

Chiral quark model of nucleon spin-flavor structure with SU(3) and axial-U(1) breakings

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The chiral quark model with a nonet of Goldstone bosons can yield an adequate description of the observed proton flavor and spin structure. In a previous publication we have compared the results of an SU(3) symmetric calculation with the phenomenological findings based on experimental measurements and SU(3) symmetry relations. In this paper we discuss their SU(3) and axial U(1) breaking corrections. Our result demonstrates the broad consistency of the chiral quark model with the experimental observations of the proton spin-flavor structure. With two parameters, we obtain a very satisfactory fit to the F/D ratios for the octet baryon masses and for their axial vector couplings, as well as the different quark flavor contributions to the proton spin. The result also can account for not only the light quark asymmetry $\bar{u} - \bar{d}$ but also the strange quark content \bar{s} of the proton sea. SU(3) breaking is the key in reconciling the \bar{s} value as measured in the neutrino charm production and that as deduced from the pion nucleon σ term. [S0556-2821(98)02301-7]

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I. INTRODUCTION

A significant part of the nucleon structure study involves nonperturbative QCD. As the structure problem may be very complicated when viewed directly in terms of the fundamental degrees of freedom (current quarks and gluons), it may well be useful to break the problem into two stages. One first identify the relevant effective degrees of freedom in terms of which the description for such nonperturbative physics will be simple, intuitive and phenomenologically correct; at the next stage, one then elucidates the relations between these nonperturbative degrees of freedom in terms of the QCD quarks and gluons. For the nonperturbative phenomena taking place just inside the confinement scale, the chiral quark model (χ QM) suggests that the relevant degrees of freedom as being the internal Goldstone bosons (GB), constituent quarks, which can be thought of as just the quarks propagating in the QCD vacuum, for this energy range with its chiral condensate. The hope is that, without waiting for a final explication of the detailed mechanism for chiral symmetry breaking and confinement, we can yet achieve a simple description of the hadron structure.

Our investigation has been built upon the prior work of Eichten, Hinchliffe, and Quigg [1], who applied the χ QM idea [2] to the proton flavor and spin problem. In our previous publication [3], we have argued on phenomenological and theoretical grounds for the inclusion of a flavor-SU(3) singlet meson with a coupling to the constituent quark having an opposite sign to the octet coupling, $g_0 \approx -g_8$. In this picture, we have been able to account for much of the observed proton spin and flavor structure which is puzzling from the view point of naive constituent quark model: the $\bar{u} - \bar{d}$ asymmetry (as measured by the deviation from the Gottfried sum rule [4,5] and by the cross section difference of the Drell-Yan processes on proton and neutron targets [6]), a significant strange quark content \bar{s} (as indicated [7] by the

value of the pion-nucleon sigma term $\sigma_{\pi N}$ [8,9]), as well as the various quark flavor contributions to the proton spin (as deduced from the violation of the Ellis-Jaffe sum rule [10–14]). Furthermore, the chiral quark model predicts that the antiquarks in a nucleon are not significantly polarized. We have suggested that this feature is consistent with our picture of the baryon magnetic moments being built up from those of the constituent quarks having Dirac moments [15]. In the meantime, the Spin Muon Collaboration (SMC) has presented their data on their semi-inclusive spin asymmetry measurements indicating the antiquark polarizations $\Delta \bar{u}$ and $\Delta \bar{d}$ being consistent with zero [16], thus providing further support for this χ QM explanation of the proton spin-flavor puzzle.

The phenomenological success of this chiral quark model requires that the basic interactions between Goldstone bosons and constituent quarks being feeble enough that the perturbative description is applicable. This is so, even though the underlying phenomena of spontaneous chiral symmetry breaking and confinement are, obviously, nonperturbative.

Our previous calculation has been performed in the SU(3) symmetric limit, and we have compared the results to phenomenological values which have been deduced by using SU(3) symmetry relations as well. For example the various quark flavor contributions to the proton spin, such as the strange quark polarization Δs , have been extracted after using the SU(3) symmetric F/D ratio for hyperon decays [10]. Similarly, the extraction of the strange quark content $f_s = (s + \bar{s}) / [\sum_q (q + \bar{q})]$ from the experimental value of $\sigma_{\pi N}$ involves the same sort of SU(3) symmetry relation among octet baryon masses [7]. It is gratifying that the agreements are in the 20 to 30 % range, indicating that the broken-U(3) chiral quark picture [3] is, perhaps, on the right track.

