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SPIN–STRUCTURE FUNCTION OF THE NEUTRON (^{3}HE): SLAC RESULTS*

Z.–E. Meziani**
Department of Physics, Stanford University, Stanford, California 94305

Representing the E–142 Collaboration
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

Abstract

A first measurement of the longitudinal asymmetry of deep-inelastic scattering of polarized electrons from a polarized ^{3}He target at energies ranging from 19 to 26 GeV has been performed at SLAC. The spin-structure function of the neutron g_1^n has been extracted from the measured asymmetries allowing for a test of the Ellis-Jaffe and Bjorken sum rules. The Quark Parton Model (QPM) interpretation of the nucleon spin-structure function is examined in light of the new results.

Introduction

In his pioneering work of 1966 and 1970, Bjorken [1] suggested that large asymmetries could be observed in deep-inelastic polarized-electron scattering off polarized-nucleon targets. Furthermore, he derived a fundamental relation known as the Bjorken sum rule. The test of the latter, described by Feynman [2] as one that would have a decisive influence on the future of high-energy physics, requires a measurement of both proton and neutron spin-structure functions. In the early seventies—given the perceived technical difficulties of polarized target developments—a measurement using a polarized-proton target was viewed as feasible, while that of a polarized-neutron target was, if not impossible, at least a very complicated task. Theoretical work initiated by Gilman [3], within the framework of SU(3) symmetry, focused on writing separate sum rules for the proton and the neutron. It was further developed by Ellis and Jaffe [4], who assumed that the strange sea in the nucleon was unpolarized, and derived what is known as the Ellis–Jaffe sum rule (E–J) for the proton and the neutron.

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**Present address: Physics Department, Temple University, Philadelphia, PA 19122.

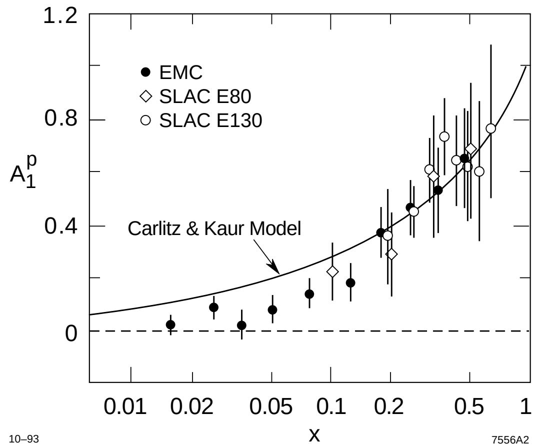

Fig. 1. World results for proton asymmetries A_1^p, and the QPM model [10]

Two early experiments performed in 1976 (E–80) [7] and in 1983 (E–130) [8] by the Yale–SLAC collaboration at SLAC on a polarized proton target confirmed the suggestion of Bjorken giving grounds to the naive picture of the QPM. While a good agreement with the QPM prediction was observed in the x region dominated by the valence quarks, no comparison was possible in the region of sea quarks due to a limited kinematic coverage. A first experimental test of the E–J sum rule found it to be fulfilled, but with a large uncertainty due the extrapolation uncertainty of A_1^p in the unmeasured low x region. The debate on the detailed spin structure of the proton was revived in 1988, when the European Muon Collaboration (EMC) [9] reported new results on polarized muon scattering off a polarized proton target extending the measurements of A_1^p to low values of x. An evaluation of the E–J sum rule on the proton using the new proton data displayed a two standard and a half deviation from the predicted value. A QPM analysis of the spin structure of the proton in terms of its flavor components revealed a small net total spin contribution of the quarks, with a large negative strange-sea quarks component. It was clear that more experiments were needed to set limits on various speculations arising from these results, and to im prove our understanding of the nucleon spin structure. The world proton asymmetry data are summarized in Fig. 1, with a QPM prediction [10] consistent with the E–J sum rule.

