F/D ratio in hyperon β decays and the spin distribution in the nucleon

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It is shown that hyperon β decay data can be well accommodated within the framework of Cabibbo's SU(3) symmetric description if one allows for a small SU(3) symmetry breaking proportional to the mass difference between strange and nonstrange quarks. The F/D ratio does not depend sensitively on the exact form of the symmetry breaking, and the best fits are close to the value previously used in the analysis of deep inelastic scattering of electrons or muons on polarized nucleons. The total quark helicity and strange quark polarization in the nucleon are discussed. [S0556-2821(96)02315-6]

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I. INTRODUCTION

The spin-dependent Gamow-Teller matrix elements, for transitions between members of the baryon octet [1], acquired renewed interest after measurements were made of the deep inelastic scattering (DIS) of polarized leptons by polarized protons and neutrons [2–7], which provided valuable information about the spin structure of the nucleon. One of the most important quantities measured in polarized DIS is the longitudinal spin structure function g_1. In the quark parton model, the spin structure function g_1 is directly related to the quark spin densities $\Delta u(x)$, $\Delta d(x)$, $\Delta s(x)$, etc., where $\Delta q(x) \equiv q_\uparrow(x) - q_\downarrow(x) + \overline{q_\uparrow}(x) - \overline{q_\downarrow}(x)$.

To deduce the various quark spin densities from the g_1 data, one usually assumes that baryons may be assigned to a SU(3)-flavor octet and uses the relation between the quark spin densities and weak matrix elements F and D from hyperon semileptonic decays. By using the earlier F/D value, the European Muon Collaboration (EMC) data led to the unexpected conclusion [2] that the quarks carry at most a small part of the spin of either nucleon and, furthermore, that there is a significant contribution from ''strange'' quarks, which necessarily come from the ''sea'' of quark-antiquark pairs. This has led to many different suggestions for resolution of what has come to be called the ''spin crisis'' [8–10]. Among these is a suggestion [11,12] that the conclusions may be distorted because the F/D value obtained from the hyperon semileptonic decays are based on exact SU(3)-flavor symmetry. SU(3)-symmetry-breaking effects may significantly change the value.

There are many attempts to evaluate the SU(3)-breaking effects in the bag model or in the quark model, by applying center-of-mass corrections [13–15] or by including one-gluon exchange interactions [16,17] or both [18]. The size of the corrections depends on the model and assumptions used to describe the symmetry-breaking effects, and on the ''existing'' data to be fitted. Some authors used their own data and concluded [19] that there is no signal for the breakdown of Cabibbo's SU(3) symmetric description. According to Ref. [15], however, an overall fit to the existing data using a broken SU(3) scheme is better than that from the assumption of perfect SU(3) symmetry. Another approach, using the chiral effective Lagrangian for baryons [20], calculated SU(3)-symmetry-breaking corrections to axial vector currents of the baryon octet arising from meson loops. The size of corrections was found to be surprisingly large (the loop correction is almost as large as the lowest order result) which should already have raised suspicion. In a subsequent paper [20], including the spin-3/2 baryon decuplet in the intermediate state, the meson loop correction to the axial vector currents is significantly reduced but still substantial ($\simeq$30–50 %). However, corrections due to higher baryon resonances, which in principle should be included in the intermediate states, have been ignored in the calculation and may change the result still further. Thus it appears that the validity of Cabibbo's SU(3)-symmetric description is far from settled. Most recently, instead of model-dependent calculations, an approach [21] based on phenomenological analysis of hyperon β decay data has been suggested to estimate the SU(3)-symmetry-breaking effects. The authors present evidence for a strong variation of the F/D parameter between various transitions.

In Sec. II, we consider another approach based on a general discussion [24] of SU(3) flavor symmetry and its possible breaking and show that the hyperon β decay data are adequately represented by at most a small deviation from Cabibbo's SU(3) symmetric description, which can be well accommodated within the framework of the usual assumption of a small SU(3) breaking proportional to the mass difference between strange and nonstrange quarks. In Sec. III, the consequences for the quark spin distribution in the nucleon are discussed. A brief summary is given in Sec. IV.

