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THE SPIN-DEPENDENT STRUCTURE FUNCTION OF THE DEUTERON

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Abstract

The SMC collaboration at CERN has recently measured the spin-dependent structure function $g_1^d(x)$ of the deuteron. The data taken cover the kinematical region $1 \text{ GeV}^2 < Q^2 < 30 \text{ GeV}^2$ and $0.006 < x < 0.6$. The first moment Γ_1^d of $g_1^d(x)$ is found to be two standard deviations below the prediction of the Ellis-Jaffe sum-rule. The inferred quark contribution to the proton spin is $\Delta\Sigma = 0.06 \pm 0.20 \pm 0.15$. When combined with the result of EMC for the proton Γ_1^p , the difference $\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05 \pm 0.04$ is deduced, in good agreement with the fundamental Bjorken sum rule. Comparison with other experiments shows that in the region of x where the measurements overlap, the SMC deuteron data agree with the combination of EMC data for the proton and the recent E142 data for the neutron.

1 Introduction

Studies of unpolarised nucleon structure functions have shown[1] that the quarks have half-integral spin. The question how the quark spins account for the nucleon spin has been raised only recently, after the EMC collaboration at CERN has published a measurement[2] on the spin-dependent structure function of the proton, extending the previous measurements from SLAC [3, 4] to lower x values. Interpretation of these data in the frame of the quark-parton model has shown that the quarks essentially do not contribute to the proton spin. This unexpected finding has stimulated a large amount of theoretical work providing several alternative explanations. On the experimental side, new data have been taken, measuring for the first time the deuteron[5] and the neutron[6] spin-dependent structure functions. Here I report the first results on the deuteron polarised structure function $g_1^d(x)$ obtained by the Spin Muon Collaboration (SMC) at CERN.

2 Polarised structure functions. Sum rules

For lepton scattering with both polarised beam and polarised target one has access to the two spin-dependent structure functions, $g_1(x)$ and $g_2(x)$. They are related to the virtual photon asymmetry $A_1(x)$ [8] by the relation $A_1 = (g_1 - \eta^2 g_2)/F_1 \simeq g_1/F_1$. In the quark-parton model[7] $A_1(x)$ can also be expressed by:

$$A_1 = \frac{\frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x) - q_i^\downarrow(x)]}{\frac{1}{2} \sum_i e_i^2 [q_i^\uparrow(x) + q_i^\downarrow(x)]} \quad (1)$$

In other words the $g_1(x)$ structure function can be interpreted as the difference between the probability to find partons of flavor i having their spins parallel, and those having their spins opposite to the spin of the target nucleon respectively. For three quark flavors and after integrating over x , we obtain the first moment of the proton structure function $g_1^p(x)$:

$$\int_0^1 g_1^p(x) dx = \frac{1}{2} \left[\frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right] \quad (2)$$

where we have defined $\Delta q = \int_0^1 dx [q^\uparrow(x) - q^\downarrow(x)]$. Interchanging u and d quarks gives the corresponding expression for the neutron. Polarised lepton scattering thus measures the charge-squared weighted fraction of the nucleon spin carried by each quark flavor. Neglecting the deuteron D-state, the sum of the proton and neutron becomes:

$$\int_0^1 g_1^d(x) dx = \frac{1}{18} [4(\Delta u + \Delta d + \Delta s) + (\Delta u + \Delta d - 2\Delta s)] \quad (3)$$

The second term in the right-hand side ($\Delta u + \Delta d - 2\Delta s$) is the flavor non-singlet component. It is given by $3F - D$, where F and D are the SU(3) couplings determined experimentally in low-energy hyperon beta decay. The singlet term ($\Delta u + \Delta d + \Delta s$) is the fraction of the proton spin $\Delta\Sigma$ carried by the quarks. From the EMC data on the proton this number was found to be $\Delta\Sigma = 0.12 \pm 0.10 \pm 0.14$, which is consistent with the statement that the quarks do not contribute to the proton spin. This result has triggered an enormous interest, both theoretical and experimental. The theoretical situation has been reviewed in several recent publications[9, 10].

