Flavor violation in Higgs-boson couplings to baryons

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The $\frac{1}{2}^+$ baryon mass spectrum is studied to determine the $\bar{u}u$, $\bar{d}d$, and $\bar{s}s$ contents in the nucleon. We find that higher-order symmetry-breaking terms in the mass operator are necessary to estimate $\langle p|\bar{u}u|p\rangle$, $\langle p|\bar{d}d|p\rangle$, and $\langle p|\bar{s}s|p\rangle$ in a self-consistent way. We also assess the scalar (pseudoscalar) Higgs-boson couplings to baryons.

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I. INTRODUCTION

There have been several attempts [1,2] in the literature to study the relationships among the baryon masses. In the simplest model [3] of chiral-symmetry breaking, the mass of a baryon may be viewed as the expectation value of the trace of the QCD energy-momentum tensor θ^μ_μ. At zero momentum transfer, θ^μ_μ is [4]

$$\theta^\mu_\mu = \sum m_q \bar{q}q - \frac{9\alpha_s}{8\pi}(G_{\mu\nu})^2 , \quad (1)$$

where $G_{\mu\nu}$ is the gluon field strength and q runs over the light quarks u, d, and s. The first-order mass relations that follow from (1) may be summarized below:

$$\begin{aligned} m_p &= M_0 + Um_u + Dm_d + Sm_s , \\ m_n &= M_0 + Dm_u + Um_d + Sm_s , \\ m_{\Sigma^+} &= M_0 + Um_u + Sm_d + Dm_s , \\ m_{\Sigma^-} &= M_0 + Sm_u + Um_d + Dm_s , \\ m_{\Xi^0} &= M_0 + Dm_u + Sm_d + Um_s , \\ m_{\Xi^-} &= M_0 + Sm_u + Dm_d + Um_s , \end{aligned} \quad (2)$$

where $M_0 = \langle p|\theta^\mu_\mu|p\rangle = -\frac{9}{2}\langle p|(\alpha_s/4\pi)GG|p\rangle$, $U = \langle p|\bar{u}u|p\rangle$, $D = \langle p|\bar{d}d|p\rangle$, and $S = \langle p|\bar{s}s|p\rangle$. We have omitted the pair (Λ, Σ^0) in (2) but shall return to them later on. Also, we shall have to consider the electromagnetic contributions which have not been included in Eq. (2).

It is tempting to fit U, D, and S to the baryon mass spectrum. Unfortunately, the appearance of four parameters in the six relations leaves the set (2) subject to two constraints:

$$m_p - m_n + m_{\Sigma^-} - m_{\Sigma^+} + m_{\Xi^0} - m_{\Xi^-} = 0 , \quad (3)$$

$$\frac{m_{\Sigma^+} - m_{\Sigma^-}}{m_{\Xi^0} - m_{\Xi^-}} = \frac{m_{\Xi^0} + m_{\Xi^-} - m_p - m_n}{m_{\Sigma^+} + m_{\Sigma^-} - m_p - m_n} . \quad (4)$$

Relation (3) is the well-known Coleman-Glashow mass formula.

Recently, Cheng [5] has used the relations in (2) to fit the quantities $(U-S)$ and $(D-S)$ to the baryon mass spectrum:

$$U - S = (m_s - \hat{m})^{-1}(m_{\Xi^0} + m_{\Xi^-} - m_p - m_n)/2 \simeq 2.6 , \quad (5)$$

$$D - S = (m_s - \hat{m})^{-1}(m_{\Sigma^+} + m_{\Sigma^-} - m_p - m_n)/2 \simeq 1.8 , \quad (6)$$

where $\hat{m} = (m_u + m_d)/2$. However, owing to the underlying constraints (3) and (4), it is clear that the above expressions for $(U-S)$ and $(D-S)$ cannot be unique. Indeed, one can also write down from (2) the relations

$$U - S = (m_u - m_d)^{-1}(m_{\Sigma^+} - m_{\Sigma^-}) , \quad (7)$$

$$D - S = (m_u - m_d)^{-1}(m_{\Xi^0} - m_{\Xi^-}) , \quad (8)$$

in place of (5) and (6). Inserting the standard values for the quark masses one finds

$$U - S \approx 2.4 , \quad D - S \approx 1.9 \quad (9)$$

to be compared with (5) and (6).