To take the next step is, however, much more difficult. The phenomenological values Δs and f_s are sensitive to SU(3) breaking effects, which can only be introduced in the

TABLE I. Transition probability for GB emission by constituent quarks, with a being that for the process $u_+ \rightarrow \pi^+ d_-$, and with other processes reduced by SU(3) breaking suppression factors. The subscripts \pm represent the helicities of the quarks, being parallel or antiparallel to the proton helicity. The subscript 0 indicates that the quark and antiquark pair combine to form a spin zero state. Hence the antiquarks, in the leading order of perturbation, have no net polarization.

$u_+ \rightarrow$	$d_+ \rightarrow$	Probability
$u_+ \rightarrow (u\bar{d})_0 d_-$	$d_+ \rightarrow (d\bar{u})_0 u_-$	a
$u_+ \rightarrow (u\bar{s})_0 s_-$	$d_+ \rightarrow (d\bar{s})_0 s_-$	$\epsilon^2 a$
$u_+ \rightarrow (u\bar{u})_0 u_-$	$d_+ \rightarrow (d\bar{d})_0 d_-$	$\left(\frac{\delta+2\zeta+3}{6}\right)^2 a$
$u_+ \rightarrow (d\bar{d})_0 u_-$	$d_+ \rightarrow (u\bar{u})_0 d_-$	$\left(\frac{\delta+2\zeta-3}{6}\right)^2 a$
$u_+ \rightarrow (s\bar{s})_0 u_-$	$d_+ \rightarrow (s\bar{s})_0 d_-$	$\left(\frac{\delta-\zeta}{3}\right)^2 a$

extraction process in a model-dependent way. Consequently these phenomenological quantities would have large uncertainty if no SU(3) symmetry is assumed. Correspondingly, it is difficult to perform a χ QM calculation away from the SU(3) symmetric limit: SU(3) breaking is introduced by different quark masses $m_s > m_{u,d}$ and by the nondegenerate Goldstone boson (GB) masses $M_{K,\eta} > M_\pi$, and the axial U(1) breaking by $M_{\eta'} > M_{K,\eta}$. Since these are Goldstone modes propagating inside hadrons, they are expected to have effective masses different from the physical pseudoscalar meson masses. Apparently, in order to study such symmetry breaking effect in detail, one would need a theory of these GBs propagating in the intermediate range between the confinement scale and the energy scale below which the spontaneous chiral symmetry breaking takes place: $\Lambda_{\text{conf}} < \Lambda < \Lambda_{\chi\text{sb}}$.

Nevertheless, some effort has already been made in the study of the symmetry breaking effects on the phenomenological values. Several authors have obtained results suggesting that both Δs and f_s will be reduced by such effects [17–20]. It is then worthwhile to see what sort of pattern would the chiral quark model suggest for such corrections, to see whether they are compatible with the modified physical data, as well as yielding an overall agreement with phenomenology at the better-than-20% level. Our purpose in this paper is to present such a schematic SU(3) and axial U(1) breaking calculation to demonstrate the broad consistency of our chiral quark model with the observational data.

II. CHIRAL QM CALCULATION WITH SU(3) BREAKING

The SU(3) breaking effects will be introduced [21] in the amplitudes for GB emission by a quark, simply through the insertion of a suppression factor: ϵ for kaons, δ for eta, and ζ for eta prime mesons, as these strange-quark-bearing GBs are presumably more massive than the pions. Thus the probability $a \propto |g_8|^2$ are modified for processes involving strange quarks, as shown in Table I, where we have already substituted-in the quark content of the GBs. The suppression

factors enter into the amplitudes for $u_+ \rightarrow (u\bar{u})_0 u_-$ and $u_+ \rightarrow (d\bar{d})_0 u_-$ processes, etc., because they also receive contributions from the η and η' GBs.

