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Flavor asymmetry of sea quarks in the unquenched quark model

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The flavor asymmetry of the nucleon sea is studied in the framework of the unquenched quark model in which the effects of quark-antiquark pairs ($u\bar{u}$, $d\bar{d}$, and $s\bar{s}$) are taken into account via a microscopic, QCD-inspired, quark-antiquark creation mechanism. The inclusion of the $q\bar{q}$ pairs leads to an excess of $\bar{d}$ over $\bar{u}$, in agreement with the experimental data for the proton. In addition, the results for the flavor asymmetry of all ground-state octet and decuplet baryons are presented. The isospin symmetry leads to simple relations among the flavor asymmetries of octet and decuplet baryons. The flavor asymmetry of the Σ^+ hyperon is predicted to be very similar to that of the proton and much larger than that for the Ξ^0 hyperon. A comparison with other approaches shows large differences in the predictions for the flavor asymmetries of the hyperons.

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Introduction. From an experimental point of view, the flavor asymmetry between $\bar{u}$ and $\bar{d}$ quarks in the proton is now well established [1–8]; for review, see also Refs. [9,10]. It is well known [11,12] that perturbative QCD is not able to account for this asymmetry. In fact, for quark-antiquark pairs created perturbatively, the sea quarks generated by leading twist evolution, i.e., from gluon splitting, are flavor symmetric with the same amount of $u\bar{u}$ as $d\bar{d}$ and $s\bar{s}$. Thus the flavor asymmetry of the nucleon sea is assumed to have a nonperturbative origin, and since currently it is still a big challenge to perform calculations from the first principles of QCD in the nonperturbative region, one has to try to understand the situation with effective models of hadrons, in terms of constituent quark degrees of freedom and/or meson-baryon degrees of freedom.

The flavor content of the nucleon sea provides an important test for models of the nucleon structure. The quark-parton model predicts a flavor symmetric sea that leads to the Gottfried sum rule $S_G = 1/3$ [13], whereas any deviation from this value is an indication of the $\bar{d}/\bar{u}$ asymmetry of the nucleon sea, thus providing a clean evidence of the existence of nonperturbative higher Fock components (such as qqq-$q\bar{q}$ configurations) in the proton wave function. The first clear evidence of a flavor asymmetric sea and a related violation of the Gottfried sum rule came in 1991 from the New Muon Collaboration (NMC) [1], which was later confirmed in Drell-Yan experiments [4–7] that probe the ratio $\bar{u}/\bar{d}$, as well as in semi-inclusive deep-inelastic scattering (SIDIS) experiments [8]. All these experiments show evidence that there are more $\bar{d}$ quarks in the proton than there are $\bar{u}$ quarks [10].

Many phenomenological models have been applied to the flavor asymmetry of the nucleon sea, e.g., meson-cloud models [14–16] (see Ref. [17] for other references), chiral quark models, in which there is a direct coupling of the pseudoscalar octect mesons to the quarks [18,19], and statistical models [20,21]. In particular, it was shown in the framework of the meson-cloud model that the surrounding pion cloud is, qualitatively, at the origin of the asymmetry of the proton, since the proton can change into a neutron by emitting a $\pi^+(u\bar{d})$, as first noted by Thomas [14] and later evaluated by Henley and Miller [22].

Whereas these models give a fairly good description of the current data for the proton, notable differences exist between their predictions for other members of the baryon octet [23]. In particular, this was discussed for Λ^0 [24,25] and $\Sigma^{\pm}$ [26–29]. The Λ^0 is charge neutral and has a short lifetime, but Λ^0 fragmentation processes can be used to reveal its quark distributions, as discussed in Refs. [23–25], while for the Σ, Drell-Yan experiments with Σ beams on protons and deuterium have been suggested [23,26,27,29].

It is the aim of this Rapid Communication to study the flavor asymmetry of the sea quarks in the framework of the constituent quark model (CQM). Hereto the effect of the quark-antiquark pairs ($u\bar{u}$, $d\bar{d}$, and $s\bar{s}$) has to be included at the quark level. Recently, we introduced the unquenched quark model [30] in which the effects of hadron loops are taken into account in an explicit and systematic form via a microscopic, QCD-inspired, quark-antiquark creation mechanism. In this Rapid Communication, we show that this model gives rise to an excess of $\bar{d}$ over $\bar{u}$, in agreement with the experimental data for the flavor asymmetry of the proton.

