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ABSTRACT

Magnetic moments and g_A/g_V provide information on the correlations among quark spins and flavors in the proton. I compare this information with the deep inelastic polarized data from EMC which has been claimed to show that very little of the proton's spin is due to the quarks. The possibility that there is significant polarization of strange quarks within protons is discussed.

INTRODUCTION

Inelastic lepton scattering from nucleons at high momentum transfer measures the number densities of charged constituents, $q(x)$, $\bar{q}(x)$, as a function of the Bjorken variable x (essentially the ratio of the constituent and target longitudinal momenta in an infinite momentum frame). There is a weak dependence of these distributions on the momentum transfer, Q^2, but I shall suppress this in much of what follows.

If the beam and target are polarized, one can extract the helicity-dependent distributions for quarks or antiquarks polarized parallel $\left(q^{\uparrow}(x)\right)$ or antiparallel $\left(q^{\downarrow}(x)\right)$ to the target polarization. I shall define $\Delta q(x) \equiv q^{\uparrow}(x) - q^{\downarrow}(x)$; $q(x) \equiv q^{\uparrow}(x) + q^{\downarrow}(x)$, and similarly for antiquarks, $\bar{q}$.

Data are presented in two ways.[1-3] One is in terms of the polarization asymmetry

$$A(x) = \sum_i e_i^2 \left(\Delta q_i(x) + \Delta\bar{q}_i(x)\right) / \sum_i e_i^2 \left(q_i(x) + \bar{q}_i(x)\right), \qquad (1)$$

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(note that $-1 < A < +1$). The other involves the polarized structure function

$$g_1(x) = \frac{1}{2} \sum_i e_i^{\,2} \left(\Delta q_i(x) + \Delta \bar{q}_i(x)\right), \tag{2}$$

thus

$$g_1(x) \equiv A(x)\, F_1(x). \tag{3}$$

In advance of the data, the expectations were that

(i) At $x > 0.2$ where valence quarks dominate, $A(x)$ should be large and positive.[3,4] This follows from intuition developed for constituent valence quarks in baryon spectroscopy where the Pauli principle requires $\Delta u > 0$, $\Delta d < 0$. As the charge-squared weighting of Δu is four times that of Δd in protons, so $A^p(x > 0.2) > 0$. Data confirm this brilliantly. For a neutron target, it is Δd that is weighted 4:1 relative to Δu, hence these tend to cancel and one predicts[4] a small (zero?) asymmetry on the neutron.

(ii) Form $g_1(x)$, which directly shows the charge weighted helicity-dependent distributions and integrate over all x.[5,6] If it were not for the charge weightings, this would measure the net $\Delta q + \Delta\bar{q}$ $\left(\Delta q \equiv \int_0^1 dx \Delta q(x) = \text{net quark polarization}\right)$.

Explicitly, in the quark parton model

$$I^p \equiv \int dx\, g_1^p(x) = \frac{1}{2}\left\{\frac{3}{9}\,\Delta u + \frac{1}{9}\,(\Delta u + \Delta d + \Delta s)\right\} + \left(\Delta q_i - \Delta \bar{q}_i\right). \tag{4}$$

The surprise[2] is that $I^p(\text{EMC}) \approx 0.12$ and is almost saturated by[7] $\Delta u(\approx 0.75)$ leaving

$$\sum_i (\Delta q + \Delta \bar{q})_i \approx 0, \tag{5}$$

hence, the much-advertised claim that maybe "none of the proton's spin polarization is carried by quarks". This is a misinterpretation of Eq. (5). The valence quarks are highly polarized (point (i) above); thus, the interpretation of Eq. (5) is that something cancels or hides it. Candidates include a highly polarized sea spinning opposite to the valence quarks, orbital angular momentum, or gluon polarization.[8-10]