A. The flavor content

From Table I, one can immediately read off the antiquark number \bar{q} in the proton after the emission of one GB by the initial proton state $[(2u+d) \rightarrow \dots]$:

$$\bar{u} = \frac{1}{12} [(2\zeta + \delta + 1)^2 + 20] a, \quad (1)$$

$$\bar{d} = \frac{1}{12} [(2\zeta + \delta - 1)^2 + 32] a, \quad (2)$$

$$\bar{s} = \frac{1}{3} [(\zeta - \delta)^2 + 9\epsilon^2] a. \quad (3)$$

For the quark number in the proton, we have

$$u = 2 + \bar{u}, \quad d = 1 + \bar{d}, \quad s = \bar{s}, \quad (4)$$

because, in the quark sea, the quark and antiquark numbers of a given flavor are equal. We shall also make use the notion ‘‘quark flavor fraction in a proton’’ f_q defined as

$$f_q = \frac{\langle \bar{q}q \rangle_p}{\langle \bar{u}u + \bar{d}d + \bar{s}s \rangle_p} = \frac{q + \bar{q}}{3 + 2(\bar{u} + \bar{d} + \bar{s})}, \quad (5)$$

where q 's in the proton matrix elements $\langle \bar{q}q \rangle_p$ are the quark field operators, and in the last term they stand for the quark numbers in the proton.

B. The spin content

In the limit when interactions are negligible, we have the proton wave function for the spin-up state as

$$|p_+\rangle = \frac{1}{\sqrt{6}} (2|u_+u_+d_-\rangle - |u_+u_-d_+\rangle - |u_-u_+d_+\rangle).$$

This implies that the probability of finding u_+, u_-, d_+ , and d_- are $\frac{5}{3}, \frac{1}{3}, \frac{1}{3}$, and $\frac{2}{3}$, respectively, leading to the naive quark model prediction of $\Delta u = u_+ - u_- = \frac{4}{3}$, $\Delta d = -\frac{1}{3}$, and $\Delta s = 0$. After emission of one GB, which flips the quark helicity (see Table I), we have

$$\begin{aligned} \Delta u = & \frac{4}{3} [1 - \Sigma P_1] + \frac{1}{3} P_1(u_- \rightarrow u_+) + \frac{2}{3} P_1(d_- \rightarrow u_+) \\ & - \frac{5}{3} P_1(u_+ \rightarrow u_-) - \frac{1}{3} P_1(d_+ \rightarrow u_-), \end{aligned}$$

$$\begin{aligned} \Delta d = & -\frac{1}{3} [1 - \Sigma P_1] + \frac{1}{3} P_1(u_- \rightarrow d_+) + \frac{2}{3} P_1(d_- \rightarrow d_+) \\ & - \frac{5}{3} P_1(u_+ \rightarrow d_-) - \frac{1}{3} P_1(d_+ \rightarrow d_-), \end{aligned}$$

$$\begin{aligned} \Delta s = & \frac{1}{3}P_1(u_- \rightarrow s_+) + \frac{2}{3}P_1(d_- \rightarrow s_+) - \frac{5}{3}P_1(u_+ \rightarrow s_-) \\ & - \frac{1}{3}P_1(d_+ \rightarrow s_-), \end{aligned} \quad (6)$$

where $P_1(d_+ \rightarrow s_-) = \epsilon^2 a$ is the probability of a spin-up d quark flipping into a spin-down s quark (through the emission of K^+), as displayed in Table I, etc. The combination $[1 - \Sigma P_1]$ stands for the probability of ‘‘no GB emission,’’ with ΣP_1 being the total probability of emitting one GB (π^+ , π^0 , K , η , η'):

$$1 - \Sigma P_1 = 1 - \left(1 + \frac{1}{2} + \epsilon^2 + \frac{\delta^2}{6} + \frac{\zeta^2}{3}\right)a. \quad (7)$$

After plugging in the probabilities in Eq. (6), we obtain the various quark contributions to the proton spin:

$$\Delta u = \frac{4}{3} - \frac{21 + 4\delta^2 + 8\zeta^2 + 12\epsilon^2}{9}a, \quad (8)$$

$$\Delta d = -\frac{1}{3} - \frac{6 - \delta^2 - 2\zeta^2 - 3\epsilon^2}{9}a, \quad (9)$$

