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The controversial role of strangeness in the spin structure of the nucleon

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Abstract. Although the srangeness content of the nucleon is small, it has played a major role in provoking puzzles and controversies in our understanding of the internal structure of the nucleon, particularly as concerns the spin structure. We recall the role of the strange polarization in precipitating the 'spin crisis in the parton model' and discuss our present knowledge of the shape and sign of $\Delta s(x)$.

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1 Introduction: the 'spin crisis in the parton model'

A misjudgement of the significance of strangeness was behind the 'spin crisis in the parton model' [1] which arose from the famous EMC experiment on polarized deep inelastic scattering of leptons on protons [2] in 1988.

We shall use the following notation:

$$\Delta q = \int_0^1 dx \Delta q(x) \tag{1}$$

where $\Delta q(x)$ is the polarized parton density *i.e.* the difference in the number densities of quarks polarized along and opposite to the longitudinal polarization of a proton taken to be moving along the OZ axis and 100 % polarized in that direction. Note that Δq is referred to as the first moment of the quark density.

There are three particularly useful flavour combinations of the first moments:

$$a_3 = \Delta u + \Delta \bar{u} - \Delta d - \Delta \bar{d} \tag{2}$$

which transforms like the third component of an isospin triplet,

$$a_8 = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} - 2(\Delta s + \Delta \bar{s}) \tag{3}$$

which transforms like the eighth component of a flavour octet, and

$$\Delta \Sigma = \sum_f (\Delta q_f + \Delta \bar{q}_f) \tag{4}$$

which is a flavour singlet.

Because a_3 and a_8 are directly connected to the hadronic matrix elements of two of the currents belonging to the octet of axial-vector Cabibbo currents that control weak interactions, there is a very beautiful connection between the high energy physics of deep inelastic scattering (DIS) and the low energy physics of β-decay. Thus, according to the Bjorken sum rule, a_3 is known from neutron β-decay: $a_3 = 1.267 \pm 0.0035$, and assuming $SU(3)$ flavour symmetry holds for hyperon β -decays, $a_8 = 0.585 \pm 0.025$.

Now the EMC measured the first moment of the spin dependent structure function g_1 of the proton

$$\Gamma_1^p = \int dx g_1^p(x) \tag{5}$$

which is given by

$$\Gamma_1^p = \frac{1}{12}\left[a_3 + \frac{1}{3}(a_8 + 4a_0)\right] \tag{6}$$

where a_0 is the hadronic matrix element of a flavour singlet operator.

Knowing the values of a_3 and a_8, the EMC measurement implied

$$a_0^{EMC} \simeq 0 \tag{7}$$

But in the naive parton model

$$a_0 = \Delta \Sigma \tag{8}$$

where $\Delta \Sigma$ is given by (4).

In 1974 Ellis -Jaffe [3] suggested that one could ignore $\Delta s + \Delta \bar{s}$ implying that

$$a_0 \simeq a_8 \simeq 0.59 \tag{9}$$

Thus the EMC result (7) is in gross contradiction with Ellis-Jaffe.

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Moreover, given the physical meaning of the $\Delta q(x)$ it is clear that

$$\Delta\Sigma = 2S_z^{quarks} \tag{10}$$

where S_z^{quarks} is the longitudinal component of the total spin of the quarks. The EMC measurement therefore seems to imply $S_z^{quarks} = 0$ and there appears to be a crisis, since, naively, from one's experience of building quark models of the nucleon and baryon resonances, one would expect almost all of the proton's spin to be carried by the spin of its quarks. This inspired Anselmino and me to write a paper entitled: A crisis in the parton model: where, oh where, is the proton's spin? [1].

2 The effect of QCD

The QCD world is not the same as the naive parton model and two new features have to be taken into account: Q^2 dependence and renormalization scheme dependence.

Thus:

1) In most schemes $\Delta\Sigma$ varies with Q^2 so maybe it does not make sense to compare it to the spin carried by the quarks.

2) The expression for a_0 depends on the scheme. In *physical schemes*, where $\Delta\Sigma$ does *not* vary with Q^2

$$a_0 = \Delta\Sigma - \frac{3\alpha_s(Q^2)}{2\pi}\Delta G(Q^2) \tag{11}$$

where $\Delta G(Q^2)$ is the first moment of the polarized gluon density.

