# WHERE IS THE PROTON'S SPIN?

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## ABSTRACT

There has been much recent excitement arising from the claim by the EMC collaboration[1] that none of the proton's spin is carried by quarks. There are many textbooks, including those written by some members of this audience, which assert that the proton's spin is carried by quarks. I will review the history of deep inelastic scattering of polarized leptons from polarized protons, culminating in this most recent dramatic claim. I will show that, for the last decade, data have appeared consistent with predictions of the quark model and highlight what the new and potentially exciting data are. I will conclude with suggestions for the future.

## QUARK-PARTONS

Inelastic lepton scattering, $ep \to eX$, at large momentum transfer $Q^2$ reveals the probability distributions of quarks, antiquarks, and (indirectly) gluons $\left(q(X,Q^2),\ \bar{q}(X,Q^2),\ g(X,Q^2)\right)$ as functions of their fractional longitudinal momentum x.[2] We view the proton as built of three valence quarks and a sea of $q\bar{q}$ pairs. Thus, denoting the up and down quark flavors by u and d, we have

$$p \equiv uud + q\bar{q}$$

$$n \equiv ddu + q\bar{q}$$

where the "ocean" of $q\bar{q}$ pairs is common to both. The ocean constituents are found to peak as $x \to 0$ and die out for $x \gtrsim 0.2$; the valence quark distributions peak at $x \simeq 1/3$, extending over the entire range $0 < x < 1$.

For the valence distributions in the proton** clearly

$$\int_0^1 dx\, u_v(x) = 2 \quad ; \quad \int_0^1 dx\, d_v(x) = 1.$$

As u and d are a flavor doublet with similar masses, one might expect

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**Distributions by convention always refer to the proton. For a neutron interchange d and n everywhere.

that $u(x) = 2d(x)$ everywhere. However, this is not so; as $x \to 1$ $u(x) \gg d(x)$, the u flavor has a harder distribution than the d.

Although these are unpolarized distributions, this is where spin is playing a role behind the scenes. In QED the magnetic interaction between $e^-$ and $p^+$ splits the $^3S_1$ and $^1S_0$ energy levels in hydrogen. In QCD the chromomagnetic interaction has an analogous effect on the quarks. The energies of the quarks are perturbed according to their relative spin orientations. The Pauli principle applied to the colored quarks of QCD implies that the uu pair must be in overall $S = 1$, whereas a ud pair is equally likely to be $S = 0$ or $S = 1$. Thus u flavors tend to find themselves undergoing chromomagnetic energy perturbations in an overall $S=1$ pair configuration, thus having their energy raised relative to the d flavors. Hence, qualitatively, the momentum (x) distribution of $u(x)$ will be harder than $d(x)$, as seen empirically.[2]

Thomas and I have even quantified this in the framework of the MIT bag model.[3] Using the known strength of the overall energy shift (given by the $\Delta$-N mass difference), we calculated the perturbed $u(x)$, $d(x)$, and hence the ratio of the structure functions for unpolarized scattering from neutron and proton $\left(F^n/F^p(x)\right)$. Clearly, one has rather good evidence here for the presence of chromomagnetic (spin-dependent) effects.

This also has implications for the spin-dependent polarizations as $x \to 1$, as I will show later.

## POLARIZED PROTONS

Inelastic scattering of polarized leptons from polarized targets at large momentum transfer, $e^{\uparrow\downarrow}p^{\uparrow\downarrow} \to eX$, reveals the probability distributions of the polarized constituents $q^{\uparrow\downarrow}(x)$, $\bar{q}^{\uparrow\downarrow}(x)$, and indirectly $g^{\uparrow\downarrow}(x)$, where $\uparrow\downarrow$ denote the constituent polarized parallel or antiparallel to the target.

We shall define

$$q_i(x) \equiv q_i^{\uparrow}(x) + q_i^{\downarrow}(x) \tag{1}$$

$$\Delta q_i(x) \equiv q_i^{\uparrow}(x) - q_i^{\downarrow}(x), \tag{2}$$

and the polarization asymmetry

$$A_i(x) \equiv \Delta q_i(x)/q_i(x) \tag{3}$$

for quark flavor i.

Experiments most directly measure $A(x)$. There are interesting sum rules[4,5] involving $\Delta q(x)$; to confront these, one needs to multiply the measured $A(x)$ by unpolarized data on $q(x)$ from some other experiment, thereby introducing extra systematic uncertainties. Bear this in mind later when we discuss the recent EMC experiment.