II. SU(3)-SYMMETRY-BREAKING EFFECTS

In the quark model, which provides an explicit realization of Cabibbo's theory connecting strangeness-conserving and strangeness-changing weak interactions, the primary weak current responsible for transitions between hadrons is

$$j_W^\mu = \bar{q}\frac{\lambda_W}{2}\gamma^\mu(1+\gamma_5)q, \tag{1}$$

with

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$$\lambda_W = [\lambda_1 + i\lambda_2]\cos\theta_C + [\lambda_4 + i\lambda_5]\sin\theta_C,$$

where λ_i $(i = 1,2, \ldots ,8)$ denote the Gell-Mann matrices and q represents the triplet (u, d, s) of basic quark fields. Equation (1) requires that weak transition elements necessarily transform as a component of an SU(3) octet. If baryons are assigned to a SU(3) octet, represented in matrix form by

$$\frac{1}{\sqrt{2}}\sum \lambda_i B_i = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda^0 \end{pmatrix}, \tag{2}$$

the SU(3)-octet matrix elements between baryons can be written, in the symmetric limit (we are concerned only with the values for $q^2 \to 0$, i.e., zero four-momentum transfer), as

$$D\,\mathrm{Tr}(\overline{B}\{\lambda_W, B\}_+) + F\,\mathrm{Tr}(\overline{B}[\lambda_W, B]_-), \tag{3}$$

which can also be written as $a_0\mathrm{Tr}(\overline{B}B\lambda_W) + b_0\mathrm{Tr}(\overline{B}\lambda_W B)$, with $a_0 = D - F$ and $b_0 = D + F$. However, the SU(3)-flavor symmetry is only approximate for strangeness-changing processes. If SU(3)-symmetry-breaking effects cannot be ignored, the expressions for the matrix elements must be generalized.

We assume that the breaking of SU(3)-flavor symmetry is due to a term which transforms like the eighth generator of SU(3). This would be the case, for example, if SU(3) breaking arose entirely from a mass difference between strange and (degenerate [22]) nonstrange quarks. To first order in the symmetry-breaking interaction, transforming like λ_8, the most general SU(3) structure of the weak matrix elements between baryons can be written as

$$\begin{aligned} &a_0\mathrm{Tr}(\overline{B}B\lambda_W) + b_0\mathrm{Tr}(\overline{B}\lambda_W B) + a\mathrm{Tr}(\overline{B}B\{\lambda_W, \lambda_8\}_+) \\ &\quad + b\mathrm{Tr}(\overline{B}\{\lambda_W, \lambda_8\}_+ B) + d\mathrm{Tr}(\overline{B}\lambda_8\lambda_W B) \\ &\quad + k[\mathrm{Tr}(\overline{B}\lambda_W)\mathrm{Tr}(B\lambda_8) + \mathrm{Tr}(\overline{B}\lambda_8)\mathrm{Tr}(B\lambda_W)]/2, \end{aligned} \tag{4}$$

where the first two terms are the ones given in Eq. (3) and the others are SU(3)-symmetry-breaking corrections. The corresponding symmetry-breaking parameters a, b, d, and k should be small relative to a_0 and b_0 for such a perturbative expansion to be valid. Vector coupling constants are not affected to first order [23,24]. For the ratio of axial-vector to vector amplitudes, Eq. (4) yields [24]

$$(G_A/G_V)_{n\to p} = F + D + 2b, \tag{5}$$

$$(G_A/G_V)_{\Lambda\to p} = F + D/3 + a/3 - 2b/3 - d/3 - k, \tag{6}$$

$$(G_A/G_V)_{\Sigma^-\to n} = F - D + a - d, \tag{7}$$

$$(G_A/G_V)_{\Xi^-\to\Lambda} = F - D/3 + 2a/3 - b/3 + 4d/3 + k, \tag{8}$$

where we have listed only those transitions for which these ratios are relatively well measured [25]:

$$(G_A/G_V)_{n\to p} = 1.2573 \pm 0.0028, \tag{9}$$

$$(G_A/G_V)_{\Lambda\to p} = 0.718 \pm 0.015, \tag{10}$$

$$(G_A/G_V)_{\Sigma^-\to n} = -0.340 \pm 0.017, \tag{11}$$

$$(G_A/G_V)_{\Xi^-\to\Lambda} = 0.25 \pm 0.05. \tag{12}$$

Let us first discuss the SU(3)-symmetry scheme. Figure 1 exhibits the results reported in Eqs. (9)–(12) under the assumption that SU(3)-symmetry-breaking effects are negligible; viz., all breaking parameters are zero: $a = b = d = k = 0$ in Eqs. (5)–(8). We see that the (G_A/G_V) ratios for the best-measured transitions (9)–(11) yield, within the errors, a unique solution for F and D. While the line corresponding to the central value of (G_A/G_V) for the less accurately measured $\Xi^- \to \Lambda$ transition does not pass exactly through the same (F,D) point, a downward shift of $(G_A/G_V)_{\Xi^-\to\Lambda}$ by an amount equal to the quoted error is sufficient to bring it into agreement with the others. Hence it seems that no significant SU(3)-symmetry-breaking effect is needed to describe the existing (G_A/G_V) data. It is also interesting to note that the favored solution for F and D obtained from data (9)–(11) is not too different from that predicted by the static SU(6)-symmetric model with suitable relativistic recoil corrections ($\simeq$ 25% reduction [14]).

While there does not seem to be any compelling evidence demanding the inclusion of SU(3)-breaking effects, it may be worthwhile to see what is obtained if one takes the data, Eqs. (9)–(12), at face value and seeks a solution allowing any one of the symmetry-breaking parameters in Eq. (4) to be nonzero. We search in the three-dimensional space F, D, ϵ (where ϵ denotes one of four possible small symmetry-breaking parameters a, b, d, or k) to find the minimum of the quantity χ^2. The results are listed in Table I.

As expected, it takes only a small nonzero value of any of these to obtain a statistically satisfactory solution. The fifth column, with a d-type correction, shows the best agreement between the calculated and the measured (G_A/G_V) ratios, and may be the only indication that inclusion of SU(3)-breaking effects is required. The best fits under the assumption that SU(3)-symmetry breaking arises from terms of the type a or b yield values which, in view of the quoted errors, are indistinguishable from zero, i.e., do not call for any correction at all. Similarly, the evidence for nonzero k is marginal.

The averages of the results listed in Table I

$$\langle F\rangle = 0.462, \quad \langle D\rangle = 0.794, \quad \langle F/D\rangle = 0.582, \tag{13}$$

are consistent with those previously used in the analysis of deep inelastic scattering on polarized nucleons [26]:

$$F = 0.459 \pm 0.008, \quad D = 0.798 \pm 0.008,$$

$$F/D = 0.575 \pm 0.016. \tag{14}$$

For illustration, Fig. 2 shows the best fit for a k-type solution. Comparing Fig. 2 and Fig. 1, one sees that after