It was thus hoped that one could have a reasonable $\Delta\Sigma \simeq 0.6$ and still obtain a very small a_0, say $\simeq 0.2$ at $Q^2 = 1GeV^2$. But this requires $\Delta G \simeq 1.7$ at $Q^2 = 1GeV^2$. Alas the latest information (still pretty rough) suggests a much smaller value of ΔG than needed. Fig.1 (from Bradamante [4]) shows the current situation.

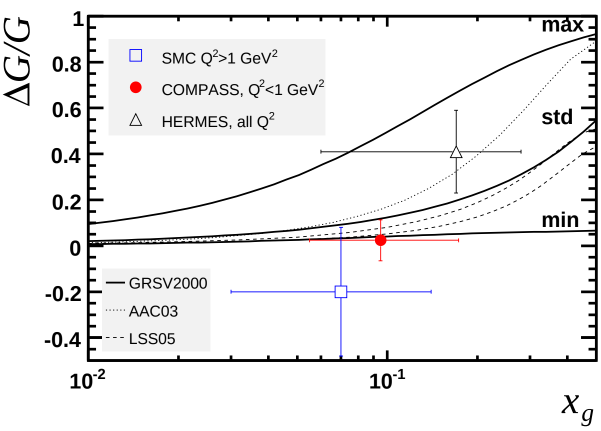

Fig. 1. Comparison of $\Delta G/G$ measurements from COMPASS, SMC and HERMES. Curves show various parametrizations from NLO fits in the $\overline{MS}$ scheme.

Moreover these new measurements are consistent with the results from several analyses of polarized DIS, which typically give $\Delta G(Q^2 = 1GeV^2) \simeq 0.29 \pm 0.32$, whereas we hoped for something like 1.7.

Conclusion: the crisis sparked by a misjudgement of $\Delta s + \Delta\bar{s}$ is still with us!

3 Attempts to measure $\Delta s(x)$

There are two possibilities: via polarized DIS or polarized semi-inclusive DIS (SIDIS).

Recall that DIS only depends on $\Delta q(x) + \Delta\bar{q}(x)$. So we can obtain information on $\Delta s(x) + \Delta\bar{s}(x)$.

In SIDIS we could, in principle obtain $\Delta s(x)$ and $\Delta\bar{s}(x)$ separately, but that is for the future!

3.1 Results from polarized DIS

Aside from one small issue there is general agreement between several analyzes: see fig.2

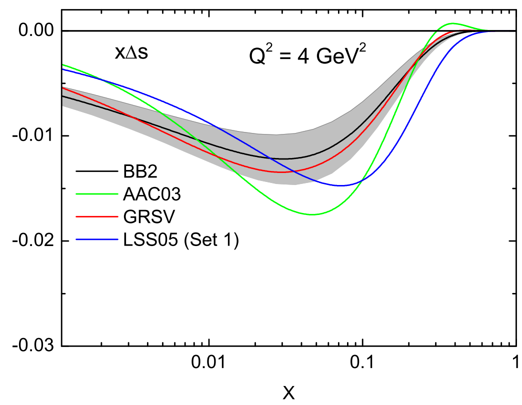

Fig. 2. $x\Delta s(x)$ vs x from various NLO fits to polarized DIS in the $\overline{MS}$ scheme.

What causes the disagreement at moderate to large x? Surprisingly—-*positivity i.e.* the requirement that

$$|\Delta s(x)| \leq s(x) \tag{12}$$

As shown in fig.3 the data seem to want a large negative $\Delta s(x)$ at moderate values of x. So there is a clash with positivity and the result is that the shape of $\Delta s(x)$ is sensitive to the input *unpolarized* density. In the figure the polarized analyses BB2, AAC03 and GRSV utilized the unpolarized strangeness density of GRV98, whereas LSS05(Set 1) used the unpolarized strangeness density of MRST'02. It is seen that LSS05 is incompatible with the unpolarized GRV density.

There is an important lesson to be learned here. Analyzers of the polarized data should be aware of this sensitivity and should use the latest available unpolarized densities when imposing positivity.

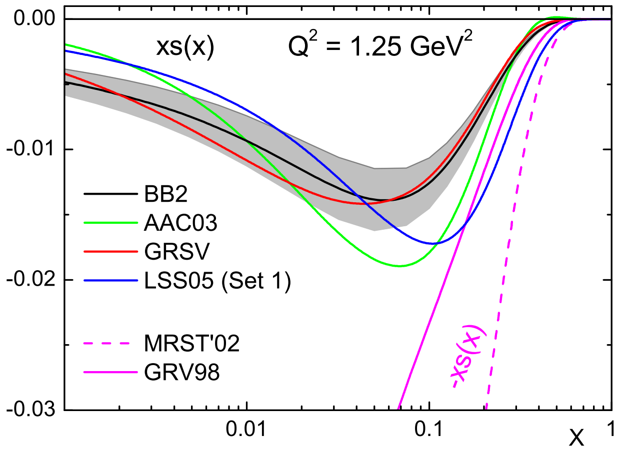

Fig. 3. Comparison of $x\Delta s(x)$ and two versions of $xs(x)$.