An early prediction for $A^{p,n}(x)$ was made[6] within a simple picture, where the nucleon consists of three valence quarks in the standard 56,L=0 of SU(6), as deduced from its static properties.[2] In this model, independent of x, one has[2,6] in a proton

$$u^{\uparrow} = 5/3,\ u^{\downarrow} = 1/3 \quad , \quad d^{\uparrow} = 1/3,\ d^{\downarrow} = 2/3, \tag{4}$$

thus u = 2, d = 1 as expected, and

$$\Delta u = 4/3 \quad , \quad \Delta d = -1/3. \tag{5}$$

Notice that d quarks are preferentially polarized "against the stream". (For a neutron interchange $u \leftrightarrow d$ and $\Delta u \leftrightarrow \Delta d$ everywhere.)

The asymmetry on a polarized nucleon is the sum or the individual quark contributions weighted by their squared changes,

$$A = \sum_i \{e_i{}^2\ \Delta q_i(x)\} / \sum_i e_i{}^2\ q_i(x) \tag{6}$$

$(e_u^2 = 4/9,\ e_d^2 = 1/9)$. Hence in this model, at any x,

$$A^p = 5/9 \quad , \quad A^n = 0. \tag{7}$$

Trivially Eq. (5) satisfies a sum rule

$$\int dx(\Delta u - \Delta d) = 5/3. \tag{8}$$

The integrand involves $\Delta \sim \langle S_3 \rangle$ and $(u-d) \sim \langle I_3 \rangle$. Having integrated over all x, this describes the target overall

$$\int dx(\Delta u - \Delta d) = \langle S_3 I_3 \rangle_N = \left| \frac{g_A}{g_V} \right|_{np} , \tag{9}$$

and in the last step we have exploited the fact that the measured $g_A/g_V$ for neutron beta decay after an isotopic rotation probes $\langle S_3 I_3 \rangle$ (Refs. 2 and 7). Thus, one sees that integrals over deep inelastic polarized distributions can be related to $(g_A/g_V)$. We also recover the famous result of static SU(6) that $(g_A/g_V)_{np} = 5/3$.

If we relax the specific model (Eq. 4), we can still obtain a sum rule. Restricting attention to valence quarks, we have (denoting $u^p \equiv d^n \equiv u$, etc.)

$$\sum_i e_i{}^2\ \Delta q_i^p(x) = \frac{4}{9}\ \Delta u(x) + \frac{1}{9}\ \Delta d(x) \tag{10}$$

$$\sum_i \rho_i{}^2\ \Delta q_i^n(x) = \frac{1}{9}\ \Delta u(x) + \frac{4}{9}\ \Delta d(x), \tag{11}$$

and so

$$\int dx \sum_i e_i{}^2 (\Delta q_i^p - \Delta q_i^n)(x) = \frac{1}{3} \int dx(\Delta u - \Delta d)(x) \equiv \frac{1}{3} \frac{g_A}{g_V} . \tag{12}$$

If $F_1(x)$ is the (transverse) unpolarized structure function (where $2F_1(x) \equiv \sum_i e_i^2 q_i(x)$), then the integrand on the left-hand side is $2\left(A^p F_1(x) - A^n F_1(x)\right)$ and Eq. (12) becomes

$$\int dx\left(A^p F_1^p - A^n F_1^n\right)(x) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| . \tag{13}$$

Thus we have a polarization sum rule analogous to the famous unpolarized sum rule[2]

$$\int dx\left(F_1^p - F_1^n\right)(x) = \frac{1}{6} . \tag{14}$$

The product $AF_1(x) \equiv g_1(x)$ by definition, and so we see that Eq. (13) is Bjorken's sum rule[4]

$$\int_0^1 dx\left(g_1^p(x) - g_1^n(x)\right) = \frac{1}{6}\left|\frac{g_A}{g_V}\right| \tag{15}$$

Inclusion of a sea of $q\bar{q}$ does not affect this sum rule for the p–n difference.

To write a sum rule for the proton alone, Ellis and Jaffe made the (<u>a priori</u>) reasonable assumption[5] that polarized $s\bar{s}$ pairs could be ignored. The sum rule requires knowledge of $g_A/g_V$ not just for the nucleon but for other analogous quantities for the octet of baryons. These are summarized in the F/D ratio[5] and the sum rule becomes $\left(I \equiv \int dx g_1\right)$

$$I_n^p = \frac{1}{12}\left|\frac{g_A}{g_V}\right|_{np} \left\{\pm 1 + \frac{5}{3}\,\frac{3F/D-1}{F/D+1}\right\} . \tag{16}$$

Hence $I^p - I^n$ recovers Bjorken's sum rule Eq. (15).