The point is that, since the experimental values of the baryon masses do not satisfy the constraints (3) and (4) exactly, there is no reason to expect that the values of the parameters U, D, and S determined from other sources will match (5) and (6) favorably. In this connection mention may be made of the work of Gasser [6] in which the ratio $R = (m_s - \hat{m})/(m_d - m_u)$ was computed from the baryon mass values. Accounting for the lowest-order corrections [which are $O(m_s^{1/2})$], three estimates of R were arrived at [7] corresponding to the mass differences $m_p - m_n$, $m_{\Sigma^+} - m_{\Sigma^-}$ and $m_{\Xi^0} - m_{\Xi^-}$ which were different from one another.

Following the European Muon Collaboration (EMC) measurement [8] of the proton spin in deep-inelastic polarized μp scattering there has been a revival of interest to estimate the parameters U, D, and S. The EMC analysis points to the possibility that the fraction of the proton spin carried by its quark constituents is negligible leading to the expectation that the proton may possess some $\bar{s}s$ leakage. The purpose of this work is to make contact with the baryon mass spectrum and work out reliable estimates of the quantities U, D, and S. These will then be used to study the scalar Higgs-boson–baryon couplings. We shall also investigate the role of the axial anomaly to determine the pseudoscalar Higgs-boson couplings to baryons. We shall show that these depend crucially on the gluon-helicity component.

II. THE MASS OPERATOR AND ITS MODIFICATION

The mass relations (2) actually emerge as the expressions for the eigenvalues of the operator

$$\mathcal{M}=M_0'+2K_1I_3+2K_2I_3Y+2K_3Y+2K_4(\mathbf{I}^2-Y^2/4) \tag{10}$$

where $\mathbf{I}$, I_3, and Y stand for the isospin, its third component, and the hypercharge, respectively. We get from (10)

$$\begin{aligned}
m_p&=M_0'+K_1+K_2+2K_3+K_4\ ,\\
m_n&=M_0'-K_1-K_2+2K_3+K_4\ ,\\
m_{\Sigma^+}&=M_0'+2K_1+4K_4\ ,\\
m_{\Sigma^0}&=M_0'+4K_4\ ,\\
m_{\Sigma^-}&=M_0'-2K_1+4K_4\ ,\\
m_{\Xi^0}&=M_0'+K_1-K_2+K_3+K_4\ ,\\
m_{\Xi^-}&=M_0'-K_1+K_2-K_3+K_4\ ,\\
m_\Lambda&=M_0'\ .
\end{aligned} \tag{11a}$$

The equivalence with (2) is easily established if we set

$$\begin{aligned}
&K_1=\tfrac{1}{4}(S-U)(m_d-m_u)\ ,\\
&K_2=\tfrac{1}{4}(2D-U-S)(m_d-m_u)\ ,\\
&K_3=\tfrac{1}{4}(S-U)(m_s-\hat{m})\ ,\quad K_4=\tfrac{1}{6}(2D-U-S)(m_s-\hat{m}),\\
&M_0'=M_0+\tfrac{1}{3}(U+S)(\hat{m}+2m_s)-\tfrac{1}{3}D(m_s-4\hat{m})\ .
\end{aligned} \tag{11b}$$

We therefore conclude that to obtain a consistent fit to the baryon mass spectrum, the mass operator (10) is not adequate and calls for a modification.

The simplest way to modify (10) is to incorporate [1] higher-order symmetry-breaking effects. Such effects mostly come from the SU(3) corrections which are next-to-leading order, electromagnetic corrections, combined SU(3)-isospin violation, and combined SU(3)-electromagnetic shifts.

Within the framework of chiral perturbation theory evaluation of higher-order corrections necessarily involves estimating nonanalytic corrections. In fact, one may even go beyond [6] chiral perturbation theory and consider a model for the cloud of virtual particles around baryons and mesons. The latter approach does not consider chiral perturbation for the electromagnetic part of the mass shift since chiral perturbation theory breaks down [6] in this case. In the following, however, we prefer the scheme of Minkowski and Zepeda [1] which consists of a modification of the mass operator. This simple-minded model replaces the operator $\mathcal{M}$ by M, which reads

$$M=\mathcal{M}+K_2'I_3Y+aY^2+bQ^2+cQ^2Y\ . \tag{12}$$

Note the difference with (10): In the expression (12) the additional terms appearing with the coefficients a, b, K_2', and c take care of the higher-order SU(3) corrections and electromagnetic contributions along with the combined effects of these. The exclusion of the nonanalytic terms means that the parameters a, b, K_2', and c only give an estimate of the order of magnitude and a hint of the higher-order symmetry-breaking trend. A positive aspect of the mass operator M is that it does allow a consistent fit of the various parameters in terms of the octet-baryon masses thereby enabling us to extract meaningful information on the flavor-breaking parameters U, D, and S.