However, it does not seem to be widely appreciated that the F/D of Ref. 16 was much constrained by an outdated value of the neutron lifetime, and that Ref. 16 chose "to omit from (their) fit the neutron decay correlation (which yields) $g_A = 1.258 \pm 0.009$, which differs significantly from the result 1.239 ± 0.009 required by the neutron lifetime measurements". The value accepted as correct today[18] differs by some 3σ from the old value, and this, together with other data on hyperon beta decays,[16,18,19] shows that F/D is much smaller than the old value. Flavor symmetry breaking causes a spread in values of F/D, depending on which partial set of data one uses; indeed, the symmetry breaking even calls into question the utility of the F/D parameter,[20] and so Refs. 17 and 21 set up their analyses without direct reference to F/D. Translating their work into F/D, one finds that the value subsumed in Ref. 17 is F/D = 0.56 consistent with that implicit in Ref. 21 and, within errors, with the fitted value in Ref. 22. Reference 23 obtained an even smaller value of F/D = 0.545 ± 0.02. Recent improvements in the Σn beta decay data, in particular, may raise F/D to 0.58 (Ref. 24), but nowhere as high as the 0.63 used previously.

The magnitudes for Δs implied by these values for F/D are

$$F/D = 0.548 \pm 0.01 \rightarrow \Delta s = -0.12 \pm 0.06 \text{ Ref. 23} \tag{19}$$

$$F/D = 0.58 \pm 0.01 \rightarrow \Delta s = -0.15 \pm 0.08 \text{ Ref. 24.} \tag{20}$$

Thus we see that the magnitude of the (negative) strange polarization may be only half as big as that previously assumed. The QCD-corrected value of the Ellis-Jaffe sum rule falls from 0.19 (the cited value when F/D = 0.63) to 0.17 if F/D = 0.56, thereby reducing the statistical significance of the much-advertised failure of this sum rule.

What independent information exists on Δs? Elastic neutrino-proton scattering can, in principle, probe this quantity,[32] and a fit to these data give

$$\Delta s = -0.15 \pm 0.09.$$

Note that this agrees with the revised value in the present paper arising from the smaller F/D and the revised EMC integral (Ref. 29).

One should also be aware that the neutrino experiment is also consistent

One can cancel out some charge weighting effects by looking at the difference of proton and neutron for which

$$I^p - I^n = \frac{1}{6}(\Delta u - \Delta d) \equiv \frac{1}{6}\left|\frac{g_A}{g_V}\right| , \tag{6}$$

which is Bjorken's sum rule.[5] The various g_A in the baryon octet give information on the differences of Δu, Δd, and Δs which are summarized by a measured parameter known as F/D. To extract the sum, Δq, we need the proton integral (Eq. (4)) or information on neutral current form factors

$$\tilde{g}_A(\nu p + \nu p) = \Delta u - \Delta d - \Delta s. \tag{7}$$

I shall discuss this at the end of the talk. Preceding that, I shall discuss the question of Δs, since the measured F/D and the measured I^p can be combined to extract a value for Δs. This appears to be substantial; EMC claiming that

$$\Delta s = -0.23 \pm 0.08. \tag{8}$$

Implications and criticisms of this startling result will occupy the latter half of this talk. First, I will discuss what we know about the (constituent) quark polarization from static properties of the nucleon (magnetic moments, g_A/g_V) and review the extent to which the new insights do or do not require revision of this simple picture.

SPIN POLARIZATION OF VALENCE (CONSTITUENT) QUARKS

In the constituent quark model where $L_z = 0$ the charges and the magnetic moments of neutron and proton place the following constraints on the probabilities for finding the flavors and spin correlations of "valence" quarks,

$$u_v = 2d_v \quad \frac{\mu_n}{\mu_p} = -\frac{2}{3} \quad \Delta u_v = -4\Delta d_v. \tag{9}$$

