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Sea-quark flavor content of octet baryons and intrinsic five-quark Fock states

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Sea-quark content of the octet baryons are investigated by employing an extended chiral constituent quark approach, which embodies higher Fock five-quark components in the baryons wave functions. The well-known flavor asymmetry of the nucleon sea $\bar{d}-\bar{u}$, is used as input to predict the probabilities of $\bar{u}$, $\bar{d}$, and $\bar{s}$ in the nucleon, Λ, Σ, and Ξ baryons, due to the intrinsic five-quark components in the baryons wave functions.

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I. INTRODUCTION

Though the baryon's valence quark distributions are known to be flavor asymmetric, until recently those of the sea quarks were assumed to be symmetric. However, Thomas [1] predicted that the pion cloud dressing the proton can generate an enhancement of the light antiquarks flavor asymmetry, $\bar{d}-\bar{u}$. The experimental benchmark in the flavor sea-quark content of the proton appeared about one decade later due to the pioneer measurements by the New Muon Collaboration, which showed [2] a significant excess of the anti-down relative to anti-up quark in the proton sea, as a function of the parton momentum fraction (Bjorken-x)

$$\bar{d}-\bar{u}=\int_0^1[\bar{d}_p(x)-\bar{u}_p(x)]dx=0.147\pm 0.039. \quad (1)$$

This unexpected large asymmetry between the down and up antiquarks distribution in the nucleon was confirmed by other measurements in various $0\leqslant x\leqslant 1$ ranges at CERN [3], Fermilab [4–6], and DESY [7].

Those measurements imply the breaking of the so-called Gottfried sum rule [8], which expressed in terms of parton distribution [9], has the following form:

$$\begin{aligned}\mathcal{I}_G &= \int_0^1\left[F_2^p(x)-F_2^n(x)\right]\frac{dx}{x}\\ &= \frac{1}{3}-\frac{2}{3}\int_0^1[\bar{d}_p(x)-\bar{u}_p(x)]dx, \end{aligned}\quad (2)$$

where F_2^p and F_2^n are the proton and the neutron structure functions. A symmetric sea assumption gives the Gottfried sum rule: $\mathcal{I}_G=\frac{1}{3}$. [Note that the original sum rule published by Gottfried [8] was much simpler and rather naive; for steps having led to the above expression (see, e.g., Sec. 2.2 in Ref. [10]).]

Evidence for the breaking of the Gottfried sum rule motivated a large amount of effort to understand the origins of the nucleon sea, either perturbative or nonperturbative, as reviewed by several authors [10–14]. Perturbative mechanisms are generated by the gluons splitting into quark-antiquark pairs. The only nonperturbative gluonic process is due to gluon condensate [15], as investigated in the soliton based approaches. Other sources of the nonperturbative mechanisms are being extensively studied, as summarized in the following.

In the meson cloud scheme, a variety of approaches has been developed; namely, bag model [1,16,17], light-cone meson-baryon fluctuations of intrinsic $q\bar{q}$ pairs [18–20], one-pion-exchange [21], meson-baryon effective Lagrangian [22–24], and quantum fluctuations of the baryon [25]. The light antiquarks are generated by the nucleon fluctuations into Fock states $|\pi N\rangle$ and/or $|\pi\Delta\rangle$. Then, $\bar{u}$ arises from $|\pi^-\Delta^{++}\rangle$, $\bar{d}$ from $|\pi^+n\rangle$ and $|\pi^+\Delta^\circ\rangle$, while $u\bar{u}$ and $d\bar{d}$ related to π° are assumed to annihilate. A rather comprehensive set of fluctuations includes the following Fock states [23]: $|\pi N\rangle, |\rho N\rangle, |\omega N\rangle, |\pi\Delta\rangle, |\rho\Delta\rangle, |K\Lambda\rangle, |K^*\Lambda\rangle, |K\Sigma\rangle, |K^*\Sigma\rangle$. Finally, reggeizing [21] the virtual mesons was a significant step in the meson cloud approaches.

A more evolved meson cloud formulation is based on the large-N_c limit of QCD, where the baryons are treated as chiral solitons *via* collective excitations of mesons [26–31]. In the same line, chiral constituent quark models (χCQM) [23,32–39] concentrate on the meson cloud, where the virtual pion couples directly to a quark. It is worth pointing out that within a χCQM [36] the breaking of the Gottfried sum rule also for baryons other than the nucleon is predicted. Moreover, dedicated studies on the quark-antiquark decomposition in the sea quark are also being extensively performed within effective QCD [40–43], lattice QCD [44–46], and statistical balance [47,48].

A pertinent nonperturbative source is due to genuine higher Fock components in the baryon wave function. In 1981, in order to interpret the large cross section of charmed particle production in hadron collisions, Brodsky and collaborators [40,41] postulated the existence of the $|uudc\bar{c}\rangle$ configuration in the proton; called the BHPS model. That approach was recently extended [42,43] to the light quarks sector, describing nicely data for $\bar{d}-\bar{u}$ and $\bar{u}+\bar{d}-s-\bar{s}$.

The present work is dedicated to the investigation of the flavor sea components, arising from the five-quark components, in the ground-state baryons; namely, N, Λ, Σ, and Ξ. Our formalism is based on an extended chiral constituent quark approach and embodies all possible five-quark mixtures in the baryons wave functions. Such higher Fock components have

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been proven to be quite significant in describing the properties of baryons, their electromagnetic and strong decays [49–60].

In order to fix the only adjustable parameter of our model, we use as input the result extracted from the measurement performed by the FNAL E866/NuSea Collaboration [6]

$$\bar{d} - \bar{u} = 0.118 \pm 0.012. \tag{3}$$

Using our model, we put forward predictions on the probabilities of $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$. Comparisons with results from other works are also reported.

The present manuscript is organized in the following way: in Sec. II, we present our theoretical formalism, which includes the wave functions and couplings between three- and five-quark components. Expressions for the couplings and the five-quark configurations energies are derived and all of the relevant associated orbital-flavor-spin configurations are singled out. Numerical results are given in Sec. III, putting forward predictions for the probabilities of different five-quark configurations, as well as those of the sea-quark content of the baryons. Finally, we conclude in Sec. IV with a summary.

II. THEORETICAL FRAME

In order to investigate the sea-quark content of the octet baryons, we employ the extended constituent quark model (E-χCQM), in which wave function for a baryon is expressed as

$$|\psi\rangle_B = \frac{1}{\sqrt{\mathcal{N}}}\left[|QQQ\rangle + \sum_{i,n_r,l} C_{in_rl}|QQQ(Q\bar{Q}), i, n_r, l\rangle\right], \tag{4}$$

where the first term is the conventional wave function for the baryon with three constituent quarks, and the second term is a sum over all possible higher Fock components with a $Q\bar{Q}$ pair. Here we denote light quark-antiquark pair as $Q\bar{Q} \equiv q\bar{q}$ (with $q \equiv u, d$,) and strange quark-antiquark pairs as $Q\bar{Q} \equiv s\bar{s}$. Different possible orbital-flavor-spin-color configurations of the four-quark subsystems in the five-quark system are numbered by i; n_r and l denote the inner radial and orbital quantum numbers, respectively. Finally, $C_{in_rl}/\sqrt{\mathcal{N}} \equiv A_{in_rl}$ represents the probability amplitude for the corresponding five-quark component.