To spell out the model more clearly, the principal assumption which goes into it is that the terms with coefficients K_1, K_2, K_3, and K_4 present in $\mathcal{M}$ arise dominantly from the first-order symmetry and electromagnetic interactions so that the relations (11b) and $K_1/K_2=2K_3/3K_4$ remain valid even when the electromagnetic shifts are subtracted and higher-order effects are allowed in K_1, K_2, K_3, and K_4. Our aim would be to separate all these four parameters into a first-order tadpole and an electromagnetic piece so that the terms bQ^2 and cQ^2y in (12) can account for the electromagnetic shifts and SU(3) violation in electromagnetic mass shifts, respectively.

To pin down the parameters, let us write down the explicit expressions of the baryon masses which follow from (12):

$$\begin{aligned}
m_p&=M_0'+K_1+K+2K_3+K_4+a+b+c\ ,\\
m_n&=M_0'-K_1-K+2K_3+K_4+a\ ,\\
m_{\Sigma^+}&=M_0'+2K_1+4K_4+b\ ,\\
m_{\Sigma^0}&=M_0'+4K_4\ ,\\
m_{\Sigma^-}&=M_0'-2K_1+4K_4+b\ ,\\
m_{\Xi^0}&=M_0'+K_1-K-2K_3+K_4+a\ ,\\
m_{\Xi^-}&=M_0'-K_1+K-2K_3+K_4+a+b-c\ ,\\
m_\Lambda&=M_0'\ ,
\end{aligned} \tag{13}$$

where $K=K_2+K_2'$.

From (13) one finds

$$K_1=\tfrac{1}{4}(m_{\Sigma^+}-m_{\Sigma^-}) ,$$
$$K_4=\tfrac{1}{4}(m_{\Sigma^0}-m_\Lambda) ,$$
$$b=\tfrac{1}{2}(m_{\Sigma^+}+m_{\Sigma^-}-2m_{\Sigma^0}) ,$$
$$2K+b+c=m_p-m_n-\tfrac{1}{2}(m_{\Sigma^+}-m_{\Sigma^-}) ,\quad (14)$$
$$-2K-b+c=m_{\Xi^0}-m_{\Xi^-}-\tfrac{1}{2}(m_{\Sigma^+}-m_{\Sigma^-}) ,$$
$$4K_3+2a-b=\tfrac{3}{2}(m_n-m_{\Sigma^-}-m_{\Sigma^0}-m_\Lambda)+\tfrac{1}{2}(m_p-m_{\Sigma^+}+m_{\Xi^-}-m_{\Xi^0}) ,$$
$$8K_3+2c=m_p+m_n-m_{\Xi^0}-m_{\Xi^-} .$$

Solving, we get[1]

$$K_1=-2.02\pm0.02 \text{ MeV} ,\quad K_3=-94.75\pm0.12 \text{ MeV} ,$$
$$K_4=19.23\pm0.03 \text{ MeV} ,\quad K=0.85\pm0.15 \text{ MeV} ,\quad (15)$$
$$a=-6.96\pm0.1 \text{ MeV} ,\quad b=0.85\pm0.03 \text{ MeV} ,$$
$$c=0.19\pm0.3 \text{ MeV} .$$

The mass operator (12), however, is not the complete story. One must take into account the first-order tadpole (t) and electromagnetic (em) contributions to the K parameters. To isolate these, we note that the electromagnetic shifts may be parametrized by

$$M=M^0_{\text{em}}+2K_1^{\text{em}}Q+2K_2^{\text{em}}Q_d+bQ^2+CQ^2Y , \quad (16)$$

where $Q_d=I_3Y+\frac{1}{3}(\mathbf{I}^2-\frac{1}{4}Y^2-1)$.

Comparing (16) and (12) it follows that $K_3^{\text{em}}=\frac{1}{2}K_1^{\text{em}}$ and $K_4^{\text{em}}=\frac{1}{3}K_2^{\text{em}}$ where K_1^{em} and K_2^{em} are

$$K_1^{\text{em}}=\tfrac{1}{4}(m_{\Sigma^+}-m_{\Sigma^-})_{\text{em}}=-0.05\pm0.03 \text{ MeV} ,$$
$$K_2^{\text{em}}=\tfrac{1}{2}[(m_{\Xi^-}-m_{\Xi^0})_{\text{em}}+2K_1^{\text{em}}-b+c] \quad (17a)$$
$$=0.12\pm0.11 \text{ MeV} .$$