Finally, we present the predictions for the flavor asymmetry of all ground-state octet and decuplet baryons, derive simple relations among them based on isospin symmetry, and make a comparison with the predictions for the flavor asymmetries of the Σ^+ and Ξ^0 hyperons in different approaches.

Unquenched quark model. In this section, we present a procedure for unquenching the quark model [30] in which the effects of quark-antiquark pairs are introduced explicitly into the CQM via a $^3P_0$ pair-creation mechanism. The present

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approach is a generalization of the unitarized quark model by Törnqvist *et al.* [31], and was motivated by later work by Geiger and Isgur on the flux-tube breaking model in which they showed that the CQM emerges as the adiabatic limit of the flux-tube model to which the effects of $q\bar{q}$ pair creation are added as a perturbation [32]. Our approach is based on a CQM to which the quark-antiquark pairs with vacuum quantum numbers are added as a perturbation. The pair-creation mechanism is inserted at the quark level and the one-loop diagrams are calculated by summing over all possible intermediate states.

Under these assumptions, the baryon wave function consists of a zeroth-order three-quark configuration plus a sum over all possible higher Fock components due to the creation of ${}^3P_0$ quark-antiquark pairs. To leading order in pair creation, the baryon wave function can be written as

$$|\psi_A\rangle = \mathcal{N}\left[|A\rangle + \sum_{BClJ}\int d\vec{k}\,|BC\vec{k}lJ\rangle \frac{\langle BC\vec{k}lJ|T^\dagger|A\rangle}{M_A - E_B - E_C}\right] \tag{1}$$

where $T^\dagger$ is the ${}^3P_0$ quark-antiquark pair creation operator [33], A is the baryon, B and C represent the intermediate baryon and meson, and M_A, E_B, and E_C are their respective energies, $\vec{k}$ and l are the relative radial momentum and orbital angular momentum of B and C, and J is the total angular momentum $\vec{J} = \vec{J}_B + \vec{J}_C + \vec{l}$. The ${}^3P_0$ quark-antiquark pair-creation operator $T^\dagger$ is written as [33]

$$\begin{aligned} T^\dagger = {} & -3\gamma_0 \int d\vec{p}_4\, d\vec{p}_5\, \delta(\vec{p}_4+\vec{p}_5)\, C_{45}\, F_{45}\, e^{-r_q^2(\vec{p}_4-\vec{p}_5)^2/6} \\ & [\chi_{45}\,\mathcal{Y}_1(\vec{p}_4-\vec{p}_5)]^{(0)}_0\, b_4^\dagger(\vec{p}_4)\, d_5^\dagger(\vec{p}_5). \end{aligned} \tag{2}$$

Here, $b_4^\dagger(\vec{p}_4)$ and $d_5^\dagger(\vec{p}_5)$ are the creation operators for a quark and an antiquark with momenta $\vec{p}_4$ and $\vec{p}_5$, respectively. The quark-antiquark pair is characterized by a color singlet wave function C_{45}, a flavor singlet wave function F_{45}, a spin triplet wave function χ_{45} with spin $S = 1$, and a solid spherical harmonic $\mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)$, which indicates that the quark and antiquark are in a relative P wave. The operator $T^\dagger$ creates a pair of constituent quarks with an effective size, thus the pair creation point is smeared out by a Gaussian factor whose width r_q was determined from meson decays to be approximately 0.25–0.35 fm [32,34–36]. In our calculations, we take the average value $r_q = 0.30$ fm. The dimensionless constant γ_0 is the intrinsic pair-creation strength which was determined from strong decays of baryons as $\gamma_0 = 2.60$ [37]. The matrix elements of the pair-creation operator $T^\dagger$ were derived in explicit form in the harmonic oscillator basis [33,38].

We use the harmonic oscillator limit of algebraic models of hadron structure [39–42] to calculate the baryon and meson energies appearing in the denominator of Eq. (1), as was done in Ref. [30]. In these algebraic models, the mass operators for baryons and mesons consist of a harmonic oscillator term and a Gürsey-Radicati term which reproduces the splitting of the SU(6) multiplets without mixing the harmonic oscillator wave functions. As a consequence, the baryon and meson wave functions have good flavor symmetry and depend on a single oscillator parameter, which, following [32], is taken to be $\hbar\omega_{\text{baryon}} = 0.32$ GeV for the baryons and $\hbar\omega_{\text{meson}} = 0.40$ GeV for the mesons.