$$\Delta s = -\epsilon^2 a. \quad (10)$$

C. The SU(3) parameters: D and F

It has been pointed out in our previous paper [3] that, since a SU(3) symmetric calculation would not alter the relative strength of quantities belonging to the same SU(3) multiplet, our symmetric calculation cannot be expected to improve on the naive quark model results such as the axial vector coupling ratio $F/D = 2/3$, which differs significantly from the generally quoted phenomenological value of $F/D = 0.575 \pm 0.016$ [22]. To account for this difference we must include the SU(3) breaking terms

$$\begin{aligned} \frac{F}{D} &= \frac{\Delta u - \Delta s}{\Delta u + \Delta s - 2\Delta d} \\ &= \frac{2}{3} \cdot \frac{6 - a[2\delta^2 + 4\zeta^2 + (1/2)(3\epsilon^2 + 21)]}{6 - a(2\delta^2 + 4\zeta^2 + 9\epsilon^2 + 3)}. \end{aligned} \quad (11)$$

Similarly discussion holds for the F/D ratio for the octet baryon masses. Here we choose to express this in terms of the quark flavor fractions as defined by Eq. (5):

$$\begin{aligned} \frac{f_3}{f_8} &= \frac{f_u - f_d}{f_u + f_d - 2f_s} = \frac{1 + 2(\bar{u} - \bar{d})}{3 + 2(\bar{u} + \bar{d} - 2\bar{s})} \\ &= \frac{1}{3} \cdot \frac{3 + 2a[2\zeta + \delta - 3]}{3 + 2a[2\zeta\delta + (1/2)(9 - \delta^2 - 12\epsilon^2)]}. \end{aligned} \quad (12)$$

The SU(6) prediction $\frac{1}{3}$ should be compared to the phenomenological value of 0.21 [23].

In the SU(3) symmetry limit of $\delta = \epsilon = 1$, we can easily check that Eqs. (11) and (12) reduce, independent of a and ζ , to their naive quark model values.

III. NUMERICS

What impact do these SU(3) and U(1)_A breaking suppression factors have on the comparison of chiral quark results with phenomenological quantities? Here we shall put in a few numbers. Again our purpose is not so much as finding the precise best-fit values, but using some simple choice of parameters to illustrate the structure of chiral quark model. In this spirit we shall pick the suppression factors for the K and η amplitudes to be comparable: $\epsilon \approx \delta$. As for the suppression factor ζ for the η' emission amplitude, since the symmetric calculation [3] favors $\zeta \approx -1$, and since η' is extra heavy, i.e., axial U(1) is broken, we will simply pick $\zeta \approx -\frac{1}{2}\epsilon$. Thus, for the numerical consideration, we start with the simple approximation of

$$\epsilon = \delta = -2\zeta. \quad (13)$$

Perhaps the most significant part of the chiral quark picture is its explanation of the isospin asymmetry of the quark sea, which the New Muon Collaboration (NMC) has measured to be [4]

$$\bar{u} - \bar{d} = \frac{3}{2} \left(\int_0^1 dx F_2^{p-n}(x) - \frac{1}{3} \right) \approx -0.15. \quad (14)$$

From Eqs. (1), (2), the χ QM expression for this difference is

$$\bar{u} - \bar{d} = \left[\frac{2\zeta + \delta}{3} - 1 \right] a. \quad (15)$$

With the approximation of Eq. (13), this suggests that we pick the emission probability $a \approx 0.15$. As for the suppression factors, we shall take the illustrative value of $\epsilon = \delta = -2\zeta \approx 0.6$. If one wishes to, one can interpret these values as the relative strength of the propagator factors:

$$\Gamma_\pi : \Gamma_K : \Gamma_\eta : \Gamma_{\eta'} = 1 : \epsilon : \delta : |\zeta|,$$

where

$$\Gamma_\pi = \frac{1}{\langle Q^2 \rangle + M_\pi^2}, \text{ etc. with } \langle Q^2 \rangle \approx 0.35 \text{ GeV}^2.$$

In Table II, we summarize the results of such a numerical calculation. They are compared to the phenomenological values, and to the predictions by the naive quark model and by the χ QM with SU(3) symmetry, respectively.

We should mention that, in this crude model calculation, we cannot specify the detailed Bjorken- x dependence of the various quark densities. Namely, all the densities should be taken as those averaged over the entire range of x . In this connection, one should be careful in making a comparison of the antiquark density ratio of \bar{u}/\bar{d} , which our model (with the stated parameters) yields a value of 0.63, while the NA51 Collaboration [6] measured it to have a value of $0.51 \pm 0.04 \pm 0.05$ at a specific point of $x = 0.15$.

