Polarized Strange Quarks in the Proton and the Validity of Quantum Chromodynamics

F. E. Close

Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6373
and Department of Physics, University of Tennessee, Knoxville, Tennessee 37996-1200
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Recent claims that the European Muon Collaboration (EMC) data on polarized proton structure functions violate quantum chromodynamics are shown to be unfounded and driven by the use of an incorrect or outdated value of the F/D ratio for hyperon decays. Conclusions from the EMC experiment as to the amount of strange-sea polarization are rather sensitive to this value. Contrary to some statements in the literature, elastic-neutrino-scattering data are consistent with vanishing strange polarization.

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Quantum chromodynamics (QCD) is an essential part of the standard model of particle physics, the validity of which is assumed in more ambitious attempts to build grand unified theories. While details of QCD theory remain to be solved (such as the nature of confinement and the spectroscopy of hadrons containing gluonic excitations), there is a rather general assumption that the theory is correct, in particular the applicability of perturbation theory (PQCD) to inclusive processes at large momentum transfer. This belief is based on a substantial quantity of data accumulated and refined over the last two decades and recorded in detail (see the proceedings of any conference on high-energy physics, e.g., Ref. 1). If (P)QCD were somehow proved to be incorrect, then the foundations of much of modern particle physics would crumble.

Physical Review Letters has published an article entitled[2] "Evidence against Perturbative QCD from Polarized Deep-Inelastic Scattering." Given the enormity of the claim it is disturbing that so little comment or clear refutation has appeared. Ellis and Karliner have argued[3] that the claim of Preparata and Soffer (Ref. 2) is flawed, but Preparata, Ratcliffe, and Soffer[4] have counterattacked and even gone further with their claim to quantify the failure of QCD. I will argue here that Ellis and Karliner are, in principle, correct and that the counterattack of Ref. 4, and indeed the claims to overthrow QCD, arise *inter alia* from an overestimation of the amount of polarization in the strange sea. Specifically, the claims for a strange polarization exceeding 20% drawn from the recent inelastic-proton-polarization data[5] are erroneous, based on an outdated value for the F/D parameter for baryon β decays.[6] Support for a large polarized sea has also been claimed to exist in the data on elastic neutrino scattering (Ref. 7); however, close examination of that paper shows that it does not necessarily support polarized strangeness and that zero polarization is equally acceptable.

The essence of Ref. 2 is that the standard QCD-based analysis of the European Muon Collaboration (EMC) polarization data[5] leads to a value for the net polarization of the strange sea

$$\Delta s \equiv \int dx\, \Delta s(x) \equiv \int dx [s^{\uparrow}(x) - s^{\downarrow}(x)] \tag{1}$$

(where $s^{\uparrow\downarrow}$ refer to the densities of strange quarks or antiquarks polarized parallel or antiparallel to the proton) which is larger than allowed given what we know of

$$s(x) \equiv s^{\uparrow}(x) + s^{\downarrow}(x)\,, \tag{2}$$

and hence that

$$|\Delta s(x)| \leq s(x)\,. \tag{3}$$

The conflict appears when one compares $\Delta s \equiv \int dx\, \Delta s(x)$ with $s \equiv \int dx\, s(x)$. The simple bound $|\Delta s| \leq s$ is not useful since $s(x) \sim x^{-1}$ due to diffraction and so $s \to \infty$. Therefore Ref. 2 addresses the more relevant bound $\Delta s \leq s_{\rm ND}$ where $s_{\rm ND}$ is the nondiffractive (finite) contribution to s. To abstract $s_{\rm ND}$, one must prescribe how to remove the infinity, and Ellis and Karliner[3] show how the claims of Ref. 2 can be utterly changed if a different prescription is used.

A standard reaction to Ref. 2 is that it is the arbitrary removal of the infinity that is at fault, and thereby no confrontation with QCD ensues. This is surely a significant part of the truth but not the whole story; the focus of attention on s and $s_{\rm ND}$ has obscured the fact that an incorrect value of Δs is being extracted from the data. It is the determination and magnitude of this quantity that is the main subject of this present paper.

Given the integral I_p of the polarized structure function $g_1^p(x,Q^2)$, one extracts Δs,

$$I_p \equiv \int dx\, g_1^p(x,Q^2)$$
$$= \frac{1}{18}\left(\frac{g_A}{g_V}\right)\left(\frac{9f-1}{f+1} - \frac{\alpha_s(Q^2)}{\pi}\frac{3f+1}{f+1}\right) + \frac{\Delta s}{3}\,, \tag{4}$$

where $f \equiv F/D$ with $\alpha_s(Q^2) = 0.27$, $g_A/g_V = 1.259 \pm 0.004$, and $I_p = 0.116 \pm 0.022$. The sensitivity of Δs to

f can be gauged from the approximation

$$\Delta s \simeq f - 0.40 \pm 0.07\,. \qquad (5)$$

Note that the paradoxically "large" value of Δs used in Ref. 2 is due to the seemingly harmless assumption, "we have taken $F/D = 2/3$." The widely used value, following the much-quoted fit of Ref. 6, is

$$F/D = 0.63 \pm 0.02 \rightarrow \Delta s = -0.23 \pm 0.09\,. \qquad (6)$$

Note already that $|\Delta s|$ is smaller than that used in Ref. 2. If the sea is flavor independent, then Eq. (6) summarizes the widely accepted interpretation of the EMC polarized-structure-function data[5] where a significant negative polarization of the sea cancels out the positive polarization of the valence quarks.