The EMC analysis used the widely accepted value of F/D = 0.63 ± 0.02 from Bourquin et al. standard paper.[8] Thus

$$I^p \simeq 0.2 \tag{17}$$

is the anticipated value for successful saturation of the sum rule if QCD corrections are ignored. The EMC data claim[1]

$$I^p_{EMC} = 0.113 \pm 0.012 \pm 0.026, \tag{18}$$

and it is this rather significant short fall that has excited so much attention.[9-13] However, recent improvements in the neutron lifetime[14] and other data on hyperon beta decays[15] show that F/D is much smaller than this. The value of F/D subsumed in Ref. 10 is F/D = 0.56, consistent with that implicit in Ref. 11 and, within errors, consistent with the fitted values in Ref. 13. Reference 16 obtained an even smaller value of $F/D = 0.545 \pm 0.02$. Recent improvements in the $\Sigma n$ decay data in particular may raise F/D to 0.58 (Ref. 17) but nowhere as high as the 0.63 used previously. When combined with pQCD modifications to the sum rule, the saturation value for $I_p$ could be as low as 0.17 and the statistical significance of the shortfall is less dramatic.

Further systematic errors in the data analysis (e.g., the difference in $g_1$ and hence $I_p$) if one used BCDMS structure functions[18] for $F_1$ rather than EMC,[19] and uncertainties in $\sigma_L/\sigma_T$ tend to increase $I_p$ and one has no more than a $1\sigma$ discrepancy.[20] Sivers et al.[21] have made a detailed study of possible errors and conclude that they could be substantial.

## EARLY MODELS AND DATA ON THE ASYMMETRY

The original valence quark model of Ref. 6 implicitly predicted that $A^p = 5/9$ for all x. As $x \to 0$ an (unpolarized) sea would dilute this, causing $A(x \to 0) \to 0$,[22] while SU(6) symmetry breaking[23,2] was predicted to cause

$$A^{n,p}(x \to 1) \to 1.$$

Thus by the 1978 international conference, one had the first emerging data in lovely agreement with the predictions of the quark model.[24] Over a substantial range of x, the latest data agree remarkably well with those early predictions.

In more modern theory the $x \to 1$ SU(6) breaking is driven by chromomagnetic effects (one-gluon exchange). The Pauli spin-dependent energy shifts discussed in Section 1 preferentially boost $u^\uparrow(x)$, not just $u(x)$. In the MIT bag model Thomas and I have computed[3] the x dependence of $A^p(x \to 1)$, normalized globally to the $\Delta$-N mass splitting. Thus, one can relate low-energy, static properties of the nucleon to deep inelastic spin polarization. This is a significant success for the underlying QCD theory.

In the early work it was assumed that the $q\bar{q}$ sea is unpolarized. Intuitively the $q\bar{q}$ cloud is some form of vacuum polarization and should have no preferred orientation. However, Sivers and I then realized[25] that some part, at least, of the sea will be polarized.

The quark-gluon interaction in QCD shares many properties with the electron-photon interaction in QED. In particular, it conserves helicity. Consequently a polarized (valence) quark that radiates a gluon transmits polarization information to that gluon and, in turn, to $q\bar{q}$ emerging from the subsequent $g \to q\bar{q}$. If $q_v(x \to 1) \sim (1-x)^3$, then $\Delta g(x) \sim +(1-x)^4$ and $\Delta\bar{q}(x) \sim +(1-x)^5$. This could give substantial gluon polarization, preferentially aligned with the target polarization.

Chiapetta et al.[26] have studied the QCD evolution of these basic "tree" diagrams. If gluons carry 30% of the proton's spin at the $Q^2 \simeq O(10\ \text{GeV}^2)$, then the EMC data are well described. As $Q^2$ increases, the net quark helicity is conserved, but $\Delta g(Q^2)$ grows. Possibly interesting consequences for growth of $L_z(Q^2)$ within the proton have been discussed in Refs. 27 and 28. The essential origin of this is that evolution is driven by the increasing phase space for radiation as $Q^2$ increases with consequent growth in $p_T^{(max)}$ of the gluons. Thus it is the increasing $\langle p_T(Q^2)\rangle$ that is interpreted as increasing $\langle L_Z\rangle$.