We first define the quantities of physics interest, following with a description of the ^{3}He (neutron) spin structure function measurement carried out at SLAC by the E–142 collaboration. Finally, in light of the new results, we examine the spin structure of the nucleon, and present the crucial test of the Bjorken sum rule with a coherent set of assumptions.

Asymmetries and Sum Rules

In deep-inelastic scattering, the measured longitudinal asymmetry $A^{\parallel}$ can be determined experimentally by measuring the difference over the sum in cross sections of polarized electrons on polarized nucleons between states where the spins are parallel and antiparallel [5,6],

$$A^{\parallel} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = \frac{1-\epsilon}{(1-\epsilon R)\ W_1(Q^2,\nu)} \left[M(E + E'\cos\theta)\ G_1(Q^2,\nu) - Q^2 G_2(Q^2,\nu) \right] . \tag{1}$$

Here $\sigma^{\uparrow\uparrow}$ ($\sigma^{\downarrow\uparrow}$) is the inclusive $d^2\sigma^{\uparrow\uparrow}/d\Omega d\nu$ ($d^2\sigma^{\downarrow\uparrow}/d\Omega d\nu$) differential scattering cross section for longitudinal target spins parallel (antiparallel) to the incident electron spins. A corresponding relationship exists for scattering of longitudinally polarized electrons off a transversely polarized target where a transverse asymmetry is defined [6]:

$$A^{\perp} = \frac{\sigma^{\downarrow\leftarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\downarrow\leftarrow} + \sigma^{\uparrow\leftarrow}} = \frac{(1-\epsilon)E'}{(1-\epsilon R)\ W_1(Q^2,\nu)} \left[(MG_1(Q^2,\nu) + 2EG_2(Q^2,\nu))\ \cos\theta \right] , \tag{2}$$

where

$$R = \frac{W_2}{W_1}\left(1 + \frac{\nu^2}{Q^2}\right) - 1 \ ; \qquad \epsilon = \left[1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\ \tan^2\frac{\theta}{2}\right]^{-1} . \tag{3}$$

Here $\sigma^{\downarrow\leftarrow}(\sigma^{\uparrow\leftarrow})$ is the inclusive scattering cross section for beam-spin antiparallel (parallel) to the beam momentum, and for target-spin direction transverse to the beam momentum and towards the direction of the scattered electron. In all cases, G_1 and G_2 are the spin-dependent structure functions, whereas W_1 and W_2 are the spin-averaged structure functions; R is the ratio of longitudinal-to-transverse virtual-photoabsorption cross sections; ϵ is the virtual photon polarization; M is the mass of the nucleon; Q^2 is the square of the four-momentum of the virtual photon; E is the incident electron energy; E' is the scattered electron energy; $\nu = (E - E')$ is the electron energy loss; and θ is the electron scattering angle.

The system of Eqs. (1) and (2) allows for the separate determination of G_1 and G_2, knowing W_2 and W_1. In the scaling limit (ν and Q^2 large), these structure functions are predicted to depend only on the Bjorken variable $x = Q^2/2M\nu$, yielding

$$\begin{aligned} MW_1(\nu,Q^2) &\rightarrow F_1(x) \ , & \nu W_2(\nu,Q^2) &\rightarrow F_2(x) \ , \\ M^2\nu G_1(\nu,Q^2) &\rightarrow g_1(x) \ , & M\nu^2 G_2(\nu,Q^2) &\rightarrow g_2(x) \ . \end{aligned} \tag{4}$$

The experimental asymmetries $A^{\parallel}$ and $A^{\perp}$ are related to the virtual photon-nucleon longitudinal and transverse asymmetries, A_1 and A_2 respectively, via

$$\begin{aligned} A^{\parallel} &= D(A_1+\eta A_2 \ , & A^{\perp} &= d(A_2-\zeta A_1) \ , \\ D &= (1-E'\epsilon/E)/(1+\epsilon R) \ , & \eta &= \epsilon\sqrt{Q^2}/(E-E'\epsilon) \ , \\ d &= D\sqrt{2\epsilon/(1+\epsilon)} \ , & \zeta &= \eta(1+\epsilon)/2\epsilon \ . \end{aligned} \tag{5}$$

