

Pion- and strangeness-baryon σ terms in the extended chiral constituent quark model

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(Received 29 April 2015; published 2 July 2015)

Within an extended chiral constituent quark formalism, we investigate contributions from all possible five-quark components in the octet baryons to the pion-baryon ($\sigma_{\pi B}$) and strangeness-baryon (σ_{sB}) sigma terms: $B \equiv N, \Lambda, \Sigma, \Xi$. The probabilities of the quark-antiquark components in the ground-state baryon octet wave functions are calculated by taking the baryons to be admixtures of three- and five-quark components, with the relevant transitions handled *via* the 3P_0 mechanism. Predictions for $\sigma_{\pi B}$ and σ_{sB} obtained by using input parameters taken from the literature are reported. Our results turn out to be, in general, consistent with the findings *via* lattice QCD and chiral perturbation theory.

DOI: 10.1103/PhysRevD.92.014002

PACS numbers: 12.39.-x, 12.38.Lg, 14.20.Jn, 14.65.Bt

I. INTRODUCTION

The pion-baryon sigma terms ($\sigma_{\pi B}$) provide critical information on the nature of explicit chiral symmetry breaking in QCD, the extent of the breaking, and the decomposition of the mass of the ground-state baryons, which can be related to the quark-antiquark ($Q\bar{Q}$) components in the baryons, with $Q\bar{Q} \equiv u\bar{u}, d\bar{d}, s\bar{s}$. Also of great interest are the strangeness-nucleon sigma terms (σ_{sN}) arising exclusively from the strange sea quark-antiquark pairs.

The pion-nucleon σ term is the most studied one since the late 1960s [1,2] and its seminal value was reported in Ref. [3]: $\sigma_{\pi N} = 45 \pm 8$ MeV, which was obtained by analysis of the πN data available in the late 1980s and by taking into account the current algebra result generated by the quark masses. As discussed later, various results reported in the literature agree with that canonical value within 2σ . A recent comprehensive study [4], within the covariant baryon chiral perturbation theory and using SAID phase shift analysis [5] as well as the LQCD data published in 2009 and 2011 led to $\sigma_{\pi N} = 45 \pm 6$ MeV. However, the extraction of $\sigma_{\pi N}$ from the πN scattering data appears still to be challenging [6–9]; for a comprehensive recent account on the πN phenomenology, see Ref. [10].

With respect to the strangeness sigma terms σ_{sB} , there is no experimental guidance. However, a recent work [11], based on a QCD sum rule approach, put forward a (almost) linear correlation between the ϕ -meson mass-peak shift in nuclear matter and the value of σ_{sN} .

On the other hand, for more than a decade, intensive theoretical efforts have been deployed to predict the sigma terms. Those investigations are based on chiral perturbation

theory, chiral extrapolation, and the chiral Lagrangian, often using LQCD data; see, e.g., Refs. [12–20] and references therein. A general trend in those results is reaching values for $\sigma_{\pi N}$ around 55 MeV.

In parallel, several collaborations are refining the LQCD calculations and putting forward predictions for sigma terms; see, e.g., Refs. [21–24] and references therein. The LQCD results for $\sigma_{\pi N}$ turn out to be mostly in the range of 30–40 MeV.

In the present paper we focus on the quark-antiquark $Q\bar{Q}$ components of the intrinsic five-quark Fock states in the baryon wave functions at the origin of nonperturbative phenomena; for a recent review see Ref. [25]. Our formalism is based on an extended chiral constituent quark approach and embodies all possible five-quark mixtures in the baryon wave functions, with the mechanism of transition between three- and five-quark components in the baryons treated within the 3P_0 quark-antiquark creation frame [26–28].

Actually, in a series of papers [29–32] we successfully studied contributions from the genuine five-quark components in the baryons to various observables, namely, the hadronic and electromagnetic decays of baryon resonances [29,30], flavor asymmetry of the nucleon sea $\bar{d} - \bar{u}$ [31] and the strangeness magnetic form factor of the proton [32].

In this paper we extend our studies to the pion-baryon sigma terms ($\sigma_{\pi B}$) and strangeness-baryon ones (σ_{sB}); $B \equiv N, \Lambda, \Sigma, \Xi$.

The present manuscript is organized in the following way: in Sec. II, after a brief presentation of the theoretical frame, we give explicit expressions for sigma terms, relating them to the quark-antiquark pair probabilities. Numerical results for $\sigma_{\pi B}$ and σ_{sB} are reported in Sec. III and compared to the outcomes from other approaches referred to above. Finally, Sec. IV contains a

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summary and conclusions. Quark-antiquark probabilities in the five-quark components for all four ground-state octet baryons are tabulated in Appendix.