In the present case, we consider the ground states of baryon octet, whose parities are positive, so that the orbital quantum number l must be an odd number $1, 3, \ldots, 2n+1$. The total spin S of a five-quark system can only be $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$, so l cannot be higher than 3 to combine with S, forming spin $\frac{1}{2}$ for the baryons considered here. All of the five-quark configurations with $l = 1$ and $n_r = 0$, which may form higher Fock components in the proton [51], can directly be extended to other baryons of the octet. We will discuss later the five-quark configurations with $l = 3$ and $n_r \neq 0$.

The coefficients C_{in_rl} in Eq. (4) can be related to the coupling between the valence three-quark and the corresponding five-quark components

$$C_{in_rl} = \frac{\langle QQQ(Q\bar{Q}), i, n_r, l|\hat{T}|QQQ\rangle}{M_B - E_{in_rl}}, \tag{5}$$

where $\hat{T}$ is a model-dependent coupling operator, M_B the mass of baryon B and E_{in_rl} the energy of the five-quark component, as discussed in the next two subsections.

A. Couplings between three- and five-quark components for baryon octet

Here we use a ${}^3P_0$ version for the transition coupling operator $\hat{T}$

$$\hat{T} = -\gamma \sum_j \mathcal{F}^{00}_{j,5}\mathcal{C}^{00}_{j,5}C_{\mathrm{OFSC}}\Bigg[\sum_m \langle 1, m; 1, -m|00\rangle \chi^{1,m}_{j,5} \times \mathcal{Y}^{1,-m}_{j,5}(\vec{p}_j - \vec{p}_5)b^\dagger(\vec{p}_j)d^\dagger(\vec{p}_5)\Bigg], \tag{6}$$

where γ is a dimensionless constant of the model as discussed later, $\mathcal{F}^{00}_{i,5}$ and $\mathcal{C}^{00}_{i,5}$ denote the flavor and color singlet of the quark-antiquark pair $Q_i\bar{Q}$ in the five-quark system, and C_{OFSC} is an operator to calculate the orbital-flavor-spin-color overlap between the residual three-quark configuration in the five-quark system and the valence three-quark system.

To derive the matrix elements of $\hat{T}$ between the three- and five-quark configurations, we need explicit wave functions for the latter ones. As shown in Ref. [51], if we limit the orbital quantum and radial quantum numbers to $l = 1$ and $n_r = 0$, respectively, then, there are 24 different five-quark configurations, which can form possible components in the proton. For the four-quark subsystem in these five-quark configurations, the orbital wave functions are $[4]_X$ or $[31]_X$, flavor wave functions $[31]_F$, $[22]_F$, or $[211]_F$, and spin wave functions $[4]_S$, $[31]_S$, or $[22]_S$. Explicit forms of these wave functions for the proton can be found in Refs. [51,61] and using the same approach allows inferring the wave functions for the other octet baryons. Notice that there are two separate classes of wave functions with the flavor symmetry $[31]_F$, relation and difference between these two are explained in Ref. [51]. Here we denote these two as $[31]^1_F$ and $[31]^2_F$. So the total number of five-quark configurations goes up from 24 to 34. The $SU(2)$ Clebsch-Gordan (C-G) coefficients for the combinations of the four classes of four-quark flavor configurations with an antiquark to form the required four categories of isospin eigenstates N, Λ, Σ, and Ξ are listed in Table I.

As discussed above, we have to consider the five-quark configurations with $l = 3$. In this case, total spin S of the five-quark system should be $\frac{5}{2}$, so that the spin wave function of the four-quark subsystem in such five-quark configurations must be $[4]_S$, namely completely symmetric. Our calculations show that the couplings of a three-quark system to that set of five-quark configurations vanish. Consequently, five-quark configurations with $l = 3$ cannot exist in the ground state of baryon octet.

With respect to the five-quark configurations with $n_r \geqslant 1$, the probabilities of these excitations in the octet baryons turn out to be negligible, because on the one hand the matrix elements of the coupling transition operator $\hat{T}$ between three-quark and $n_r \geqslant 1$ five-quark components are much smaller

TABLE I. $SU(2)$ Clebsch-Gordan coefficients for the five-quark components with $q\bar{q}$.

		$[31]^1_F$	$[31]^2_F$	$[22]_F$	$[211]_F$
p	$uudu\bar{u}$	$\sqrt{\frac{2}{3}}$	0	0	0
	$uudd\bar{d}$	$\sqrt{\frac{1}{3}}$	0	1	0
n	$uddu\bar{u}$	$\sqrt{\frac{1}{3}}$	0	-1	0
	$uddd\bar{d}$	$\sqrt{\frac{2}{3}}$	0	0	0
Λ	$udsu\bar{u}$	0	$\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$
	$uusd\bar{d}$	0	$\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$
Σ^+	$uusu\bar{u}$	$\sqrt{\frac{3}{4}}$	0	0	0
	$uusd\bar{d}$	$\sqrt{\frac{1}{4}}$	1	1	-1
Σ^0	$udsu\bar{u}$	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$
	$uusd\bar{d}$	$-\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{2}}$	$-\sqrt{\frac{1}{2}}$
Σ^-	$ddsu\bar{u}$	$\sqrt{\frac{1}{4}}$	1	-1	1
	$ddsd\bar{d}$	$\sqrt{\frac{3}{4}}$	0	0	0
Ξ^0	$ussu\bar{u}$	$\sqrt{\frac{2}{3}}$	0	$-\sqrt{\frac{2}{3}}$	0
	$ussd\bar{d}$	$\sqrt{\frac{1}{3}}$	1	$-\sqrt{\frac{1}{3}}$	-1
Ξ^-	$dssu\bar{u}$	$\sqrt{\frac{1}{3}}$	1	$-\sqrt{\frac{1}{3}}$	1
	$dssd\bar{d}$	$\sqrt{\frac{2}{3}}$	0	$-\sqrt{\frac{2}{3}}$	0

than those for $n_r = 0$, and on the other hand the energies should be at least several hundreds MeV higher.

Consequently, we consider only the five-quark configurations with $l = 1, n_r = 0$ as candidates of higher Fock components in the octet baryons. The derived matrix elements T for the 34 five-quark configurations show that only 17 configurations survive and matrix elements T for all other ones vanish. We list the former configurations in Table II. The results for T are listed in Tables III–V. Note that the full coupling matrix elements is obtained by multiplying each term listed in the tables by a common factor V

$$V = \gamma\omega_5 C_{35}, \tag{7}$$

with

$$C_{35} \equiv \left(\frac{2\omega_3\omega_5}{\omega_3^2 + \omega_5^2}\right)^3, \tag{8}$$

where ω_3 and ω_5 are the harmonic oscillator parameters for the three- and five-quark components in baryons. The parameter ω_3 can be inferred from the empirical radius of the proton *via* $\omega_3 = 1/\sqrt{\langle r^2\rangle}$, which yields $\omega_3 \simeq 246$ MeV if we take $\sqrt{\langle r^2\rangle} = 1$ fm. Moreover, if the confining potential for the quarks is taken to be color dependent [62], we can simply

TABLE II. Orbital-flavor-spin configurations for the five-quark states, relevant to the ground-state octet baryons.

