac{g_1^R(x,Q^2)}{F_1^R(x,Q^2)} = \frac{1}{D(x,Q^2)}\frac{1}{P_e}\frac{1}{P_3}\frac{1}{f_3}\frac{\eta^{\uparrow\downarrow}(x,Q^2)-\eta^{\uparrow\uparrow}(x,Q^2)}{\eta^{\uparrow\downarrow}(x,Q^2)+\eta^{\uparrow\uparrow}}(x,Q^2) \qquad (9)$$

where $\eta^{\uparrow\uparrow}$ and $\eta^{\uparrow\downarrow}$ represent the counting rates of electrons corrected for deadtime, backgrounds, and contamination and normalized to the number of incident electrons, and P_3 and P_e are the ^{3}He and electron polarizations. The dilution factor, f_3, is the fraction of events originating from ^{3}Heout of the total number of events from the other target material (*i.e.* N_2) and the target end windows. For E-142, f_3 is determined directly with measurements using a glass reference cell with variable pressures of ^{3}He enabling separation of contributions due to scattering from ^{3}He from those due to to an empty target cell.

The quantities g_1^R and F_1^R relate to the First Order Born quantities of interest through radiative corrections. Internal spin dependent radiative corrections are applied using the calculations of Kukhto and Shumeiko [11]. Spin independent external radiative corrections were carried out following the procedure of Mo and Tsai [12]. For E142 these corrections can be appreciable amounting to a relative change in the asymmetry ranging from 30% at low x to 5% at high x. The spin dependent structure function for ^{3}He can then be determined from the corrected asymmetry and spin independent values of $F_1(x, Q^2)$, however it is generally applied that the asymmetry is independent of Q^2 (this is consistent with all available data) and therefore the value for $g_1(x)$ depends on the value for Q^2. For E142, the experiment's average of $< Q^2 > = 2$ (GeV/c)^2 was choosen. In subsequent analyses, the E142 and other data were evaluated at higher $< Q^2 >$ for intercomparison.

The results are the First Order Born values for g_1^3 for ^{3}He, and nuclear physics corrections must be made to extract g_1^n. Nuclear physics effects are smearing due to nuclear motion, the EMC effect and polarization of the neutron (less than 1) and the proton (not 0). In ^{3}He, the strongest components of the nuclear ground state wave function are those with the two protons in a spatially symmetric s-state and therefore a spin-singlet, *i.e.* the proton spins are paired. Therefore the neutron spin is parallel to the spin of ^{3}He in a polarized target. In reference [13], it is shown that the polarization of the neutron and proton in polarized ^{3}He are $P_n = 87\%$ and $P_p = -2.7\%$. Corrections for these polarizations are applied in order to extract the neutron asymmetry from the measured ^{3}He asymmetry. For the proton correction, the asymmetry results from EMC were taken. At the present level of precision, no other assumptions need be made about the spin dependence in deep inelastic scattering from polarized ^{3}He, though the role of the other corrections is discussed in reference [14]. Thus g_1^n is extracted from g_1^3 according to

$$g_1^3 = P_n g_1^n + 2P_p g_1^p \qquad (10)$$

4. Comparisons of Experimental Results

The analysis and interpretation of the experiments can be confirmed only by over-constraint, that is several experiments. For example, we use polarized ^{3}He to extract the spin dependent structure function of the neturon which is highly polarized in a polarized

^{3}He nucleus. In polarized D, both the neutron and proton are highly polarized , and the extraction of the neutron structure function is subject to different systematic effects. Also, the nuclear structure questions that are necessary to study the neutron are different for D and ^{3}He.

Measurements of the proton spin structure function by EMC [7], the deuteron structure function by SMC [8], and the neutron structure function by E-142 together with extrapolations to $x = 0$ and $x = 1$ and corrections for finite Q^2 are used to determine all three quark flavor polarizations. The results are summarized in Table 1 which includes the most recent results from EMC, SMC and E-142 and E143

Sum Rules for Spin Dependent Structure Functions

Experiment	$< Q^2 >$	Γ_1	Sum Rule at $< Q^2 >$
EMC g_1^p [7]	10.7 $(GeV/c)^2$	0.126± 0.018	0.175
SMC g_1^d [8]	4.7 $(GeV/c)^2$	0.023± 0.025	0.069
EMC/SMC $\Gamma_1^p - \Gamma_1^n$	4.6 $(GeV/c)^2$	0.189 ± 0.003	0.180
E142 g_1^n [10]	2 $(GeV/c)^2$	-0.022± 0.011	0.021 ± 0.018
E143 g_1^p [9]	3 $(GeV/c)^2$	0.127± 0.011	0.160 ± 0.006
E143 g_1^d [15]	3 $(GeV/c)^2$	0.042± 0.005	0.069 ± 0.004
E143 Γ_1^n	3 $(GeV/c)^2$	0.037± 0.014	
E142/3 $\Gamma_1^p - \Gamma_1^n$		0.149± 0.014	0.171 ± 0.008
E143 $\Gamma_1^p - \Gamma_1^n$	3 $(GeV/c)^2$	0.163± 0.019	0.171 ± 0.008

