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## Chiral Quark Description of the Proton Spin and Magnetic Moment Structure

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The existing baryon spin and magnetic moment data are shown to be consistent with the chiral quark model prediction of a negatively polarized quark sea which has unpolarized antiquarks and a positive orbital motion. We also provide a simple calculation which explains why in our model the magnetic moment contribution by the quark sea must be proportional to that by the valence quarks.

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### I. The chiral quark idea

The study of the hadron structure is an outstanding non-perturbative QCD problem. We have suggested in our recent papers [1-4] that the chiral quark model (XQM) can provide a simple description of the baryon structure in terms of the non-perturbative degrees of freedom (DOFs) of *constituent quarks* and internal *Goldstone bosons* (GBs). The basic idea [5] is that, as one proceeds to longer distance scales, the growth of the QCD quark-gluon coupling will trigger the spontaneous breakdown of the chiral symmetry before reaching the confinement regime. Thus even in the interior of hadron we have a nontrivial vacuum: with  $q\bar{q}$  pair condensate and light-mass Goldstone boson excitations. Quarks propagating in such a vacuum in the hadron interior will gain an extra mass, much in the same way of quarks and leptons gaining their Lagrangian masses by the electroweak symmetry breakdown (the Higgs mechanism). In this picture, even though the constituent quarks are heavy because of their "gluonic interactions" (i.e. with the vacuum condensate) they behave as point-particles. When we reorganize our description of the hadron structure in terms of these new DOFs the theory become much simpler. Phenomenological results are consistent with the postulate that the effective couplings among the constituent quarks and internal GBs are not strong so that, in terms of these DOFs, a perturbation expansion can again be applied.

We have put forward the proposition that the non-valence part of the hadron structure can be described by such a chiral dynamics. In particular the  $\gamma_5$  coupling of GB to a

quark reduces to the same non-relativistic spin-dependent structure as the gluon-quark coupling. Thus although the spin-spin hyperfine structure in the hadron spectrum have commonly been imputed to gluon exchanges, it is equally consistent for us to attribute them to GB exchanges. In fact the success of our model calculations suggests that the remanent gluon couplings (after factoring out the chiral symmetry breakings and confinement) are negligible.

## II. Spin & magnetic moment structure of the quark sea

This above-mentioned GB spin-dependent coupling will cause a quark spin-flip in an emission of a GB by a constituent quark:

$$q_{\pm} \rightarrow q'_{\mp} + GB \rightarrow q'_{\mp} + (\bar{q}'q)_0. \quad (2.1)$$

The subscripts denote the helicity states. We shall call the three quarks (in S-wave state) of the naive quark model (NQM) as the valence *quarks* and all the other quarks (and antiquarks) broadly as the *quark sea*. The processes in (2.1) lead to a quark sea ( $q'\bar{q}'q$ ) which is polarized (as given by  $q'_{\mp}$ ) in the opposite direction to the baryon spin. In this way, we find that the quark contribution to the baryon spin is substantially reduced from that of the NQM, in agreement with the phenomenological result obtained by several generations of deep inelastic polarized lepton-nucleon scattering experiments [6,7]. Namely, the total quark polarization of the proton  $\Delta\Sigma = \sum_{q=u,d,s} \Delta q$  is composed of two components:

$$\Delta\Sigma = \Delta\Sigma_{valence} + \Delta\Sigma_{sea} \quad (2.2)$$

with the valence contribution being given by the NQM:

$$\Delta\Sigma_{valence} = 1 \quad (2.3)$$

and a negatively polarized sea

$$\Delta\Sigma_{sea} < 0. \quad (2.4)$$

This reduction of the quark contribution to the proton spin  $\frac{1}{2}$  is compensated by the orbital angular momentum contribution of the sea:

$$\frac{1}{2}\Delta\Sigma + \langle L_Z \rangle = \frac{1}{2}. \quad (2.5)$$

Namely, the  $\chi QM$  interprets the experimental data showing the proton spin being made up mostly by something other than quark spins,  $\Delta\Sigma \simeq 0.3$ , as due to a significant orbital angular momentum of the sea  $\langle L_Z \rangle \simeq 0.35$ . This comes about as follows. In the basic GB emission process (2.1), the final state quark  $q'$  and  $(\bar{q}'q)$ , because of the requirement of angular momentum conservation, must be in a relative P-wave state in order to balance the quark spin-flip. This translates into the condition of

$$\frac{1}{2}\Delta\Sigma_{sea} + \langle L_Z \rangle = 0. \quad (2.6)$$

Clearly the combination of Eqs. (2.2), (2.3) and (2.6) implies the proton spin composition of Eq. (2.5).

