Evidence for SU(3) symmetry breaking from hyperon production

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We examine the SU(3) symmetry breaking in hyperon semileptonic decays (HSD) by considering two typical sets of quark contributions to the spin content of the octet baryons: set 1 with SU(3) flavor symmetry and set 2 with SU(3) flavor symmetry breaking in the HSD. The quark distributions of the octet baryons are calculated with a successful statistical model. Using an approximate relation between the quark fragmentation functions and the quark distributions, we predict the polarizations of the octet baryons produced in e^+e^- annihilation and semi-inclusive deep lepton-nucleon scattering in order to reveal the SU(3) symmetry breaking effect on the spin structure of the octet baryons. We find that the SU(3) symmetry breaking significantly affects the hyperon polarization. The available experimental data on the Λ polarization seem to favor the theoretical predictions with SU(3) symmetry breaking. We conclude that there is a possibility to get collateral evidence for SU(3) symmetry breaking from hyperon production. The theoretical errors for our predictions are discussed.

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I. INTRODUCTION

Proton spin has remained an interesting problem for more than one decade. The quark-spin content of the nucleon is usually extracted according to the data on polarized deep inelastic lepton-nucleon scattering and hyperon semileptonic decays (HSD) with the SU(3) flavor symmetry assumption. However, some current analyses have shown that the effect of SU(3) symmetry breaking in HSD on the quark-spin content of the octet baryons is significant [1–3]. The effect has been estimated by the chiral quark soliton model [1] and large N_c QCD [2]. Consistent results were obtained separately by different approaches. However, there is a lack of external evidence for the SU(3) symmetry breaking. In order to view the SU(3) flavor symmetry breaking effect as a whole, we should broaden our vision from the nucleon to all octet baryons since the effect is related to the octet hyperon semileptonic decays. Hyperon production is a very important source from which we can get information on the spin properties of the octet hyperons. The Λ hyperon is of special interest in this respect since its decay is self-analyzing with respect to its spin direction due to the dominant weak decay $\Lambda \to p\pi^-$ and the particularly large asymmetry of the angular distribution of the decay proton in the Λ rest frame. So polarization measurements are relatively simple to perform and the polarized fragmentation functions of quarks to the Λ can be measured. Also, the fragmentation of quarks to Σ and Ξ hyperons can be investigated experimentally since the detection technique for Σ and Ξ hyperons is gradually maturing and will allow measurement of various quark to hyperon fragmentation functions [4–6]. On the other hand, recent investigations indicate that the quark fragmentation functions seem to have a relation to the corresponding quark distributions via an approximate relation [7]. Thus, it is of great significance to examine the influence of the SU(3) symmetry breaking on the spin properties of the octet hyperons from fragmentation.

Based on the known experimental data of HSD constants and the first moment of the spin structure function of the proton in deep inelastic scattering (DIS), we can extract the quark contributions to the spin content of the octet baryons. In order to obtain the quark distributions of the octet baryons, we need some theoretical models. The quark distributions of the nucleon have been precisely measured by a combination of various deep inelastic scattering processes [8] and Drell-Yan processes [9]. With decades of experiments, our knowledge of the quark distributions for the nucleon is more or less clear concerning the bulk features of momentum, flavor, and helicity distributions. For the other octet baryons, we can predict the quark distributions only by means of some successful models that produce the quark structure of the nucleon. Recently, a statistical model for polarized and unpolarized parton distributions of the nucleon has been presented by Bhalerao *et al.* [10]. The model can reproduce almost all the data on the nucleon structure functions $F_2^p(x,Q^2)$, $F_2^p(x)-F_2^n(x)$ and the parton sum rules. We find that the model is suitable for studying the SU(3) symmetry breaking effect on the quark spin properties of octet baryons since quark contributions to the spin content are important inputs of the model. According to some constraints, we determine two typical sets of parton density functions (PDFs) for the octet baryons at an initial scale: set 1 with SU(3) flavor symmetry and set 2 with SU(3) flavor symmetry breaking in HSD. Then we relate the PDFs to fragmentation functions at the initial scale by using an approximate relation between the quark distributions and the fragmentation functions. Finally, we employ the two sets of fragmentation functions evolved to predict octet baryon polarizations in e^+e^- annihilation, polarized charged lepton DIS, and neutrino DIS in order to reveal the influence of SU(3) symmetry breaking on baryon production.

The paper is arranged as follows. In Sec. II, we will re-extract the quark contributions to the spin content of the octet baryons based on some known experimental data in

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order to obtain reasonable central values for them. In Sec. III we present the quark spin structure of all octet baryons based on a successful statistical model at an initial scale. In Sec. IV, we relate the fragmentation functions to the corresponding quark distributions and evolve them to a higher energy scale. Then, we predict spin observables for the octet baryons produced in e^+e^- annihilation, charged lepton DIS, and neutrino DIS. We find that one can get possible collateral evidence for SU(3) symmetry breaking from hyperon production. A brief summary with some discussion of the theoretical uncertainties is given in Sec. V.

II. QUARK CONTRIBUTIONS TO SPIN CONTENT OF OCTET BARYONS

The standard way to determine quark contributions to the spin content of a baryon in the $J^P=\frac{1}{2}$ octet is based on two pieces of information. One comes from the first moment of the spin structure function $g_1^p(x)$ of the proton:

$$I_p=\int_0^1 g_1^p(x)dx=\frac{1}{18}(4\Delta U+\Delta D+\Delta S)\left(1-\frac{\alpha_s}{\pi}+\cdots\right), \tag{1}$$

which is obtained in deep inelastic lepton-proton scattering experiments. According to the experimental data for I_p [11], one has

$$\Gamma_p=4\Delta U+\Delta D+\Delta S=2.42\pm 0.26. \tag{2}$$

Another piece of information comes from the hyperon semileptonic decay constants F and D which are usually obtained from the empirical values for the ratios of the axial-vector to vector coupling constants g_A/g_V via

$$(g_A/g_V)^{(n\to p)}=F+D, \quad (g_A/g_V)^{(\Sigma^-\to n)}=F-D \tag{3}$$

with exact flavor SU(3) symmetry. However, there are some uncertainties in the analysis since F and D can also be obtained by combining any other two ratios of axial-vector to vector coupling constants g_A/g_V of six known weak semileptonic decays [12,13]. With various combinations, it is found that there exist large uncertainties in the central values of F and D as follows:

$$F=0.40\text{–}0.55, \quad D=0.70\text{–}0.89, \tag{4}$$

which shows that the theoretical error due to using the exact SU(3) symmetry in describing the hyperon semileptonic decays is about 15%. Thus, the obtained quark spin content of the proton $\Delta\Sigma=\Delta U+\Delta D+\Delta S$ based on the constants F and D can be any value in the range [0.02,0.30], which implies that SU(3) symmetry breaking plays an essential role in extracting $\Delta\Sigma$ from the experimental data. For this reason, the SU(3) symmetry breaking effect has recently been considered in the chiral quark soliton model and large N_c QCD. The same algebraic structure of the ratios of axial-vector to vector coupling constants for known weak semileptonic decays with dynamical parameters was obtained by two different approaches [1,2]. In order to obtain model independent results, one can fix the dynamical parameters by fitting them to the data for the known six weak semileptonic decays instead of calculating them within a specified model. The quark contributions ΔQ $(Q=U,D,S)$ to the spin content of the octet baryons given by Kim *et al.* [3] in this way are listed in Table I.