The sum $\sum \Delta q_f$ is interpreted as the contribution of the quark spins to the total spin of the nucleon.

$$\Delta s = -0.09 \pm 0.02 \qquad\qquad \sum \Delta q_f = 0.30 \pm 0.06$$

If we assume SU_3 symmetry of the quark sea, the valence quarks carry about 0.3 + 3(0.09) = 0.57 of the nucleon spin, and the up and down valence quarks are indeed highly polarized. The coupling of valence quark to sea quark spins is presumably through the gluon spin, and the gluons must account for a significant part of the nucleon spin along with possible quark orbital angular momentum. Several experiments have been proposed at RHIC and elsewhere to directly probe the gluon polarization.

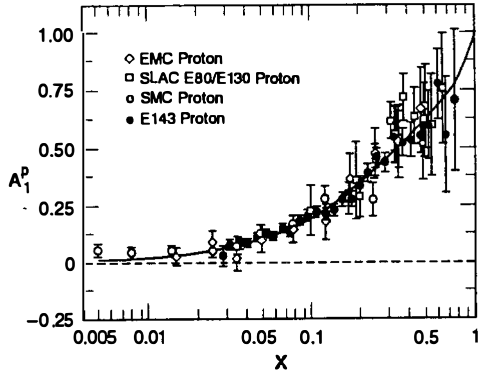

Figure 2. Results for the asymmetry, A_1^p vs x. from CERN EMC/SMC and SLAC E130 and E143. The systematic error from E143 is indicated.

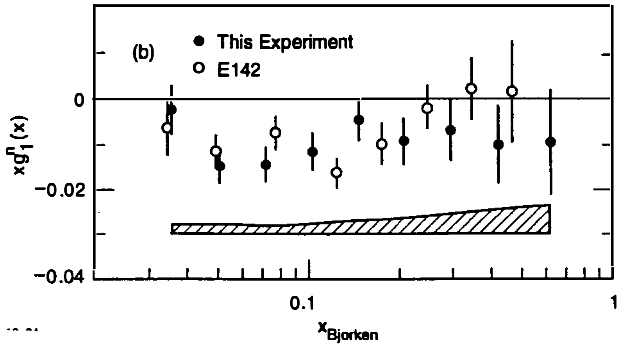

Figure 3. Results for xg_1^n vs $\log x$ from E142 (^{3}He) and from the E143 measurement of g_1^d. The slashed area represents the E143 systematic error.

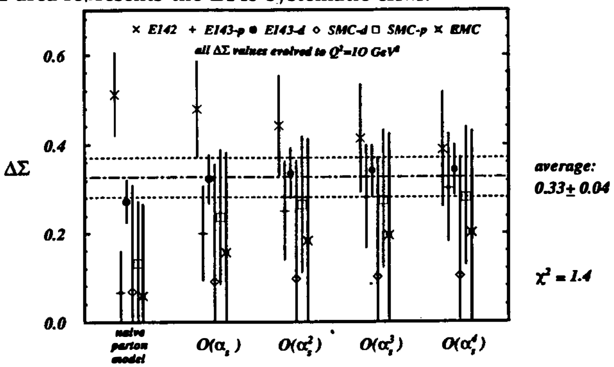

Figure 4. Corrections to order α_s^4 for the integrals Γ_1 for the spin structure function measurements from reference [16]

The comparison of results derived from experiment and from theory for the Bjorken Sum Rule have the complication that the experiments are performed at different $< Q^2 >$ as is clear from table 1. In figure 4 we show an analysis which indicates the effects of the Q^2 dependence on the interpretation of the extracted integrals of g_1[16] are corrected to the same $< Q^2 >$ and up to 4th order in $\alpha_s(Q^2)$, the strong interaction coupling constant.

5. Outlook and conclusions

The spin structure of the nucleons has been studied with increasing precision and over a broadening kinematic range in recent years. Recent data combined with theoretical work have provided a picture consistent with a nucleon in which the valence quark spin is partly cancelled by a polarized quark sea and in which gluons and orbital angular momentum conribute to the total nucleon spin. The experimental programs at CERN and SLAC with distinct polarized beams and targets provide data that continue to increase the confidence in the results and provide data a broadening kinematic range. The importance of the Q^2 dependence has been demonstrated, leading the way to the important new experiments with 50 GeV polarized electron beams at SLAC. At DESY, a new program has recently begun taking data with a polarized ^3He target internal to the HERA storage ring which provides a new experimental technique and promises to explore exclusive Deep Inelastic Scattering Channels to tag the flavor or the struck quark in an event. Within the next five years, a precise picture of the quark spin structure of the nucleon should be limited only by the kinematic range in x and Q^2. An ambitious, but technically feasible goal for the future is the measurement at $x << 0.01$ with colliding beams of polarized protons and leptons at HERA.

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