The proton (neutron) spin structure function is extracted in the finite Q^2 region following the relation

$$g_1^{p(n)} = \left[A_1^{p(n)}F_1^{p(n)} + A_2^{p(n)}F_1^{p(n)}\left(\frac{2Mx}{\nu}\right)^{1/2}\right]\Big/\left(1+\frac{2Mx}{\nu}\right) \ , \tag{6}$$

where $F_1^{p(n)}$ is the spin averaged structure function of the proton (neutron). Within the QPM interpretation, $F_1^{p(n)}(x)$ and $g_1^{p(n)}(x)$ are related to the momentum distribution of the constituents as

$$F_1(x) = \frac{1}{2}\sum\nolimits_{i=1}^{f} z_i^2\left[q_i^{\uparrow}(x)+q_i^{\downarrow}(x)\right] \ , \qquad g_1(x) = \frac{1}{2}\sum\nolimits_{i=1}^{f} z_i^2\left[q_f^{\uparrow}(x)-q_f^{\downarrow}(x)\right] \ , \tag{7}$$

where i runs over the number of flavors, z_i are the quark fractional charges, and $q_i^{\uparrow}$, $(q^{\downarrow})_i$ are the quark plus antiquark momentum distributions for quark and antiquarks spins parallel (antiparallel) to the nucleon spin. Using the following set of assumptions—quark current algebra, isospin symmetry, SU(3) symmetry in the decay of the baryon octet, and zero net polarization for the strange-sea quarks—the Ellis–Jaffe sum rule on the proton (neutron) is expressed to first order correction in α_s as follows [11]:

$$I^{p(n)} = \int_0^1 g_1^{p(n)}(x)\,dx = \frac{1}{12}\frac{g_A}{g_V}\left\{\left[1(-1)+\frac{5}{3}\left(\frac{3F-D}{F+D}\right)\right] - \frac{\alpha_s}{\pi}\left[1(-1)+\frac{7}{9}\left(\frac{3F-D}{F+D}\right)\right]\right\} , \tag{8}$$

where α_s is the QCD strong coupling constant, and F and D are the SU(3) invariant matrix elements of the axial vector current. From neutron β decay, we obtain $(g_A/g_V) = F+D = 1.2573\pm0.0028$. Following [11], we use $F = 0.459\pm0.008$ and $D = 0.798\mp0.008$, giving $F/D = 0.575\pm0.016$. Within the QPM interpretation, we rewrite I^n in terms of quark polarizations $\Delta q \equiv \int_0^1 dx[q^{\uparrow}(x)-q^{\downarrow}(x)]$ at finite Q^2 :

$$I^n = \frac{2}{9}\,(\Delta u - 2\Delta d + \Delta s)\,\left(1-\frac{\alpha_s}{\pi}\right) + \frac{1}{9}\,(\Delta u + \Delta d - 2\Delta s)\,\left(1-\frac{\alpha_s}{3\pi}\right) \ . \tag{9}$$

The primary motivation of the E–142 measurement of the neutron spin structure function is the test of the Bjorken sum rule. The later is insensitive to the details of nucleon structure but depends solely on quark current algebra and isospin symmetry. It is expressed as the difference between the proton and the neutron spin structure function $g_1(x,Q^2)$ integrals. The Bjorken sum rule is expressed to first order in α_s as

$$I^p - I^n = \int_0^1 g_1^p(x,Q^2) - g_1^n(x,Q^2)\,dx = \frac{1}{12}\,\frac{g_A}{g_V}\left[1 - \frac{\alpha_s(Q^2)}{\pi}\right]. \tag{10}$$

Higher order PQCD [12], as well as higher twist [13] corrections, although not included in Eq. (10), are important in the analysis of the Bjorken sum rule and must be considered at low Q^2.