TABLE I. ΔQ in the broken SU(3) analysis of Ref. [3].

Baryon	ΔU	ΔD	ΔS
p	0.72 ± 0.07	-0.54 ± 0.07	0.33 ± 0.51
n	-0.54 ± 0.07	0.72 ± 0.07	0.33 ± 0.51
Σ^+	0.73 ± 0.17	-0.37 ± 0.19	-0.18 ± 0.39
Σ^0	0.18 ± 0.08	0.18 ± 0.08	-0.18 ± 0.39
Σ^-	-0.37 ± 0.19	0.73 ± 0.17	-0.18 ± 0.39
Λ^0	-0.02 ± 0.17	-0.02 ± 0.17	1.21 ± 0.54
Ξ^-	0.02 ± 0.16	-0.14 ± 0.21	1.50 ± 0.60
Ξ^0	-0.14 ± 0.21	0.02 ± 0.16	1.50 ± 0.60

One can see from Table I that the results have very big errors and some of their central values are beyond the physics region although they could be meaningful with their errors. The central values of the total quark spin content of the Λ and Ξ hyperons are larger than 1. In addition, the quark spin content $\Delta\Sigma=0.51$ of the nucleon is out of the range [0.02,0.3] which corresponds to different combinations of the known six semileptonic decay constants. The large errors in the results are mainly due to a very large experimental error in the data for the $\Xi^-\to\Sigma^0$ decay. In order to improve the central values of the quark contributions to the spin content, we redo the analysis by adopting the data for the first moment I_p of the proton spin structure function g_1^p instead of using the data for the $\Xi^-\to\Sigma^0$ decay, since our knowledge of g_1^p seems to be a little better than that of $(g_A/g_V)^{(\Xi^-\to\Sigma^0)}$. Following Ref. [3], we can express the ratios of axial-vector to vector coupling constants for five semileptonic decays and Γ_p as

$$A_1=(g_A/g_V)^{(n\to p)}=-14r+2s-44x-20y-4z+8q, \tag{5}$$

$$A_2=(g_A/g_V)^{(\Sigma^+\to\Lambda)}=-9r-3s-42x-6y+15q, \tag{6}$$

$$A_3=(g_A/g_V)^{(\Lambda\to p)}=-8r+4s+24x-2z-6q, \tag{7}$$

$$A_4=(g_A/g_V)^{(\Sigma^-\to n)}=4r+8s-4x-4y+2z+4q, \tag{8}$$

$$A_5=(g_A/g_V)^{(\Xi^-\to\Lambda)}=-2r+6s-6x+6y-2z+6q, \tag{9}$$

$$\Gamma_p=-24r+132s-48x-66y+6z+48q, \tag{10}$$

where r, s, x, y, z, and q are dynamical parameters within the chiral quark model. We can fix these parameters by solving the above set of equations with the central values of the experimental data [11–13]. The six parameters are found to be $x=0.00035405$, $s=0.00398698$, $y=0.00006039$, q

$=0.00214004$, $z=-0.02560072$, and $r=-0.08189920$. With the obtained parameters, we find

$$(g_A/g_V)^{(\Xi^-\rightarrow\Sigma^0)}=-14r+2s+22x+10y+2z-4q=1.103, \tag{11}$$

which is close to the experimental value 1.278 ± 0.158. With our new set of parameters, quark contributions to the spin content of the octet baryons as listed in Table I are in the physical region. In addition, the total spin contribution $\Delta\Sigma=0.08$ for the nucleon is in the interval $[0.02,0.3]$ which covers the range obtained by different combinations of the known six semileptonic decay constants. All of these facts indicate that the central values of the quark contributions to the spin content of the octet baryons obtained above are reasonable. Based on them, we will do further analysis of the SU(3) symmetry breaking effect in HSD.

III. QUARK DISTRIBUTIONS OF OCTET BARYONS

We have a large amount of data to constrain the shape of the quark distributions of the nucleon and check various theoretical models for the quark distributions. Starting from the SU(6) quark model wave function of the nucleon, the quark diquark spectator model [14,15] can give the shape of the valence quark distributions. The nonperturbative effects such as gluon exchanges can be effectively described by introducing mass differences in the constituent quarks and the diquark spectators. On the other hand, in consideration of the minimally connected tree graphs of hard gluon exchange, it was found that the behavior of quark distributions at large Bjorken x obeys some counting rules [16] and has a "helicity retention" property [17]. Furthermore, it has recently been found that the input-scale parton densities in the nucleon may be quasistatistical in nature [18–20]. With a statistical model, a vast body of polarized and unpolarized nucleon structure functions can be well described [10] even including the proper $\overline{d}-\overline{u}$ to explain the Gottfried sum rule. The above three models predict different ratios $d(x)/u(x)$ for the nucleon,

$$\left(\frac{d(x)}{u(x)}\right)_{diquark}\rightarrow 0,$$

$$\left(\frac{d(x)}{u(x)}\right)_{PQCD}\rightarrow \frac{1}{5},$$

$$\left(\frac{d(x)}{u(x)}\right)_{statistical}\rightarrow 0.22.$$

It is interesting that the ratio $d(x)/u(x)|_{x\rightarrow 1}=0.22$ predicted by the statistical model is very close to the perturbative QCD (PQCD) prediction. The most recent analysis [21,22] of experimental data for several processes seems to support the PQCD and statistical predictions for the unpolarized quark flavor structure of the nucleon at $x\rightarrow 1$. In addition, there are fewer free parameters in the statistical model than in the PQCD based analysis. All this motivates us to extend the statistical model from the nucleon to the octet hyperons.

Following Ref. [10], the parton number density dn^{IMF}/dx in the infinite-momentum frame (IMF) can be related to the density dn/dE in the octet baryon B rest frame by

$$\frac{dn^{IMF}}{dx}=\frac{M_B^2 x}{2}\int_{xM_B/2}^{M_B/2}\frac{dE}{E^2}\,\frac{dn}{dE}, \tag{12}$$

where M_B is the mass of the baryon B and E is the parton energy in the baryon rest frame. It should be pointed out that Eq. (12) is an assumption even for massless quarks since it assumes that quarks can be boosted using a purely kinematic transformation, which is in general not true in an interacting theory, especially not in a strongly interacting theory such as QCD. However, the reasonableness of the model has been tested by its successful application to the prediction of quark distributions of the nucleon. Extending the model from the nucleon to other members of the octet can provide an independent check of the same mechanism that produces the flavor and spin structure of the nucleon and enrich our knowledge of the nucleon.