II. THEORETICAL FRAME

The content of our extended chiral constituent quark model (E χ CQM) was developed in Refs. [31,32]. Hence, in Sec. II A, we briefly report on the main features of the formalism. In Sec. II B we give explicit expressions for the light and strange quark-antiquark pairs probabilities in the octet baryons. Sigma terms are then expressed in terms of those probabilities in Sec. II C.

A. Chiral constituent quark approach

The wave function for the baryon B is expressed as

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

where the first term is the conventional wave function for the baryon with three constituent quarks ($q \equiv u, d$) and the second term is a sum over all possible higher Fock components with a $Q\bar{Q}$ pair; $Q\bar{Q} \equiv u\bar{u}, d\bar{d}, s\bar{s}$. 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, while $C_{in_r,l}/\sqrt{\mathcal{N}}$ represents the probability amplitude for the corresponding five-quark component.

The coefficient $C_{in_r,l}$ for a given five-quark component can be related to the transition matrix element between the three- and five-quark configurations of the studied baryon. To calculate the corresponding transition matrix element, we use a 3P_0 version for the transition coupling operator \hat{T} ,

$$\hat{T} = -\gamma \sum_j \mathcal{F}_{j,5}^{00} \mathcal{C}_{j,5}^{00} C_{\text{OFSC}} \sum_m \langle 1, m; 1, -m | 00 \rangle \chi_{j,5}^{1,m} \times \mathcal{Y}_{j,5}^{1,-m}(\vec{p}_j - \vec{p}_5) b^\dagger(\vec{p}_j) d^\dagger(\vec{p}_5), \quad (2)$$

with γ a dimensionless constant of the model, $\mathcal{F}_{i,5}^{00}$ and $\mathcal{C}_{i,5}^{00}$ the flavor and color singlet of the quark-antiquark pair $Q_i\bar{Q}$

in the five-quark system, and C_{OFSC} 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.

The probability of the sea quark-antiquark pairs in the baryon B and the normalization factor read, respectively,

$$\mathcal{P}_B^{Q\bar{Q}} = \frac{1}{\mathcal{N}} \sum_{i=1}^{17} \left[\left(\frac{T_i^{Q\bar{Q}}}{M_B - E_i^{Q\bar{Q}}} \right)^2 \right], \quad (3)$$

$$\mathcal{N} \equiv 1 + \sum_{i=1}^{17} \mathcal{N}_i = 1 + \sum_{i=1}^{17} \sum_{Q\bar{Q}} \left[\left(\frac{T_i^{Q\bar{Q}}}{M_B - E_i^{Q\bar{Q}}} \right)^2 \right], \quad (4)$$

where the first term in Eq. (4) is due to the valence three-quark state, while the second term comes from the five-quark mixtures.

The probabilities $\mathcal{P}_B^{Q\bar{Q}}$ provide us with all needed matrix elements to extract the σ terms.

Finally, the 17 possible different five-quark configurations can be classified in four categories (Table I) with respect to the orbital and spin wave functions of the four-quark subsystem, with characteristics summarized below, using the shorthand notation for the Young tableaux.

- (i) $[31]_X$ and $[22]_S$: The total spin of the four-quark subsystem is 0.
- (ii) $[31]_X$ and $[31]_S$: The total spin of the four-quark subsystem is 1, combined to the orbital angular momentum $L_{[31]_X} = 1$, the total angular momentum of the four-quark subsystem can be $J = 0, 1, 2$, and to form the proton spin 1/2, only the former two are possible alternatives. In the present case, we take the lowest one $J = 0$.
- (iii) $[4]_X$ and $[22]_S$: That the total angular momentum of the four-quark subsystem is 0.
- (iv) $[4]_X$ and $[31]_S$: The total spin of the four-quark subsystem should be $S_{[31]} = 1$; here we assume that the combination of $S_{[31]}$ with the orbital angular momentum of the antiquark leads to $J = S_4 \oplus L_{\bar{q}} = 0$.