i	1	2	3	4	5
Config.	$[31]_X[4]_{FS}[22]_F[22]_S$	$[31]_X[4]_{FS}[31]^1_F[31]_S$	$[31]_X[4]_{FS}[31]^2_F[31]_S$	$[31]_X[31]_{FS}[211]_F[22]_S$	$[31]_X[31]_{FS}[211]_F[31]_S$
i	6	7	8	9	10
Config.	$[31]_X[31]_{FS}[22]_F[31]_S$	$[31]_X[31]_{FS}[31]^1_F[22]_S$	$[31]_X[31]_{FS}[31]^2_F[22]_S$	$[31]_X[31]_{FS}[31]^1_F[31]_S$	$[31]_X[31]_{FS}[31]^2_F[31]_S$
i	11	12	13	14	15
Config.	$[4]_X[31]_{FS}[211]_F[22]_S$	$[4]_X[31]_{FS}[211]_F[31]_S$	$[4]_X[31]_{FS}[22]_F[31]_S$	$[4]_X[31]_{FS}[31]^1_F[22]_S$	$[4]_X[31]_{FS}[31]^2_F[22]_S$
i	16	17			
Config.	$[4]_X[31]_{FS}[31]^1_F[31]_S$	$[4]_X[31]_{FS}[31]^2_F[31]_S$			

TABLE III. Transition coupling (T_i) and energy due to the hyperfine interaction and mass difference between strange and light quark (ΔE_i) for the five-quark configurations with light $q\bar{q}$ pairs and $L_{4q} = 1$ in the octet baryons. The first row for each configuration with number i is the coupling T_i, followed by rows for the energy ΔE_i.

i	N	Λ	Σ	Ξ
1	$\frac{\sqrt{3}}{9}$	$\frac{\sqrt{2}}{6}$	$\frac{\sqrt{6}}{18}$	$\frac{\sqrt{2}}{6}$
	$-\frac{1}{3}(56P_0^\pi + 28P_1^\pi)$	$\delta m - \frac{1}{3}(28P_0^\pi + 14P_1^\pi + 28P_0^K + 14P_1^K)$	$\delta m - \frac{1}{3}(28P_0^\pi + 14P_1^\pi + 28P_0^K + 14P_1^K)$	$2\delta m - \frac{1}{9}(8P_0^\pi + 4P_1^\pi + 152P_0^K + 76P_1^K + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$
2	$\frac{\sqrt{6}}{9}$	0	$\frac{4\sqrt{3}}{27}$	$\frac{\sqrt{3}}{9}$
	$-\frac{1}{9}(128P_0^\pi + 64P_1^\pi)$	– –	$\delta m - \frac{1}{9}(24P_0^\pi + 12P_1^\pi + 104P_0^K + 52P_1^K)$	$2\delta m - \frac{1}{9}(8P_0^\pi + 4P_1^\pi + 112P_0^K + 56P_1^K + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$
3	0	$\frac{\sqrt{2}}{6}$	$\frac{\sqrt{6}}{54}$	$\frac{\sqrt{2}}{18}$
	–	$\delta m - \frac{1}{9}(84P_0^\pi + 42P_1^\pi + 44P_0^K + 22P_1^K)$	$\delta m - \frac{1}{9}(84P_0^\pi + 42P_1^\pi + 44P_0^K + 22P_1^K)$	$2\delta m - \frac{1}{9}(48P_0^\pi + 24P_1^\pi + 72P_0^K + 36P_1^K + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$
4	0	$\frac{\sqrt{2}}{18}$	$\frac{\sqrt{6}}{18}$	$\frac{\sqrt{6}}{18}$
	–	$\delta m - \frac{1}{36}(193P_0^\pi + 31P_1^\pi + 283P_0^K + 69P_1^K)$	$\delta m - \frac{1}{36}(193P_0^\pi + 31P_1^\pi + 283P_0^K + 69P_1^K)$	$2\delta m - \frac{1}{18}(50P_0^\pi + 14P_1^\pi + 183P_0^K + 41P_1^K - 5P_0^{s\bar{s}} + 5P_1^{s\bar{s}})$
5	0	$\frac{\sqrt{2}}{18}$	$\frac{\sqrt{6}}{18}$	$\frac{\sqrt{6}}{18}$
	–	$\delta m - \frac{1}{18}(91P_0^\pi + 17P_1^\pi + 113P_0^K + 19P_1^K)$	$\delta m - \frac{1}{18}(91P_0^\pi + 17P_1^\pi + 113P_1^K + 19P_1^K)$	$2\delta m - \frac{1}{9}(20P_0^\pi + 8P_1^\pi + 73P_0^K + 11P_1^K + 9P_0^{s\bar{s}} + 3P_1^{s\bar{s}})$
6	$\frac{\sqrt{2}}{9}$	$\frac{\sqrt{3}}{9}$	$\frac{1}{9}$	$\frac{\sqrt{3}}{9}$
	$-\frac{1}{18}(158P_0^\pi + 10P_1^\pi)$	$\delta m - \frac{1}{18}(79P_0^\pi + 5P_1^\pi + 79P_0^K + 5P_1^K)$	$\delta m - \frac{1}{18}(79P_0^\pi + 5P_1^\pi + 79P_0^K + 5P_1^K)$	$2\delta m - \frac{1}{27}(13P_0^\pi - P_1^\pi + 211P_0^K + 17P_1^K + 13P_0^{s\bar{s}} - P_1^{s\bar{s}})$
7	$\frac{\sqrt{6}}{9}$	0	$\frac{4\sqrt{3}}{27}$	$\frac{\sqrt{3}}{9}$
	$-\frac{1}{9}(73P_0^\pi - P_1^\pi)$	– –	$\delta m - \frac{1}{9}(-5P_0^\pi - 15P_1^\pi + 78P_0^K + 14P_1^K)$	$2\delta m - \frac{1}{9}(-4P_1^\pi + 73P_0^K + 7P_1^K - 4P_1^{s\bar{s}})$
8	0	$\frac{\sqrt{2}}{6}$	$\frac{\sqrt{6}}{54}$	$\frac{\sqrt{2}}{18}$
	–	$\delta m - \frac{1}{36}(229P_0^\pi + 27P_1^\pi + 63P_0^K - 31P_1^K)$	$\delta m - \frac{1}{36}(229P_0^\pi + 27P_1^\pi + 63P_0^K - 31P_1^K)$	$2\delta m - \frac{1}{18}(78P_0^\pi + 18P_1^\pi + 73P_0^K - 9P_1^K - 5P_0^{s\bar{s}} - 5P_1^{s\bar{s}})$
9	$-\frac{\sqrt{2}}{9}$	0	$-\frac{4}{27}$	$-\frac{1}{9}$
	$-\frac{1}{27}(148P_0^\pi - 4P_1^\pi)$	– –	$\delta m - \frac{1}{81}(71P_0^\pi - 59P_1^\pi + 373P_0^K + 47P_1^K)$	$2\delta m - \frac{1}{81}(29P_0^\pi - 17P_1^\pi + 134P_0^K + 10P_1^K + 13P_0^{s\bar{s}} - 25P_1^{s\bar{s}})$
10	0	$-\frac{\sqrt{6}}{18}$	$-\frac{\sqrt{2}}{54}$	$-\frac{\sqrt{6}}{54}$
	–	$\delta m - \frac{1}{162}(595P_0^\pi + 41P_1^\pi + 293P_0^K - 65P_1^K)$	$\delta m - \frac{1}{162}(595P_0^\pi + 41P_1^\pi + 293P_0^K - 65P_1^K)$	$2\delta m - \frac{1}{81}(180P_0^\pi + 36P_1^\pi + 235P_0^K - 31P_1^K + 29P_0^{s\bar{s}} - 17P_1^{s\bar{s}})$

obtain the relation between ω_3 and ω_5 as

$$\omega_5 = \sqrt{\frac{5}{6}}\omega_3, \tag{9}$$

which leads to $\omega_5 \simeq 225$ MeV.