In consideration of the finite size effect of the baryon, dn/dE can be expressed as the sum of volume, surface, and curvature terms,

$$dn/dE=gf(E)(VE^2/2\pi^2+aR^2E+bR), \tag{13}$$

with the usual Fermi or Bose distribution function $f(E)=1/[e^{(E-\mu)/T}\pm 1]$. In Eq. (13), g is the spin-color degeneracy factor, V is the baryon volume, and R is the radius of a sphere with volume V. The parameters a and b in Eq. (13) have been determined by fitting the structure function data for the proton. We choose the same values of them for other octet baryons, i.e., $a=-0.376$ and $b=0.504$. Then, $n_{q(\overline{q})}^{\uparrow(\downarrow)}$, which denotes the number of quarks (antiquarks) with spin parallel (antiparallel) to the baryon spin can be written as

$$n_{q(\overline{q})}^{\uparrow(\downarrow)}=g\int_0^{M_B/2}\frac{VE^2/2\pi^2+aR^2E+bR}{e^{(E-\mu_{q(\overline{q})}^{\uparrow(\downarrow)})/T}+1}dE. \tag{14}$$

Similarly, the momentum fractions carried by the quark q (antiquark $\overline{q}$) and gluon G can be expressed as

$$M_{q(\overline{q})}^{\uparrow(\downarrow)}=\frac{4g}{3M_B}\int_0^{M_B/2}\frac{E(VE^2/2\pi^2+aR^2E+bR)}{e^{(E-\mu_{q(\overline{q})}^{\uparrow(\downarrow)})/T}+1}dE, \tag{15}$$

$$M_G^{\uparrow(\downarrow)}=\frac{4g}{3M_B}\int_0^{M_B/2}\frac{E(VE^2/2\pi^2+aR^2E+bR)}{e^{(E-\mu_G^{\uparrow(\downarrow)})/T}-1}dE. \tag{16}$$

Hence, the quark numbers and the parton momentum fractions have to satisfy the following seven constraints:

TABLE II. Chemical potentials (μ) and temperature (T) (in MeV) for set 1 ΔQ.

Baryon	ΔU	ΔD	ΔS	$\Delta\Sigma$	$\mu_u^\uparrow$	$\mu_u^\downarrow$	$\mu_d^\uparrow$	$\mu_d^\downarrow$	$\mu_s^\uparrow$	$\mu_s^\downarrow$	T
p	0.82	−0.44	−0.10	0.28	209.6	87.0	41.0	106.6	−7.3	7.3	62.2
n	−0.44	0.82	−0.10	0.28	41.0	106.6	209.5	87.0	−7.3	7.3	62.3
Σ^+	0.82	−0.10	−0.44	0.28	203.7	86.3	−7.3	7.3	40.9	105.4	71.6
Σ^0	0.36	0.36	−0.44	0.28	99.0	46.6	99.0	46.6	40.8	104.9	76.4
Σ^-	−0.10	0.82	−0.44	0.28	−7.3	7.3	203.5	86.3	40.9	105.4	71.9
Λ^0	−0.17	−0.17	0.62	0.28	60.7	85.6	60.7	85.6	118.5	27.7	74.0
Ξ^-	−0.10	−0.44	0.82	0.28	−7.3	7.3	40.7	104.6	201.1	85.8	75.9
Ξ^0	−0.44	−0.10	0.82	0.28	40.7	104.7	−7.3	7.3	201.2	85.8	75.7

$$n_q^\uparrow + n_q^\downarrow - n_{\bar{q}}^\uparrow - n_{\bar{q}}^\downarrow = N_Q, \tag{17}$$

$$n_q^\uparrow - n_q^\downarrow + n_{\bar{q}}^\uparrow - n_{\bar{q}}^\downarrow = \Delta Q, \tag{18}$$

$$\sum_q (M_q^\uparrow + M_q^\downarrow + M_{\bar{q}}^\uparrow + M_{\bar{q}}^\downarrow) + (M_G^\uparrow + M_G^\downarrow) = 1, \tag{19}$$

where $q = u$, d, and s. N_Q is the quark number of the baryon B. In order to describe the spin structure of the baryon, it is necessary to distinguish between $\mu_{q(\bar{q})}^\uparrow$ and $\mu_{q(\bar{q})}^\downarrow$. We assume that the gluon is not polarized at the initial scale and hence $\mu_G^\uparrow = \mu_G^\downarrow = 0$. Thus at the input scale $\Delta G(x) = 0$ and the gluon polarization comes from QCD evolution. In addition, it has been noticed that $\mu_{\bar{q}}^\uparrow = -\mu_q^\downarrow$ and $\mu_{\bar{q}}^\downarrow = -\mu_q^\uparrow$ [10]. Therefore, by solving seven coupled nonlinear equations (17)–(19), we can determine seven unknowns, namely, $\mu_u^\uparrow$, $\mu_u^\downarrow$, $\mu_d^\uparrow$, $\mu_d^\downarrow$, $\mu_s^\uparrow$, $\mu_s^\downarrow$, and T. For Λ and Σ^0, the seven equations reduce to five since the u and d quarks in these two hyperons are expected to be equal due to isospin symmetry.

The important inputs for the statistical model are the quark contributions to the spin content of the baryon. We have noticed that the SU(3) flavor symmetry breaking in HSD has a significant effect on the extraction of the quark contribution ΔQ to the spin of the octet baryons. In order to check the effect of SU(3) symmetry breaking, we adopt two sets of typical ΔQ: set 1 corresponds to the SU(3) symmetry case with the same $\Delta\Sigma = 0.28$ for all octet baryons [23]; set 2 corresponds to the SU(3) broken case with ΔQ obtained in the last section. The corresponding solutions of $\mu_q^\uparrow$, $\mu_q^\downarrow$ ($q = u$, d, s), and T for set 1 and set 2 ΔQ's are listed in Table II and Table III, respectively. With these values of the chemical potentials and temperature, the unpolarized and polarized parton distributions in the octet baryons can be obtained directly from Eq. (12).

We find that the SU(3) symmetry breaking effect on the quark spin structures of the octet hyperons is significant. Therefore, the octet hyperons are suitable laboratories to examine SU(3) symmetry breaking in HSD.

IV. OCTET BARYON POLARIZATIONS FROM FRAGMENTATION

Unfortunately, we cannot check the SU(3) symmetry breaking effect on the obtained quark distributions of the octet hyperons by means of structure functions in DIS scattering since they cannot be used as a target due to their short lifetimes. Also one obviously cannot produce a beam of charge-neutral hyperons such as Λ. For this reason, some efforts have been made to model fragmentation functions for the Λ [24–26]. On the other hand, there have been attempts to connect the quark distributions with the quark fragmentation functions, so that one can explore the quark structure of hyperons by means of hyperon production from quark fragmentation. The connection is the so called Gribov-Lipatov (GL) relation [7]

$$D_q^h(z) \sim z q_h(z), \tag{20}$$

where $D_q^h(z)$ is the fragmentation function for a quark q splitting into a hadron h with longitudinal momentum fraction z, and $q_h(z)$ is the quark distribution for finding the quark q carrying a momentum fraction $x = z$ inside the had-

TABLE III. Chemical potentials (μ) and temperature (T) (in MeV) for set 2 ΔQ.