IV. DISCUSSION AND CONCLUSION

In our previous publication [3], we have demonstrated that the chiral quark model with a nonet of GBs can, in the

TABLE II. Comparison of χ QM with phenomenological values. Antiquark number difference $\bar{u} - \bar{d}$ follows from the violation of Gottfried sum rule as measured by NMC [4]. The χ QM results for the antiquark density ratio \bar{u}/\bar{d} are the x -averaged quantities, while the NA51 Collaboration [6] measurement is at a specific point of $x=0.15$. The strange to nonstrange quark ratio in the sea $2\bar{s}/(\bar{u} + \bar{d})$ is from the CCFR measurement and analysis [24] as discussed in the text, see Eq. (18). The strange quark fraction f_s value is based on $\sigma_{\pi N} = 45$ MeV and the no-strange-quark limit-value of $(\sigma_{\pi N})_0 = 25$ MeV, calculated by using the SU(3) symmetric baryon mass F/D ratio [8,9], and the quark-fraction ratio f_3/f_8 is similarly calculated by using the octet baryon masses [23]. The axial vector coupling F and D are from Ref. [22]. Quark spin contribution Δq 's, based on the SU(3) symmetric axial vector coupling F/D ratio, are from summary review in [14]. The antiquark polarization values $\Delta\bar{u}$ and $\Delta\bar{d}$ are from the recent SMC measurement on semi-inclusive processes [16]. Possible downward revision of the phenomenological values by SU(3) breaking effects, as discussed in the text, are indicated by the symbol ($\downarrow?$).

	Phenomenological values	Naive QM	χ QM SU ₃ symmetric $\epsilon = \delta = -\zeta = 1$ $a = 0.11$	χ QM broken SU ₃ $\epsilon = \delta = -2\zeta = 0.6$ $a = 0.15$
$\bar{u} - \bar{d}$	0.147 ± 0.026	0	0.146	0.15
\bar{u}/\bar{d}	$(0.51 \pm 0.09)_{x=0.15}$	1	0.56	0.63
$\frac{2\bar{s}}{\bar{u} + \bar{d}}$	≈ 0.5	0	1.86	0.60
$\sigma_{\pi N} : f_s$	0.18 ± 0.60 ($\downarrow?$)	0	0.19	0.09
f_3/f_8	0.21 ± 0.05	$\frac{1}{3}$	$\frac{1}{3}$	0.20
g_A	1.257 ± 0.03	$\frac{5}{3}$	1.12	1.28
$(F/D)_A$	0.575 ± 0.016	$\frac{2}{3}$	$\frac{2}{3}$	0.57
$(3F - D)_A$	0.60 ± 0.07	1	0.67	0.57
Δu	0.82 ± 0.06	$\frac{4}{3}$	0.78	0.87
Δd	-0.44 ± 0.06	$-\frac{1}{3}$	-0.33	-0.41
Δs	-0.11 ± 0.06 ($\downarrow?$)	0	-0.11	-0.05
$\Delta\bar{u}, \Delta\bar{d}$	-0.02 ± 0.11	0	0	0

SU(3) symmetric limit with the singlet coupling $g_0 \approx -g_8$, yield an adequate accounting of the observed proton spin and flavor structure. In this paper, we have presented a calculation which takes into account, schematically, the SU(3) symmetry breaking effects due to the heavier strange quark, $m_s > m_{u,d}$ and $M_{K,\eta} > M_{\pi}$, as well as the axial U(1) breaking due to $M_{\eta'} > M_{K,\eta}$. We find the resulting phenomenology having been significantly improved.