The presence of this positive contribution by the orbital motions in the quark sea  $\langle L_Z \rangle > 0$  also resolves the *spin puzzle* of why the NQM can yield a satisfactory account of the baryon magnetic moments even though its spin content prediction has been found to be incomplete [4].

The sea contribution  $\mu(B)_{sea}$  to the baryon magnetic moment

$$\mu(B) = \mu(B)_{valence} + \mu(B)_{sea} \quad (2.7)$$

is itself composed of two components: the quark spin and orbital motion contributions. It then follows from the conservation condition of Eq. (2.6) that this sum is suppressed because of the opposite sign nature of its components.

$$\mu(B)_{sea} = \mu(B)_{spin} + \mu(B)_{orbit} \simeq 0 \quad (2.8)$$

This reduction means that even though the NQM valence quark contribution to the spin is significantly different from the phenomenological value, for a magnetic moment calculation we can still use the valence quark alone  $\mathcal{P}(B) \simeq \mu(B)_{valence}$  if at the same time the orbital contribution is ignored. This explains why NQM can be successful in its accounting of the baryon magnetic moments.

### III. Anomalous quark magnetic moments by the chiral quark sea

When we separate the spin and the orbital angular momentum contributions, we are using the non-relativistic approximation, which can provide us with an intuitive physical picture of the hadron structure. In a relativistic loop diagram calculation both the spin and orbital contribution will be automatically included. Such a loop correction will result in an anomalous magnetic moment for the quarks. The suppression discussed in Sec. 2 simply corresponds to the statement that in the chiral quark field theory such anomalous moments are very small. This is supported by existent chiral quark loop calculations [8].

In this connection, we note a curious feature of our non-relativistic calculation [4]: both the sea spin and orbital contributions are directly proportional to the valence moments in the  $SU_3$  limit: For example, the orbital contribution from a process of GB emission by quark  $q_i$ :

$$\mu(i)_{orbit} = \kappa(i)_{orbit} \mu(i)_{valence} \quad (3.1)$$

with

$$\kappa(i)_{orbit} = \kappa^q(i)_{orbit} + \kappa^{GB}(i)_{orbit} \quad (3.2)$$

where the RHS terms correspond to the final state quark and GB orbital contributions, respectively. In particular, one finds that, for the quark orbital part  $\kappa^q(i)_{orbit}$ , the singlet-GB contributes an *equal* amount (but opposite in sign) when compared to the total octet-GB contributions. In the following we shall demonstrate the generality of this result:  $\mu(i)_{orbit} \propto \mu(i)_{valence}$ .

An equivalent way of saying that the sea quark moment contribution to a quark  $q_i$  is proportional to the valence contribution is that it is proportional to the valence charge  $\sim Q_{ii}$  (as the magnetic moment in the  $SU_3$  limit is proportional to the charge).  $Q_{ij}$  is the charge matrix in the quark flavor space with  $i, j = 1, 2, 3$ . The  $\kappa^q(i)_{orbit}$  contribution must be contained in the GB loop diagram with the photon leg attached to the intermediate quark line, see Fig. 1. With degenerate masses, the momentum integral can be taken out as common factor, the total  $SU_3$  octet GB loop contribution is proportional to the sum of the coupling matrix products:

$$g_8(i) = \sum_{a,j,k} \lambda_{ij}^a Q_{jk} \lambda_{ki}^a \tag{3.3}$$

where  $\lambda_{ij}^a$  is the Gell-Mann matrix elements representing the trilinear coupling for a GB (with flavor index  $a = 1, 2, \dots, 8$ ) joint with two quark lines (with indices  $i$  and  $j$ ). Using the identity

$$\sum_a \lambda_{ij}^a \lambda_{ki}^a = 2 \left( \delta_{ii} \delta_{jk} - \frac{1}{3} \delta_{ij} \delta_{ki} \right), \tag{3.4}$$

the above coupling sum can be reduced to

$$g_8(i) = 2 \left( \delta_{ii} \text{tr} Q - \frac{1}{3} Q_{ii} \right) = -\frac{2}{3} Q_{ii} \tag{3.5}$$

which indeed equals (and opposite-in-sign) to the contribution coming from the singlet GB loop:

$$g_0(i) = \sum_{j,k} \sqrt{\frac{2}{3}} \delta_{ij} Q_{jk} \sqrt{\frac{2}{3}} \delta_{ki} = \frac{2}{3} Q_{ii}. \tag{3.6}$$

Namely, we have demonstrated the general proportionality of such loop contribution to the external line quark charges, hence the result of  $\mu(i)_{orbit} \propto \mu(i)_{valence}$ . The correct identification with our non-relativistic calculation is evidenced by the correct relative octet, versus the singlet, GB contributions.