Baryon	ΔU	ΔD	ΔS	$\Delta\Sigma$	$\mu_u^\uparrow$	$\mu_u^\downarrow$	$\mu_d^\uparrow$	$\mu_d^\downarrow$	$\mu_s^\uparrow$	$\mu_s^\downarrow$	T
p	0.78	−0.48	−0.22	0.08	206.7	90.0	38.1	109.6	−16.1	16.1	62.2
n	−0.48	0.78	−0.22	0.08	38.1	109.6	206.7	90.0	−16.1	16.1	62.3
Σ^+	0.56	−0.18	−0.60	−0.22	185.8	105.4	−13.1	13.1	29.2	117.1	72.0
Σ^0	0.19	0.19	−0.60	−0.22	86.7	59.0	86.7	59.0	29.1	116.4	76.4
Σ^-	−0.18	0.56	−0.60	−0.22	−13.1	13.1	185.7	105.3	29.2	117.0	72.3
Λ^0	0.03	0.03	0.65	0.71	75.3	70.9	75.3	70.9	120.7	25.6	74.1
Ξ^-	0.08	−0.13	0.91	0.86	5.8	−5.8	63.2	82.2	207.0	79.2	75.9
Ξ^0	−0.13	0.08	0.91	0.86	63.3	82.2	5.8	−5.8	207.1	79.3	75.7

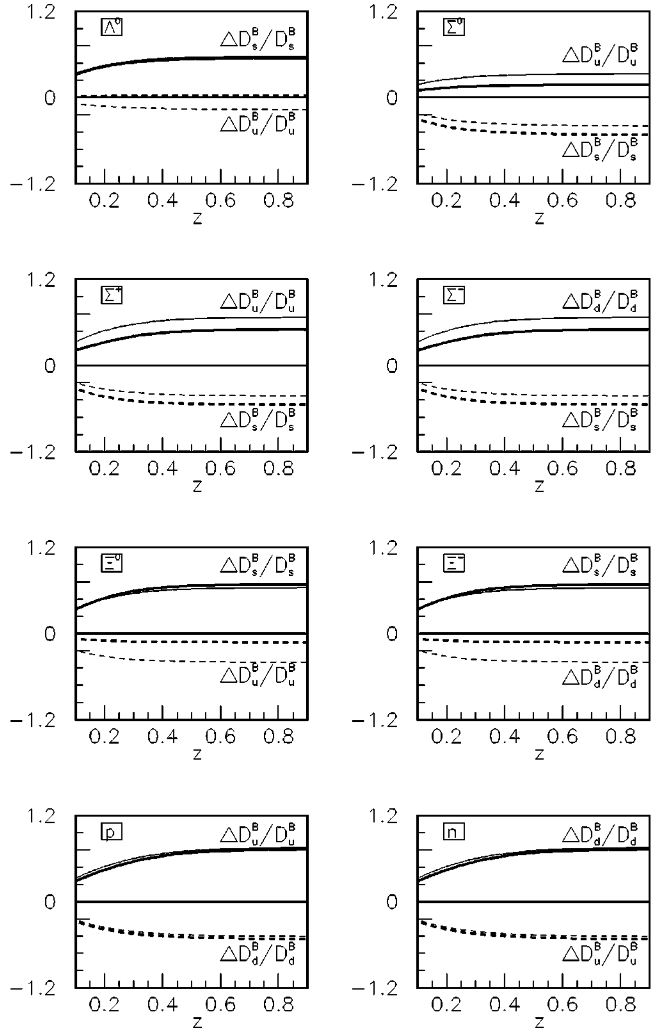

FIG. 1. The spin structure of the fragmentation functions for the octet baryons. The solid and dashed curves are for the dominant and nondominant quarks, respectively. The thin and thick curves correspond to the set 1 and set 2 fragmentation functions.

ron h. The GL relation should be considered as an approximate relation near $z \to 1$ on the energy scale Q_0^2 [27,28]. It is interesting to note that such a relation provided a successful description of the available Λ polarization data in several processes [15,29], based on quark distributions of the Λ in the quark diquark model, PQCD based counting rules analysis, and a statistical model. Thus we still use Eq. (20) as an ansatz to relate the quark fragmentation functions for the octet baryons to the corresponding quark distributions at an initial scale. Then, the quark fragmentation functions are evolved from the initial scale to the experimental energy scale. We use the evolution package of Ref. [30] suitably modified for the evolution of fragmentation functions in leading order, taking the initial scale $Q_0^2 = M_B^2$ and $\Lambda_{QCD} = 0.3$ GeV. In Fig. 1, the spin properties of the set 1 (thin curves) and set 2 (thick curves) fragmentation functions are presented at $Q^2 = 4$ GeV^2. From Fig. 1, we find that the difference between the two sets of fragmentation functions for the nucleon is very small. However, the SU(3) symmetry breaking effect on the fragmentation functions for the octet hyperons is significant and it might be detected via hyperon production. For this reason, we use the obtained fragmentation functions to predict spin observables for the various hyperon production processes.

We need some experimental data to examine the SU(3) symmetry breaking effect on the quark spin structure of the octet baryons. There has been some recent progress in the measurement of polarized Λ production. Longitudinal Λ polarization in e^+e^- annihilation at the Z pole has been measured by several collaborations [31–33]. The HERMES Collaboration at DESY [34] and the E665 Collaboration at Fermilab [35] have reported their results for longitudinal spin transfer to the Λ in polarized positron DIS. Very recently, measurement results for Λ polarization in charged current interactions were obtained by the NOMAD Collaboration [36]. We can check whether the SU(3) symmetry breaking effect in Λ production is supported by the available experimental data. In order to obtain some more information on SU(3) symmetry breaking, we also predict polarizations for other octet baryons produced in e^+e^- annihilation, charged lepton DIS, and neutrino DIS.

A. Octet baryon polarization in e^+e^- annihilation

Within the framework of the standard model of electroweak interactions, the quarks and antiquarks produced in e^+e^- annihilation near the Z pole are polarized due to the interference between the vector and axial-vector couplings, even though the initial e^+ and e^- beams are unpolarized. Then the polarized quarks and antiquarks lead to the polarization of baryons produced by fragmentation. Theoretically, the baryon (B) polarization can be expressed as

$$P_B = -\frac{\sum_q \hat{A}_q[\Delta D_q^B(z) - \Delta D_{\bar{q}}^B(z)]}{\sum_q \hat{C}_q[D_q^B(z) + D_{\bar{q}}^B(z)]}, \tag{21}$$

where $\hat{A}_q$ and $\hat{C}_q$ ($q = u$, d, and s) can be found in Refs. [15,26], and $D_q^B(z)$ $[D_{\bar{q}}^B(z)]$ and $\Delta D_q^B(z)$ $[\Delta D_{\bar{q}}^B(z)]$ are the unpolarized and polarized quark q (antiquark $\bar{q}$) to baryon B fragmentation functions. With the two sets of fragmentation functions obtained, we can check whether there exist some SU(3) symmetry breaking effects on the baryon polarizations. Our theoretical predictions for the octet baryon polarizations at the Z pole are shown in Fig. 2. We find from Fig. 2(a) that the prediction with SU(3) symmetry breaking is closer to the experimental data than the prediction with SU(3) symmetry, although both predictions are only qualitatively compatible with the experimental data. From Fig. 2, one can see that the SU(3) symmetry breaking effect on the octet hyperon polarization is much more significant than on the nucleon polarization. For Σ^0 production, the SU(3) symmetry breaking effect leads to changes in the sign of the polarization. The effect is also obvious for $\Sigma^{\pm}$ production.