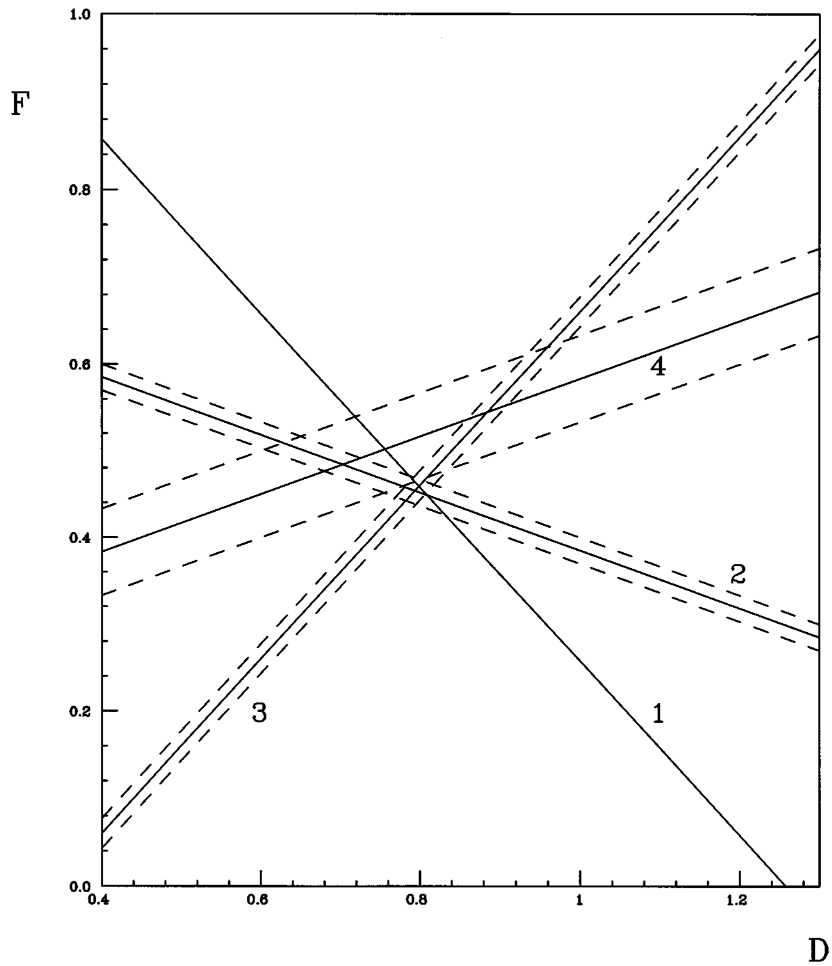

FIG. 1. $F-D$ relations determined by experimental values for various baryonic transitions, assuming no SU(3) breaking. Line 1, $n\rightarrow p$; line 2, $\Lambda\rightarrow p$; line 3, $\Sigma^-\rightarrow n$; line 4, $\Xi^-\rightarrow\Lambda$.

inclusion of SU(3)-breaking in Cabibbo's scheme, the lines corresponding to $\Lambda\rightarrow p$ and $\Sigma^-\rightarrow n$ are both slightly shifted up and the only significant change is for the line corresponding to $\Xi^-\rightarrow\Lambda$. All lines now intersect at one point which gives a unique solution of F and D for a given parameter set. A similar discussion can be made for a-, b-, and d-type solutions.

It may be noted that all SU(3)-symmetry-breaking parameters considered in this paper are significantly smaller than the SU(3)-symmetric parameters F and D. Compared to the result given in [21], our F/D value for a given symmetry-breaking parameter set is unique for the known baryon decay modes. It suggests that the entire pattern of existing hyperon semileptonic decay data can be very well described in a framework which is basically SU(3)-flavor symmetry with small SU(3)-symmetry-breaking effects. Therefore, there is no evidence of *strong* violation for SU(3) symmetry in hyperon β decay data.

III. QUARK SPIN DISTRIBUTIONS IN THE NUCLEON

As we mentioned in the Introduction, the quark spin distributions deduced from the g_1 data depend on the F/D ratio. In the QCD-corrected quark parton model, we have

TABLE I. One-parameter fit.

	$b,d,k=0$ $a=-0.0024$	$a,d,k=0$ $b=0.0027$	$a,b,d=0$ $k=0.0123$	$a,b,k=0$ $d=0.0297$	Data [25]
F	0.4581	0.4576	0.4610	0.4721	
D	0.7992	0.7943	0.7963	0.7852	
F/D	0.573	0.576	0.579	0.601	
$(G_A/G_V)_{n\rightarrow p}$	1.2573	1.2573	1.2573	1.2573	1.2573 ± 0.0028
$(G_A/G_V)_{\Lambda\rightarrow p}$	0.723	0.721	0.714	0.724	0.718 ± 0.015
$(G_A/G_V)_{\Sigma^-\rightarrow n}$	-0.343	-0.337	-0.335	-0.343	-0.340 ± 0.017
$(G_A/G_V)_{\Xi^-\rightarrow\Lambda}$	0.190	0.192	0.208	0.250	0.25 ± 0.05
χ^2	1.61	1.42	0.86	0.20	