E–142 Measurement

The experiment used the SLAC polarized electron beam at the three "magic" energies 19.4, 22.7, and 25.5 GeV, so that the electron spin is longitudinal as it enters End Station A. The electron beam helicity was reversed randomly on a pulse-to-pulse basis, allowing for the cancellation of many of the beam systematic errors. This was achieved by reversing the laser beam circular polarization used for photoemission from the AlGaAs photocathode in the electron source. The delivered beam polarization (P_l) was measured by a single arm Moller polarimeter and found to be stable at an average value of $(38.8 \pm 1.6)\%$, where the uncertainty is dominated by the measurement of the foil magnetization.

The target was a newly-built 30-cm-long, high-pressure double cell filled with a mixture of ^{3}He, rubidium, and nitrogen [14]. With end windows approximately 0.012-cm thick, this target operated at number density of 2.3×10^{20} atoms/cm^2 (8.6 atm at 0°C) . Polarization of ^{3}He was achieved by optically pumping the rubidium vapor, which transfered its polarization to the ^{3}He nuclei by spin exchange collisions. The small added quantity of nitrogen (1.9×10^{18} atoms/cm^3) increased the optical pumping efficiency. The ^{3}He polarization (P_t) was measured with an NMR setup and observed to be variying slowly during the experiment, between 30% and 40% with a relative uncertainty $\Delta P_t/P_t$ of 7%. The polarization of the target was reversed frequently as a mean to cancel systematic effects.

Data were collected using two single-arm spectrometers at scattering angles of 4.5° and 7° [15], covering a kinematical range of $0.03 < x < 0.6$ and $Q^2 > 1$ (GeV/c)^2. In each spectrometer arm, the electron detector package consisted of two threshold Čerenkov counters, six planes of hodoscopes, and a 24-radiation-length shower counter composed of 200 lead-glass blocks. The momentum resolution (rms) from hodoscope tracking was $\Delta E'/E' \sim 3\%$, and the shower energy resolution was typically $15\%/\sqrt{E'(\mathrm{GeV})}$.

The experimental raw counting asymmetry Δ was converted to the experimental asymmetry $A^{\parallel}$, using the relation

$$\Delta = \frac{(N^{\uparrow\downarrow} - N^{\uparrow\uparrow})}{(N^{\uparrow\downarrow} + N^{\uparrow\uparrow})} \quad , \qquad A^{\parallel} = \frac{\Delta}{P_b P_t f} \quad , \tag{11}$$

where $N^{\uparrow\downarrow}$ ($N^{\uparrow\uparrow}$) represents the rate of scattered electrons for each bin of x and Q^2 when the electron beam helicity is antiparallel (parallel) to the target spin, and f is the dilution factor that corresponds to the fraction of events that originated from scattering off the neutron in ^{3}He.

Small corrections for deadtime, pair-electron contamination, and misidentified pions were applied. These corrections are x dependent, and dominate in the low x region. The largest systematic uncertainty in the measurement of $A^{\parallel}$ comes from the determination of the dilution factor f. This factor was measured using glass cell runs, with variable pressures of ^{3}He to separate the scattering contribution of ^{3}He from that of glass, and was found to be 0.11 ± 0.02. False asymmetries were measured to be consistent with zero by comparing data with target spins in opposite directions.

External radiative corrections were evaluated using the Mo and Tsai method [17], and found to be small because of the relatively thin target ($\sim$ 0.3% radiation length). Internal radiative corrections were more important, and were evaluated using the exact procedure of Kukhto and Shumeiko [16]. The total radiative corrections amounted to a relative change of the asymmetry ranging from 30% at low x to 15% at large x. Recent studies by several groups [18–20] have concluded that in deep-inelastic scattering a polarized ^{3}He nucleus target can be regarded as a good model of a polarized neutron, provided a small correction for the S' and D states is applied. To extract the neutron asymmetry from the measured ^{3}He asymmetry, we followed the method described in [19], allowing for a correction from the polarization of the two protons in ^{3}He (~ -2.7% per proton) and a correction for the polarization of the neutron in ^{3}He ($\sim$87%).