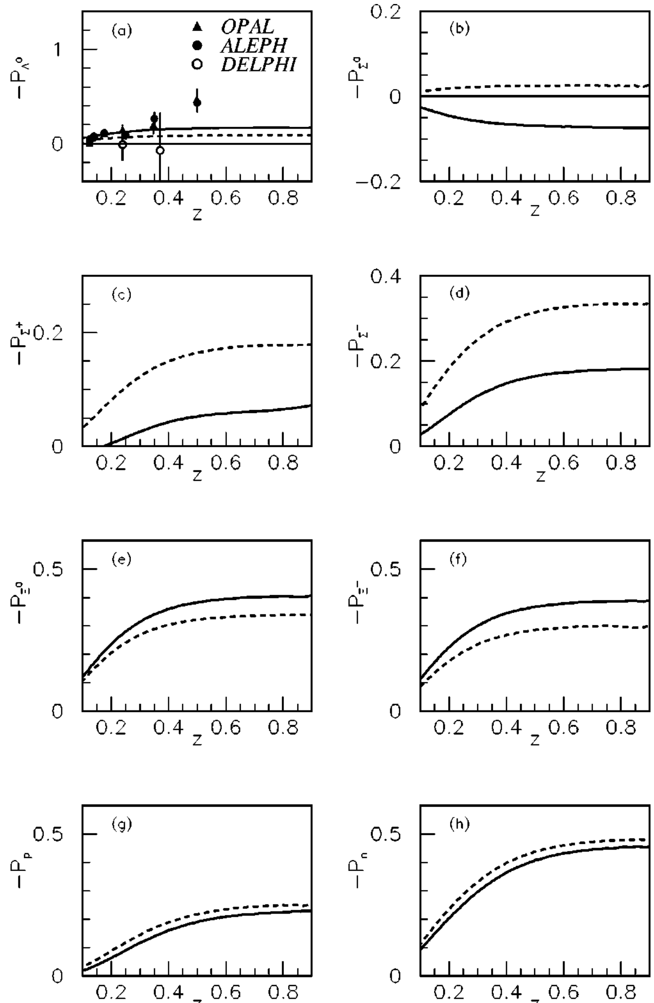

FIG. 2. The longitudinal octet baryon polarizations P_B in e^+e^- annihilation at the Z pole. The dashed and solid curves are the predictions using the set 1 and set 2 fragmentation functions for the octet baryons, respectively. The experimental data are taken from Refs. [31–33].

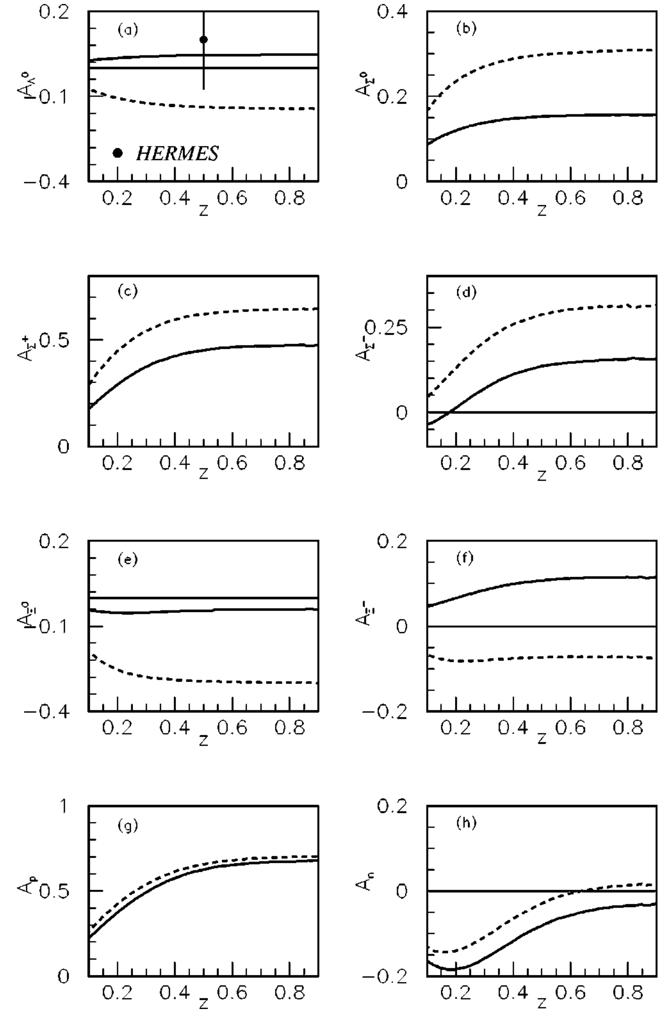

FIG. 3. The predictions of the z dependence for the spin transfers to octet baryons in polarized charged lepton DIS on a proton target. The dashed and solid curves are the predictions using the set 1 and set 2 fragmentation functions for the octet baryons, respectively. The HERMES data are taken from Ref. [34].

Therefore, the SU(3) symmetry breaking effect might be observed via hyperon production in e^+e^- annihilation, especially for Σ production.

B. Spin transfer to octet baryon in charged lepton deep inelastic scattering

In the deep inelastic scattering of a longitudinally polarized charged lepton on an unpolarized nucleon target, the polarization of the beam leads the struck quark to be polarized and its spin will be transferred to the baryon produced via quark fragmentation. The longitudinal spin transfer to the produced baryon B is given in the quark-parton model by

$$A_B(x,z)=\frac{\sum_q e_q^2[q^N(x,Q^2)\Delta D_q^B(z,Q^2)+(q\to\overline{q})]}{\sum_q e_q^2[q^N(x,Q^2)D_q^B(z,Q^2)+(q\to\overline{q})]}, \tag{22}$$

where $q^N(x,Q^2)$ is the quark distribution of the target nucleon, and will be adopted as the CTEQ5 set 1 parametrization from [37] in our numerical calculation. The spin transfers to the octet baryons can be calculated with the two sets of fragmentation functions and the results are shown in Fig. 3.

From Fig. 3, we find that the SU(3) symmetry breaking effect on the spin transfers to octet hyperons is much stronger than on the spin transfer to the nucleon. For the Λ and Ξ^- hyperons, the sign of the spin transfer is changed due to the SU(3) symmetry breaking effect. The reason for this big change lies in that the SU(3) symmetry breaking effect leads to a positively polarized u quark fragmentation function whereas SU(3) symmetry gives a negatively polarized u quark fragmentation function (cf. Tables II and III). There have been preliminary data from the HERMES Collaboration [34] on Λ production. It is interesting that the SU(3) symmetry breaking effect on the spin transfer to Λ makes the prediction consistent with the HERMES data point, which indicates that inclusion of the SU(3) symmetry breaking effect improves the spin structure of the Λ. The modifications for other hyperons due to SU(3) symmetry breaking are also significant. Therefore, the spin transfers to hyperons in charged lepton DIS are another set of suitable observables to check the existence of SU(3) symmetry breaking in HSD. Although the present data are not sufficient to draw a quantitative conclusion, it seems that the data favor somewhat the case in which the SU(3) symmetry breaking effect works.