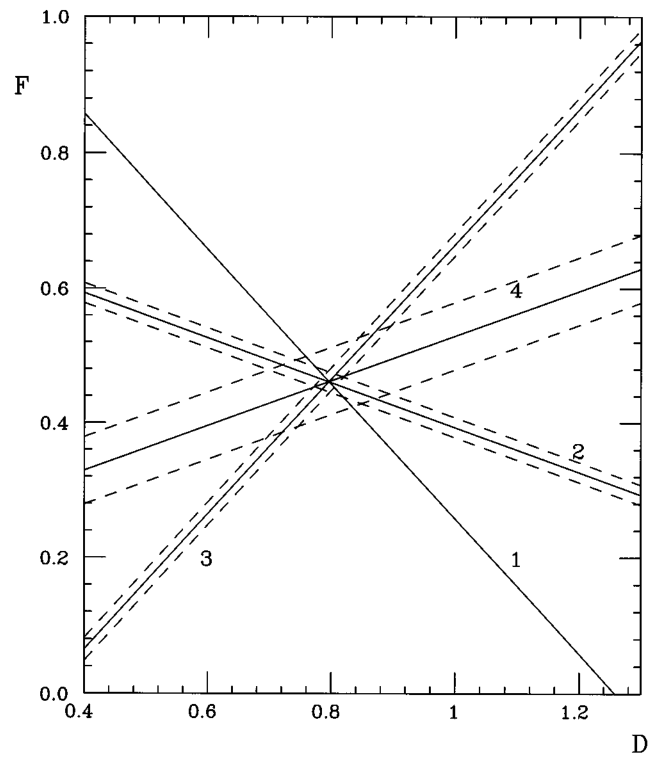

FIG. 2. $F-D$ relations, as in Fig. 1, allowing for k-type SU(3) breaking with $k=0.0123$. Line 1, $F+D=1.2573\pm0.0028$; line 2, $F+D/3+k=0.714\pm0.015$; line 3, $F-D=-0.335\pm0.017$; line 4, $F-D/3-k=0.208\pm0.050$.

$$\Gamma_1^p \equiv \int_0^1 g_1^p(x)dx = \frac{C_{\rm NS}}{18}[2\Delta u - \Delta d - \Delta s] + \frac{C_S}{9}\Delta\Sigma, \tag{15}$$

where $\Delta u = \int_0^1 \Delta u(x)dx$ and $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ represents the fraction of the proton spin carried by all the quarks and antiquarks, i.e., the net total quark helicity, and where $C_{\rm NS}=1-y-3.5833y^2-20.2133y^3-O(130)y^4$ and $C_S=1-y/3-0.5495y^2-O(2)y^3$, with $y\equiv\alpha_s/\pi$, are QCD correction coefficients for nonsinglet and singlet terms [27]. To simplify the notation, we have omitted the variable Q^2 in the quantities listed above. It should be noted that the anomalous gluon contributions [28] and higher twist effects [29] are not included in (15). The magnitude of the former is still a subject of debate and the latter is expected to be only a small correction except at the low Q^2 value (for example, the E142 Γ_1^n data). Combining Eq. (15) and the two relations

$$\left(\frac{G_A}{G_V}\right)_{n\to p} = F + D = \Delta u - \Delta d, \tag{16}$$

$$(G_A/G_V)_{\Sigma^-\to n} = F - D = \Delta d - \Delta s, \tag{17}$$

one obtains

$$\Gamma_1^{p(n)} = \frac{C_{\rm NS}}{12}(G_A/G_V)_{n\to p}\left[+(-)1 + \frac{R-1/3}{R+1}\right] + \frac{C_S}{9}\Delta\Sigma; \tag{18}$$

hence, the data $\Delta\Sigma$ and Δs deduced from Γ_1^p depend on F/D value used as input in Eq. (18).

Using $(G_A/G_V)_{n\to p}=1.254\pm0.006$, $F/D=0.632\pm0.062$, and $\alpha_s=0.27$ the EMC data [2] $(\Gamma_1^p)_{\rm expt}=0.126\pm0.018$ led to

$$\Delta\Sigma = 0.12\pm0.17, \quad \Delta s = -0.19\pm0.06. \tag{19}$$

However, if instead, using $\langle F/D\rangle = 0.582\pm0.008$ and the same $C_{\rm NS}=1-\alpha_s/\pi$ and $C_S=1-\alpha_s/3\pi$ as used in the EMC analysis [2], one obtains

$$\Delta\Sigma = 0.14\pm0.17, \quad \Delta s = -0.15\pm0.06. \tag{20}$$

One can see that by using a smaller $\langle F/D\rangle$ value, $\Delta\Sigma$ increases and the magnitude of Δs decreases. However, in contrast with the change of Δs, the total quark helicity $\Delta\Sigma$ is not sensitive to $\langle F/D\rangle$. This is consistent with the result given by Lipkin and Lichtenstadt [30]. On the other hand, if we use $C_{\rm NS}$ up to $(\alpha_s/\pi)^4$ and C_S up to $(\alpha_s/\pi)^3$ as given in [27], then (20) becomes

$$\Delta\Sigma = 0.19\pm0.17, \quad \Delta s = -0.13\pm0.06. \tag{21}$$

Comparing Eq. (21) with Eq. (20), one sees that $\Delta\Sigma$ significantly increases after inclusion of higher order QCD radiative corrections, which are very important in spin analysis, especially at the moderate Q^2 range where the experiments were performed.