B. Energies of five-quark components

The five-quark configurations listed in Tables III–V share the same energy if we neglect the hyperfine interaction between the quarks and the constituent mass difference between the light and strange quarks; we denote this energy as E_0. Then, the energy of a given five-quark configuration with number i reads

$$E_i = E_0 + \Delta E_i, \tag{10}$$

where,

$$\Delta E_i \equiv E_i^h + n_i^s \delta m, \tag{11}$$

TABLE IV. T_i and ΔE_i for the five-quark configurations with $s\bar{s}$ pairs and $L_{4q} = 1$ in the octet baryons. Conventions are the same as in Table III.

i	N	Λ	Σ	Ξ
1	$\frac{\sqrt{6}}{18}$	0	$\frac{\sqrt{3}}{9}$	0
	$2\delta m - \frac{1}{3}(28P_0^{\pi} + 14P_1^{\pi} + 28P_0^{K} + 14P_1^{K})$	–	$3\delta m - \frac{1}{9}(8P_0^{\pi} + 4P_1^{\pi} + 152P_0^{K} + 76P_1^{K} + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	–
2	0	0	$\frac{\sqrt{2}}{9}$	$\frac{2}{9}$
	–	–	$3\delta m - \frac{1}{9}(8P_0^{\pi} + 4P_1^{\pi} + 112P_0^{K} + 56P_1^{K} + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	$4\delta m - \frac{1}{9}(104P_0^{K} + 52P_1^{K} + 24P_0^{s\bar{s}} + 12P_1^{s\bar{s}})$
3	$\frac{\sqrt{6}}{18}$	$\frac{\sqrt{3}}{9}$	0	0
	$2\delta m - \frac{1}{9}(84P_0^{\pi} + 42P_1^{\pi} + 44P_0^{K} + 22P_1^{K})$	$3\delta m - \frac{1}{9}(48P_0^{\pi} + 24P_1^{\pi} + 72P_0^{K} + 36P_1^{K} + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	–	–
4	$\frac{\sqrt{6}}{18}$	$\frac{1}{9}$	0	0
	$2\delta m - \frac{1}{36}(193P_0^{\pi} + 31P_1^{\pi} + 283P_0^{K} + 69P_1^{K})$	$3\delta m - \frac{1}{18}(50P_0^{\pi} + 14P_1^{\pi} + 183P_0^{K} + 41P_1^{K} - 5P_0^{s\bar{s}} + 5P_1^{s\bar{s}})$	–	–
5	$\frac{\sqrt{6}}{18}$	$\frac{1}{9}$	0	0
	$2\delta m - \frac{1}{18}(91P_0^{\pi} + 17P_1^{\pi} + 113P_0^{K} + 19P_1^{K})$	$3\delta m - \frac{1}{9}(20P_0^{\pi} + 8P_1^{\pi} + 73P_0^{K} + 11P_1^{K} + 9P_0^{s\bar{s}} + 3P_1^{s\bar{s}})$	–	–
6	$\frac{1}{9}$	0	$\frac{\sqrt{2}}{9}$	0
	$2\delta m - \frac{1}{18}(79P_0^{\pi} + 5P_1^{\pi} + 79P_0^{K} + 5P_1^{K})$	–	$3\delta m - \frac{1}{27}(13P_0^{\pi} - P_1^{\pi} + 211P_0^{K} + 17P_1^{K} + 13P_0^{s\bar{s}} - P_1^{s\bar{s}})$	–
7	0	0	$\frac{\sqrt{2}}{9}$	$\frac{2}{9}$
	–	–	$3\delta m - \frac{1}{9}(-4P_1^{\pi} + 73P_0^{K} + 7P_1^{K} - 4P_1^{s\bar{s}})$	$4\delta m - \frac{1}{9}(78P_0^{K} + 14P_1^{K} - 5P_0^{s\bar{s}} - 15P_1^{s\bar{s}})$
8	$\frac{\sqrt{6}}{18}$	$\frac{\sqrt{3}}{9}$	0	0
	$2\delta m - \frac{1}{36}(229P_0^{\pi} + 27P_1^{\pi} + 63P_0^{K} - 31P_1^{K})$	$3\delta m - \frac{1}{18}(78P_0^{\pi} + 18P_1^{\pi} + 73P_0^{K} - 9P_1^{K} - 5P_0^{s\bar{s}} - 5P_1^{s\bar{s}})$	–	–
9	0	0	$-\frac{\sqrt{6}}{27}$	$-\frac{2\sqrt{3}}{27}$
	–	–	$3\delta m - \frac{1}{81}(29P_0^{\pi} - 17P_1^{\pi} + 134P_0^{K} + 10P_1^{K} + 13P_0^{s\bar{s}} - 25P_1^{s\bar{s}})$	$4\delta m - \frac{1}{81}(373P_0^{K} + 47P_1^{K} + 71P_0^{s\bar{s}} - 59P_1^{s\bar{s}})$
10	$-\frac{\sqrt{2}}{18}$	$-\frac{1}{9}$	0	0
	$2\delta m - \frac{1}{162}(595P_0^{\pi} + 41P_1^{\pi} + 293P_0^{K} - 65P_1^{K})$	$3\delta m - \frac{1}{81}(180P_0^{\pi} + 36P_1^{\pi} + 235P_0^{K} - 31P_1^{K} + 29P_0^{s\bar{s}} - 17P_1^{s\bar{s}})$	–	–

with E_i^h the energy caused by hyperfine interaction between quarks, n_i^s the number of strange quarks in the corresponding five-quark system, and $\delta m = m_s - m$ the mass difference between the constituent strange and light quarks. To consider the hyperfine interaction between quarks, we employ the flavor-spin-dependent version in the chiral constituent quark model [62],

$$H_h = -\sum_{i<j} \vec{\sigma}_i \cdot \vec{\sigma}_j \left[\sum_{a=1}^{3} V_\pi(r_{ij}) \lambda_i^a \lambda_j^a + \sum_{a=4}^{7} V_K(r_{ij}) \lambda_i^a \lambda_j^a + V_\eta(r_{ij}) \lambda_i^8 \lambda_j^8 \right], \tag{12}$$

where λ_i^a denotes the Gell-Mann matrix acting on the ith quark, $V_M(r_{ij})$ is the potential of the M meson-exchange interaction between ith and jth quark. Since the hyperfine interaction between a quark and an antiquark is negligible, after taking into account the overall symmetry of the wave functions, H_h can simply be replaced by an operator acting on the first two quarks

$$H_h = -6\vec{\sigma}_1 \cdot \vec{\sigma}_2 \left[\sum_{a=1}^{3} V_\pi(r_{12}) \lambda_1^a \lambda_2^a + \sum_{a=4}^{7} V_K(r_{12}) \lambda_1^a \lambda_2^a + V_\eta(r_{12}) \lambda_1^8 \lambda_2^8 \right]. \tag{13}$$

TABLE V. T_i and ΔE_i for the five-quark configurations with $L_{4q} = 0$ in the octet baryons. Upper (first set for i = 11–17) and lower (second set for i = 11–17) panels are for the configurations with light $q\bar{q}$ and $s\bar{s}$ pairs, respectively. Conventions are the same as in Table III.

