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CHIRAL QUARK PERSPECTIVE OF THE PROTON SPIN AND FLAVOR PUZZLES*

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Abstract: The chiral quark model wih a broken-U(3) symmetry gives a simple and unified account for the various proton spin and flavor puzzles, as well as the octet baryon magnetic moments.

I. THE PROTON SPIN & FLAVOR PUZZLES

Ever since the 1960's it has been known that the simple nonrelativistic quark model gives a good approximate description of low energy hadron physics. In particular, the simple quark model (sQM) can give a good account of the baryonic spectroscopy and magnetic moments. The proton is pictured to be composed of three almost-free constituent quarks confined within a distance on the order of a fermi. There is no quark sea in the sQM.

However, in recent years experimental findings, by EMC, SMC, E142, E143 [1], NMC and NA51 [2] have been interpreted as indicating that the proton has a spin and flavor structure that deviates significantly from the sQM expectations. Namely, the effects associated with the quark sea have been found to be not negligible. For example, in sQM the proton spin comes simply from the addition of its constituent quark spins. For each q-flavor quark contribution to the proton spin $\Delta q = (q_\uparrow - q_\downarrow) + \left(\overline{q}_\uparrow - \overline{q}_\downarrow\right) \equiv \Delta_q + \Delta_{\overline{q}}$, we have

$$\Delta u = \frac{4}{3},\ \Delta d = -\frac{1}{3},\ \Delta s = 0,\ \Delta\Sigma = 1, \tag{1}$$

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$\Delta\Sigma$ being the sum. An analysis using octet baryon weak axial charges and the polarized lepton-nucleon DIS data [1] has shown that the Ellis-Jaffe sum rule [3] is violated, and it gives the spin components [4] :

$$\Delta u = 0.83,\ \Delta d = -0.42,\ \Delta s = -0.10,\ \Delta\Sigma = 0.31 \tag{2}$$

with an estimated error of 0.06 for each flavor's contribution. This discrepancy is puzzling in view of the fact that the same sQM spin structure (1) leads to a fairly good description of the octet baryon magnetic moments. We note that each $(\Delta q)_{\rm exptl}$ in (2) is more negative than the corresponding $(\Delta q)_{\rm sQM}$ in (1). This means that the quark sea must be polarized strongly in the opposite direction to the proton spin.

The magnetic moment of a baryon is related to the quark and antiquark polarizations as

$$\begin{aligned}\mu_B &= \sum_{q=u,d,s} \left[(\Delta_q)_B\,\mu_q + (\Delta_{\overline{q}})_B\,\mu_{\overline{q}}\right] \\ &= \sum \left[(\Delta_q)_B - (\Delta_{\overline{q}})_B\right]\mu_q \equiv \sum \left(\widetilde{\Delta q}\right)_B \mu_q .\end{aligned} \tag{3}$$

Using flavor-$SU(3)$ one can relate all $\left(\widetilde{\Delta q}\right)_B$ to proton's $\widetilde{\Delta q}$. An analysis using both the octet baryon $\mu_B's$, which are related to the *difference* of the quark and antiquark polarizations inside the proton, and the proton spin's quark components (2), to the *sum,* shows that antiquark polarizations inside the proton $\Delta_{\overline{q}}$ is small [5].

The NMC measurement of the muon scatterings off proton and neutron target shows that the Gottfried sum rule is violated [2]. This has been interpreted as showing a proton quark sea being not symmetric with respect to the u and d quark pairs: $\overline{d} > \overline{u}$. The conclusion has been confirmed by the asymmetry measurement (by NA51) in the Drell-Yan process with proton and neutron targets, which yield $\overline{d} \simeq 2\overline{u}$ at the quark momentum $x = 0.18$. These results contradict our expectation of $\overline{d} \simeq \overline{u}$: since u-, d-quarks are similar in mass and the quark sea should be created by the flavor-independent gluon emissions. In fact there had long been some indication that the flavor content of the proton quark sea may not be as simple as one would expect. The size of the pion-nucleon sigma term [6] of 45 MeV means that the OZI rule for the strange quark is strongly violated, and this can be translated into a statement that the fraction of strange quarks in the proton, averaged over all momenta, is not small, $f_s \simeq 0.18$.

II. PROTON SPIN & FLAVOR CONTENTS IN THE CHIRAL QUARK MODEL

The basic idea of chiral quark model [7] is that the energy scale associated with chiral symmetry breaking is much larger than the QCD confinement scale. Thus in the interior of a hadron (but not so short a distance when perturbative QCD becomes operative) the relevant degrees of freedom are the *quasiparticles* of quarks, gluons, and the Goldstone bosons of chiral symmetry. Here, the quarks propagate in a ground state filled with $\overline{q}q$ condensates and gain in mass giving a constituent quark mass around a third of the nucleon mass. The quark-gluon interactions of the underlying QCD bring about the chiral symmetry breaking and Goldstone excitations. But, when the description is organized in terms of the quasiparticle effective fields, the remanent gluon coupling is expected to be small. Thus the most important interaction in this regime is the coupling among the internal Goldstone bosons and quarks. In Ref. [8] and [9] it has been suggested that such interactions can yield a simple and natural explanation of the spin and flavor puzzles.

