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Valence quark polarization in the nucleon and the deuteron data

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ABSTRACT

Within the framework of the so-called *valon* model, we argue that a substantial part of the nucleon spin, about 40%, is carried by the polarized valence quarks. The remaining is the result of cancelations between gluon polarization and the orbital angular momentum, where the gluon polarization is the dominant one. It is shown that the sea quark contributions to the spin of any hadron is simply marginal and consistent with zero. Our findings point to a substantially smaller value for a_8 than inferred from hyperon β decay, suggesting that full $SU(3)$ symmetric assumption needs to be reconsidered. New and emerging experimental data tend to support this finding. Finally, we show that within the model presented here the experimental data on the polarized structure functions $g_1^{p,n,d}$ are reproduced.

1. Introduction

The most direct tool and sensitive test for probing the quark and gluon substructure of hadrons is the polarized Deep Inelastic Scattering (DIS) processes. In such experiments detailed information can be extracted on the shape and magnitude of the spin dependent parton distributions, $\delta q_f(x, Q^2)$. Deep inelastic scattering reveals that the nucleon is a rather complicated object consisting of an infinite number of quarks, anti-quarks, and gluon. Contributions from these components to the spin structure of hadron is an ongoing source of debates. Substantial activities, both in theory and in experiment, are performed to disentangle various contributions. The analysis of [1] reveals that the gluon and the orbital angular momentum contribute to the spin of nucleon with opposite signs. It turns out that the contribution from gluon polarization is the dominant factor, accounting for about 60% of the spin of proton. This still leaves a substantial amount of nucleon spin to come from quark sector: valence and sea. Expectations are that the sea is localized in the low x region and the valence quark is dominant at $x \geqslant 0.3$. The role of sea quark is although still unclear, but both theoretical [1] and experimental investigations [2–4] point in the direction that it should be marginal. The purpose of this Letter is to investigate valence and sea quark contributions to the nucleon spin. COMPASS Collaboration has recently published accurate data on the spin structure of deuteron [4] and has measured semi-inclusive difference asymmetry, $A^{h^+-h^-}$, for hadrons of opposite charge in the kinematic region $0.006 < x < 0.7$. These measurements determine the valence polarization and allows for the evaluation of the first moment of $\Delta u_v + \Delta d_v$. COMPASS Collaboration have used a hybrid procedure, in that they have taken the MRST04 leading order parametrization of the unpolarized parton distributions along with the leading order fit of DNS polarized parton distributions [5] to evolve values of $\Delta u_v + \Delta d_v$ to a common Q^2 value fixed at 10 $(\text{GeV}/c)^2$. The message of this experiment is threefold. First, they provide a set of accurate data on g_1^d, which is valuable in its own right. Secondly, they imply that the total sea quark contributions to the spin of nucleon is consistent with zero. This finding is in agreement with the earlier results from HERMES Collaboration [2,3] thus, reinforcing the point further. Neither group, however, provide an explanation for their findings. Thirdly, it seems that their results can accommodate both positive and negative gluon polarization, ΔG.

It is important to investigate the implications of the new set of COMPASS data in an attempt to offer some explanations for these findings. The majority of the theoretical studies have been focused on the singlet component of the polarized structure function in order to explain its smallness. This has led to the assumption that the non-singlet component is rather well understood. Experimental evidence for this assumption comes from the confirmation of the Bjorken sum rule which relates the first moments of g_1^p and g_1^n. However, the Bjorken sum rule depends merely on the fundamental $SU(2)$ isospin symmetry between the matrix elements of charged and neutral axial currents and therefore expected to hold, does not entirely fix the first moment of non-singlet component of g_1^p. This component, in the leading order, depends on a_8 which is under the assumption of $SU(3)_f$ symmetry usually taken to be $3F - D = 0.579 \pm 0.025$. Information that can be obtained from baryonic β decay is highly limited and only provides information

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about the first moment of non-singlet part of g_1^p. As a result, when it is used to extract sea quark contributions to the proton spin, the outcome becomes less reliable. In the model described in the next section, we will show that the calculations in the framework of NLO perturbation theory, shows that the sea quark contribution to the spin of proton is essentially consistent with zero and the value for a_8 is substantially different from 0.579 ± 0.025, a result that seems confirmed by the emerging experiments.