In the above we have used $(m_{\Sigma^+}-m_{\Sigma^-})_{\text{em}}=-0.2\pm0.1$ MeV and $(m_{\Xi^0}-m_{\Xi^-})_{\text{em}}=-1.0\pm0.5$ MeV, which have been obtained [6] taking the Born terms as a measure for the contribution to isospin breaking. We also note [6] the estimate $(m_p-m_n)_{\text{em}}=0.7\pm0.3$ MeV, which is within the error margin of what is obtained from (16):

$$(m_p-m_n)_{\text{em}}=2K_1^{\text{em}}+2K_2^{\text{em}}+b+c=1.1\pm0.6 . \quad (17b)$$

Subtracting the electromagnetic part, the tadpole terms turn out to be

$$K_1^t=-1.97\pm0.01 \text{ MeV} ,$$
$$K_3^t=-94.73\pm0.10 \text{ MeV} ,\quad (18)$$
$$K_4^t=19.19\pm0.02 \text{ MeV} ,$$
$$K_2^t=(3K_4^tK_1^t)/(2K_3^t)=0.6\pm0.001 \text{ MeV} .$$

The key point to note is that the ratio $(S-U)/(S+U-2D)$ emerges as

$$\frac{S-U}{S+U-2D}=-\frac{2}{3}\frac{K_3^t}{K_4^t}=3.29\pm0.002 . \quad (19)$$

Furthermore,

$$(m_u-m_d)(U-D)=2(K_1^t+K_2^t)=-2.74\pm0.02 . \quad (20)$$

It should be stressed that although we have included electromagnetic effects to perform a precise calculation, the results are only mildly sensitive to such effects. Indeed with the electromagnetic part set equal to zero, one finds

$$(S-U)/(S+U-2D)=-\tfrac{2}{3}(K_3/K_4)=3.28\pm0.002 , \quad (21)$$

which is very close to the estimate (19).

III. ESTIMATES OF U, D, AND S

Scaling the quark masses at 1 GeV and using [9] the most recent improved values to three loops, viz. $m_u=5.2\pm0.5$ MeV, $m_d=9.2\pm0.5$ MeV, and $m_s=162\pm15$ MeV we obtain from (19) and (20)

$$U-D=0.69\pm0.02 ,\quad (22)$$
$$U+D-2S=3.26\pm0.04 .$$

These imply

$$U-S=1.97\pm0.03 ,\quad (23)$$
$$D-S=1.29\pm0.01 ,$$

indicating that the difference with the estimates (5), (6) is about 30%. A part of this difference may be attributed to the inclusion of the higher-order effects in the mass operator and the rest to the improved values of the quark masses which have been used as inputs. Be that as it may, it is comforting to note that the parameters in the modified mass operator have been determined consistently and so the estimates of $(U-S)$ and $(D-S)$ in (23) appear to be more trustworthy than the first-order solutions.

IV. SCALAR HIGGS-BARYON COUPLING

A. Higgs coupling and the role of S

The scalar-Higgs-boson (ϕ) couplings to baryons appear in the Lagrangian[2] of the form $L=\sum_i(m_i/v)\bar{i}i\Phi$ where the summation on i runs over both the light (q) and heavy (Q) marks and $v\approx250$ GeV is the vacuum expectation value of ϕ. The heavy (Q) quark expansion [10] of

[1]We are using the mass values (in MeV) 938.27, 939.57, 1115.63, 1189.37, 1192.55, 1197.43, 1314.9, 1321.32 for p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^- respectively.

[2]The Lagrangian corresponds to the simple case [3] of a doublet of Higgs bosons.

Shifman, Vainshtein, and Zakharov (SVZ) sets

$$\bar{Q}Q=-(\alpha_s/12\pi m_Q)GG+O(\lambda^3/m_Q^3)\ , \tag{24}$$

where λ is the QCD scale parameter. It follows that

$$\begin{aligned} vg_{\phi NN}&=[m_u(U-S)+m_d(D-S)+(m_u+m_d+m_s)S]\\ &\quad-\langle p|(\alpha_s/4\pi)GG|p\rangle\ ,\\ vg_{\phi\Sigma\Sigma}&=[m_u(U-S)+m_s(D-S)+(m_u+m_d+m_s)S]\\ &\quad-\langle p|(\alpha_s/4\pi)GG|p\rangle\ , \qquad (25)\\ vg_{\phi\Xi\Xi}&=[m_s(U-S)+m_u(D-S)+(m_u+m_d+m_s)S]\\ &\quad-\langle p|(\alpha_s/4\pi)GG|p\rangle\ , \end{aligned}$$

where we have taken $n_Q=3$.