The 56, $L_z = 0$ wave function of the nonrelativistic quark model (NRQM) satisfies (9) but it is by no means unique. A hybrid state, where a gluon $(J_z = \pm 1)$ is partnered by qqq in 70 (required by the Pauli principle for qqq in color 8) satisfies Eq. (9) for the coherent combination[11] $g(^2 8 + {}^4 8)$ where the superscripts refer to the 2S+1 of the net spin of the qqq system. The "valence quarks" here are significantly depolarized relative to 56. One can also have a significant polarized sea without destroying the magnetic moment relations. This is because

$$\frac{\mu_n}{\mu_p} = \frac{2\Delta d-\Delta u+(-2\Delta\bar{u}+\Delta\bar{d}+R\Delta\bar{s})}{2\Delta u-\Delta d+(-2\Delta\bar{u}+\Delta\bar{d}+R\Delta\bar{s})}, \tag{10}$$

where $R = m_d/m_s \approx 3/5$. The electrical neutrality of the sea tends to shield its contribution. A detailed fit is made in Ref. 12.

The $(g_A g_V)$ for the octet of baryons also relate to the spin polarized probabilities such as

$$\left(\frac{g_A}{g_V}\right)_{np} = \Delta u_v - \Delta d_v + -5\Delta d_v, \tag{11}$$

where we used Eq. (9). Thus immediately

$$\Delta d_v = -0.25;\ \Delta u_v = 1. \tag{12}$$

In the 56 NRQM one would have[3)]

$$\Delta d_v = -1/3;\ \Delta u_v = 4/3;\ \Delta u_v + \Delta d_v = 1, \tag{13}$$

and the entire spin polarization comes from the quarks. However, from Eq. (12) we see that

$$\Delta u_v + \Delta d_v \approx 3/4, \tag{14}$$

and so, in advance of the EMC data, only naive "quarkists" would have expected 100% for Δq_v. Anyone who worked with four-component spinors, of which the MIT bag is a specific model example, knew that the "orbital dilution" in the lower components played an essential role.[13)] In fact, the Δq_v expectation is even less than Eq. (14). When one makes a best fit to all of the baryon octet g_A/g_V, one finds

$$\Delta q_v (\equiv 3F-D) = 0.55 \pm 0.10. \tag{15}$$

Note the appearance of F and D which summarizes the g_A/g_V. This parameter will appear later. Note that many analyses of the polarization data use[2,6,10,15)] $F/D = 0.63$ (Ref. 16). However, this value fitted a value of the neutron lifetime that we now know to have been incorrect.[17,18)] The correct current value[19-25)] is lower than 0.63 and is dependent upon assumptions about SU(3) flavor breaking.

The earliest predictions for the deep inelastic polarization asymmetry in the valence-dominated region assumed that all Δq and q (valence) have the same x dependence. Thus (see Refs. 3 and 4 for origins of these formulae)

$$A^n(x) = 4\Delta d + \Delta u \to 0,$$

(the zero following immediately from Eq. (9)) and

$$A^p(x) = \frac{5}{3}(-\Delta d) + \frac{1}{3}(g_A/g_V).$$

The prediction that $A^p > 0$ is non-trivial as a priori it could be anywhere in the range $-1 < A < +1$. The presence of a $q\bar{q}$ sea as $x \to 0$ was expected to cause $A(x \to 0) \to 0$. The other qualitative expectation[26,27] was that $A(x \to 1) \to 1$ as follows.

The valence picture above implicitly assumed that $u_v(x) = 2d_v(x)$ for all x. However, unpolarized data show this to be untrue in that it would require that

$$\frac{F_1^n(x)}{F_1^p(x)} = 2/3.$$

In practice, this ratio drops as $x \to 1$, suggesting that the $u(x \to 1) \gg d(x \to 1)$, a phenomenon which follows from spin dependence via single gluon exchange. Chromomagnetic hyperfine energy shifts split the Δ-N masses and elevate $u(x \to 1)$ over $d(x \to 1)$. They also cause $u^{\uparrow}(x \to 1)$ to dominate over $u^{\downarrow}(x \to 1)$, which the consequence that $A^{p,n}(x \to 1) \to 1$. Thus, a qualitative expectation for A^p emerged:

$$A^p(x \to 0) \to 0;\ A^p(x \simeq 1/3) = 1/3\left|\frac{g_A}{g_V}\right|;\ A^p(x \to 1) \to 1.$$

These predictions turned out to be remarkably well verified and even agree with the latest EMC data.