2. The model

As in [1], our approach in addressing the above issues is based on the so-called *valon model*. In this model a nucleon is composed of three dressed valence quarks, the valons. Each valon has its own internal structure which can be probed at high enough Q^2. At low Q^2, a valon behaves as a valence quark. The internal structure of a valon is calculated in the next-to-leading order in QCD. We have worked in $\overline{MS}$ scheme with $\Lambda_{\rm QCD} = 0.22$ GeV and $Q_0^2 = 0.283$ GeV^2. The details are given in [1]. It turns out that in a polarized valon the sea quark polarization is consistent with zero, whereas the valence quark carries almost entire spin of the valon. In fact, as it is evident from Fig. 1, for $Q^2 \geqslant 1$ GeV^2 the value of $\delta\Sigma_{\rm valon} \simeq 0.88$ and remains so, almost independent of Q^2. Between $Q_0^2 = 0.283$ GeV^2 and ~ 1 GeV^2 it decreases from unity to 0.88. For the same range the value of $\delta q_{\rm sea}$ for individual flavor is around -0.002 and hence, marginal. The fact that sea quark polarization in the valon is consistent with zero can be understood on the theoretical grounds. The valon structure is generated by perturbative dressing in QCD. In such processes with massless quarks, helicity is conserved and therefore, the hard gluons cannot induce sea polarization perturbatively. So, it appears that $\delta\Sigma_{\rm valon}$ is very close to unity. However, the gluon polarization in a valon is positive and increases with Q^2, making the spin picture of a valon rather bluer. Spin of a valon is $\frac{1}{2}$ and the following sum rule applies

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_z. \tag{1}$$

This picture shows that the gluon polarization in a valon is almost entirely compensated by the negative orbital angular momentum contribution. We would like to make it clear that in this work we have not attempted to solve evolution equation for L_z; it is determined simply by evaluating other quantities in Eq. (1) and then solving it for L_z. In Fig. 2, we present the total orbital angular momentum of the partons in a valon. P.G. Ratcliffe [6] was the first to argue that the orbital angular momentum has a negative contribution to the spin of proton. In a remarkable paper by Ji, Tang, and Hoodbhoy [7] it is shown that in the nucleon both the orbital angular momentum and the helicity of gluon grow with opposite signs. It is also shown that the total orbital angular momentum carried by quark and gluon is negative; a conclusion that we have also arrived at. In a recent paper [8] Anthony Thomas has also concluded that based on the standard features of the non-perturbative structure of the nucleon, the majority of the proton spin comes from the orbital angular momentum of u and $\bar{u}$ quarks. Having specified the various components that contribute to the spin of a valon, we now turn to the hadron structure, which is obtained by a convolution integral as follows

$$g_1^h(x, Q^2) = \sum_{\rm valon} \int_x^1 \frac{dy}{y} \delta G_{\rm valon}^h(y) g_1^{\rm valon}\left(\frac{x}{y}, Q^2\right) \tag{2}$$

where $\delta G_{\rm valon}^h(y)$ is the helicity of the valon in the hosting hadron and $g_1^{\rm valon}(\frac{x}{y}, Q^2)$ is the polarized structure function of the valon. The latter, say, for a U-type valon, is simply given by