However, it does not seem to be widely appreciated that the F/D of Ref. 6 was much constrained by an outdated value of the neutron lifetime, and by a bad choice. Reference 6 chose "to omit from (their) fit the neutron-decay correlation (which yields) $g_A = 1.258 \pm 0.009$ and which differs significantly from the result 1.239 ± 0.009 required by the neutron-lifetime measurements." The value of the neutron lifetime accepted today[8] differs by some 3σ from the old value, and agrees with the modern $g_A = 1.259 \pm 0.004$. This, together with other data on hyperon β decays,[6,8,9] shows that F/D is really much smaller than the value obtained in Ref. 6.

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,[10] and so Refs. 11 and 12 set up their analyses without direct reference to F/D. This has obscured part of the reason for those works having rather different conclusions than Refs. 2–4. Translating their work into F/D, one finds that the value subsumed in Ref. 11 is $F/D = 0.56$, consistent with that implicit in Ref. 12 and, within errors, with the fitted value in Ref. 13. Reference 14 obtained an even smaller value of $F/D = 0.548 \pm 0.01$. Recent improvements in the Σn β-decay data in particular may raise F/D to 0.58 (Ref. 15), but there is general agreement that *it is not as high as the 0.63 being widely used.*

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

$$F/D = 0.548 \pm 0.01 \rightarrow \Delta s = -0.152 \pm 0.07 \text{ (Ref.14)}\,,$$

$$F/D = 0.56 \rightarrow \Delta s = -0.164 \pm 0.07 \text{ (Ref.11)}\,, \qquad (7)$$

$$F/D = 0.58 \pm 0.01 \rightarrow \Delta s = -0.181 \pm 0.07 \text{ (Ref.15)}\,.$$

Thus we see that the magnitude of the (negative) strange polarization is reduced and, at the 1σ level, could be less than half as big as that previously assumed. This significantly alters the conclusions of Refs. 2–4; 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. The sensitivity of the EMC analysis to small errors has been commented on already;[11] the claim that perturbative QCD fails is the most extreme example of this sensitivity known to me.

We now repeat the analysis of Ellis and Karliner[3] but with the newer, less dramatic, values for Δs. They construct a hypothetical but possible s-quark polarization density $\Delta s(x)$ of the form

$$\Delta s(x) = c x^{-\alpha} \text{ for } x < x_0\,,$$

$$\Delta s(x) = s(x) \text{ for } x > x_0\,,$$

where x_0 is fixed by requiring continuity in $\Delta s(x)$ and $\alpha \simeq 0$ is assumed from Regge behavior. If one attempts to satisfy $\Delta s = -0.23$, then $x_0 \simeq 0.05$, a value which Ref. 4 has attacked as being "totally unrealistic, leaving no space for the Pomeron contribution above $x = 0.03$ which is definitely at variance with experimental information." But note how sensitive this is to Δs. If, instead, $\Delta s = -0.11$ [consistent with Eq. (7) at better than 1σ], then $x_0 \gtrsim 0.1$, and no essential conflict with the Pomeron in other data ensues. One concludes that when the modern smaller value of F/D is employed in the EMC data analysis, the sea polarization falls and the net polarization of valence and sea rises above the much-quoted zero. The particular construction of Ellis and Karliner avoids the countercriticism of Ref. 4 and shows that there is no necessary conflict with PQCD.

The argument of Ref. 4 that the Bjorken sum rule fails, and with it PQCD, is similarly flawed.

Preparata, Ratcliffe, and Soffer[4] have taken I_p, Eq. (1), and also I_n,

$$I_n = \frac{1}{9}\left(\frac{g_A}{g_V}\right)\left(\frac{3f-2}{f+1} + \frac{\alpha}{\pi}\frac{1}{f+1}\right) + \frac{1}{3}\Delta s\,. \qquad (8)$$

They use their argument from Ref. 2 that I_p and Δs are incompatible, but assume that I_n and Δs will satisfy Eq. (8) and hence conclude that

$$I_p - I_n \leq 0.134\,, \qquad (9)$$

whereas in PQCD the Bjorken sum rule is

$$I_p - I_n = \frac{1}{6}\frac{g_A}{g_V}\left(1 - \frac{\alpha}{\pi}\right) = 0.191 \pm 0.002\,, \qquad (10)$$

in conflict with Eq. (9). However, now that we have shown that the example of Ref. 3 allows Δs to be compatible with I_p and Eq. (4), there need, in turn, be no conflict with the Bjorken sum rule, Eq. (10).

Finally, there is the question of what independent information exists on Δs. Elastic neutrino-proton scattering can, in principle, probe this quantity[7] and a fit to these data gives

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

Note that this agrees with the revised value in the present paper arising from the smaller F/D, thus reinforcing our refutation of the claimed PQCD failure.

One should also be aware that the neutrino experiment is also consistent with $\Delta s=0$ which, in advance of the controversial EMC experiment, was the expectation.

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

$$g_A/g_V \simeq 1.25 = \Delta u - \Delta d\,,$$

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. 7.)

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

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

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. 7 also makes another, less well-advertised, fit. They constrain $\Delta s=0$ and find that in this case $M_A = 1.06 \pm 0.05$ 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. 7 is that "M_A and η (Δs) are strongly correlated." Thus, Ref. 7 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 therefore need reevaluation. In particular, there need be no conflict with perturbative quantum chromodynamics. Nonetheless, it may be interesting to note that the ability to satisfy the bounds on Δs with the acceptable prescription of Ref. 3 is at the margins.

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Note added.—A recent upward revision of I_p to $0.126 \pm 0.010 \pm 0.015$ (Ref. 16) adds 10% net spin to previously claimed values (see Ref. 11), decreases the strange polarization in magnitude by about 4%, and makes it even easier to satisfy the bounds.

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