TABLE I. Categories (2nd line) and configurations (lines 3–8) for five-quark components.

i	Category/Config	i	Category/Config	i	Category/Config	i	Category/Config
	(I) $[31]_X[22]_S$:		(II) $[31]_X[31]_S$		(III) $[4]_X[22]_S$		(IV) $[4]_X[31]_S$
1	$[31]_X[4]_{FS}[22]_F[22]_S$	5	$[31]_X[4]_{FS}[31]_F^1[31]_S$	11	$[4]_X[31]_{FS}[211]_F[22]_S$	14	$[4]_X[31]_{FS}[211]_F[31]_S$
2	$[31]_X[31]_{FS}[211]_F[22]_S$	6	$[31]_X[4]_{FS}[31]_F^2[31]_S$	12	$[4]_X[31]_{FS}[31]_F^1[22]_S$	15	$[4]_X[31]_{FS}[22]_F[31]_S$
3	$[31]_X[31]_{FS}[31]_F^1[22]_S$	7	$[31]_X[31]_{FS}[211]_F[31]_S$	13	$[4]_X[31]_{FS}[31]_F^2[22]_S$	16	$[4]_X[31]_{FS}[31]_F^1[31]_S$
4	$[31]_X[31]_{FS}[31]_F^2[22]_S$	8	$[31]_X[31]_{FS}[22]_F[31]_S$			17	$[4]_X[31]_{FS}[31]_F^2[31]_S$
		9	$[31]_X[31]_{FS}[31]_F^1[31]_S$				
		10	$[31]_X[31]_{FS}[31]_F^2[31]_S$				

B. Quark-antiquark pair probabilities

Starting from Eq. (4), we give explicit expressions for the light quark-antiquark pairs ($u\bar{u}$ and $d\bar{d}$) probabilities for the octet baryon components ($\mathcal{P}_B^{q\bar{q}}$) in terms of the five-quark probabilities per configuration ($P_B(i)$, $i = 1-17$) and the relevant squared Clebsch-Gordan coefficients ($[\text{CG}]_{jk}$), i.e.,

$$\begin{aligned} [\text{CG}]_{11} &= 1, & [\text{CG}]_{12} &= 1/2, & [\text{CG}]_{13} &= 1/3, \\ [\text{CG}]_{14} &= 1/4, & [\text{CG}]_{23} &= 2/3, & [\text{CG}]_{34} &= 3/4. \end{aligned} \quad (5)$$

In the present work, the probability amplitudes are calculated within the most commonly accepted $Q\bar{Q}$ pair creation mechanism, namely, the 3P_0 model. Then, the $Q\bar{Q}$ pair is created anywhere in space with the quantum numbers of the QCD vacuum 0^{++} , corresponding to 3P_0 [26]. This model has been successfully applied to the decay of mesons and baryons [27,28] and has recently been employed to analyze the sea flavor content of the ground states of the $SU(3)$ octet baryons [31] by taking into account the $SU(3)$ symmetry breaking effects. The probabilities of light quark-antiquark pairs for each of the ground-state baryons in terms of the relevant configurations ($P_B(i)$) are given below.

(i) Proton:

$$\begin{aligned} \mathcal{P}_p^{u\bar{u}} &= [\text{CG}]_{23}[P_p(3) + P_p(5) + P_p(9) \\ &\quad + P_p(12) + P_p(16)], \end{aligned} \quad (6)$$

$$\begin{aligned} \mathcal{P}_p^{d\bar{d}} &= [\text{CG}]_{13}[P_p(3) + P_p(5) + P_p(9) + P_p(12) \\ &\quad + P_p(16)] + [\text{CG}]_{11}[P_p(1) + P_p(8) + P_p(15)]. \end{aligned} \quad (7)$$

(ii) Neutron:

$$\mathcal{P}_n^{u\bar{u}} = \mathcal{P}_p^{d\bar{d}}; \quad \mathcal{P}_n^{d\bar{d}} = \mathcal{P}_p^{u\bar{u}}. \quad (8)$$

(iii) Λ :

$$\begin{aligned} \mathcal{P}_\Lambda^{u\bar{u}} &= [\text{CG}]_{12}[P_\Lambda(1) + P_\Lambda(2) + P_\Lambda(4) + \mathcal{P}_\Lambda(6) \\ &\quad + P_\Lambda(7) + P_\Lambda(8) + P_\Lambda(10) + P_\Lambda(11) \\ &\quad + P_\Lambda(13) + P_\Lambda(14) + P_\Lambda(15) + P_\Lambda(17)], \end{aligned} \quad (9)$$

$$\mathcal{P}_\Lambda^{d\bar{d}} = \mathcal{P}_\Lambda^{u\bar{u}}. \quad (10)$$

(iv) Σ^+ :

$$\begin{aligned} \mathcal{P}_{\Sigma^+}^{u\bar{u}} &= [\text{CG}]_{34}[P_\Sigma(3) + P_\Sigma(5) + P_\Sigma(9) \\ &\quad + P_\Sigma(12) + P_\Sigma(16)], \end{aligned} \quad (11)$$