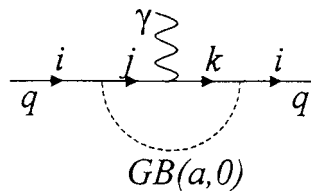


FIG. 1. Octet (a) and singlet (0) GB loop contributions to the quark ( $q_i$ ) magnetic moment.

#### IV. Unpolarized antiquarks in the sea

**Another** distinctive XQM prediction about the quark sea is that, although the sea is strongly polarized as discussed above, the antiquarks in this sea is, at the leading perturbative order, unpolarized  $A_{\bar{q}} = 0$ . As we can see from the basic GB emission process of (2.1), the antiquark of the sea arises through the spin zero GB channel:

$$\sqrt{\frac{1}{2}}(\bar{q}' + q - \bar{q}' - q_+)y \quad (4.1)$$

Thus the probabilities for  $\bar{q}'$  being spin-up and spin-down are equal. Because of this absence of the antiquark polarization, the polarization factors entering calculations of the spin content ( $A_q + \Delta_{\bar{q}}$ ) and magnetic moment content ( $A_q - \Delta_{\bar{q}}$ ) are the same. This simplifies the relation between the spin and magnetic moment structure of the baryon.

Furthermore, there is tentative experimental evidence in support of such a spin structure in the quark sea. The inclusive lepton nucleon scattering gives the quark contribution to the proton spin, in the form of  $A_q = A_q + \Delta_{\bar{q}}$ , which is the sum of the quark and antiquark contributions together. More information of the spin structure can be obtained from polarized semi-inclusive DIS, where in addition to the scattered lepton some specific hadron  $\mathbf{h}$  is also detected.

$$l + N \rightarrow l + h + X \quad (4.2)$$

The (longitudinal) spin asymmetry of the inclusive process can be expressed in terms of quark distributions:

$$A_1 \simeq \frac{\sum_q e_q^2 (\Delta_q + \Delta_{\bar{q}})}{\sum_q e_q^2 (q + \bar{q})} \quad (4.3)$$

Similarly one can measure the spin-asymmetry in a semi-inclusive case:

$$A_1^h \simeq \frac{\sum_q e_q^2 (\Delta_q D_q^h + \Delta_{\bar{q}} D_{\bar{q}}^h)}{\sum_q e_q^2 (q D_q^h + \bar{q} D_{\bar{q}}^h)} \quad (4.4)$$

where  $D_q^h$ , the fragmentation function for a quark  $q$  to produce the hadron  $\mathbf{h}$ , is assumed to be spin-independent. Separating  $\Delta_{\bar{q}}$  from  $\Delta_q$  is possible because  $D_{\bar{q}}^h \neq D_q^h$ . For example, given the quark contents such as  $\pi^+ \sim (ud)$  and  $\pi^- \sim (\bar{u}d)$ , we expect

$$D_u^{\pi^+} \gg D_{\bar{u}}^{\pi^+}, \quad D_{\bar{d}}^{\pi^+} \gg D_d^{\pi^+}, \quad \text{and} \\ D_u^{\pi^-} \ll D_{\bar{u}}^{\pi^-}, \quad D_{\bar{d}}^{\pi^-} \ll D_d^{\pi^-}.$$

In this way the SMC collaboration [9] made a fit of their semi-inclusive data showing that they are not in contradiction to the XQM expectation of  $\Delta_{\bar{q}} \simeq 0$ .

## V. Conclusion

The conclusion we wish to draw is that the spin and magnetic moment data are consistent with the  $\chi QM$  predictions: (A) a significantly polarized quark sea in the direction opposite to the baryon spin, and yet (B) the antiquarks in the sea are not significantly polarized, and (C) there should also be a sizable amount of orbital angular momentum which because of conservation law just cancels the quark polarization of the sea. This diminishes the quark sea contribution and allows for a successful description of the baryon magnetic moments by the NQM.

All this is a part of a unified description [3] that can also give a satisfactory account of the flavor structure of the proton quark sea:  $\bar{d} \gg \bar{u}$  and a strong violation of the OZI rule for the strange quark  $\bar{s} \neq 0$ .

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