Recently Close and Thomas[28] showed that, within the framework of the MIT bag model, one could relate the x-dependent distortion of the valence distributions to the measured chromomagnetic energy shift in the Δ-N masses. All of this suggests that the valence quark polarizations measured in polarized deep inelastic scattering are similar to the polarizations of the constituent quarks manifested in low-energy spectroscopy. This is an important constraint on model builders. The memory of the constituent quark spins is not lost as one proceeds to the deep inelastic: the valence quarks are highly polarized.

If, as is being claimed, the quarks and antiquarks contribute (within errors) nothing to the net spin polarization of the proton, then we must conclude that something is canceling the contribution of the valence quarks. Candidates include orbital angular momentum polarized gluons or a negatively polarized sea.

We already noted that in the constituent limit it is over naive to ignore orbital angular momentum. The presence of polarized gluons may be probed by studying the polarization dependence of direct photon production or spin dependence of heavy flavor production; a polarized sea may affect the inclusive production of hadrons[33,34] and fast $K^-(s\bar{u})$ production may be a tag for scattering from the sea.[34]

Dziembowski et al.[35] have studied the relation between constituent quarks and partons. They view the constituent quarks as being a conglomerate of partons-quarks, antiquarks, and gluons, thus

$$q_i^{\lambda_i}(x,Q^2) = \sum_{v,\lambda_v} \int_x^1 \frac{dy}{y} G_{v/N}^{\lambda_v}(y)\, q_{i/v}^{\lambda_i\lambda_v}\left(\frac{x}{y},\ Q^2\right),$$

where the λ are helicity labels. The constituent quark distributions $G_{v/N}(y)$ reflect the dynamics that binds the quarks to form hadrons, and are determined by a light-cone nucleon wavefunction. The constituent quark structure functions $q(x/y,\ Q^2)$ are adapted from Altarelli et al.[36] together with Carlitz and Kaur's ansatz[37] for the spin of soft valence partons within a polarized constituent quark.

This picture of partons convoluted within constituents generates some effective $L_z \neq 0$ but not enough to account for the spin deficit claimed by EMC. The data seem to fall below the model systematically for $x < 0.1$. If these small x data survive further experiments, then it seems that polarization of the sea (not included in Ref. 35) must be allowed for. This naturally leads to the question of whether there are polarized strange quarks in the proton.

POLARIZED STRANGE QUARKS?

One exciting possibility is that the EMC data imply a large polarization of strange quarks and/or antiquarks within the proton. If true, this could have significant consequences. In particular, it could modify earlier analyses of electroweak parity violation in deuterium where Campbell *et al.* argue,[15] the polarized strange quarks could give contributions that dominate over electroweak radiative corrections. An extreme claim has appeared in the literature that the large value for Δs is in conflict with perturbative QCD. If true, this would be devastating. This claim comes about, in part, because an incorrect value of F/D has been used in the analyses. It is this parameter, and its implications for Δs, that I will now discuss.

Given the integral, I_p, of the polarized structure function $g_1^P(x,Q^2)$, one extracts Δs (including new QCD corrections)

$$I_p \equiv \int dx g_1^P(x,Q^2) = \frac{1}{18}\left(\frac{g_A}{g_V}\right)\left[\frac{9f-1}{f+1} - \frac{\alpha_s(Q^2)}{\pi}\frac{3f+1}{f+1}\right] + \frac{\Delta s}{3}, \tag{16}$$

where $f \equiv F/D$ with $\alpha_s(Q^2) = 0.27$, $g_A/g_V = 1.254 \pm 0.006$ and $I_p = 0.126 \pm 0.022$. A feeling for the sensitivity of Δs to f can be gauged from the approximate relation

$$\Delta s = (f-0.40) \pm 0.07. \tag{17}$$

The widely used value, following the much-quoted fit of Ref. 16 has been

$$F/D = 0.63 \pm 0.02 \rightarrow \Delta s = -0.23 \pm 0.09. \tag{18}$$

If the sea is flavor-independent, then Eq. (18) summarizes the widely accepted interpretation of the EMC polarized structure function data where a significant negative polarization of the sea cancels out the positive polarization of the valence quarks.