Without any specific value of S we are at a loss to determine $g_{\phi NN}$, $g_{\phi\Sigma\Sigma}$, and $g_{\phi\Xi\Xi}$ from (25). To have a rough assessment of these couplings, one has to vary S in some interval to get a picture of the behavior of the Higgs-boson–baryon couplings. In Fig. 1, such a variation has been done which indicates that for S spanning between $0.2<S<3.0$, the Higgs-boson couplings run according to

$$\begin{aligned} 1.0\times10^{-3}&<g_{\phi NN}<2.6\times10^{-3}\ ,\\ 1.8\times10^{-3}&<g_{\phi\Sigma\Sigma}<3.4\times10^{-3}\ , \qquad (26)\\ 2.3\times10^{-3}&<g_{\phi\Xi\Xi}<3.8\times10^{-3}\ , \end{aligned}$$

where we have used (23) as input values. Note further that in the present scheme the above range of S is consistent with 95 MeV $<\langle p(-\alpha_s/4\pi)GG|p\rangle<$ 204 MeV. In this interval we also have 57 MeV $<Um_u+Dm_d+Sm_s<$ 551 MeV.

The results in (26) clearly demonstrate that inclusion of an $\bar{s}s$ component in the nucleon pushes up the Higgs-boson coupling by a factor of 2 or so. Without any strangeness contamination in the nucleon one essentially recovers the SVZ result which for the ϕNN coupling is about 1×10^{-3}.

B. Higgs-boson coupling and the pion-nucleon σ term

One may try to reconcile [3] the estimates in (26) with the pion-nucleon term value. An average obtained from the phase-shift analysis and dispersion calculation gives [11,12][3]

$$\sigma=(60\pm12)\ \text{MeV}\ . \tag{27}$$

As is well known, (27) is rather on the high side unless compromise is made on a large violation of the Okubo-Zweig-Iizuka (OZI) rule.

An explicit expression for σ is[4] [3]

$$\sigma=\tfrac{1}{2}(m_u+m_d)\langle N|\bar{u}u+\bar{d}d|N\rangle\ . \tag{28}$$

One can evaluate the nucleon expectation value in terms of the baryon masses. This yields in the leading order

$$\sigma=\frac{3}{2}\frac{m_\Lambda^2-m_\Xi^2}{m_N}\left[1-\frac{2m_s}{m_u+m_d}\right]^{-1}\frac{1}{1-y}\ , \tag{29}$$

where y represents a measure of the OZI-rule violation

$$y=\frac{2\langle\bar{s}s\rangle_N}{\langle\bar{u}u+\bar{d}d\rangle_N}\ . \tag{30}$$

It is straightforward to ascertain that with $y=0$, σ turns out to be $\sim$27 MeV which is more than a factor of 2 smaller than the value in (27). On the other hand, if $\sigma\simeq60$ MeV is furnished as an input, y emerges[4] as $\frac{1}{2}$ indicating that the strangeness content in the nucleon is significantly high.

In a recent work, Cheng [3] has pointed out that a large departure from the naive OZI-rule expectation is not necessarily at variance with the deep-inelastic lepton-nucleon scattering result. It is also not out of context to keep in mind [13] that a study of the $\bar{s}s$ content in the nucleon based on the semiphenomenological data, low-energy theorems, and bag-model calculations points to a sizable magnitude for $\langle\bar{s}s\rangle_N$.

We may use the relation (28) along with (27) to estimate U, D, and S. Our results obtained from (23) are

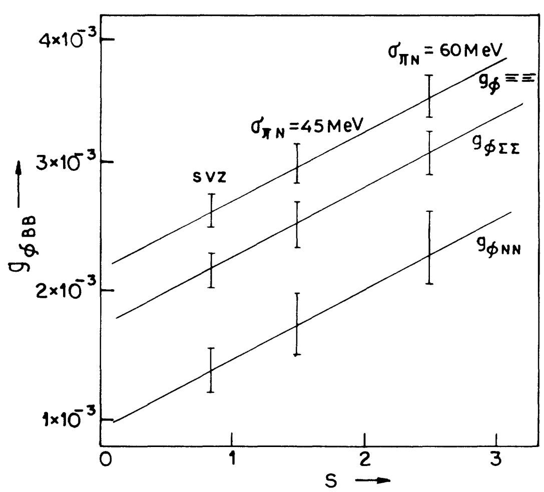

FIG. 1. Variation of the Higgs couplings $g_{\phi NN}$, $g_{\phi\Sigma\Sigma}$, and $g_{\phi\Xi\Xi}$ with $S(\equiv\langle p|\bar{s}s|p\rangle)$. The SVZ and πN σ term values have been indicated by bars.