Most recently, the E143 group obtained more accurate data of g_1^p which give $\Gamma_1^p=0.125\pm0.003$ [31] with $\alpha_s=0.35$. From this, one obtains

$$\Delta\Sigma = 0.27\pm0.04, \quad \Delta s = -0.10\pm0.02. \tag{22}$$

The difference between the central values of $\Delta\Sigma$ (and Δs) in Eq. (22) and in Eq. (21) is due to the fact that the data are taken at different Q^2 and they have different QCD correction coefficients $C_{\rm NS}(Q^2)$ and $C_S(Q^2)$. In obtaining Eq. (22), $\alpha_s=0.35$ has been used, but for Eq. (21) $\alpha_s=0.27$ was used. However, considering that the errors in Eq. (21) are quite large, the results given in Eqs. (22) and (21) are consistent within the errors.

To avoid possible ambiguity caused by SU(3)-symmetry-breaking effects, we may choose to only use the SU(2)-symmetry result (16) and do not use Eq. (17). From Eqs. (15) and (16), one can obtain a relation between $\Delta\Sigma$ and Δs,

$$c_1\Delta\Sigma - c_2\Delta s = \Gamma_1^p - c_3 \tag{23}$$

for the proton and, similarly,

$$c_1\Delta\Sigma - c_2\Delta s = \Gamma_1^n + c_3 \tag{24}$$

for the neutron, where

$$c_1 = \frac{C_{\rm NS}+4C_S}{36}, \quad c_2 = \frac{C_S}{12}, \quad c_3 = c_2\left(\frac{G_A}{G_V}\right)_{n\to p}. \tag{25}$$

Actually, Eqs. (23) and (24) are not independent, because the Bjorken sum rule

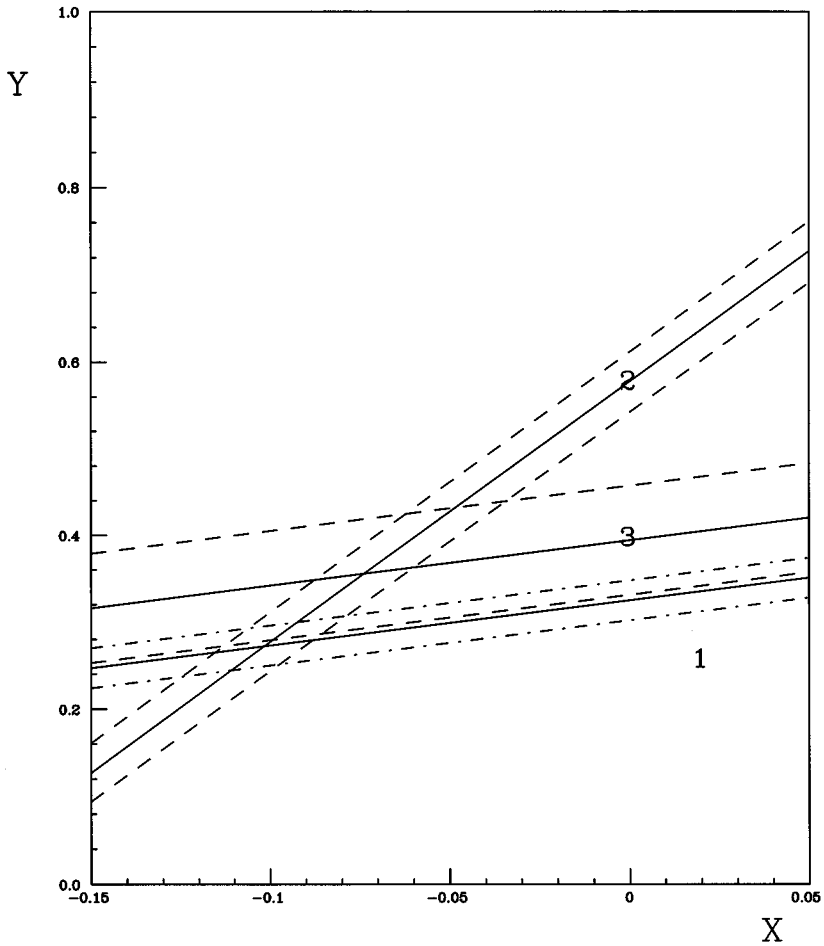

FIG. 3. Plot of total quark helicity $Y \equiv \Delta\Sigma$ and strange quark polarization $X \equiv \Delta s$ constrained by the E143 proton data [line 1, Eq. (28)], neutron data [line 3, Eq. (29)], and SU(3)-symmetry relation [line 2, Eq. (30)].