This value was based on the original value for I_p quoted by EMC,[2] namely $I_p = 0.116 \pm 0.022$. However, the revised value,[29] $I_p = 0.126 \pm 0.022$, reduces the magnitude of Δs by 0.03, and so $\Delta s = -0.20 \pm 0.09$ should replace Eq. (18).

with $\Delta s = 0$ which, in advance of the controversial EMC experiment, was the expectation.

Flavor-changing weak interactions, such as neutron beta decay, can yield

$$\frac{g_A}{g_V} = 1.25 = \Delta u - \Delta d,$$

while the zero momentum limit of $\nu p \to \nu p$ can probe

$$\tilde{g}_A(0) = \Delta u - \Delta d - \Delta s \equiv \left(\frac{g_A}{g_V}\right)\left(1 - \frac{\Delta s}{1.25}\right),$$

and so a difference between $\tilde{g}_A(0)$ and g_A/g_V can, after radiative corrections, reveal nonzero Δs. (Our $\Delta s \equiv 1.25\eta$ of Ref. 32.)

A practical problem is that $\nu p \to \nu p$ is detected by proton recoil and so an extrapolation to $\vec{q} = 0$ is needed. One fits the $q^2 \neq 0$ data with a form factor, in essence

$$\frac{1-\Delta s/1.25}{\left(1 + Q^2/M_A^2\right)^2},$$

where M_A is a mass scale to be fitted. Other experiments have determined this to have the value $M_A = 1.032 \pm 0.036$ GeV. If one fixes M_A to equal the world average, then $\Delta s = -0.15 \pm 0.09$; hence the claim to support the nonzero strange polarization. However, Ref. 32 also makes another, less well-advertised, fit. They constrain $\Delta s = 0$ and find that in this case $\Delta s = 0$; $M_A = 1.06 \pm 0.05$ GeV. Thus, one sees that $\Delta s = 0$ yields M_A consistent with the world average and hence is equally acceptable as a solution. The crucial statement in Ref. 32 is that "M_A and $\eta(\Delta s)$ are strongly correlated". Thus, Ref. 32 does not require $\Delta s < 0$ and thereby does not necessarily lend support to those who desire $\Delta s \neq 0$. Thus the question of the magnitude of the (strange) sea polarization is open. It is likely to be significantly nearer to zero than is being assumed in much of the current literature. Some of the inferences claimed from the EMC polarization data may need re-evaluation therefore. In particular, there need be no conflict with perturbative quantum chromodynamics.[30)]

POLARIZED GLUONS?

It has recently been realized[8] that the perturbative QCD correction to the singlet part of $g_1^P(x)$ effectively scales (to $O(\alpha_s^2)$) and may be important. This may be incorporated by replacing the Δq in Section 1 by $\tilde{\Delta}q \equiv \Delta q - \alpha_s/2\pi\ \Delta G$, where $\Delta G \equiv \int_0^1 dx \Delta g(x)$ and $\Delta G(x) = g_\uparrow(x) - G_\downarrow(x)$ is the polarized gluon distribution. This modifies the polarized lepton analysis, but cancels out in the expressions for (g_A/g_V) and does not enter the magnetic moment (Section 2) analysis.

One consequence is that there may be a continuity between the low-energy polarization revealed in constituent quarks (magnetic moments and spin dependence of resonance excitation) and the deep inelastic polarization.

First of all, we summarize the data on the Δq (or equivalently $\tilde{\Delta}q$) from the various (g_A/g_V).