A. F/D ratios

We wish to emphasize that the calculation presented here is more than just an exercise in parametrizing the experimental data. After fixing the two constants by the measured values, we have been able to reproduce several other phenomenological quantities. Our point is that the broken-U(3) χ QM with $m_s > m_{u,d}$ has just the right structure to account for the overall pattern of the experimental data. For example, it has been clear that in this model the SU(3) breaking terms are needed to account for the deviation F/D ratios from the SU(6) predictions [3]. But there is no *a priori* reason to expect the correction to either increase or decrease the ratio. However, our schematic calculations show that this model has the right structure to make the correction in just the right direction. Consider the axial vector coupling F/D ratio of Eq. (11). To simplify our presentation, let us expand it in powers of the emission probability a :

$$\frac{F}{D} = \frac{2}{3} \left[1 - \frac{5}{4} (1 - \epsilon^2) a + O(a^2) \right].$$

The desired correction is for the above $[\dots]$ factor to be less than one, see Table II. This is precisely what the χ QM with $m_s > m_{u,d}$ would lead one to expect because of the inequality $\epsilon^2 < 1$. Similar statement can also be made for the ratio in Eq. (12):

$$\frac{f_3}{f_8} = \frac{1}{3} \left\{ 1 - \frac{1}{3} [(1 - \delta^2) + 2(1 - 2\zeta)(1 - \delta) + 12(1 - \epsilon^2)] a + O(a^2) \right\}.$$

Parenthetically, the axial vector coupling $3F - D = \Delta u + \Delta d - 2\Delta s \equiv \Delta_8$ has the structure $\Delta_8 = \Delta_8^{(0)} + \Delta_8^{(1)}$ with the symmetric term $\Delta_8^{(0)} = 1 - [(2\zeta^2 + 7)/3]a$ and the SU(3) breaking correction being

$$\Delta_8^{(1)} = \frac{1}{3} [(1 - \delta^2) - 3(1 - \epsilon^2)] a \approx -\frac{2}{3} (1 - \epsilon^2) a < 0.$$

Namely, in our χ QM, Δ_8 is reduced by SU(3) breaking effects. This is again compatible with the trend found for the phenomenological extracted value—although our model indicates that this reduction is rather moderate (from a sym-

metric value of 0.67 to corrected value of 0.57, approximately) rather than the 50% reduction as suggested in one of the $1/N_c$ studies [19].

B. Strange quark content and polarization

The χ QM naturally suggests that the nucleon strange quark content \bar{s} and polarization Δs magnitude are lowered by the SU(3) breaking effects as they are directly proportional to the amplitude suppression factors, see Eqs. (3) and (10). This is just the trend found in the extracted phenomenological values. Gasser [20], for instance, using a chiral loop model to calculate the SU(3) breaking correction to the Gell-Mann–Okubo baryon mass formula, finds that the non-strange-quark limit-value of $(\sigma_{\pi N})_0$ is modified from 25 to 35 MeV; this reduces f_s from 0.18 to 0.10, for a phenomenological value of $\sigma_{\pi N}=45$ MeV [8,9]. It matches closely our numerical calculation with the illustrative parameters, see Table II.

The strange quark content can also be expressed as the relative abundance of the strange to nonstrange quarks in the sea, which in this model is given as

$$\lambda \equiv \frac{\bar{s}}{(1/2)(\bar{u} + \bar{d})} = 4 \frac{(\zeta - \delta)^2 + 9\epsilon^2}{(2\zeta + \delta)^2 + 27} \approx 1.6\epsilon^2 = 0.6. \quad (16)$$

This can be compared to the strange quark content as measured by the CCFR Collaboration in their neutrino charm production experiment [24]:

$$\kappa \equiv \frac{\langle x \bar{s} \rangle}{(1/2)(\langle x \bar{u} \rangle + \langle x \bar{d} \rangle)} = 0.477 \pm 0.063,$$

where

$$\langle x \bar{q} \rangle = \int_0^1 x \bar{q}(x) dx, \quad (17)$$

which is often used in the global QCD reconstruction of parton distributions [25]. The same experiment found no significant difference in the shapes of the strange and non-strange quark distributions [24]:

$$x \bar{s}(x) \propto (1-x)^\alpha \frac{x \bar{u}(x) + x \bar{d}(x)}{2},$$

with the shape parameter being consistent with zero, $\alpha = -0.02 \pm 0.08$. Thus, it is reasonable to use the CCFR findings to yield

$$\lambda \approx \kappa \approx \frac{1}{2}, \quad (18)$$

which is a bit less than, but still compatible with, the value in Eq. (16) [26].