Figure 2(a) shows the results of the physics asymmetry A_1^n as a function of x. Statistical and systematic errors are presented, added in quadrature. Since no significant Q^2 dependence of the measurement was observed, data at a fixed x bin were averaged over different Q^2. The extraction of g_1^n used the measurement of the transverse asymmetry [Eq. (2)] which amounted to $A_2^n = 0.0 \pm 0.25$ over the full range in x. Figure 2(b) shows g_1^n as a function of x, obtained using Eq. (6), where F_1 was derived from a global fit to the SLAC data for R [21] and the recent NMC parametrization for F_2 [22]. Although small ($\sim$ 0.1), there is a clear trend towards negative asymmetries A_1^n in the region $0.03 < x < 0.2$.

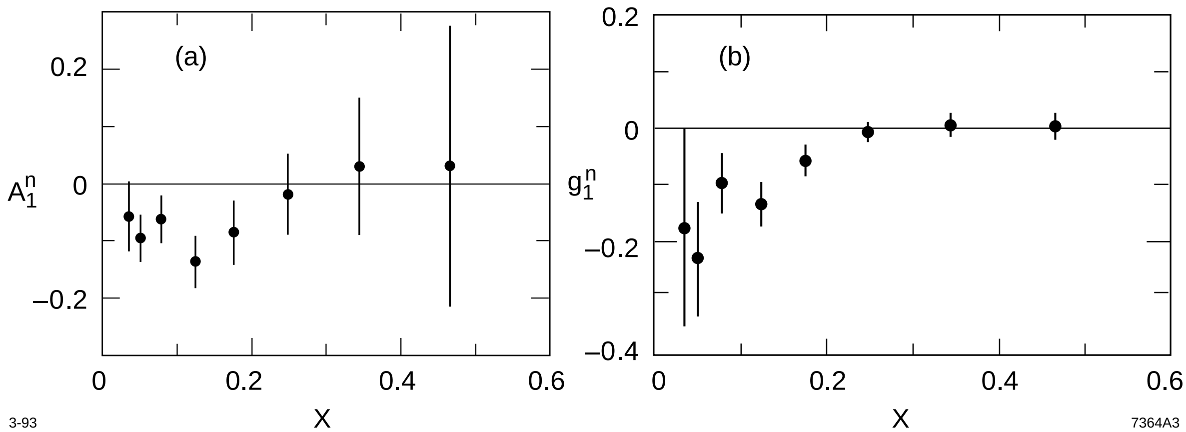

Fig. 2(a) Neutron asymmetries A_1^n and (b) spin-structure function g_1^n as a function of x.

Sum Rules Tests and Nucleon Spin Structure

To test the sum rules and interpret the spin structure of the nucleon in terms of its constituents spin, I^n is evaluated at a fixed average value Q^2. All g_1^n data points are evolved to the average value of Q^2 assuming A_1^n to be Q^2 independent. Integrating the measured range of x we find

$$\int_{0.03}^{0.6} g_1^n \left[\langle Q^2\rangle = 2(\mathrm{GeV/c})^2, x\right] \, dx \; = \; -0.019 \pm 0.007 \text{ (stat)} \pm 0.006 \text{ (syst)} \quad . \qquad (12)$$

To evaluate the missing part of the integral, we consider the low- and high-x regions separately. For $0 \leq x < 0.03$, we assume a plausible form of extrapolation of the spin-structure function $g_1^n(x) = g_1^n(x_0)(x/x_0)^\alpha$, as suggested by Regge theory [23], with $g_1(x_0 = 0.03) = -0.175$ and $0 \leq \alpha \leq 0.5$. For high-x we extrapolate $A_1(x)$, using isospin arguments and the QPM. We assume that $A_1(x) \rightarrow +1$ as $x \rightarrow 1$. After adding the contribution from the unmeasured region, we find an experimental value $I^n = \int_0^1 g_1^n(x)dx = -0.022 \pm 0.011$ at an average $\langle Q^2\rangle$ of $2(\mathrm{GeV/c})^2$. Because of the low average value of the momemtum transfer, a serious consideration might be given to the contribution of higher twist effects and higher order in the PQCD corrections.