$$\begin{aligned} \mathcal{P}_{\Sigma^+}^{d\bar{d}} &= [\text{CG}]_{14}[P_\Sigma(3) + P_\Sigma(5) + P_\Sigma(9) + P_\Sigma(12) \\ &\quad + P_\Sigma(16)] + [\text{CG}]_{11}[P_\Sigma(1) + P_\Sigma(2) + P_\Sigma(4) \\ &\quad + P_\Sigma(6) + P_\Sigma(7) + P_\Sigma(8) + P_\Sigma(10) \\ &\quad + P_\Sigma(11) + P_\Sigma(13) + P_\Sigma(14) \\ &\quad + P_\Sigma(15) + P_\Sigma(17)]. \end{aligned} \quad (12)$$

(v) Σ^0 :

$$\mathcal{P}_{\Sigma^0}^{u\bar{u}} = \mathcal{P}_{\Sigma^0}^{d\bar{d}} = [\text{CG}]_{12} \sum_{i=1}^{17} P_\Sigma(i) \quad (13)$$

$$= \frac{1}{2}(\mathcal{P}_{\Sigma^+}^{u\bar{u}} + \mathcal{P}_{\Sigma^+}^{d\bar{d}}). \quad (14)$$

(vi) Σ^- :

$$\mathcal{P}_{\Sigma^-}^{u\bar{u}} = \mathcal{P}_{\Sigma^+}^{d\bar{d}}; \quad \mathcal{P}_{\Sigma^-}^{d\bar{d}} = \mathcal{P}_{\Sigma^+}^{u\bar{u}}. \quad (15)$$

(vii) Ξ^0 :

$$\begin{aligned} \mathcal{P}_{\Xi^0}^{u\bar{u}} &= [\text{CG}]_{23}[P_\Xi(1) + P_\Xi(3) + P_\Xi(5) + P_\Xi(9) \\ &\quad + P_\Xi(12) + P_\Xi(15) + P_\Xi(16)] \\ &\quad + [\text{CG}]_{11}[P_\Xi(6) + P_\Xi(8)], \end{aligned} \quad (16)$$

$$\begin{aligned} \mathcal{P}_{\Xi^0}^{d\bar{d}} &= [\text{CG}]_{13}[P_\Xi(1) + P_\Xi(3) + P_\Xi(5) + P_\Xi(9) \\ &\quad + P_\Xi(12) + P_\Xi(15) + P_\Xi(16)] \\ &\quad + [\text{CG}]_{11}[P_\Xi(2) + P_\Xi(4) + P_\Xi(7) + P_\Xi(10) \\ &\quad + P_\Xi(11) + P_\Xi(13) + P_\Xi(14) + P_\Xi(17)]. \end{aligned} \quad (17)$$

(viii) Ξ^- :

$$\mathcal{P}_{\Xi^-}^{u\bar{u}} = \mathcal{P}_{\Xi^0}^{d\bar{d}}; \quad \mathcal{P}_{\Xi^-}^{d\bar{d}} = \mathcal{P}_{\Xi^0}^{u\bar{u}}. \quad (18)$$

For the $s\bar{s}$ component, the probabilities $\mathcal{P}_B^{s\bar{s}}$ are obtained by summing up linearly the relevant nonvanishing contributions, $P_B^{s\bar{s}}(i)$ ($i = 1, 17$).

C. Sigma terms

Having obtained the required ingredients, we focus on the pion-baryon and the strangeness-baryon σ terms as a function of the quark-antiquark pairs probabilities.

The pion-nucleon and strangeness-nucleon σ terms are defined as follows:

$$\sigma_{\pi N} = m_l \langle N | u\bar{u} + d\bar{d} | N \rangle, \quad (19)$$

$$\sigma_{sN} = m_s \langle N | s\bar{s} | N \rangle, \quad (20)$$

with $m_l \equiv (m_u + m_d)/2$ the average current mass of the up and down quarks and m_s the current mass of the strange quark.

$\sigma_{\pi N}$ can be related to the nucleon expectation value of the purely octet operator ($\hat{\sigma}$) and to the strangeness content of the nucleon (y_N), respectively,

$$\hat{\sigma} = m_l \langle N | u\bar{u} + d\bar{d} - 2s\bar{s} | N \rangle, \quad (21)$$

$$y_N = \frac{2 \langle N | s\bar{s} | N \rangle}{\langle N | u\bar{u} + d\bar{d} | N \rangle}. \quad (22)$$

Hence,

$$\sigma_{\pi N} = \frac{\hat{\sigma}}{1 - y_N}, \quad (23)$$

$$\sigma_{sN} = \frac{m_s}{m_l} y_N \sigma_{\pi N}. \quad (24)$$

In the following we give explicit expressions for $\sigma_{\pi B}$ and σ_{sB} in terms of the five-quark probabilities $\mathcal{P}_B^{Q\bar{Q}}$.