i	N	Λ	Σ	Ξ
11	0	$-\frac{\sqrt{5}}{18}$	$-\frac{\sqrt{15}}{18}$	$-\frac{\sqrt{15}}{18}$
	–	$\delta m - \frac{56}{9}P_0^{\pi} - \frac{88}{9}P_0^K$	$\delta m - \frac{56}{9}P_0^{\pi} - \frac{88}{9}P_0^K$	$2\delta m - \frac{32}{9}P_0^{\pi} - \frac{112}{9}P_0^K$
12	0	$-\frac{\sqrt{5}}{18}$	$-\frac{\sqrt{15}}{18}$	$-\frac{\sqrt{15}}{18}$
	–	$\delta m - 6P_0^{\pi} - \frac{22}{3}P_0^K$	$\delta m - 6P_0^{\pi} - \frac{22}{3}P_0^K$	$2\delta m - \frac{8}{3}P_0^{\pi} - \frac{28}{3}P_0^K - \frac{4}{3}P_0^{s\bar{s}}$
13	$-\frac{\sqrt{5}}{9}$	$-\frac{\sqrt{30}}{18}$	$-\frac{\sqrt{10}}{18}$	$-\frac{\sqrt{30}}{18}$
	$-\frac{28}{3}P_0^{\pi}$	$\delta m - \frac{14}{3}P_0^{\pi} - \frac{14}{3}P_0^K$	$\delta m - \frac{14}{3}P_0^{\pi} - \frac{14}{3}P_0^K$	$2\delta m - \frac{4}{9}P_0^{\pi} - \frac{76}{9}P_0^K - \frac{4}{9}P_0^{s\bar{s}}$
14	$-\frac{\sqrt{15}}{9}$	0	$-\frac{2\sqrt{30}}{27}$	$-\frac{\sqrt{30}}{18}$
	$-8P_0^{\pi}$	–	$\delta m + \frac{20}{9}P_0^{\pi} - \frac{92}{9}P_0^K$	$2\delta m + \frac{4}{9}P_0^{\pi} - \frac{80}{9}P_0^K + \frac{4}{9}P_0^{s\bar{s}}$
15	0	$-\frac{\sqrt{5}}{6}$	$-\frac{\sqrt{15}}{54}$	$-\frac{\sqrt{5}}{18}$
	–	$\delta m - \frac{64}{9}P_0^{\pi} - \frac{8}{9}P_0^K$	$\delta m - \frac{64}{9}P_0^{\pi} - \frac{8}{9}P_0^K$	$2\delta m - \frac{16}{3}P_0^{\pi} - \frac{32}{9}P_0^K + \frac{8}{9}P_0^{s\bar{s}}$
16	$\frac{\sqrt{5}}{9}$	0	$\frac{2\sqrt{10}}{27}$	$\frac{\sqrt{10}}{18}$
	$-\frac{16}{3}P_0^{\pi}$	–	$\delta m - \frac{4}{27}P_0^{\pi} - \frac{140}{27}P_0^K$	$2\delta m - \frac{4}{27}P_0^{\pi} - \frac{16}{3}P_0^K + \frac{4}{27}P_0^{s\bar{s}}$
17	0	$\frac{\sqrt{15}}{18}$	$\frac{\sqrt{5}}{54}$	$\frac{\sqrt{15}}{54}$
	–	$\delta m - \frac{106}{27}P_0^{\pi} - \frac{38}{27}P_0^K$	$\delta m - \frac{106}{27}P_0^{\pi} - \frac{38}{27}P_0^K$	$2\delta m - \frac{8}{3}P_0^{\pi} - \frac{68}{27}P_0^K - \frac{4}{27}P_0^{s\bar{s}}$
11	$-\frac{\sqrt{15}}{18}$	$-\frac{\sqrt{10}}{18}$	0	0
	$2\delta m - \frac{56}{9}P_0^{\pi} - \frac{88}{9}P_0^K$	$3\delta m - \frac{32}{9}P_0^{\pi} - \frac{112}{9}P_0^K$	–	–
12	$-\frac{\sqrt{15}}{18}$	$-\frac{\sqrt{10}}{18}$	0	0
	$2\delta m - 6P_0^{\pi} - \frac{22}{3}P_0^K$	$3\delta m - \frac{8}{3}P_0^{\pi} - \frac{28}{3}P_0^K - \frac{4}{3}P_0^{s\bar{s}}$	–	–
13	$-\frac{\sqrt{10}}{18}$	0	$-\frac{\sqrt{5}}{9}$	0
	$2\delta m - \frac{14}{3}P_0^{\pi} - \frac{14}{3}P_0^K$	–	$3\delta m - \frac{4}{9}P_0^{\pi} - \frac{76}{9}P_0^K - \frac{4}{9}P_0^{s\bar{s}}$	–
14	0	0	$-\frac{\sqrt{5}}{9}$	$-\frac{\sqrt{10}}{9}$
	–	–	$3\delta m + \frac{4}{9}P_0^{\pi} - \frac{80}{9}P_0^K + \frac{4}{9}P_0^{s\bar{s}}$	$4\delta m - \frac{92}{9}P_0^K + \frac{20}{9}P_0^{s\bar{s}}$
15	$-\frac{\sqrt{15}}{18}$	$-\frac{\sqrt{30}}{18}$	0	0
	$2\delta m - \frac{64}{9}P_0^{\pi} - \frac{8}{9}P_0^K$	$3\delta m - \frac{16}{3}P_0^{\pi} - \frac{32}{9}P_0^K + \frac{8}{9}P_0^{s\bar{s}}$	–	–
16	0	0	$\frac{\sqrt{15}}{27}$	$\frac{\sqrt{30}}{27}$
	–	–	$3\delta m - \frac{4}{27}P_0^{\pi} - \frac{16}{3}P_0^K + \frac{4}{27}P_0^{s\bar{s}}$	$4\delta m - \frac{140}{27}P_0^K - \frac{4}{27}P_0^{s\bar{s}}$
17	$\frac{\sqrt{5}}{18}$	$\frac{\sqrt{10}}{18}$	0	0
	$2\delta m - \frac{106}{27}P_0^{\pi} - \frac{38}{27}P_0^K$	$3\delta m - \frac{8}{3}P_0^{\pi} - \frac{68}{27}P_0^K - \frac{4}{27}P_0^{s\bar{s}}$	–	–

Then, ΔE_i in terms of E_i^h [Eq. (11)] is obtained by

$$\begin{aligned} E_i^h &= \langle QQQ(Q\bar{Q}), i, 0, 1|H_h|QQQ(Q\bar{Q}), i, 0, 1\rangle \\ &= -6\sum_{njklm}\Bigg[\left(C^{[1^4]}_{[31]_i^n[211]_n}\right)^2 C^{[31]_i^n}_{[\mathcal{FS}]_i^j[\mathcal{X}]_i^l} C^{[31]_i^n}_{[\mathcal{FS}]_i^k[\mathcal{X}]_i^m} \\ &\quad\times\Bigg(\langle[\mathcal{X}]_i^l|V_\pi(r_{12})|[\mathcal{X}]_i^m\rangle\Bigg\langle[\mathcal{FS}]_i^j\Bigg|\vec{\sigma}_1\cdot\vec{\sigma}_2\sum_{a=1}^{3}\lambda_1^a\lambda_2^a\Bigg|[\mathcal{FS}]_i^k\Bigg\rangle \\ &\quad+\langle[\mathcal{X}]_i^l|V_K(r_{12})|[\mathcal{X}]_i^m\rangle\Bigg\langle[\mathcal{FS}]_i^j\Bigg|\vec{\sigma}_1\cdot\vec{\sigma}_2\sum_{a=4}^{7}\lambda_1^a\lambda_2^a\Bigg|[\mathcal{FS}]_i^k\Bigg\rangle \\ &\quad+\langle[\mathcal{X}]_i^l|V_\eta(r_{12})|[\mathcal{X}]_i^m\rangle\langle[\mathcal{FS}]_i^j|\vec{\sigma}_1\cdot\vec{\sigma}_2\lambda_1^8\lambda_2^8|[\mathcal{FS}]_i^k\rangle\Bigg)\Bigg], \end{aligned} \tag{14}$$

where $[\mathcal{FS}]_i^N$ and $[\mathcal{X}]_i^N$ represent the Nth flavor-spin and orbital wave functions of the four-quark subsystem in the five-quark configuration with number i of the 17 five-quark configurations listed in Table II, respectively. $C^{[1^4]}_{[31]_i^n[211]^n}$, $C^{[31]_i^n}_{[\mathcal{FS}]_i^j[\mathcal{X}]_i^l}$, and $C^{[31]_i^n}_{[\mathcal{FS}]_i^k[\mathcal{X}]_m^i}$ are the S_4 Clebsch-Gordan coefficients.