The matrix elements of an observable $\hat{\mathcal{O}}$ can be calculated as

$$\mathcal{O} = \langle\psi_A \mid \hat{\mathcal{O}} \mid \psi_A\rangle = \mathcal{O}_{\text{valence}} + \mathcal{O}_{\text{sea}}, \tag{3}$$

where the first term corresponds to the contribution of the three valence quarks and the second to the higher Fock components, i.e., the presence of the quark-antiquark pairs.

In order to calculate the effects of quark-antiquark pairs on an observable, one has to evaluate the sum over all possible intermediate states in Eq. (1). The sum over intermediate meson-baryon states includes for baryons all radial and orbital excitations up to a given oscillator shell combined with all possible SU(6) spin-flavor multiplets, and for mesons all radial and orbital excitations up to a given oscillator shell and all possible nonets. This problem was solved by means of group-theoretical techniques to construct an algorithm to generate a complete set of intermediate meson-baryon states in spin-flavor space for an arbitrary oscillator shell. This property makes it possible to perform the sum over intermediate states up to saturation, and not only for the first few shells as in [32]. In addition, it allows the evaluation of the contribution of quark-antiquark pairs for any initial baryon $q_1q_2q_3$ (ground state or resonance) and for any flavor of the $q\bar{q}$ pair (not only $s\bar{s}$, but also $u\bar{u}$ and $d\bar{d}$), and for any model of baryons and mesons, as long as their wave functions are expressed in the basis of harmonic oscillator wave functions [30]. Obviously, the unquenching of the quark model has to be done in such a way as to maintain the phenomenological successes of the CQM. In applications to mesons, it was shown that the inclusion of quark-antiquark pairs does not destroy the good CQM results [43] and preserves the Okubo-Zweig-Iizuka (OZI) hierarchy [44]. In a similar way, we showed that the good CQM results for the magnetic moments of the octet baryons are also preserved by the unquenched constituent quark model (UCQM) [30].

Flavor asymmetry. The flavor asymmetry $\bar{d} - \bar{u}$ is related to the Gottfried integral [13] S_G as

$$S_G = \tfrac{1}{3} - \tfrac{2}{3}(\bar{d} - \bar{u}), \tag{4}$$

where $\bar{d} = \int_0^1 dx\bar{d}_p(x)$ and $\bar{u} = \int_0^1 dx\bar{u}_p(x)\,dx$ represent the number of $\bar{d}$ and $\bar{u}$ quarks in the proton, respectively. Under the assumption of a flavor symmetric sea, one obtains the Gottfried sum rule $S_G = 1/3$ [13], whereas any deviation from this value is an indication of a flavor asymmetry of the nucleon sea. The Gottfried integral was first determined in 1991 by the New Muon Collaboration (NMC) in muon-induced deep-inelastic scattering experiments as $S_G = 0.240 \pm 0.016$ [1], which was later re-evaluated as 0.235 ± 0.026 [2]. The measurement of the flavor asymmetry of the nucleon sea via the violation of the Gottfried sum rule by NMC was later confirmed in Drell-Yan experiments [4–7] and SIDIS experiments [8].

The observed flavor asymmetry is one of the cleanest probes of the presence of antiquarks in nucleons. Experiments show evidence that there are more $\bar{d}$ than $\bar{u}$ in the proton. In the CQM the proton is described as a uud valence quark configuration, thus a flavor asymmetry indicates the presence of higher Fock

TABLE I. The flavor asymmetry $\mathcal{A} = \bar{d} - \bar{u}$ of the ground-state octet and decuplet baryons in the unquenched harmonic oscillator quark model. The sum over intermediate states includes four shells for baryons and mesons.

Octet	$\mathcal{A}$	Decuplet	$\mathcal{A}$
p	0.151	Δ^{++}	0.109
n	–0.151	Δ^{+}	0.036
Σ^{+}	0.126	Δ^{0}	–0.036
Σ^{0}	0.000	Δ^{-}	–0.109
Σ^{-}	–0.126	Σ^{*+}	0.371
Λ^{0}	0.000	Σ^{*0}	0.000
Ξ^{0}	–0.001	Σ^{*-}	–0.371
Ξ^{-}	0.001	Ξ^{*0}	0.216
		Ξ^{*-}	–0.216
		Ω^{-}	0.000

components in the proton wave function. Here, we discuss the implications of these extra configurations for the flavor asymmetry in the framework of the unquenched quark model. In the UCQM, the flavor asymmetry of the proton, $\mathcal{A}(p)$, is calculated from the difference in the number of $\bar{u}$ and $\bar{d}$ quarks in the wave function

$$\mathcal{A}(p) = \bar{d} - \bar{u} = \langle \psi_p | \hat{\bar{d}} - \hat{\bar{u}} | \psi_p \rangle. \quad (5)$$