The first moment of g_1 can be compared to sum rule predictions. Sum rules are integrals involving combinations of structure functions. They are particularly important since they are the only reliable theoretical calculations presently available. Many of the sum rules for weak and electromagnetic interactions have been derived using current algebra, sometimes even before the experimental information was available. A sum rule for the the polarised structure functions has been obtained by Bjorken [11] using current algebra. This sum rule, which is also a rigorous consequence of QCD, relates the difference of g_1 for the proton and the neutron to the axial vector coupling constant in nucleon beta decay:

$$\Gamma_{Bj} = \int_0^1 [g_1^p(x) - g_1^n(x)] dx = \frac{1}{6} g_A \left(1 - \frac{\alpha_s(Q^2)}{\pi} \right) \quad (4)$$

The term in parenthesis is the first order QCD correction. In order to test this sum rule one needs to know both $g_1^p(x)$ and $g_1^n(x)$. Separate sum rules for the proton and the neutron have been developed by Ellis and Jaffe [12]. In order to derive them they have further assumed exact SU(3) symmetry for the baryon-octet beta decay and zero polarisation of the strange quark sea of the nucleon. The sum rules are then written:

$$\Gamma^p = \int_0^1 g_1^p(x) dx = \frac{1}{12} \left[+1 + \frac{5}{3} \frac{3F/D - 1}{F/D + 1} \right] \left(1 - \frac{\alpha_s(Q^2)}{\pi} \right) \quad (5)$$

$$\Gamma^n = \int_0^1 g_1^n(x) dx = \frac{1}{12} \left[-1 + \frac{5}{3} \frac{3F/D - 1}{F/D + 1} \right] \left(1 - \frac{\alpha_s(Q^2)}{\pi} \right) \quad (6)$$

Here higher order QCD corrections have been neglected.

3 The SMC experiment

The SMC experiment uses a polarised muon beam, a polarised deuteron target, a spectrometer to measure the scattered muon, and a beam polarimeter. The target and the spectrometer are based on the apparatus built by the EMC collaboration [15], but have been upgraded to reduce systematic uncertainties. The polarimeter is a new equipment. During data taking, we have used a beam of positive muons with an average energy of 100 GeV[16], a spill length of 2.4 s and a period of 14.4 s. The beam intensity was 4×10^7 muons per spill. The CERN muon beam is naturally polarised due to the parity vio-

Figure 1: The SMC decay polarimeter

lating nature of the $\pi \rightarrow \mu \nu_\mu$ decay. Its polarisation can be determined from the shape of the energy spectrum of the positrons from the decay $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$. Downstream of the muon spectrometer, we have built a muon decay polarimeter (Fig. 1). A 30 m long muon decay path is defined between a shower veto hodoscope which identifies the μ^+ and a dipole magnet. The parent and decay particles are tracked both before and after the analyzing magnet using multiwire proportional chambers. Identification of the decay positrons is done by measuring the energy deposited in a lead glass calorimeter. A measured spectrum, corrected for geometrical acceptance and radiative effects is shown in Fig. 2. The muon polarisation as determined by fitting the shape of this spectrum is found to be $P_\mu = -0.82 \pm 0.06$, in good agreement with Monte Carlo simulations of the beam transport[16]. The polarised target in the present experiment uses the same cryogenic components as the EMC target [2]. A superconducting solenoid provides a magnetic field of 2.5 T parallel to the beam direction. A dilution refrigerator cools the target to a temperature of about 500 mK during polarisation, and to 50 mK during frozen spin operation. The target is divided in two halves, each 40 cm long and 5 cm in diameter, separated by 20 cm. The longitudinal polarisations in the two halves are opposite in sign in order to record data with both polarisation directions simultaneously.

The target material is beads of deuterated butanol with an admixture of paramagnetic molecules. The target is polarised using the method of Dynamic Nuclear Polarisation (DNP), in which microwave power at a frequency close to the resonance of the paramagnetic electrons is applied. The typical deuteron polarisation was about 0.25 before it was

Figure 2: *Experimental muon decay spectrum as a function of the ratio y of the decay positron and parent muon energy. The spectrum was folded with acceptance and radiative correction effects.*

discovered that a substantial increase in the polarisation can be obtained by modulating rapidly the microwave frequency over a range of 30 MHz. In this way, deuteron polarisations larger than 0.40 have been routinely obtained. The polarisation is measured using 10 NMR coils embedded in the target material. The integrated NMR absorption signals were calibrated in thermal equilibrium at 1.1 K. Such absorption signals for two of the NMR coils are shown in Fig. 3. The final polarisation, averaged over the whole data taking period was $P_T = 0.35 \pm 0.02$.

In order to minimise systematic errors, we have reversed the polarisation directions in the two target halves at regular intervals. For most of our data the spins were reversed every 8 hours by rotating the field direction using the 0.2 T transverse field of a superconducting dipole coil wound on the microwave cavity. In addition, the relative orientation of the solenoid field and the target polarisation was changed once or twice per week with DNP.