C. Baryon polarizations in neutrino deep inelastic scattering

Neutrino DIS scattering on a nucleon target can also provide a source of polarized quarks and should be another important process to study the polarization of the octet baryons. For baryon B production in the current fragmentation region from neutrino and antineutrino DIS, the longitudinal polarization of B in its momentum direction can be expressed as [38],

$$P_{\nu}^{B}(x,y,z)=-\frac{[d^N(x)+\varpi s^N(x)]\Delta D_u^B(z)-(1-y)^2\overline{u}^N(x)[\Delta D_{\bar d}^B(z)+\varpi\Delta D_{\bar s}^B(z)]}{[d^N(x)+\varpi s^N(x)]D_u^B(z)+(1-y)^2\overline{u}^N(x)[D_{\bar d}^B(z)+\varpi D_{\bar s}^B(z)]}, \tag{23}$$

$$P_{\bar\nu}^{B}(x,y,z)=-\frac{(1-y)^2u^N(x)[\Delta D_d^B(z)+\varpi\Delta D_s^B(z)]-[\overline{d}^N(x)+\varpi\overline{s}^N(x)]\Delta D_{\bar u}^B(z)}{(1-y)^2u^N(x)[D_d^B(z)+\varpi D_s^B(z)]+[\overline{d}^N(x)+\varpi\overline{s}^N(x)]D_{\bar u}^B(z)}, \tag{24}$$

where the terms with the factor $\varpi=\sin^2\theta_c/\cos^2\theta_c$ (θ_c is the Cabibbo angle) represent Cabibbo suppressed contributions. The beam can be either neutrino or antineutrino, and the hadron produced can be either baryon or antibaryon. Therefore, we have four combinations of different beams and baryons produced and can get rich information on the flavor dependence of the quark fragmentation functions.

We present in Figs. 4–11 the longitudinal polarizations for the octet baryons produced in neutrino (antineutrino) DIS. For Λ production, there have been preliminary experimental data by the NOMAD Collaboration [36]. The NOMAD data have relative high precision and can be used to distinguish different predictions. The data seem to support again the set 2 prediction with SU(3) symmetry breaking. The polarizations P_{ν}^{Λ}, $P_{\nu}^{\bar\Lambda}$, $P_{\nu}^{\Xi^-}$, and $P_{\nu}^{\bar\Xi^+}$ are very valuable to us in revealing the SU(3) symmetry breaking effect. The octet hyperon polarizations are more sensitive to SU(3) symmetry breaking than the nucleon polarizations. We can also obtain some useful information on SU(3) symmetry breaking by means of the polarizations of the octet hyperons produced in neutrino (antineutrino) DIS.

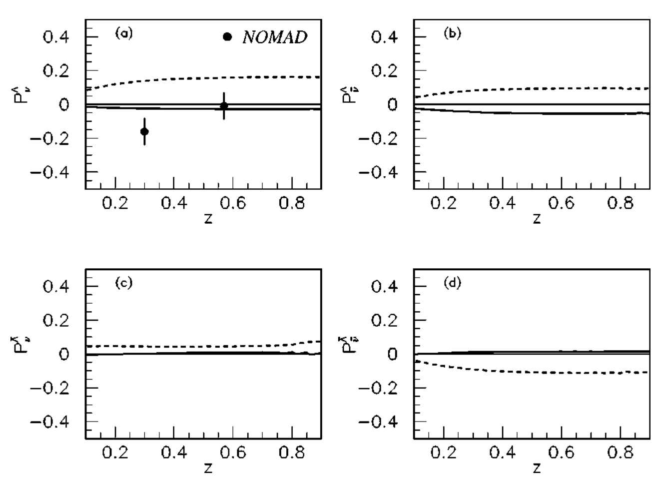

FIG. 4. The predictions of the z dependence for the hadron and antihadron polarizations of Λ in neutrino (antineutrino) DIS. The dashed and solid curves correspond to the predictions by using the set 1 and set 2 fragmentation functions with the Bjorken variable x integrated over $0.02\rightarrow0.4$ and y integrated over $0\rightarrow1$.

V. SUMMARY AND DISCUSSION

Based on the known data for semileptonic decays and lepton-nucleon deep inelastic scattering, we reextracted the quark contributions to the spin content of the octet baryons with SU(3) symmetry breaking in order to get reasonable central values for them. We constrained the quark distributions of the octet baryons at an initial scale with the two sets of typical quark contributions to the spin content of the octet baryons: one set with SU(3) flavor symmetry and another set

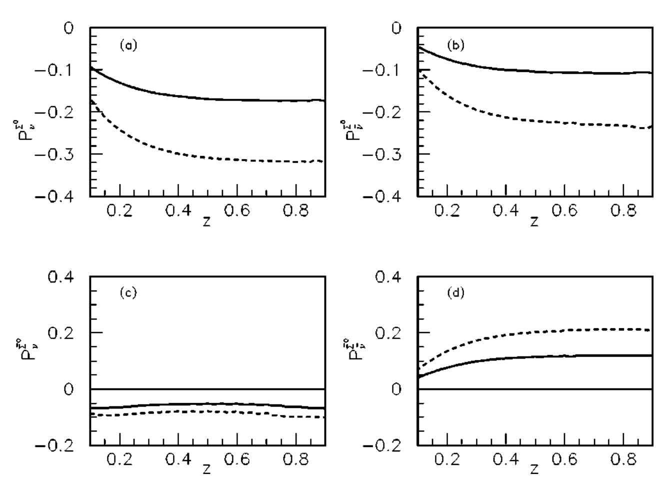

FIG. 5. The same as Fig. 4, but for predictions of z dependence for the hadron and antihadron polarizations of Σ^0 in neutrino (antineutrino) DIS.

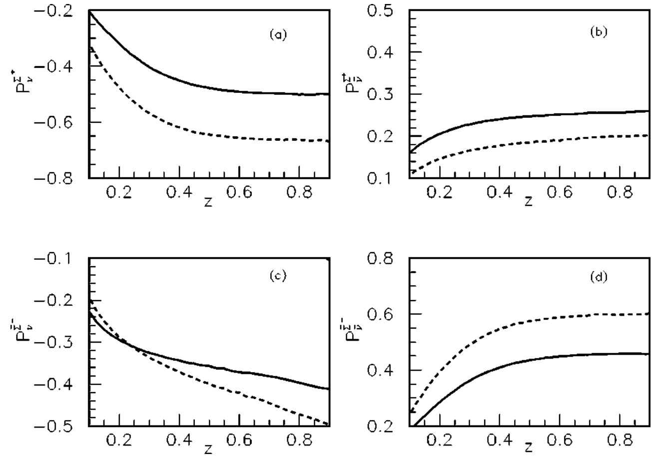

FIG. 6. The same as Fig. 4, but for predictions of z dependence for the hadron and antihadron polarizations of Σ^+ in neutrino (antineutrino) DIS.