Table I shows that the flavor asymmetry for the proton in the UCQM is 0.151, which corresponds to a value of the Gottfried integral of 0.232, remarkably close to the experimental value (see Fig. 1). At this point, it is important to stress that the present calculation was carried out without the introduction of any new parameters. All coefficients were taken from the literature and have the same values as in our study of the proton spin [30].

The main contribution to the flavor asymmetry of the proton is due to the pion loops, especially the $n\pi^{+}$ intermediate state, thus confirming in an explicit calculation the explanation given in Refs. [14,22] in the context of the meson-cloud model. In addition, we find that there are important contributions from the $\Delta\pi$ channel and, especially, from the off-diagonal terms $p\pi^{0}$-$p\eta$ and $p\pi^{0}$-$p\eta'$, which together are of the order of 15–20% of that of the $N\pi$ channel, but with the opposite sign (see Table II). The contribution of the intermediate vector mesons is very small due to a cancellation between the $n\rho^{+}$ and the $\Delta\rho$ channels and the cross terms $p\rho^{0}$-$p\omega$ and $p\pi^{0}$-$p\phi$. Table II shows that the full four-shell calculation is dominated by the contribution of the ground-state intermediate baryons and mesons (0 $\hbar\omega$). Both columns show the same qualitative behavior: dominance of the pion loops with a small negative correction of the order of 10–15% due to the off-diagonal terms involving the pseudoscalar mesons and an almost vanishing contribution from the vector mesons.

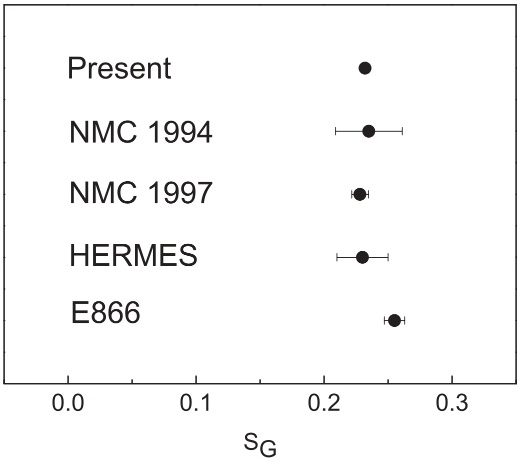

FIG. 1. Comparison between calculated value of the Gottfried integral S_G and the experimental data from NMC 1994 [1,2], NMC 1997 [3], HERMES [8], and E866 [5,7].

TABLE II. Contributions to the flavor asymmetry of the proton.

	0 $\hbar\omega$	0–4 $\hbar\omega$
$N\pi$	0.1766	0.1946
$\Delta\pi$	–0.0104	–0.0157
$N\pi\eta\eta'$	–0.0183	–0.0276
$N\rho$	0.0121	0.0496
$\Delta\rho$	–0.0034	–0.0165
$N\rho\omega\phi$	–0.0103	–0.0330
Total	0.1463	0.1514

The flavor asymmetry of the octet baryons is expected to be dominated by pion loops, whereas the other contributions are suppressed by the energy denominator in Eq. (1). For the nucleon and the Σ hyperon this is indeed the case (see, e.g., Table II for the proton), but for the cascade particles the pion loops are suppressed by the value of the SU(3) flavor coupling which is a factor of 5 smaller than that for the proton. Hence for the Ξ hyperons there is no dominant contribution. Since all contributions are roughly of the same order and small and, moreover, some with a positive and others with a negative sign, the value of the flavor asymmetry of the cascade particles is calculated to be small (see Table I).