If we assume $SU(3)_F$ symmetry in the sense that $s(\Sigma^+) \equiv d(P)$, then we may write the various g_A in terms of F, D, or Δq as follows:

g_A	F,D	$\Delta q^{(P)}$	Data
np	F + D	$\Delta u - \Delta d$	1.26 ± 0.005
Λp	$F + \frac{1}{3} D$	$\frac{1}{3}(2\Delta u - \Delta d - \Delta s)$	0.72 ± 0.02
$\Xi\Lambda$	$F - \frac{1}{3} D$	$\frac{1}{3}(\Delta u + \Delta d - 2\Delta s)$	0.25 ± 0.05
Σn	F − D	$\Delta d - \Delta s$	−0.33 ± 0.02

Thus $F/D \equiv (\Delta u - \Delta s)/(\Delta u + \Delta s - 2\Delta d)$. Extracting the individual contributions involves a correlated fit. The EMC values, corrected for F/D, become $\tilde{\Delta}u = 0.80 \pm 0.06$, $\tilde{\Delta}d = -0.45 \pm 0.06$, and $\tilde{\Delta}s = -0.15 \pm 0.06$. One possibility is that $\Delta s = 0$, so that $\tilde{\Delta}s = -\alpha/2\pi\ \Delta G$. In this case, we obtain for

$$\Delta u \equiv \tilde{\Delta}u - \tilde{\Delta}s = 0.95 \pm 0.06 \quad (21)$$

$$\Delta d \equiv \tilde{\Delta}d - \tilde{\Delta}s = -0.30 \pm 0.06. \quad (22)$$

It is interesting to note that these values are consistent with those extracted from the magnetic moments (Eq. (4)) viz

$$\Delta u_v = 1, \ \Delta d_v = -0.25.$$

The proton helicity is given by

$$\frac{1}{2} = \frac{1}{2}\,\Delta q + \left(\Delta G + L_Z\right). \qquad (23)$$

Hence $\Delta G = 3.5$ and $L_Z = -3.35$ at $Q^2 = 10\ \text{GeV}^2$. As one devalues to lower Q^2, $d/dQ^2(\Delta G + L_Z) = 0$, and the individual contributions fall. It is an open question whether the "passive" L_Z in the constituent model (i.e., the dilution of S_Z due to relativistic spinors) at low Q^2 provides a consistent picture between constituent spin polarization and "parton" polarization.

Ellis et al.[31] suggest that the modification to $\Delta q(x)$ be driven by evolution

$$\tilde{\Delta} q(x) = \Delta q(x) - \int_x^1 \frac{dy}{y}\,\Delta G(y)\sigma(x/y),$$

where $\sigma(Z)$ is the cross section for $\gamma^* g \to q\bar{q}$. If so, then $g_1^P(x \to 0) < 0$, the crossover from positive to negative moving to smaller x values as Q^2 increases.

It is tantalizing that such a picture may already be manifested at low Q^2 in the resonance region. It is well known that the prominent $D_{13}(1520)$ and $F_{15}(1690)$ resonances are excited dominantly in $\sigma_{3/2}$ when $Q^2 = 0$, but in $\sigma_{1/2}$ for $Q^2 \neq 0$. The change in helicity structure,[38] or change in sign of $g_1^P(Q^2)$, occurs at $Q^2 \simeq 0.4\ \text{GeV}^2$ for D_{13} and $Q^2 \simeq 0.7\ \text{GeV}^2$ for F_{15}. It is amusing that these correspond to $x \simeq 0.2$, and so Bloom-Gilman duality may approximately hold true even for polarized leptoproduction, with a Q^2 dependence to the x_c where $g_1^P(x_c) = 0$. The first resonance $P_{33}(1236)$ sits on top of an S-wave background; the relative Q^2 dependences are not well known. However, perturbative QCD applied to resonance excitation suggests that this excitation may also change its character with Q^2 such that its contribution to $g_1^P(x)$ changes sign at $x \to 0$. It will be interesting at CEBAF to verify if the resonance region indeed matches onto the deep inelastic, and at high energy labs to verify whether $g_1^P(z \to 0) < 0$.

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