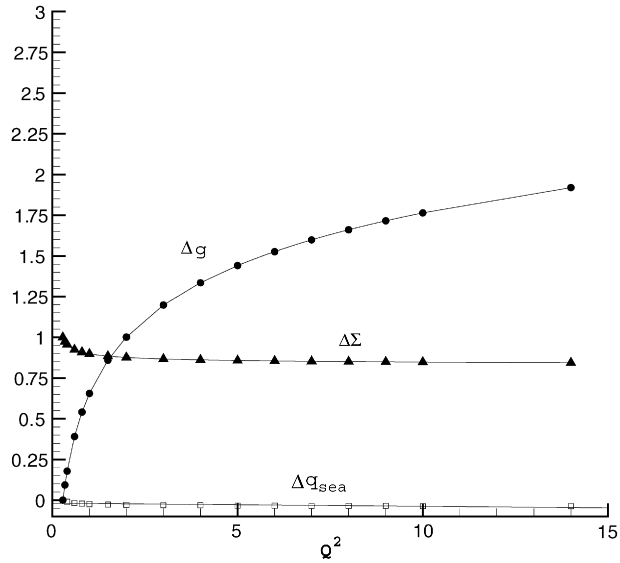

Fig. 1. First moments, $\Delta g(n=1, Q^2)$, $\Delta\Sigma(n=1, Q^2)$, and $\Delta q_{\rm sea}(n=1, Q^2)$ of various components in a valon as a function of Q^2.

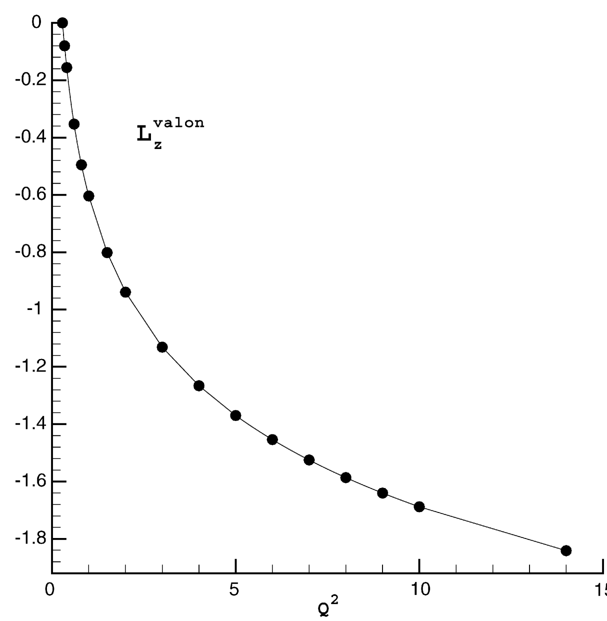

Fig. 2. Total orbital angular momentum of partons, $L_z^{\rm valon}(Q^2)$, in a valon as a function of Q^2.

$$2g_1^U(z, Q^2) = \frac{4}{9}(\delta G_{\frac{u}{U}} + \delta G_{\frac{\bar{u}}{U}}) + \frac{1}{9}(\delta G_{\frac{d}{U}} + \delta G_{\frac{\bar{d}}{U}} + \delta G_{\frac{s}{U}} + \delta G_{\frac{\bar{s}}{U}}) + \cdots. \tag{3}$$

$\delta G_{\rm valon}^h(y)$ is obtained from unpolarized valon distribution by

$$\delta G_j(y) = \delta F_j(y) G_j(y) \tag{4}$$

where $G_j(y)$ are the unpolarized valon distributions and are determined by a phenomenological argument for a number of hadrons [9–11]. The functions $\delta F_j(y)$, where j refers to U- and D-type valons, are given in [1]. In Fig. 3 the shape of $\delta G_{U,D}(y)$ are shown.

The helicity distributions of various parton types in a hadron is obtained by

$$\delta q_{\frac{i}{h}}(x, Q^2) = \sum \int_x^1 \frac{dy}{y} \delta G_{\frac{\rm valon}{h}}(y) \delta q_{\frac{i}{\rm valon}}\left(\frac{x}{y}, Q^2\right). \tag{5}$$