The excess of $\bar{d}$ over $\bar{u}$ sea quarks in the proton is related by isospin symmetry to the excess of $\bar{u}$ over $\bar{d}$ in the neutron. In general, the flavor asymmetry of the ground-state octet and decuplet baryons satisfies

$$\begin{aligned} \mathcal{A}(A) &= \langle \psi_A(I, I_3) | \hat{\bar{d}} - \hat{\bar{u}} | \psi_A(I, I_3) \rangle \\ &= \frac{I_3}{I} \langle \psi_A(I, I) | \hat{\bar{d}} - \hat{\bar{u}} | \psi_A(I, I) \rangle, \end{aligned} \quad (6)$$

where I and I_3 denote the isospin and its projection of baryon A, respectively. As a consequence, we find the relations

$$\begin{aligned} \mathcal{A}(p) &= -\mathcal{A}(n), \\ \mathcal{A}(\Sigma^{+}) &= -\mathcal{A}(\Sigma^{-}), \\ \mathcal{A}(\Xi^{0}) &= -\mathcal{A}(\Xi^{-}), \end{aligned} \quad (7)$$

for the octet baryons and

$$\begin{aligned} \mathcal{A}(\Delta^{++}) \;=\; 3\mathcal{A}(\Delta^{+}) = -3\mathcal{A}(\Delta^{0}) \;&=\; -\mathcal{A}(\Delta^{-}), \\ \mathcal{A}(\Sigma^{*+}) &= -\mathcal{A}(\Sigma^{*-}), \\ \mathcal{A}(\Xi^{*0}) &= -\mathcal{A}(\Xi^{*-}), \end{aligned} \quad (8)$$

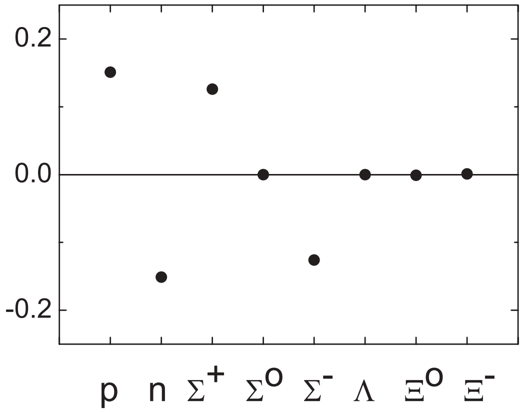

FIG. 2. Flavor asymmetry of octet baryons.

for the decuplet baryons. The flavor asymmetry vanishes identically for the octet baryons Λ and Σ^0 as well as for the decuplet baryons Σ^{*0} and Ω^-,

$$\mathcal{A}(\Lambda) = \mathcal{A}(\Sigma^0) = \mathcal{A}(\Sigma^{*0}) = \mathcal{A}(\Omega^-) = 0. \tag{9}$$

Equation (6) can be derived from the isospin symmetry of the baryon wave functions and the isovector character of the operator $\hat{\bar{d}} - \hat{\bar{u}}$, and are therefore valid for any model that uses isospin symmetry. The above symmetry relations help us to understand the results for the flavor asymmetry of the ground-state octet and decuplet baryons shown in Table I and Figs. 2 and 3.

In Table III, we show a comparison of some predictions for the flavor asymmetry of the Σ^+ and Ξ^0 hyperons relative to that of the proton. In the unquenched quark model, the flavor asymmetry of the proton is predicted to be of the same order as that of the Σ^+ hyperon and much larger than that of the cascade particle,

$$\mathcal{A}(p) \sim \mathcal{A}(\Sigma^+) \gg |\mathcal{A}(\Xi^0)|. \tag{10}$$

This behavior is very different from that obtained in the chiral quark model $\mathcal{A}(\Sigma^+) = 2\mathcal{A}(p) = 2\mathcal{A}(\Xi^0)$ [19], the balance model $\mathcal{A}(\Sigma^+) > \mathcal{A}(\Xi^0) > \mathcal{A}(p)$ [21], and the octet model $\mathcal{A}(p) > |\mathcal{A}(\Xi^0)| > \mathcal{A}(\Sigma^+)$ [26]. The values for the chiral quark model and the balance model were taken from [45]. The octet model involves the SU(3) flavor couplings between the octet baryons and mesons [26]. In this case, the relative flavor asymmetries only depend on the ratio of the SU(3) couplings $\alpha = F/D$,

$$\frac{\mathcal{A}(\Sigma^+)}{\mathcal{A}(p)} = \frac{9\alpha^2 - 10\alpha + 5}{4(\alpha + 1)},$$
$$\frac{\mathcal{A}(\Xi^0)}{\mathcal{A}(p)} = \frac{9\alpha^2 - 14\alpha + 1}{4(\alpha + 1)}. \tag{11}$$