As discussed in Sec. II A, we need to consider only the five-quark configurations with the spin of the four-quark subsystem being $[22]_S$ and $[31]_S$. Explicit calculations lead to the following matrix elements:

$$\langle[22]_{S1}|\vec{\sigma}_1\cdot\vec{\sigma}_2|[22]_{S1}\rangle = 1, \tag{15}$$

$$\langle[22]_{S2}|\vec{\sigma}_1\cdot\vec{\sigma}_2|[22]_{S2}\rangle = -3, \tag{16}$$

$$\langle[31]_{S1}|\vec{\sigma}_1\cdot\vec{\sigma}_2|[31]_{S1}\rangle = 1, \tag{17}$$

$$\langle[31]_{S2}|\vec{\sigma}_1\cdot\vec{\sigma}_2|[31]_{S2}\rangle = 1, \tag{18}$$

$$\langle[31]_{S3}|\vec{\sigma}_1\cdot\vec{\sigma}_2|[31]_{S3}\rangle = -3. \tag{19}$$

TABLE VI. Predictions for probabilities of different five-quark components in the nucleon, Λ, Σ, and Ξ. Reported values correspond to $\bar{d} - \bar{u}$ for the proton in the range 0.118 ± 0.012. Whenever the calculated probability varies in that range by less than 0.001, a single nonvanishing value is given. Upper (configurations 1 to 10) and lower (configurations 11 to 17) panels are for the configurations with $L_{4q} = 1$ and $L_{4q} = 0$, respectively.

Configuration		N	Λ	Σ	Ξ
1	$q\bar{q}$	0.146 ± 0.015	0.114 ± 0.013	0.067 ± 0.008	0.082 ± 0.009
	$s\bar{s}$	0.010 ± 0.001	0	0.020 ± 0.002	0
2	$q\bar{q}$	0.073 ± 0.007	0	0.055 ± 0.006	0.028 ± 0.003
	$s\bar{s}$	0	0	0.009 ± 0.001	0.016 ± 0.002
3	$q\bar{q}$	0	0.052 ± 0.006	0.003 ± 0.001	0.006 ± 0.001
	$s\bar{s}$	0.006 ± 0.001	0.013 ± 0.002	0	0
4	$q\bar{q}$	0	0.003± 0.001	0.010 ± 0.001	0.010 ± 0.002
	$s\bar{s}$	0.004 ± 0.001	0.003 ± 0.001	0	0
5	$q\bar{q}$	0	0.002	0.008 ± 0.001	0.008 ± 0.001
	$s\bar{s}$	0.003 ± 0.001	0.002 ± 0.001	0	0
6	$q\bar{q}$	0.006 ± 0.001	0.010 ± 0.001	0.004	0.011 ± 0.002
	$s\bar{s}$	0.002	0	0.004 ± 0.001	0
7	$q\bar{q}$	0.016 ± 0.002	0	0.017 ± 0.002	0.010 ± 0.002
	$s\bar{s}$	0	0	0.004 ± 0.001	0.009 ± 0.002
8	$q\bar{q}$	0	0.015 ± 0.002	0.001	0.002
	$s\bar{s}$	0.003 ± 0.001	0.006 ± 0.001	0	0
9	$q\bar{q}$	0.005 ± 0.001	0	0.005 ± 0.001	0.003 ± 0.001
	$s\bar{s}$	0	0	0.001	0.003 ± 0.001
10	$q\bar{q}$	0	0.004 ± 0.001	0	0.001 ± 0.001
	$s\bar{s}$	0.001	0.002	0	0
11	$q\bar{q}$	0	0.005 ± 0.001	0.019 ± 0.002	0.018 ± 0.002
	$s\bar{s}$	0.009 ± 0.001	0.006 ± 0.001	0	0
12	$q\bar{q}$	0	0.003 ± 0.001	0.007 ± 0.001	0.006 ± 0.001
	$s\bar{s}$	0.008 ± 0.001	0.006 ± 0.001	0	0
13	$q\bar{q}$	0.015 ± 0.002	0.025 ± 0.003	0.010 ± 0.001	0.028 ± 0.003
	$s\bar{s}$	0.004 ± 0.001	0	0.011 ± 0.001	0
14	$q\bar{q}$	0.041 ± 0.004	0	0.043 ± 0.005	0.026 ± 0.003
	$s\bar{s}$	0	0	0.010 ± 0.002	0.022 ± 0.003
15	$q\bar{q}$	0	0.036 ± 0.004	0.002 ± 0.001	0.005 ± 0.001
	$s\bar{s}$	0.007 ± 0.001	0.015 ± 0.002	0	0
16	$q\bar{q}$	0.012 ± 0.001	0	0.013 ± 0.002	0.008 ± 0.001
	$s\bar{s}$	0	0	0.003 ± 0.001	0.007 ± 0.001
17	$q\bar{q}$	0	0.010 ± 0.001	0	0.001 ± 0.001
	$s\bar{s}$	0.002	0.004 ± 0.001	0	0

Now we have to consider the matrix elements of the flavor operators, which are linear combinations of the spatial matrix elements of the two-body potential $V_M(r_{12})$, $M \equiv \pi, K, \eta$, which are defined as

$$P_l^M = \langle lm(r_{12})|V_M(r_{12})|lm(r_{12})\rangle, \tag{20}$$

where $|lm\rangle$ represents the spatial wave function. Within exact flavor $SU(3)$ symmetry, $P_l^\pi = P_l^K = P_l^\eta$ and explicit calculations for matrix elements of the flavor-dependent operator lead to the hyperfine interaction energies given in Ref. [51]. To analyze the flavor asymmetry of the sea-quark contents, including $\bar{u}$, $\bar{d}$, and $\bar{s}$, in the baryon octet, we have to take into account the flavor $SU(3)$ breaking, which implies $P_l^\pi \neq P_l^K \neq P_l^\eta$. In addition, we have to treat properly the three subsets of the sea components; namely, the η-exchange interaction for pairs of light quarks [$V_{u\bar{u}}(r_{12})$ or $V_{d\bar{d}}(r_{12})$], one light and one strange [$V_{u\bar{s}}(12)$ or $V_{d\bar{s}}(r_{12})$] and two strange quarks [$V_{s\bar{s}}(r_{12})$]. We take $P_l^{u\bar{u}} = P_l^{d\bar{d}} = P_l^\pi$ and $P_l^{u\bar{s}} = P_l^{d\bar{s}} = P_l^K$. The empirical values for P_l^M with $l = 0, 1$ are taken from Ref. [62]

$$P_0^\pi = 29\,\text{MeV}, \quad P_0^K = 20\,\text{MeV}, \quad P_0^{s\bar{s}} = 14\,\text{MeV}, \tag{21}$$

$$P_1^\pi = 45\,\text{MeV}, \quad P_1^K = 30\,\text{MeV}, \quad P_1^{s\bar{s}} = 20\,\text{MeV}. \tag{22}$$