[3]We work with this value but note that 25% reduction is not ruled out. As pointed out recently in Ref. [20], a smaller value of σ (45 MeV) would mean a smaller $\bar{s}s$ contamination in the nucleon (see Fig. 1).

[4]In chiral perturbation theory, one obtains [12] to 1-loop $\sigma=\hat{\sigma}(1-y)$ where $\hat{\sigma}=(35\pm5)$ MeV. With $\sigma\simeq60$ MeV, y turns out to be $\sim$0.42.

$$U=4.51\pm0.15\ ,\quad D=3.82\pm0.13\ ,\quad S=2.54\pm0.12\ . \tag{31}$$

Corresponding to the estimate of S above, the Higgs-boson–nucleon coupling is

$$g_{\phi NN}\simeq 2.3\times10^{-3}\ . \tag{32}$$

As seen from (31) and (32), the large value of S, which in turn is consistent with the present determination of the πN σ term, influences Higgs-boson–baryon couplings considerably in comparison with the naive SVZ value. The estimate provided in (32) should therefore provide insight into the nature of interaction between the Higgs scalars and nucleons. For the related phenomenology associated with the search for Higgs bosons and its implications on the neutron-nucleus limit we refer the readers to the review by Cheng [3] on this subject.

V. PSEUDOSCALAR HIGGS-BOSON–BARYON COUPLINGS

The latest EMC analysis may be summarized by defining the moments $\Delta q'$ through $\Delta q' s_\mu=\langle p,s|\bar q\gamma_\mu\gamma_5 q|p,s\rangle$, where s_μ is the proton spin vector. The available data on the structure function of the polarized proton and the results on hyperon decays lead to the estimates [14]

$$\Delta u'=(0.78\pm0.08)\ ,\quad \Delta d'=(-0.47\pm0.08)\ ,\quad \Delta s'=(-0.19\pm0.08)\ . \tag{33}$$

Their sum is

$$\sum\Delta q'=\Delta u'+\Delta d'+\Delta s'=0.12\pm0.24\ . \tag{34}$$

Note that SU(3) restricts $\Delta u'+\Delta d'-2\Delta s'=3F-D$ while from the Bjorken sum rule $\Delta u'-\Delta d'=F+D=g_A$.

The role of the axial anomaly in QCD to determine the quark spin fractions of the proton has been investigated [15] by a number of authors. In the following we shall adopt the notations of Cheng and Li [16] but pursue the analysis of Bagchi and Basu [17]. What would emerge is a new relation linking the pseudoscalar Higgs-boson couplings to the axial singlet charge.

We first of all note that the axial-divergence equations involving the QCD anomaly read

$$\partial^\mu(\bar q\gamma_\mu\gamma_5 q)=2m_q\bar q i\gamma_5 q+a\ , \tag{35}$$

where $a=(\alpha_s/2\pi)\,\mathrm{Tr}G\tilde G$ represents the anomalous piece.

In addition to $\Delta q'$, one can also define[5] the gluon helicity component Δg through

$$\langle p|a|p\rangle=-(\alpha_s/\pi)\Delta g\,2M\bar u i\gamma_5 u\ , \tag{36}$$

where u is the proton wave function.

We can thus combine Eqs. (35) and (36) to have [16]

$$2M\Delta q'=2m_q\nu_q-2M(\alpha_s/2\pi)\Delta g\ , \tag{37}$$

for each of $q=u$, d, and s where ν_q appears through $\nu_q\bar u i\gamma_5 u=\langle p|\bar q i\gamma_5 q|p\rangle$.

To look into the relation (37), let us write the nucleonic matrix elements for the divergence of the isovector and isosinglet axial currents fully:

$$\begin{aligned}2Mg_A&=(m_u+m_d)(\nu_u-\nu_d)+(m_u-m_d)(\nu_u+\nu_d)\ ,\\ 2MG_1^{(0)}&=(m_u+m_d)(\nu_u+\nu_d)\\ &\quad+(m_u-m_d)(\nu_u-\nu_d)-4M(\alpha_s/2\pi)\Delta g\ .\end{aligned} \tag{38}$$

Following Bagchi and Basu [17] we get[6,7] from (37) the sum rule

$$G_1^{(0)}=\tfrac13[3-4D/(F+D)]g_A+\tfrac23\sum\Delta q'=0.30\pm0.16\ , \tag{39}$$

where flavor-SU(3) relationships have been used

$$\begin{aligned}\Delta u'&=\tfrac13(F+D)+\tfrac13\sum\Delta q'\ ,\\ \Delta d'&=-(\tfrac23)D+(\tfrac13)\sum\Delta q'\ ,\end{aligned} \tag{40}$$

along with $g_A=1.254$ and $F/D=0.61$.