## THE NET SPIN OF THE QUARKS

Data on A(x) seem to agree rather well with model expectations. The excitement from the EMC data has to do with the integral (e.g., Eq. 16). So far, I have presented this in terms of F/D; it is more transparent for our present interest to write the integral directly in terms of the polarized distributions $\Delta q(x)$.

In the quark parton model (here on $\Delta q = \Delta q + \Delta\bar{q}$)

$$I^P = \frac{1}{2}\int dx \left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right)(x). \tag{24}$$

One can rearrange thus, relating it to $g_A/g_V$ in the octet of baryon beta decays.[10]

Thus, approximately deforming $\Delta Q \equiv \int(\Delta u+\Delta d+\Delta s)dx$ = the net quark and antiquark spin polarization in percent

$$\Delta Q = 9\left(I^P - \frac{1}{10}\left|\frac{g_A}{g_V}\right|\right).$$

Incorporating perturbative QCD corrections to this yields

$$c_o(Q^2)\Delta Q = 9\left(I^P - \left(1 - \frac{\alpha(Q^2)}{\pi}\right)\frac{1}{10}\left|\frac{g_A}{g_V}\right|\right)$$
$$\simeq 9(I^P - 0.11).$$

Here $c_o(Q^2) \simeq 1.$[29] The essential point is that $I^P$ has to be at least 0.11 if $\Delta Q > 0$. The near cancellation of $I^P$ and the pQCD modified $|g_A/g_V|$ contribution is the source of the banner headline "quarks carry none of the proton spin". However, the factor nine in front of the parenthesis causes $\Delta Q$ to increase rapidly if $I^P$ is slightly underestimated; e.g., the apparently small errors of $\pm$ .012 $\pm$ .026 cited by EMC for $I^P$ translate into $\pm$ 11 $\pm$ 24% in $\Delta Q$. Any other small errors in $I^P$ will be magnified by nearly an order of magnitude in $\Delta Q$. Given this sensitivity, I am cautious about the claims that we have evidence for vanishing $\Delta q$.

There are plans to study polarized scattering from polarized deuterons. A major hope is to extract $A^n$ and to check the Bjorken sum rule[30] (Eq. 15). However, the deuteron itself is of interest if one wants to extract information about the net quark spin.[10] Whereas

$$I^p \simeq \frac{1}{10}\,\frac{g_A}{g_V} + \frac{1}{9}\,\Delta Q,$$

one has

$$I^p + I^n \simeq \frac{1}{30}\,\frac{g_A}{g_V} + \frac{2}{9}\,\Delta Q.$$

Hence the "damaging" contribution from $g_A/g_V$ is reduced threefold and the $\Delta Q$ is enhanced by two. Consequently, the sensitivity of $\Delta Q$ to errors could be less of a problem in this case.

Even if $\Delta Q \simeq 0$, as EMC claim, this does not imply that all quarks (in particular valence quarks) are unpolarized. The magnitude of $g_A/g_V$, via Eq. (9), shows that $\Delta u$ or $\Delta d$ are non-zero; furthermore, large values of $A(x \gtrsim 0.3)$ show there is significant polarization over a large range of x. The inference in reality would be that the positive polarization of the valence quarks is being counterbalanced by something else, such as a negatively polarized sea.

There is another, more profound, suggestion in Refs. 31 and 32. Due to the anomaly[29,33] gluon polarization contributes directly to the electromagnetic polarized structure functions. The net effect is that every $\Delta l(x)$ in the present paper should be replaced by $\Delta q(x) - \alpha/2\pi\ \Delta G(x)$. If $\Delta G > 0$ (which is the case in perturbative QCD) (Section 3), then the integrated quark polarization could, in fact, be significant, even though the inferred $\Delta Q$ appears to be small. However, the presence of $\alpha/2\pi$ requires $\Delta G$ to be excessively large. It is possible that when all the errors are taken into account (see Ref. 21 for discussion), data will converge on a middle-of-the-road set of values where $\Delta q \simeq \Delta Q \simeq 0.5 \pm ?$ and $\alpha/2\pi\ \Delta G \to 0$ so that the (integrated) effect of the anomaly has little empirical consequence. However, it will be most interesting to seek direct manifestations of this effect. If $\Delta G(x \to 0)$ is large, then there could be a significant negative effect on $\Delta q(x \to 0)$ and hence $A(x \to 0)$. Carlitz et al.[32] have proposed studying the jet structure of polarized leptoproduction events. Events with no jets whose $k_T$ is larger than a given cut-off eliminate the gluon component. The cross section for these events should satisfy the sum rule.

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