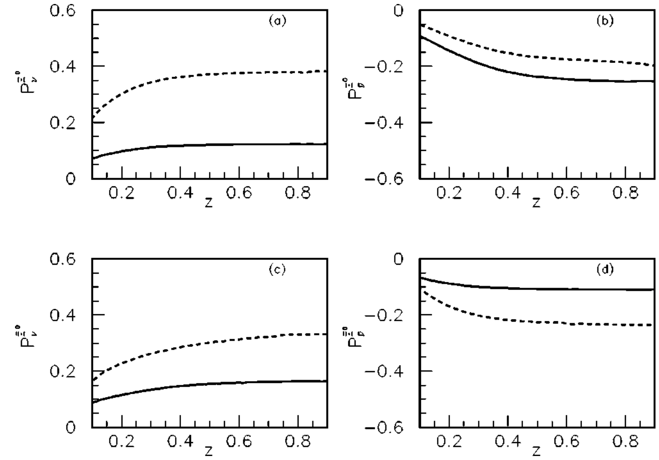

FIG. 8. The same as Fig. 4, but for predictions of z dependence for the hadron and antihadron polarizations of Ξ^0 in neutrino (antineutrino) DIS.

with SU(3) flavor symmetry breaking. By means of a statistical model, we calculated the quark distributions for the octet baryons in the rest frame and then used free boost transformations to relate the rest frame results to the IMF and made predictions about PDFs. We find that the quark distributions of the octet hyperons are much more sensitive to SU(3) symmetry breaking than those of the nucleon. In consideration of the fact that it is difficult for one to access the SU(3) symmetry breaking effect on the quark distributions of the octet hyperons, we focused our attention on exploring the possible SU(3) symmetry breaking effect on the octet baryon polarization from fragmentation. It was found that the available experimental data on Λ production seem to favor the predictions with SU(3) symmetry breaking. The spin observables in hyperon production from quark fragmentation, especially the polarization of the Σ in e^+e^- annihilation, the spin transfers in charged lepton DIS, and the polarizations in neutrino DIS for the Λ and Ξ hyperons, are very valuable to us in revealing the SU(3) symmetry breaking effect. We find that high precision measurements of the hyperon polarizations in e^+e^- annihilation, charged lepton DIS, and neutrino DIS can provide possible collateral evidence for SU(3) symmetry breaking in HSD of octet baryons.

It is worth mentioning that there exist many uncertainties in our predictions and there are many unknowns to be explored before we can arrive at a firm conclusion. We used the following three model assumptions: (1) an approximate relation between the fragmentation functions and quark distributions functions, Eq. (20); (2) the model for the symmetry breaking, Refs. [1–3]; (3) the model for the parton densities, Ref. [10]. Each of these assumptions introduces its own uncertainties into our predictions. It should be of great significance to estimate these uncertainties in order to complete our analysis. The largest uncertainty and probably the only one that can be relatively easily estimated comes from the errors on the ΔQ's. As an example, we estimate the errors on Λ production since we have some available experimental data for making a comparison with our predictions. The uncertainties for production of other hyperons are similar to the Λ case. We notice that there still exist big errors on the ΔQ's

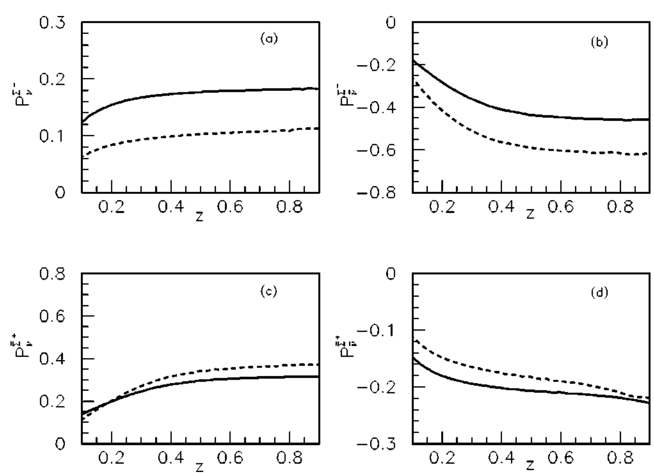

FIG. 7. The same as Fig. 4, but for predictions of z dependence for the hadron and antihadron polarizations of Σ^- in neutrino (antineutrino) DIS.

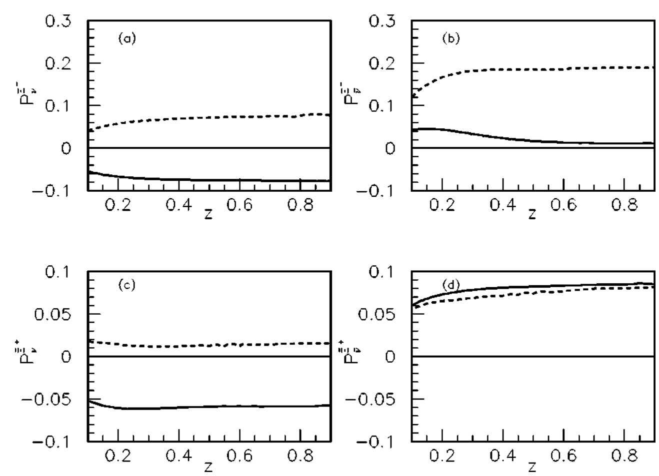

FIG. 9. The same as Fig. 4, but for predictions of z dependence for the hadron and antihadron polarizations of Ξ^- in neutrino (antineutrino) DIS.

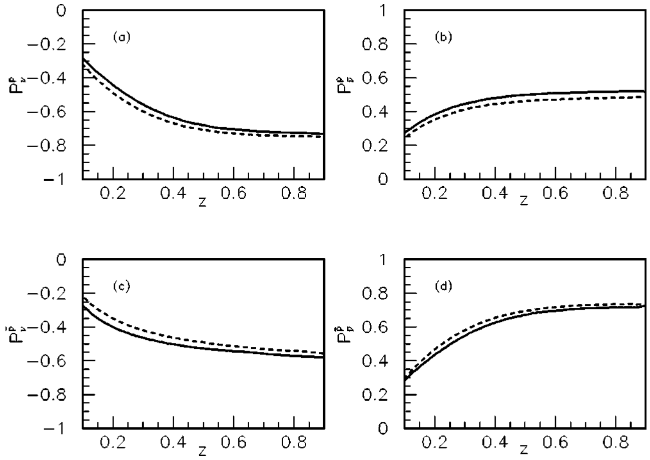

FIG. 10. The same as Fig. 4, but for predictions of z dependence for the hadron and antihadron polarizations of p in neutrino (antineutrino) DIS.

although their central values have been improved by adopting the new fit. In order to calculate the errors on the ΔQ's, we express $\Delta U = \Delta D$ and ΔS for the Λ in terms of the five semileptonic hyperon decay constants (A_i, $i = 1$–5) and Γ_p,

$$\Delta U = \frac{11}{23}A_1 - \frac{37}{69}A_2 + \frac{7}{46}A_3 + \frac{107}{46}A_4 + \frac{85}{23}A_5 - \frac{4}{23}\Gamma_p, \tag{25}$$

$$\Delta S = -\frac{54}{23}A_1 - \frac{90}{23}A_2 - \frac{243}{23}A_3 - \frac{639}{23}A_4 - \frac{66}{23}A_5 + \frac{51}{23}\Gamma_p. \tag{26}$$

We estimate the errors on the ΔQ's by simply adding all the errors on the decay constants and Γ_p in quadrature and we get

$$\Delta U = \Delta D \simeq 0.03 \pm 0.19 \tag{27}$$

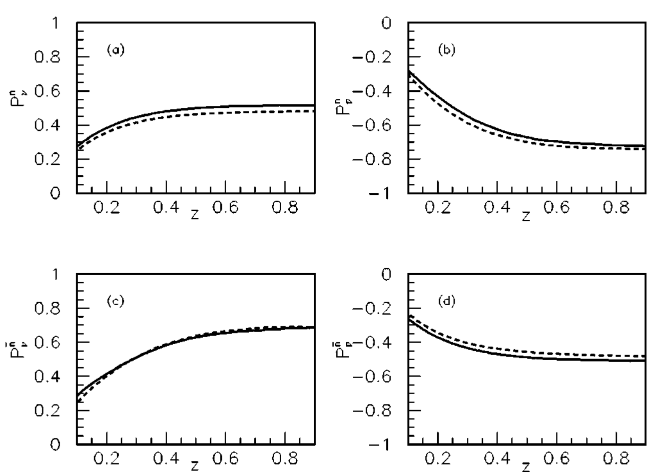

FIG. 11. The same as Fig. 4, but for predictions of z dependence for the hadron and antihadron polarizations of n in neutrino (antineutrino) DIS.