The form of the pseudoscalar Higgs-boson coupling to nucleons has been written down recently by Geng and Ng [18] for a class of models in which CP violation is induced through the scalar-pseudoscalar Higgs-boson mixings. The relevant portion of the Lagrangian reads

$$L=(2\sqrt2 G_F)^{1/2}\sum_k\beta^k[(\bar u_i\gamma_5 u)M_u+(\bar d i\gamma_5 d)M_d]H_k\ , \tag{41}$$

where M_u (M_d) are the diagonal mass matrices for the charge $\frac23$ ($-\frac13$) types of quarks, H_k is the Higgs boson, and β^k is a mixing parameter.

Separating the light (q) and heavy (Q) quarks, L may be reexpressed as

$$L=(2\sqrt2 G_F)^{1/2}\sum_k\beta^k\left[\sum m_q\bar q i\gamma_5 q+\sum m_Q\bar Q i\gamma_5 Q\right]H_k\ . \tag{42}$$

For the light quarks one has from Eq. (37)

$$\langle p|\sum_q m_q\bar q i\gamma_5 q|p\rangle=\left[\sum_q\Delta q+3(\alpha_s/2\pi)\Delta g\right]M(\bar u i\gamma_5 u)\ , \tag{43a}$$

while for the heavy quarks ($Q=b,c,t$) one may write

$$\langle p|\sum m_Q\bar Q i\gamma_5 Q|p\rangle=[3(\alpha_s/2\pi)\Delta g][M(\bar u i_{\gamma_5}u)]\ . \tag{43b}$$

[5]The replacement $\Delta q'\to\Delta q-(\alpha_s/2\pi)\Delta g$ is convention dependent [21].

[6]Relation (39) has no explicit dependence of Δg.

[7]There have been attempts to relate $\sum\Delta q'$ to the $\eta' NN$ coupling [19b].

Adding (43a) and (43b), one obtains the sum rule

$$\langle p | \sum (m_q \bar{q} i \gamma_5 q + m_Q \bar{Q} i \gamma_5 Q) | p \rangle = \left[\sum_q \Delta q' + 6(\alpha_s/2\pi)\Delta g \right] 2M(\bar{u} i \gamma_5 u) \quad (44)$$

derived previously in Ref. [18] somewhat differently.

One may now employ the sum rule (39) to write down

$$\langle p | \sum (m_q \bar{q} i \gamma_5 q + m_Q \bar{Q} i \gamma_5 Q) | p \rangle = \{ G_1^{(0)} - \tfrac{1}{3}[3 - 4D/(F+D)] g_A + (4\alpha_s/2\pi)\Delta g \} 3M(\bar{u} i \gamma_5 u) \ . \quad (45)$$

From (42) this means that the pseudoscalar Higgs-boson couplings are of the form

$$g_{H_k NN} = (2\sqrt{2} G_F)^{1/3} 3M\beta^k \{ G_1^{(0)} - \tfrac{1}{3}[3 - 4D/(F+D)] g_A + (4\alpha_s/2\pi)\Delta g \} = (2\sqrt{2} G_F)^{1/3} 3M\beta^k \{ (0.08 \pm 0.16) + 2[(\alpha_s/\pi)\Delta g] \} \ . \quad (46)$$

We thus see that $g_{H_k NN}$ depends heavily on Δg, the gluon-helicity component. For $\Delta g \simeq 0$ as is expected [19a] in some models, $g_{H_k NN}$ turns out to be proportional to the value in the first set of parentheses in Eq. (46) which, indeed, is very small. However, larger values of Δg have been claimed [19b] in the literature which may very well dominate the $\sum \Delta q'$ piece in Eq. (44).

We therefore conclude that a precise estimate of Δg will help decide the order of the pseudoscalar Higgs-boson couplings to the baryon. Conversely, any limit on the strength of interaction between nucleons and Higgs bosons will enable one to assess Δg properly.