3.2 Results from polarized SIDIS

Before looking at results consider the following constraint [5] on the first moment

$$\delta_s \equiv [\Delta s + \Delta\bar{s}] \tag{13}$$

We can rewrite the expression for Γ_1^p as

$$\Gamma_1^p(Q^2) = \frac{1}{6}\big[\frac{1}{2}a_3 + \frac{5}{6}a_8 + 2\delta_s(Q^2)\big] \tag{14}$$

or

$$a_8 = \frac{6}{5}\big[6\Gamma_1^p(Q^2) - \frac{1}{2}a_3 - 2\delta_s(Q^2)\big] \tag{15}$$

We know a_3 very accurately. Using the measured values of $\Gamma_1^p(Q^2)$ we show that $\delta_s(Q^2) \geq 0$ implies an unacceptable value for a_8.

We have to decide what value to use for $\Gamma_1^p(Q^2)$, since the result depends on the extrapolation to $x = 0$. We take two extremes:

(A) Assume perturbative QCD holds at small x (E155 etc). This yields

$$\Gamma_1^p(Q^2 = 5) = 0.118 \pm 0.004 \pm 0.007 \tag{16}$$

(B) Assume Regge behaviour at small x (E143 etc). This gives

$$\Gamma_1^p(Q^2 = 3) = 0.133 \pm 0.003 \pm 0.009 \tag{17}$$

Results: If δ_s is *positive* we find:

(A) $a_8 \leq 0.089 \pm 0.058$

(B) $a_8 \leq 0.197 \pm 0.068$

Recall that hyperon β-decay is adequately described by $SU(3)_F$ and this leads to $a_8 = 0.585 \pm 0.025$

Thus $\delta_s(Q^2) \geq 0$ implies a dramatic breaking of $SU(3)_F$, and we onclude that it is *almost* impossible to have $\delta_s(Q^2) \geq 0$.

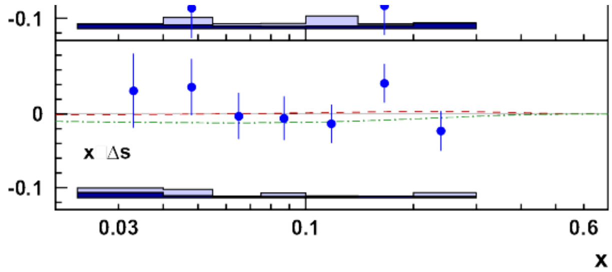

Fig. 4. HERMES results for $x[\Delta s(x) + \Delta\bar{s}(x)]$.

Now HERMES has extracted $\Delta s(x) + \Delta\bar{s}(x)$ from a study of SIDIS [6]. The results are shown in fig.4.

Within errors results are consistent with zero, and HERMES quote

$$\delta_s(Q^2 = 2.5) = 0.028 \pm 0.033 \pm 0.009 \tag{18}$$

The previous discussion suggests that the central value *cannot* be the true value unless we have totally failed to understand the connection between DIS and SIDIS . If the latter is not the case, how can we understand the HERMES results?

I think it is important to remember that HERMES uses a LO method based on so-called *purities.* I suspect that such an approach is unreliable at the values of Q^2 involved, and that the errors on the purities are somewhat underestimated in the analysis. So I strongly believe that this new 'strange quark crisis' will prove to be illusory.

4 Conclusions

Though the polarized strange quark density is undoubtedly small, thinking about it or misunderstanding it has had a mighty effect:

1) It inspired the Ellis-Jaffe sum rule, without which the appreciation of the significance of the EMC experiment might have been delayed for ages.

2) The failure to obtain consistent results for $\Delta s + \Delta\bar{s}$ from DIS and SIDIS *might* be signalling a failure in our understanding of the connection between these kinds of processes, but, as explained above, I suspect that a more mundane explanation will emerge.

Clearly, measuring $\Delta s(x)$ more accurately remains a very important and challenging task for experimentalists.

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