$$\Gamma_1^p - \Gamma_1^n = 2c_3 = \frac{C_S}{6}\left(\frac{G_A}{G_V}\right)_{n\to p}. \tag{26}$$

Therefore one cannot deduce the $\Delta\Sigma$ and Δs separately, even though we have both g_1^p and g_1^n data. It should be noted that the data Γ_1^p and Γ_1^n from the experimental measurements may not satisfy Eq. (26). Hence the right-hand side (RHS) of Eq. (23) can be different from that of Eq. (24).

To obtain $\Delta\Sigma$ and Δs separately, we need another relation between these two quantities. This can be obtained from Eqs. (16) and (17):

$$\Delta\Sigma - 3\Delta s = \left(\frac{G_A}{G_V}\right)_{n\to p} + 2\left(\frac{G_A}{G_V}\right)_{\Sigma^- \to n}. \tag{27}$$

Using most recent E143 data $\Gamma_1^p = 0.125 \pm 0.003$ and $\Gamma_1^n = -0.033 \pm 0.008$ [31], one obtains, from Eqs. (23) and (24),

$$\Delta\Sigma - 0.518\Delta s = 0.325 \pm 0.023 \quad E143 \text{ proton data}, \tag{28}$$

and

$$\Delta\Sigma - 0.518\Delta s = 0.394 \pm 0.063 \quad E143 \text{ neutron data}. \tag{29}$$

They are shown in Fig. 3 (line 1 for E143 proton data and line 3 for E143 neutron data, where $Y \equiv \Delta\Sigma$ and $X \equiv \Delta s$). If we assume that there is no strange quark polarization, $\Delta s = 0$ as predicted by the naive quark model, then $\Delta\Sigma = 0.33 \pm 0.02$ from the proton data and $\Delta\Sigma = 0.39 \pm 0.06$ from the neutron data. They are consistent within the errors (see line 1 and line 3 in Fig. 3). However, using the SU(3)-symmetry result, Eq. (27), and combining data (9) and (11), one obtains

$$\Delta\Sigma - 3\Delta s = 0.577 \pm 0.034, \tag{30}$$

which is also shown in Fig. 3 (line 2). One can see that the strange quark polarization would be negative. From Fig. 3, one obtains that the range of Δs would be

$$\Delta s = -0.12 \text{ to } -0.04 \tag{31}$$

if SU(3)-symmetry is imposed. We note that our Fig. 3 is similar to Fig. 4 in [32].

It should be noted that if one can trust the earlier ν-p and $\overline{\nu}$-p elastic scattering data, $\Delta s = -0.15 \pm 0.09$ [33–34] (which give $\Delta\Sigma \simeq 0.19$ for E143 proton data and $\Delta\Sigma \simeq 0.32$ for E143 neutron data), then the SU(3)-symmetry relation (30) is not necessary. From the results given above, one can see that combining the most recent deep inelastic lepton-nucleon scattering data and the F/D ratio deduced from the hyperon β decays, the total net quark contribution to the proton spin is still far from the naive quark model prediction and also the strange quark polarization is nonzero and negative (one of the most recent reviews on this subject is given in [35]).

IV. SUMMARY

From a general discussion of SU(3) symmetry and its breaking, we show that the hyperon β decay data can be well accommodated within the framework of the usual Cabibbo's SU(3)-symmetric description with a small SU(3)- symmetry breaking proportional to the mass difference between strange and nonstrange quarks. The F/D ratio is not far from the value previously used in the deep inelastic scattering analysis. Hence the result given by using SU(3) symmetry on hyperon β decays will not be significantly affected by SU(3)-symmetry-breaking effects. It implies that the total quark helicity is still far below naive quark model expectation and the strange quark polarization seems to be negative if one neglects the anomalous gluon contributions and higher twist effects.

After completion of this work, we have seen a paper by Ratcliffe [36] which reached a similar conclusion about SU(3) breaking.