A quark sea created through internal Goldstone boson (GB) emissions by a valence quark,

$$q_{\uparrow} \to GB + q'_{\downarrow} \to \left(q\,\overline{q'}\right)_0 \, q'_{\downarrow} \tag{4}$$

has just the desired spin polarization features. The coupling of the pseudoscalar Goldstone boson to the quarks will flip the polarization of the quark: $q_{\uparrow} \to q'_{\downarrow}$. We note that the final state $q'_{\downarrow}$ carries *all* the polarization of the quark-sea, as the pair $\left(q\,\overline{q'}\right)_0$ — coming out of the Goldstone boson — must be in the spin-zero combination:

$$\left(q\,\overline{q'}\right)_0 = \frac{1}{\sqrt{2}}\left(q_{\uparrow}\overline{q'_{\downarrow}} - q_{\downarrow}\overline{q'_{\uparrow}}\right). \tag{5}$$

In this manner, the quark sea adds a *negative* amount to each of the $\Delta q's$ in (1), and, from

(5) we also have the "no antiquark polarization" feature of $\Delta_{\overline{q}} = 0$, thus $\Delta q = \widetilde{\Delta q}$, as required by the phenomenological analysis discussed above.

The GB emissions create a quark sea having just the right flavor structures. We have the processes $u \rightarrow \pi^+ d \rightarrow u\overline{d}d$, $u \rightarrow K^+ s \rightarrow u\overline{s}s$, but not $u \rightarrow \pi^- ... \rightarrow \overline{u}d...$, because there is no charge 5/3 quarks. Even though this flavor asymmetry may be diluted somewhat by the emission of π^o, η and η' GB modes, the valence u is favored to produce $\overline{d}d$ and $\overline{s}s$, while d is favored to produce $\overline{u}u$ and $\overline{s}s$. Since proton has two valence u quarks and one valence d, this GB emission mechanism can easily produce a quark sea with more d-pairs than u-pairs, and also more strange quarks if their emissions had not been suppressed by heavier strange GB's.

We have advocated a chiral quark model with a broken $U(3) = SU(3) \times U(1)$ symmetry [9]. In this version there are two parameters which correspond to the octet GB and singlet GB couplings to quarks, g_8 and g_1. A choice of $a = 0.1$ as the probability $\propto |g_8|^2$ for the u quark to emit a π^+ (and its $SU(3)$ generalizations), and coupling ratio $\varsigma \equiv g_1/g_8 = -1.2$ has been found to give a good account for all the observed proton's spin and flavor structures, as well as the octet baryon $\mu_B's$ [5]. (See Table 1, all μ's are in nucleon magnetons.) In fitting the $\mu_B's$, we have constrained the quark moments as $\mu_u = -2\mu_d$, $\mu_s/\mu_d = 0.6$, and have adjusted the remaining independent value of μ_u to get a good fit.

III. DISCUSSION

One should keep in mind that our result is deduced basically from an $SU(3)$ symmetric calculation. The only $SU(3)$ breaking effect that has been taken into account is the different moments $\mu_s/\mu_d = 0.6$ reflecting the different constituent quark masses of $m_{u,d}$ and m_s. Thus we do not really expect a better than 20 to 30% agreements from the model predictions.

It is gratifying that an elementary calculation in a physically well-motivated model can, in a simple and unified way, account for the proton spin and flavor puzzles. Clearly, one needs to incorporate the $SU(3)$ breaking effects more systematically. To do this, and to find out the x and Q^2 dependences of the quark number and spin densities, one must know more about the GB modes propagating in the interior of the hadron. Nevertheless, the success of the chiral quark model calculations seem to indicate that the original constituent quark model is generally correct in its description of the low energy hadron physics. It only needs to be augmented by a quark sea which is perturbatively generated by the valence quarks through internal GB emissions.

	Experimental value	Chiral quark model $a = 0.1,\ \varsigma = -1.2$
$\overline{d} - \overline{u}$	0.147 ± 0.026	0.147
$\overline{u}/\overline{d}$	0.51 ± 0.09	0.53
f_s	0.18 ± 0.03	0.19
Δu	0.83 ± 0.05	0.79
Δd	-0.42 ± 0.05	-0.32
Δs	-0.10 ± 0.05	-0.10
$\Delta\Sigma$	0.31 ± 0.05	0.37
μ_p	2.79 ± 0.00	2.69
μ_n	-1.91 ± 0.00	-1.88
μ_{Σ^+}	2.48 ± 0.05	2.56
μ_{Σ^-}	-1.16 ± 0.03	-1.10
μ_{Ξ^0}	-1.25 ± 0.03	-1.37
μ_{Ξ^-}	-0.68 ± 0.03	-0.48
μ_Λ	-0.61 ± 0.01	-0.60
$\mu_{\Lambda\Sigma}$	-1.60 ± 0.08	-1.58

TABLE 1

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