A number of authors have pointed out that phenomenologically extracted value of strange quark polarization Δs is sensitive to possible SU(3) breaking corrections. While the effect is model dependent, various investigators [17–19] all conclude that SU(3) breaking correction tends to lower the magnitude of Δs . Some even suggested the possibility of

$\Delta s \approx 0$ being consistent with experimental data. Our calculation indicates that, while Δs may be smaller than 0.10, it is not likely to be significantly smaller than 0.05. To verify this prediction, it is then important to pursue other phenomenological methods that allow the extraction of Δs without the need of SU(3) relations. We recall that the elastic neutrino scatterings [27], and the measurements of longitudinal polarization of Λ in the semi-inclusive process of $\bar{\nu} N \rightarrow \mu \Lambda + X$ [28] have already given support to a nonvanishing and negative Δs . Such experimentation and phenomenological analysis should be pursued further [29].

C. Down quark polarization

It is also interesting to examine the SU(3) breaking effect on the spin contribution Δd , which should have only an indirect dependence on the strange quark. Without SU(3) breaking, we have

$$(\Delta d)^{(0)} = -\frac{1}{3} - \frac{2}{9}(1 - \zeta^2)a$$

which can hardly yield a Δd value significantly more negative than $-1/3$ as required by phenomenology, whether in the simple χ QM with an octet of GBs ($\zeta=0$), or the broken-U(3) model with $\zeta=-1$. But Eq. (9) clearly shows that it is the emission of strange-quark-bearing mesons that contributes the “wrong sign.” Hence, the suppression of such emissions, when we take $m_s > m_{u,d}$ into account, will make the d quarks in the sea more negatively polarized, see Table II. Calculationally, the strange-quark-bearing mesons enter into the expression for Δd (with the wrong sign) through the probability factor for “no GB emission” as given in Eq. (7).

D. The role of SU(3)-singlet GB

For the axial U(1) breaking, we made the parameter choice of $\zeta \approx -\epsilon/2 \approx -0.3$. It implies that a satisfactory phenomenology can be obtained with a strongly suppressed η' amplitude. In what sense then are we required to extend the traditional χ QM with an octet of GBs to the broken-U(3) version of the model? We observe that if we set $\zeta=0$, namely a decoupled η' , while the numerical results for Δq 's and f_s remain quite acceptable, the $(\bar{u} - \bar{d})_{\zeta=0} = -0.12$ becomes rather a poor fit to the known phenomenology. Indeed we find it difficult to get a good fit to all the phenomenological values with $\zeta=0$: For example, if we fix up the Gottfried sum rule violation with a some adjustment of parameter: $a = 0.175$ and $\epsilon = \delta \approx \frac{1}{2}$, we then over-correct f_3/f_8 to 0.17, f_s to 0.06, and κ to 0.36, etc. (Generally speaking, it is the flavor, rather than the spin, structure that is more sensitive to the ζ value.) Nevertheless, it is difficult to justify the inclusion of the η' meson based on such crude numerical fit. We suggest that it is the overall theoretical consistency that requires the inclusion of the SU(3)-singlet GB. For example, from the view point of $1/N_c$ expansion, in the leading term we have nine unmixed GBs. The next order nonplanar correction must be included to break this U(3) symmetry — and its attendant SU(3) symmetric quark sea [1–3], which is phenomenologically undesirable — and to give the singlet an extra heavy mass (through the axial anomaly). In our previ-

our SU(3) symmetric calculation, we found that a choice of $g_0 \approx -g_8$ yield an adequate fit for a phenomenology derived at the SU(3) symmetric level; in this paper a significantly better description has been obtained after taking into account of SU(3) and U(1)_A breakings. All this shows that our broken-U(3) chiral quark model possesses a consistent structure that can yield satisfactory phenomenological descriptions at different levels of approximation.

Note added. In addition to Refs. [17–20], we would also cite a more up-to-date discussion by Ratcliffe [Phys. Lett. B **365**, 383 (1996)], as well as a series of earlier works on flavor-symmetry breaking of the nucleon axial matrix elements, performed in the context of the Skyrme model of the

baryon, by the Syracuse group, which can be traced back starting from Park, Schechter, and Weigel [Phys. Rev. D **43**, 869 (1991)]. We also note the Skyrme discussion of the SU(3) breaking effect on the extraction of strange quark content from the pion nucleon σ term by Yabu [Phys. Lett. B **218**, 123 (1989)].

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