The muon spectrometer (shown in Fig. 4) was originally designed and constructed by the EMC collaboration and was later upgraded by the NMC and SMC collaborations. Upstream of the target, veto counters and beam hodoscopes define the portion of the useful beam phase space. In the first stage of the spectrometer charged particles are momentum analysed with a conventional large aperture dipole magnet and several sets of proportional and drift chambers. Hadrons are absorbed in an iron wall. Downstream of this wall streamer tubes, drift tubes and scintillator hodoscopes are used for muon identification and triggering.

Off-line event reconstruction programs determine the kinematics of both the incident and scattered muon and the vertex position. The incident muon momentum is measured upstream of the SMC experimental hall in a detector consisting of a dipole magnet and four planes of fast scintillator hodoscopes. The scattered muon is first identified downstream of the absorber wall. Its trajectory is then reconstructed using the drift chambers located upstream of the absorber and extrapolated through the analysing

Figure 3: NMR absorption signals used for the determination of the target polarisation.

magnet up to the interaction point. The average vertex resolution achieved is 3 cm in the direction of the beam and 0.3 mm in the transverse plane. This permits a good separation between the events originating from the upstream and downstream target cells.

Figure 4: The SMC muon spectrometer.

The entire SMC experimental set-up was simulated using a Monte Carlo simulation program. This program takes into account the experimental resolution and efficiency of all detectors, as well as the distribution of incident muons recorded during the data taking. It has been used to test the event reconstruction, to determine resolution smearing and to estimate systematic errors due to efficiency variations of the various detectors.

Cuts were applied on kinematic variables in order to minimise smearing effects, to limit the size of radiative corrections and to reject muons originating from the decay of pions produced in the target. The final data cover the kinematic range $1 \text{ GeV}^2 < Q^2 < 30$

GeV² and $0.006 < x < 0.6$. The yield of each of the two target cells can be used to determine the muon-deuteron asymmetry A_d :

$$N_u = n_u \Phi a_u \sigma_0 (1 - f P_u P_u A^d) \quad (7)$$

$$N_d = n_d \Phi a_d \sigma_0 (1 - f P_u P_d A^d), \quad (8)$$

where the subscripts u and d refer to the upstream and downstream target cells, n is the number of target nucleons, Φ the beam flux, a the apparatus acceptance, σ_0 the unpolarised cross section, f the fraction of the event yield from the deuterons in the target material (dilution factor), and P_u and $P_{u,d}$ are the beam and target polarisations. From A^d one computes the virtual photon asymmetry A_1^d using the relation:

$$A_1^d = \frac{A^d}{D} - \eta A_2^d, \quad (9)$$

Here D is a depolarisation factor that depends on the kinematics. The ηA_2^d term has been neglected and the resulting uncertainty included as a systematic error.

The combination of the two target cells for two data sets taken before and after a polarisation reversal provides four equations for the yields, from which A_1^d was extracted under the assumption that the acceptance ratio $r = a_u/a_d$ remains constant. Particular care was taken to keep this ratio r as constant as possible as a function of time by carefully monitoring the stability of the experimental set-up. The uncertainty on r was computed by simulating the variation of the detector parameters with a Monte-Carlo code.

4 Results

The final values of A_1^d are shown in Fig. 5. The data are positive for large x and become negative for x smaller than 0.05. The longitudinal spin structure function $g_1^d(x)$ is obtained from the asymmetry A_1^d using the following relation:

$$g_1^d(x) = \frac{A_1^d(x) F_2^d(x, Q^2)}{2x[1 + R(x, Q^2)]}. \quad (10)$$

Here we have assumed that $A_1^d(x)$ is independent of Q^2 and have chosen $Q^2 = 4.6$ GeV², which is the average Q^2 of our data. The values of $F_2^d(x, Q^2)$ were taken from the NMC parametrisation[17] and those of R from a global fit of the SLAC data[18]. The resulting $g_1^d(x, Q^2)$ values are all determined at the same Q^2 , so we can compute the integral of g_1^d over the measured range of x :

$$\int_{0.006}^{0.6} g_1^d(x) dx = 0.024 \pm 0.020 \text{ (stat.)} \pm 0.014 \text{ (syst.)}. \quad (11)$$

To estimate the integral in the unmeasured region at small x , the three lowest data points in x were fitted assuming that the behaviour of $g_1^d(x)$ is proportional to $x^{-\alpha}$, with $-0.5 < \alpha < 0$ [19]. This contribution amounts to -0.003 ± 0.003 . For the extrapolation to $x > 0.6$, we use a phenomenological fit which is constrained to $g_1^d(x) = 0$ at $x = 1$. This contribution amounts to 0.002 ± 0.004 . The final result for the first moment of $g_1^d(x)$ is thus (Fig. 6):

$$\Gamma_1^d = \int_0^1 g_1^d(x) dx = 0.023 \pm 0.020 \text{ (stat.)} \pm 0.015 \text{ (syst.)}. \quad (12)$$

The sum of the first moments of the spin structure functions of the proton and the neutron can be computed from Γ_1^d using the relation $\Gamma_1^p + \Gamma_1^n \simeq 2\Gamma_1^d/(1 - 1.5\omega_D)$, where

Figure 5: Virtual photon-deuteron asymmetry as a function of the Bjorken variable x . The shaded area indicates the size of the systematic errors.