C. Probabilities of sea-quark components

In Table VI our results for probabilities of $q\bar{q}$ ($q \equiv u, d$) and $s\bar{s}$ are given for each of the 17 five-quark configurations reported in Table II. Using expressions in Tables III–V, we get the probability of the sea quark in each baryon B

$$P_B^{Q\bar{Q}} = \frac{1}{\mathcal{N}} \sum_{i=1}^{17} \left[\left(\frac{T_i^{Q\bar{Q}}}{M_B - E_i^{Q\bar{Q}}} \right)^2 \right]. \tag{23}$$

TABLE VII. Predictions for the sea-quark content of the octet baryons. The experimental $\bar{d}-\bar{u}$ flavor asymmetry value for the proton $A_p = 0.118 \pm 0.012$, is used as input. (Notice that $A_n = -A_p$, $A_{\Sigma^-} = -A_{\Sigma^+}$, and $A_{\Xi^-} = -A_{\Xi^\circ}$.)

Baryon	$\bar{u}$	$\bar{d}$	$\bar{s}$	$\bar{d}-\bar{u}$	$\bar{u}+\bar{d}$	$\bar{u}+\bar{d}+\bar{s}$	Approach	Reference
p	0.098 ± 0.010	0.216 ± 0.022	0.057 ± 0.006	0.118 ± 0.012	0.314 ± 0.032	0.371 ± 0.038	E-χCQM	Present work
	0.228	0.358	–	0.130	0.586	–	χCQM	Shao *et al.* [35]
	0.033–0.325	0.163–0.455	–	0.130	0.196–0.880	–	MC	Shao *et al.* [35]
	0.176	0.294	–	0.118	0.470	–	G-BHPS	Chang-Peng [42]
	0.122	0.240	0.024	0.118	0.362	0.386	G-BHPS	Chang-Peng [43]
	0.162	0.280	0.029	0.118	0.442	0.379	G-BHPS	Chang-Peng [43]
				0.151			UqQM	Santopinto-Bijker [34]
Λ	0.139 ± 0.015	0.139 ± 0.015	0.057 ± 0.006	0	0.279 ± 0.030	0.336 ± 0.036	E-χCQM	Present work
	0.195	0.195	–	0	0.390	–	χCQM	Shao *et al.* [35]
	0.098–0.390	0.098–0.390	–	0	0.196–0.780	–	MC	Shao *et al.* [35]
Σ^+	0.100 ± 0.011	0.163 ± 0.018	0.063 ± 0.007	0.063 ± 0.007	0.263 ± 0.029	0.326 ± 0.036	E-χCQM	Present work
	0.065	0.325	–	0.260	0.390	–	χCQM	Shao *et al.* [35]
	0.049–0.164	0.341–0.839	–	0.293–0.675	0.390–1.001	–	MC	Shao *et al.* [35]
				0.126			UqQM	Santopinto-Bijker [34]
Σ^0	0.132 ± 0.015	0.132 ± 0.015	0.063 ± 0.007	0	0.263 ± 0.029	0.326 ± 0.036	E-χCQM	Present work
	0.195	0.195	–	0	0.390	–	χCQM	Shao *et al.* [35]
	0.195–0.501	0.195–0.501	–	0	0.390–1.001	–	MC	Shao *et al.* [35]
Ξ^0	0.131 ± 0.015	0.121 ± 0.014	0.057 ± 0.006	-0.009 ± 0.001	0.252 ± 0.028	0.309 ± 0.035	E-χCQM	Present work
	0.033	0.163	–	0.130	0.196	–	χCQM	Shao *et al.* [35]
	0.033–0.130	0.163–0.650	–	0.130–0.520	0.199–0.780	–	MC	Shao *et al.* [35]
				-0.001			UqQM	Santopinto-Bijker [34]

where the normalization factor reads

$$\mathcal{N} \equiv 1 + \sum_{i=1}^{17} \mathcal{N}_i \tag{24}$$

$$= 1 + \sum_{i=1}^{17} \left[\left(\frac{T_i^{u\bar{u}}}{M_B - E_i^{u\bar{u}}} \right)^2 + \left(\frac{T_i^{d\bar{d}}}{M_B - E_i^{d\bar{d}}} \right)^2 + \left(\frac{T_i^{s\bar{s}}}{M_B - E_i^{s\bar{s}}} \right)^2 \right]. \tag{25}$$

Notice that in Eq. (24) the first term is due to the valence three-quark states, while the second term comes from the five-quark mixtures.

III. NUMERICAL RESULTS AND DISCUSSION

A. Adjustable parameters

In addition to the values given in Eqs. (9), (21) and (22), for quarks masses difference, we used the common value $\delta m \equiv m_s - m_q = 120$ MeV.

To get the numerical results, we still need to determine the values for two other parameters, E_0 and V.

The first parameter E_0 [Eq. (10)] is determined from other sources, as explained below. This quantity can be calculate employing a constituent quark model approach

$$E_0 = \sum_{j=1}^{5} m_j + 7\omega_5 + 5V_0, \tag{26}$$

where m_j denote the constituent quark mass and V_0 a model parameter, which represents the energy contributed by the inharmonic part of the potential for the five-quark system. Consequently, E_0 is dependent on three parameters. The value for V_0 not being known well enough, we use the meson cloud approach to fix directly E_0. Actually, the first two five-quark configurations listed in Table II are very similar to the πN and $\pi\Delta$ meson clouds, and a commonly accepted [10] ratio for the probabilities of the former to the latter one in the nucleon is 2. Here we use this value to determine the probabilities of the various five-quark configurations for the octet baryons, which leads to

$$E_0 = 2127 \text{ MeV}. \tag{27}$$

The only adjustable parameter of our model is then V, determined using the data. The flavor asymmetry $\bar{d}-\bar{u}$ of the proton, related to the probabilities of $q\bar{q}$ components $\mathcal{P}_{5q}^{q\bar{q}}$, is given by the following expression:

$$\begin{aligned}
\mathcal{P}_{5q}^{d\bar{d}} &- \mathcal{P}_{5q}^{u\bar{u}} \\
&\equiv \bar{d}-\bar{u} \\
&= \frac{1}{\mathcal{N}} \Bigg\{ \left(\frac{T_1^{q\bar{q}}}{M_p - E_1} \right)^2 + \left(\frac{T_6^{q\bar{q}}}{M_p - E_6} \right)^2 + \left(\frac{T_{13}^{q\bar{q}}}{M_p - E_{13}} \right)^2 \\
&- \frac{1}{3} \Bigg[\left(\frac{T_2^{q\bar{q}}}{M_p - E_2} \right)^2 + \left(\frac{T_7^{q\bar{q}}}{M_p - E_7}) \right)^2 + \left(\frac{T_9^{q\bar{q}}}{M_p - E_9} \right)^2 \\
&+ \left(\frac{T_{14}^{q\bar{q}}}{M_p - E_{14}} \right)^2 + \left(\frac{T_{16}^{q\bar{q}}}{M_p - E_{16}} \right)^2 \Bigg] \Bigg\},
\end{aligned} \tag{28}$$

$T_i^{q\bar{q}}$ are linear functions of $V(\bar{u}, \bar{d})$, the value of which is adjusted by using as input the data [6] for the flavor asymmetry $\bar{d} - \bar{u}$ of the nucleon

$$\bar{d} - \bar{u} = 0.118 \pm 0.012, \tag{29}$$

leading to

$$V(\bar{u}, \bar{d}) = 570 \pm 46\,\text{MeV}. \tag{30}$$

B. Results and discussion

In Table VI our results for probabilities of five-quark components, arising from the 17 configurations given in Table II, are reported for the studied baryons.