To have a consistent comparison with the EMC analysis of the proton, where I^p was determined at a much larger average Q^2, we choose to evolve our data to the same Q^2. This was done by assuming once more that the physics asymmetry A_1^n is Q^2 independent, which has to some extent been observed on the proton data [9]. Equivalently, this implies a common Q^2-dependence of both g_1^n and F_1^n, such that A_1^n is relatively constant as Q^2 varies. Although this choice is not unique, we feel it is sensible, given the very poor low-Q^2 evaluation of higher twist effects at the present time. For example, in [24] it is argued that since the integral $\int_0^1 g_1^p(x)dx$ is very insensitive to $\langle Q^2\rangle$, a better test of the Bjorken sum rule, as well as evaluation of the quark contributions to the nucleon spin, is performed by evolving the EMC proton results to low momentum transfer. Uncertainties due to the lack of reliable calculation of higher twist effects makes this procedure not necessarily attractive.

In the QPM interpretation, we use Eq. (9) and the E–142 result at $Q^2 = 10.7$ (GeV/c)^2; namely, $I^n = -0.031 \pm 0.007 \pm 0.009$, combined with the neutron β-decay relation $\Delta u - \Delta d = g_A/g_V = 1.257\pm$ and the SU(3) symmetry in the decay of the baryon octet $\Delta d - \Delta s = F - D = -0.34 \pm 0.17$ to find the net quark polarization $\Delta u + \Delta d + \Delta s \sim 0.5$, while $\Delta s \sim -0.03$. Notice that contrary to the proton results of EMC [9] and the Spin Muon Collaboration (SMC) [26], E–142 results agree with the Ellis-Jaffe sum rule, and predicts a small strange-quark contribution to the net neutron polarization. This result is also consistent with the analysis of Ref. [25] where a bound on the strange-sea polarization $|\Delta s| \leq 0.021 \pm 0.001$ is argued.

We now turn to a fundamental test of the Bjorken sum rule, at a unified value for Q^2 of 10.7 (GeV/c)^2, using results from the EMC and E–142 experiments:

$$\begin{array}{rlcl} \text{EMC} & I^p(\langle Q^2\rangle = 10.7) & = & 0.131 \pm 0.01 \pm 0.015 \\ \text{E}-142 & I^n(\langle Q^2\rangle = 10.7) & = & -0.031 \pm 0.007 \pm 0.009 \end{array} , \tag{13}$$

with an "experimental" difference $I^p - I^n = 0.161 \pm 0.021$. This difference is now compared to the theoretical prediction of Bjorken, corrected for higher-order PQCD terms at the same value of Q^2 [12]:

$$I^{p-n} = \frac{1}{6}\frac{g_A}{g_V}\left[1 - \frac{\alpha_s}{\pi} - 3.58\left(\frac{\alpha_s}{\pi}\right)^2 - 20.4\left(\frac{\alpha_s}{\pi}\right)^3 \ldots\right] = 0.185 \pm 0.004 \ .$$

We observe that within approximately one standard deviation, the Bjorken sum rule is verified.

In conclusion, the Ellis-Jaffe sum rule is confirmed by the E–142 results to within one standard deviation. The QPM interpretation of E–142 results lead to a small (few percent at most) strange-sea quark contribution to the nucleon net polarization, but a large total quark contribution to the spin of the nucleon ($\sim 50\%$). Within the available uncertainty of the existing proton and the new neutron data, the Bjorken sum rule is verified when the comparison is performed at high-Q^2. A more reliable and precise test at high-Q^2 is desirable. This should be achieved as we enter a new generation of proposed experiments that will be performed at CERN (SMC), HERA (Hermes), and SLAC (E–154, E–155) on the proton, deuteron, and ^{3}He.

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