The values in Table III are obtained using the values of F and D as determined from neutron and hyperon β decay [46], which correspond to $\alpha = 0.577$. The value used in [26] is slightly different, $\alpha = 0.60$. It is interesting to note that the octet model corresponds to a special case of the unquenched quark model in which only the contributions of the ground-state octet baryons and the ground-state octet pseudoscalar mesons are taken into account in the so-called closure limit, in which the intermediate baryon-meson states are degenerate in energy. In this case, the results of the UCQM can be obtained in closed analytic form as $\mathcal{A}(\Sigma^+)/\mathcal{A}(p) = 7/20 = 0.35$ and $\mathcal{A}(\Xi^0)/\mathcal{A}(p) = -13/20 = -0.65$, very close to the numerical values of the octet couplings in Eq. (11) and Table III. The relation between the unquenched quark model, the meson-cloud model, and the chiral-quark model will be discussed in more detail in a separate publication [47].

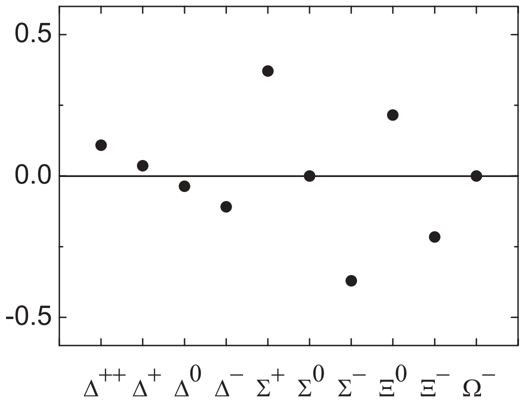

FIG. 3. Flavor asymmetry of decuplet baryons.

TABLE III. Relative flavor asymmetries of octet baryons.

Model	$\mathcal{A}(\Sigma^+)/\mathcal{A}(p)$	$\mathcal{A}(\Xi^0)/\mathcal{A}(p)$	Ref.
Unquenched CQM	0.833	−0.005	present
Chiral QM	2	1	[19]
Balance model	3.083	2.075	[21]
Octet couplings	0.353	−0.647	[26]

In order to distinguish between the predictions of the different models and to obtain a better understanding of the nonperturbative structure of QCD, new experiments are needed to measure the flavor asymmetry of hyperons. In particular, the flavor asymmetry of charged Σ hyperons can be obtained from Drell-Yan experiments using charged hyperon beams on the proton [26,27] or by means of backward $K^\pm$ electroproduction [48].

Summary and conclusions. In this Rapid Communication, we presented a study of the flavor asymmetry in the nucleon sea in the unquenched quark model in which the contributions of the quark loops ($u\bar{u}$, $d\bar{d}$, and $s\bar{s}$) are taken into account in a systematic and explicit way via a $^3P_0$ coupling mechanism. It was found that the contribution of the $q\bar{q}$ pairs leads to an excess of $\bar{d}$ over $\bar{u}$ quarks in the proton, in agreement with the experimental data. Although we agree with the meson-cloud model that the main contribution comes from the pion loops, we find in addition an important contribution from the off-diagonal pion-η terms.

We also investigated the flavor asymmetry of the other ground-state octet and decuplet baryons. There exist simple relations between the flavor asymmetries, e.g., the excess of $\bar{d}$ over $\bar{u}$ in the proton is equal to the excess of $\bar{u}$ over $\bar{d}$ in the neutron, and similar relations for the Δ and the hyperons. Since these relations only depend on the isospin symmetry of the baryon wave functions, they are valid for any model with isospin symmetry.

In the unquenched quark model, the flavor asymmetry of the Σ^+ hyperon was found to be similar to that of the proton and much larger than that of the Ξ^0 hyperon. A comparison with other models of nucleon structure (chiral quark model, statistical balance model, and the octet couplings of the meson-cloud model) shows that the predictions of the flavor asymmetry of the Σ^+ and Ξ^0 hyperons relative to that of the proton vary enormously. It would therefore be of the utmost interest to measure the flavor asymmetry of hyperons, for example, as suggested in [27] to use the Drell-Yan process in hyperon-induced dilepton production with $\Sigma^\pm$ beams on protons, $\Sigma^\pm p \to \ell^+\ell^- + X$ (e.g., at CERN). A different type of measurement of the flavor asymmetry of the Σ^+ would be backward K^+ electroproduction (e.g., at the 12-GeV upgraded JLAB [48]). Hyperon physics may open new windows to probe the sea content of baryons, to discriminate between different models of hadron structure, and ultimately to understand the nonperturbative structure of the hadrons.

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