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[1] For an earlier review, see J.- M. Gaillard and G. Sauvage, Ann. Phys. Nucl. Part. Sci. **34**, 351 (1984).
[2] J. Ashman *et al.*, Phys. Lett. B **206**, 364 (1988); Nucl. Phys. **B328**, 1 (1989).
[3] EMC Collaboration, B. Adeva *et al.*, Phys. Lett. B **302**, 534 (1993).
[4] B. Adeva *et al.*, Phys. Lett. B **302**, 553 (1993); **320**, 400 (1994); D. Adams *et al.*, *ibid.* **329**, 399 (1994); **336**, 125 (1994).
[5] P. L. Anthony *et al.*, Phys. Rev. Lett. **71**, 959 (1993).
[6] K. Abe *et al.*, Phys. Rev. Lett. **74**, 346 (1995); **75**, 25 (1995).
[7] E143 Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **76**, 587 (1996).
[8] M. Anselmino, A. Efremov, and E. Leader, Phys. Rep. **261**, 1 (1995).
[9] R. L. Jaffe, Phys. Today **48** (9), 24 (1995).
[10] F. E. Close, Report No. hep-ph/9509251, 1995 (unpublished).
[11] H. Lipkin, Phys. Lett. B **230**, 135 (1989).
[12] A. Schafer, Phys. Lett. B **208**, 175 (1988).
[13] J. Bartelski *et al.*, Phys. Rev. D **29**, 1035 (1984).
[14] M. Beyer and S. K. Singh, Z. Phys. C **31**, 421 (1986).
[15] J. F. Donoghue, B. R. Holstein, and S. W. Klimt, Phys. Rev. D **35**, 934 (1987).
[16] H. Høgaasen and F. Myhrer, Phys. Rev. D **37**, 1950 (1988).
[17] L. J. Carlson, R. J. Oakes, and C. R. Willcox, Phys. Rev. D **37**, 3197 (1988).
[18] T. Yamguchi, K. Tsushima, Y. Kohyama, and K. Kubodera, Nucl. Phys. **A500**, 429 (1989).
[19] M. Bouquin *et al.*, Z. Phys. C **12**, 307 (1982); **21**, 1 (1983); **21**, 17 (1983).
[20] E. Jenkins and A. V. Manohar, Phys. Lett. B **255**, 558 (1991); **259**, 353 (1991).
[21] E. Ehrnsberger and A. Schafer, Phys. Lett. B **348**, 619 (1995).
[22] For a discussion of isospin-breaking effects from the mass difference between up and down quarks and electromagnetic interactions, see G. Karl, Phys. Lett. B **328**, 149 (1994).
[23] R. E. Behrend and A. Sirlin, Phys. Rev. Lett. **4**, 186 (1960).
[24] M. Ademollo and R. Gatto, Phys. Rev. Lett. **13**, 264 (1964).
[25] Particle Data Group, L. Montanet *et al.*, Phys. Rev. D **50**, 1173 (1994)
[26] F. E. Close and R. G. Roberts, Phys. Lett. B **316**, 165 (1993).
[27] S. A. Larin, Phys. Lett. B **334**, 192 (1994).
[28] G. Altarelli and G. Ross, Phys. Lett. B **212**, 391 (1988); A. V. Efremov and O. V. Teryaev, Dubna Report No. JINR-E2-88-287, 1988 (unpublished); R. D. Carlitz, J. D. Collins, and A. H. Mueller, Phys. Lett. B **214**, 229 (1988).
[29] G. G. Ross and R. G. Roberts, Phys. Lett. B **322**, 425 (1994); E. Stein, P. Gornicki, L. Mankiewicz, and A.Schafer, *ibid.* **343**, 369 (1995); **353**, 107 (1995).
[30] H. J. Lipkin, Phys. Lett. B **337**, 157 (1994); J. Lichtenstadt and H. J. Lipkin, *ibid.* **353**, 119 (1995).
[31] T. J. Liu, Ph.D. thesis, University of Virginia, 1995.
[32] J. Ellis and M. Karliner, Phys. Lett. B **313**, 131 (1993).
[33] L. H. Ahrens *et al.*, Phys. Rev. D **35**, 785 (1987).
[34] D. Kaplan and A. Manobar, Nucl. Phys. B **310**, 527 (1988); J. Ellis and M. Karliner, Phys. Lett. B **213**, 73 (1988).
[35] J. Ellis and M. Karliner, Invited lectures at the International School of Nucleon Spin Structure, Erice, August 1995, Report No. hep-ph/9601280, and reference therein (unpublished).
[36] P. G. Ratcliffe, Phys. Lett. B **365**, 383 (1996).