The configuration $[31]_X[4]_{FS}[22]_F[22]_S$ turns out to be the dominant one for all of the considered ground state baryons. The following most important ones are $[31]_X[4]_{FS}[31]_F^2[31]_S$ for Λ and $[31]_X[4]_{FS}[31]_F^1[31]_S$ for the other three baryons; $[4]_X[31]_{FS}[22]_F[31]_S$ plays also a significant role for Ξ. Finally, the other major configurations are $[4]_X[31]_{FS}[31]_F^2[22]_S$ for Λ and $[4]_X[31]_{FS}[31]_F^1[22]_S$ for the three other baryons. Added up contributions from those configurations, embody the $q\bar{q}$ components at the level of 83% for N, 72% for Λ and about 65% for Σ and Ξ. In the case of $s\bar{s}$ the contributions from different configurations show much less variations than in the case of $q\bar{q}$.

Predictions of our model for the sea-quark content of the octet baryons, in particle basis, are given in Table VII, with, in addition, extracted values for $\bar{d} - \bar{u}$, $\bar{u} + \bar{d}$ and $\bar{u} + \bar{d} + \bar{s}$.

Our result for the total sea probability in the proton (Table VII, seventh column) is close to those reported by Chang and Peng [43]. This latter work is a generalization of the approach developed by Brodsky and collaborators [40,41] (G-BHPS) investigating $uudc\bar{c}$ five-quark components in the proton. The most significant difference between our results and those in Ref. [43] concerns the $s\bar{s}$ component.

For $u\bar{u}$ and $d\bar{d}$ components of the sea in all baryons studied here, predictions have been reported by Shao and collaborators [35], both in chiral quark (χCQM) and meson cloud (MC) approaches. The chiral quark results [35] show significant discrepancies with our findings. The most drastic case concerns the proton and only results for Ξ° agree in the two approaches within 2σ. Notice that in Ref. [35] effects arising from the $SU(3)$ symmetry breaking have not been included. Results coming from the meson cloud span a rather large ranges which include our results, except in the case of Σ° and, to a lesser extent, Ξ°. In Ref. [35] the same probability has been introduced for πN, $\pi\Lambda$, and $\pi\Sigma$, which is an ad hoc assumption.

Within a QCD-inspired unquenched quark model (UqQM) flavor asymmetries for ground-state baryons were investigated [34]. Compared to our results, the main trend of the UqQM predictions show an overestimate. However the relative flavor asymmetry A_{Ξ°/A_p turns out to be by far much closer within UqQM and our results as compared with those reported by Shao and collaborators [35].

In the case of Σ^+ sea, we find $\bar{d} > \bar{u} > \bar{s}$, as in the case of the proton. Our results endorse findings in meson cloud sector (e.g., within light-cone meson-baryon fluctuations [20] and meson-baryon effective Lagrangian [22] approaches).

Another relevant quantity is the suppression factor (κ) of the nucleon strange quark content with respect to the nonstrange sea quarks

$$\kappa = \frac{\int_0^1 [xs(x) + x\bar{s}(x)]dx}{\int_0^1 [x\bar{u}(x) + x\bar{d}(x)]dx} \approx \frac{2P_{s\bar{s}}}{P_{u\bar{u}} + P_{d\bar{d}}}, \tag{31}$$

where $\kappa = 1$ would indicate a flavor $SU(3)$ symmetric sea, while the CCFR collaboration [63] has reported $\kappa = 0.48 \pm 0.05$ (see also Ref. [64]). The present work leads to $\kappa = 0.4$, in good enough agreement with the data. In Ref. [65], investigating the NuTeV anomaly [66] within a pentaquark model [49], that quantity was fixed at $\kappa \approx 0.5$, and provided $P_{s\bar{s}} = (3\text{–}20)\%$. The upper limit of $P_{s\bar{s}}$ allows explaining about 10% of the anomaly within that approach. Other possible sources to partially explain the NuTeV anomaly can be found in Ref. [67]. Notice that the present work leads to $P_{s\bar{s}} = (5.7 \pm 0.6)\%$.

IV. CONCLUSION

An extended chiral constituent quark model, embodying genuine five-quark mixture in the ground-state baryon octet wave functions, was presented, focusing on the sea-quark content. The formalism leads to a model with only one adjustable parameter, the value of which is fixed using the measured flavor excess of $\bar{d}$ over $\bar{u}$ in the proton.

We examined all possible 34 five-quark configurations in baryon octet and showed that only 17 of them, corresponding to the orbital quantum number $l = 1$ and radial quantum number $n_r = 0$, are relevant to the higher Fock components in the ground-state octet baryons. Our formalism allows determining contributions from each of the 17 orbital-flavor-spin configurations and identifying the most significant ones for each baryon. One configuration, $[31]_X[4]_{FS}[22]_F[22]_S$, comes out as the dominant one for all the four investigated baryons. Five other configurations play major roles in one or another baryon. We put forward predictions of our complete model for the percentage per flavor, of the sea-quark content for N, Λ, Σ, and Ξ. Finally, our predictions showed that the five-quark mixture in those baryons is around 30%, of which about one fifth is due to the strange quark.

Better understanding of this nonperturbative mechanism is of course of paramount importance in the hadron spectroscopy and description of properties of baryons. But, this realm has also a crucial role in other issues related to foreseen measurements [e.g., using electromagnetic probes, proton-proton collisions, neutrino scattering, weakly interacting massive particles (WIMPs) search] as outlined below. A comprehensive tomography of the nucleon is a part of the physics program [68] of the Jefferson Laboratory (JLab) 12 GeV upgrade.

Strange sea-quark content of the nucleon is also an important component in the processes in high-energy hadron colliders, such as W production mechanisms investigated at the LHC. A recent work [69] shows that the W-boson production at the RHIC and LHC proton-proton colliders, would provide a unique opportunity in extracting the $\bar{d}/\bar{u}$ flavor asymmetry in the proton. Another recent investigation [70] emphasizes that finding, and access to rich information on the intrinsic sea-quark content of the proton, within the fixed-target experiment (AFTER) thanks to the LHC beam.

Using a Tevatron-based neutrino beam, the high-energy neutrino scattering experiment [71], Neutrino Scattering On Glass (NuSOnG), can allow measuring the strange sea in the nucleon through charged current opposite sign dimuon production via the following two-step reactions:

$$\nu_\mu + N \to \mu^- + c + X; \quad c \to s + \mu^+ + \nu_\mu, \tag{32}$$

$$\bar{\nu}_\mu + N \to \mu^+ + \bar{c} + X; \quad \bar{c} \to \bar{s} + \mu^- + \bar{\nu}_\mu, \tag{33}$$

improving significantly the data accuracy compared to that released by the NuTeV Collaboration [66].

Moreover, as emphasized in Ref. [72], the strange content of the nucleon is an important ingredient in the dark matter search. Actually, the WIMP coupling to the nucleon would proceed through coupling of the Higgs boson to the scalar quark content of the nucleon. The dark matter cross section has been found dominated by the strange quark content of the proton, see Ref. [73] and references therein.

Future measurements will allow us deepening our understanding, of both perturbative and nonperturbative mechanisms, on the origins of antiquarks in the baryons, and their intrinsic sea-quark content.

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