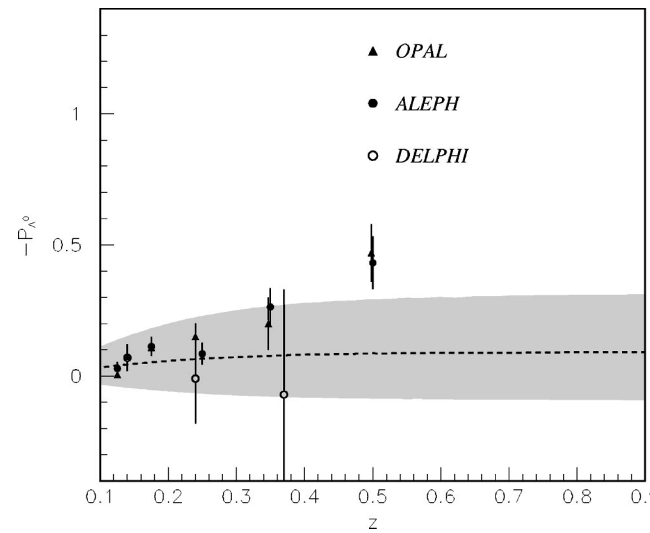

FIG. 12. The same as Fig. 2(a), but the single solid curve has been replaced by a band due to the consideration of errors on the ΔQ's ($Q = U$, D, and S). The dashed curve is for the SU(3) symmetry case.

and

$$\Delta S \simeq 0.65 \pm 0.78. \tag{28}$$

The errors on the ΔQ's are still large although their central values seem to be more reasonable than those in the original fit of Ref. [3]. With the errors, ΔS may vary in the range $[-0.13, 1.43]$ and $\Delta U = \Delta D$ in the range $[-0.16, 0.22]$. The value $\Delta S = 0.62$ for the SU(3) symmetry case is in the range of ΔS with errors for the SU(3) symmetry breaking case, but the value $\Delta U = \Delta D = -0.17$ for the SU(3) symmetry case stays at the edge of the band of the ΔU (ΔD) for the SU(3) symmetry breaking case. Therefore, the theoretical errors for our predictions are supposed to be very large.

Let us analyze the three processes for Λ production before looking into the effects of errors. First, in consideration of the fact that strange quark polarization is much larger than u and d quark polarizations in the Λ, and according to the relative magnitudes of the constants $\hat{A}_q$ and $\hat{C}_q$ in Eq. (21) for $q = u$, d, and s, we note that the strange quark dominates the Λ polarization in e^+e^- annihilation. Second, we find that the spin transfer to Λ in charged lepton DIS can be approximated by

$$A_\Lambda \sim \frac{\Delta D_u^\Lambda(z)}{D_u^\Lambda(z)}, \tag{29}$$

due to the charge factor for the u quark. Finally, the Λ polarization in neutrino DIS is also mainly controlled by

$$P_\nu^\Lambda \sim -\frac{\Delta D_u^\Lambda(z)}{D_u^\Lambda(z)}. \tag{30}$$

To sum up, the Λ polarization in e^+e^- annihilation is sensitive to the error on the ΔS's, and the spin transfer to Λ in

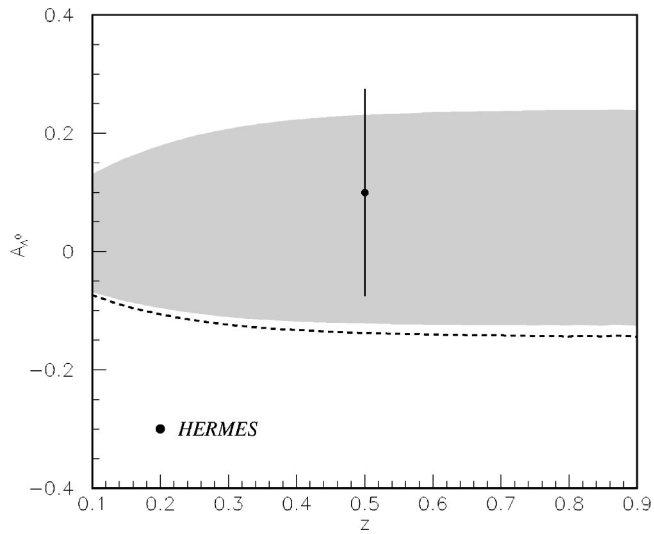

FIG. 13. The same as Fig. 3(a), but the single solid curve has been replaced by a band due to the consideration of errors on the ΔQ's ($Q=U$, D, and S). The dashed curve is for the SU(3) symmetry case.

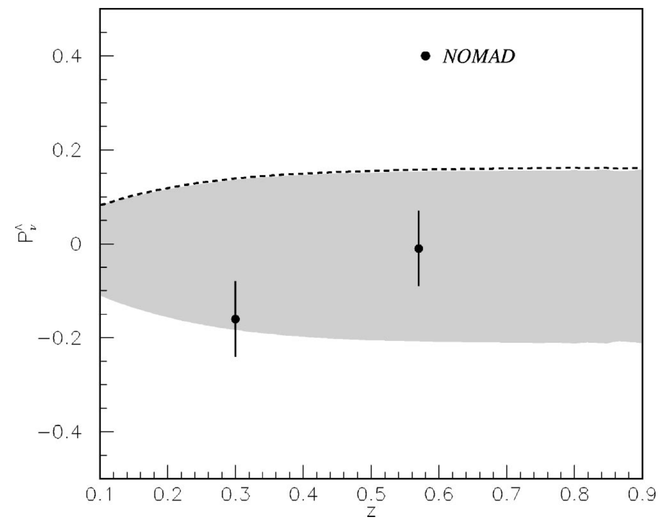

FIG. 14. The same as Fig. 4(a), but the single solid curve has been replaced by a band due to the consideration of errors on the ΔQ's ($Q=U$, D, and S). The dashed curve is for the SU(3) symmetry case.

charged lepton DIS and the Λ polarization in neutrino DIS are sensitive to the error on the ΔU's.

Now, let us have a detailed check of the numerical results. With the physics allowed value ranges of ΔS and ΔU for the Λ, we estimate the errors for our predictions of the Λ polarization in e^+e^- annihilation, the spin transfer to Λ in charged lepton DIS, and the Λ polarization in neutrino DIS. The numerical results are shown as bands in Figs. 12–14. The predictions with SU(3) symmetry are also shown in Figs. 12–14 as dashed curves as a comparison. As expected, the theoretical errors for our predictions are indeed very large. However, the available experimental data seem to favor the predictions with SU(3) symmetry breaking even with the errors on ΔQ included. Therefore, high precision measurements of the semileptonic hyperon decay constants and the hyperon polarizations are crucially important in order to get distinguishable evidence for SU(3) symmetry breaking from hyperon production.

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