VI. CONCLUDING REMARKS

We have investigated in this paper the role of flavor violation in the Higgs-boson couplings to the baryons. To this end, we have analyzed the baryon mass spectrum carefully and estimated the content of $\bar{u}u$, $\bar{d}d$, and $\bar{s}s$ pairs in the proton. We have found that a modification of the baryon mass is called for so that the baryon masses may be determined in a self-consistent way. Our estimates of the quantities U, D, and S have been used to determine the scalar Higgs-boson couplings to the nucleons and hyperons and consistency with the present value of the pion-nucleon σ term is sought. We have also derived a sum rule linking the gluon-helicity component to the pseudoscalar Higgs-boson–nucleon couplings.

[1] P. Minkowski and A. Zepeda, Nucl. Phys. **B164**, 25 (1980).

[2] C. Quigg, in *Gauge Theories in High Energy Physics*, Proceedings of the Les Houches Summer School in Theoretical Physics, Les Houches, France, 1981, edited by M. K. Gaillard and R. Stora (North-Holland, Amsterdam, 1983).

[3] T. P. Cheng, Phys. Rev. D **38**, 2869 (1988).

[4] T. Muta, *Foundations of Quantum Chromodynamics* (World Scientific, Singapore, 1987).

[5] H. Y. Cheng, Phys. Lett. B **219**, 347 (1989).

[6] J. Gasser, Ann. Phys. (N.Y.) **136**, 62 (1981).

[7] H. Leutwyler, Nucl. Phys. **B337**, 108 (1990).

[8] J. Ashman *et al.*, Nucl. Phys. **B328**, 1 (1990).

[9] S. Narison, *QCD Spectral Sum Rules* (World Scientific, Singapore, 1989).

[10] A. I. Vainshtein, V. I. Zakharov, and M. A. Shifman, Pis'ma Zh. Eksp. Teor. Fiz. **22**, 123 (1975) [JETP Lett. **22**, 55 (1975)]; E. Witten, Nucl. Phys. **B104**, 445 (1976).

[11] J. Gasser and H. Leutwyler, Phys. Rep. **87**, 77 (1982).

[12] J. Gasser, Report No. BUTP - 89/27, 1989 (unpublished).

[13] J. F. Donoghue and Ch. R. Nappi, Phys. Lett. **168B**, 105 (1986); V. M. Khatsymovsky, I. B. Khriplevich, and A. R. Zhitaitsky, Z. Phys. C **36**, 455 (1987).

[14] See, for a review, H. Fritzsch, Mod. Phys. Lett. A **5**, 1815 (1990).

[15] R. Decker, Th. Leize, and M. Nowakouski, Phys. Lett. B **244**, 497 (1990); B. Bagchi and A. Lahiri, J. Phys. G **16**, L239 (1990); X. Ji, Phys. Rev. Lett. **65**, 408 (1990); Riazuddin and Fayyazuddin, Phys. Rev. D **41**, 3517 (1990); A. E. Dorokhov and N. I. Kocheler, Phys. Lett. B **245**, 609 (1990); M. C. Birse, *ibid.* **249**, 291 (1990); G. Veneziano, Mod. Phys. Lett. A **17**, 1605 (1989); G. M. Shore and G. Veneziano, Phys. Lett. B **244**, 75 (1990); T. Hatsuda, Nucl. Phys. **B329**, 376 (1990).

[16] T. P. Cheng and L.-F. Li, Phys. Rev. Lett. **62**, 1441 (1989); Phys. Lett. B **234**, 165 (1990).

[17] B. Bagchi and S. Basu, Phys. Lett. B **268**, 112 (1991).

[18] C. Q. Geng and J. Ng, Phys. Lett. B **243**, 451 (1990).

[19a] J. Ellis and M. Karliner, Phys. Lett. B **213**, 73 (1988); G. Clement and J. Stern, *ibid.* **220**, 238 (1989); Z. Ryzak, *ibid.* **217**, 325 (1989).

[19b] A. V. Efremov, J. Soffer, and N. A. Tornqvist, Phys. Rev. Lett. **64**, 1495 (1990); **66**, 2683 (1991).

[20] J. Gasser and H. Leutwyler, Phys. Lett. B **253**, 252 (1991).

[21] A. V. Manohar, Phys. Rev. Lett. **65**, 2511 (1990); **66**, 289 (1991); R. Jaffe and A. V. Manohar, Nucl. Phys. **B337**, 409 (1990); G. Bodwin and R. Qiu, Phys. Rev. D **41**, 2755 (1990); U. Ellwanger and B. Stech, Phys. Lett. B **241**, 409 (1990); Z. Phys. C **49**, 683 (1991).