ω_D is the probability of the deuteron to be in a D-state. Using The Paris potential result $\omega_D = 0.058$ [20], we find $\Gamma_1^p + \Gamma_1^n = 0.049 \pm 0.044$ (stat.) ± 0.032 (syst.). The Ellis-Jaffe sum rules [12] predict $\Gamma_1^p + \Gamma_1^n = 0.187 \pm 0.010$. This prediction is more than 2 standard deviations above the measured value.

Figure 6: Integral of $g_1^d(x)$ as a function of the lower integration limit x_m . The open circle represents the extrapolation to $x = 1$.

The value of Γ_1^d can also be expressed in terms of matrix elements of the axial vector currents as shown in eq. (3). Using the value $1/\sqrt{3}(3F - D) = 0.397 \pm 0.020$ as derived from hyperon decay, assuming SU(3) symmetry [13], we obtain:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.06 \pm 0.20 \pm 0.15. \quad (13)$$

This value indicates that the quark contribution to the proton spin is compatible with zero. The deduced strange quark contribution is $\Delta s = -0.21 \pm 0.09 \pm 0.07$. The result

on Γ_1^d allows us to test the Bjorken sum rule [11], which predicts at $Q^2=4.6$ $(\text{GeV}/c)^2$:

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6} g_A \left[1 - \frac{\alpha_s(Q^2)}{\pi} \right] = 0.191 \pm 0.002 \quad (14)$$

From our experiment and using the first moment of the proton [2], we find:

$$\Gamma_1^p - \Gamma_1^n = 0.20 \pm 0.05 \pm 0.04, \quad (15)$$

in agreement with the prediction of the Bjorken sum rule.

Figure 7: The deuteron structure function $xg_1^d(x)$ using the SMC data (open circles) and the combined EMC data on the proton plus E142 data on the neutron (solid boxes).

The deuteron structure function results presented here are in good agreement with the results obtained previously by the EMC experiment:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.12 \pm 0.10 \text{ (stat.)} \pm 0.14 \text{ (syst.)}. \quad (16)$$

but disagree with the conclusion of the E142 collaboration[21]:

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s = 0.57 \pm 0.11 \quad (17)$$

We have checked that the data taken by these various experiments are consistent. To do this we have used the relation $g_1^d = (g_1^p + g_1^n)(1 - \frac{3}{2}\omega_D)$ which allows us to construct "deuteron" data from the EMC experiment on the proton and from the E142 experiment on the neutron. We have further assumed that the measured virtual photon asymmetries scale with Q^2 . Within this assumption we can use the $F_2(x, Q^2)$ parametrisation[17] to "rescale" the E142 and EMC data from 2 and 10.7 $(\text{GeV}/c)^2$ respectively, to 4.6 $(\text{GeV}/c)^2$, which is the average Q^2 of SMC. This procedure minimizes the uncertainty coming from the combination of data taken at different Q^2 values. The constructed deuteron $g_1^d(x)$ data thus obtained are shown in Fig. 7 together with the data from the present experiment. We conclude that in the region of overlap ($0.03 < x < 0.6$) the data are in very good agreement.

In order to explain the difference between the SMC and E142 results one should then consider higher order QCD corrections[22] on one hand, and reexamine the extrapolation to $x = 0$ on another hand. Higher order QCD corrections[23, 24] are significant at 2 $(\text{GeV}/c)^2$ and become negligible at 10 $(\text{GeV}/c)^2$, so they mainly affect the E142 data. The extrapolations to $x = 0$ are done in all experiments using Regge behaviour for the shape of the $g_1(x)$ structure function at low x . The contribution of the extrapolation to the first moment of $g_1(x)$ is however strongly dependent on the value of the lowest- x data points; in addition it is presently not clear if the Regge behaviour is still valid for x values as large as 0.03, as assumed in Ref. [6]. Further data on the proton and the deuteron are expected to clarify these questions.

In conclusion we have measured for the first time the polarised structure function g_1^d of the deuteron. We have found that the first moment of g_1^d is smaller than the prediction of Ellis-Jaffe sum rule. The contribution of the quark spins to the nucleon spin is compatible with zero. The deduced difference between the first moment of the proton and the neutron is in good agreement with the fundamental Bjorken sum rule.

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