(i) Nucleon:

$$\sigma_{\pi N} = \frac{3 + 2(\mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}})}{3 + 2(\mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}} - 2\mathcal{P}_N^{s\bar{s}})} \hat{\sigma}, \quad (25)$$

$$y_N = \frac{2\mathcal{P}_N^{s\bar{s}}}{3 + 2(\mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}})}. \quad (26)$$

(ii) S = -1 hyperons ($Y \equiv \Lambda, \Sigma$):

$$\sigma_{\pi Y} = \frac{2 + 2(\mathcal{P}_Y^{u\bar{u}} + \mathcal{P}_Y^{d\bar{d}})}{3 + 2(\mathcal{P}_Y^{u\bar{u}} + \mathcal{P}_Y^{d\bar{d}})} \sigma_{\pi N}, \quad (27)$$

$$\begin{aligned} \sigma_{sY} &= \frac{1 + 2\mathcal{P}_Y^{s\bar{s}}}{2\mathcal{P}_Y^{s\bar{s}}} \sigma_{sN} \\ &= \frac{m_s}{m_l} \frac{1 + 2\mathcal{P}_Y^{s\bar{s}}}{3 + 2(\mathcal{P}_Y^{u\bar{u}} + \mathcal{P}_Y^{d\bar{d}})} \sigma_{\pi N}. \end{aligned} \quad (28)$$

(iii) S = -2 hyperons Ξ :

$$\sigma_{\pi \Xi} = \frac{1 + 2(\mathcal{P}_\Xi^{u\bar{u}} + \mathcal{P}_\Xi^{d\bar{d}})}{3 + 2(\mathcal{P}_\Xi^{u\bar{u}} + \mathcal{P}_\Xi^{d\bar{d}})} \sigma_{\pi N}, \quad (29)$$

$$\sigma_{s\Xi} = \frac{2 + 2\mathcal{P}_\Xi^{s\bar{s}}}{2\mathcal{P}_\Xi^{s\bar{s}}} \sigma_{sN} = \frac{m_s}{m_l} \frac{2 + 2\mathcal{P}_\Xi^{s\bar{s}}}{3 + 2(\mathcal{P}_\Xi^{u\bar{u}} + \mathcal{P}_\Xi^{d\bar{d}})} \sigma_{\pi N}. \quad (30)$$

III. RESULTS AND DISCUSSION

The probabilities per configuration, introduced in Sec. II B and intervening in Eqs. (25)–(30), are reported in Appendix, Tables V and VI. Using values for the probabilities in the latter Tables and equations in Secs. II B and II C, we calculated the σ terms per configuration and per baryon.

Before moving to the presentation of our results a comment on the uncertainties is in order. The parameters of our extended constituent quark model are reported in Ref. [31]. The only source of uncertainty in the probabilities (Tables V and VI) comes from a common factor of the matrix elements of the transitions between three- and five-quark components and was found [31] to be $V = 570 \pm 46$ MeV, by successfully fitting the experimental data for the proton flavor asymmetry $\bar{d} - \bar{u}$. For the σ terms, two additional entities contribute to the uncertainties, namely, the nonsinglet component $\hat{\sigma} = 33 \pm 5$ MeV as extracted within the chiral perturbation theory [33] and the PDG masses ratio [34] $m_s/m_l = 27.5 \pm 1.0$. Accordingly, no parameters were adjusted in the frame of the present work.

Detailed results for the nucleon are given in Table II. From Eq. (26) it can be inferred that the strangeness content parameter y_N per configuration (Table II, column 3) is $\approx 2/3 \mathcal{P}_B^{s\bar{s}}(i)$, given that for any configuration, $2(\mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}}) \ll 3$ (Table V, column 6). That approximation almost holds also for the results per category, but breaks at the level of 25% for the full calculation embodying all 17 configurations (Table II, last row of column 3), due to the (sizable) probabilities of five-quark components in the nucleon (Table V, last row); $\mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}} = 0.313$ and $\mathcal{P}_N^{s\bar{s}} = 0.058$. It is worth noting that out of the 17 five-quark configurations in the nucleon, only 3 of them contribute to both light and $s\bar{s}$ pair probabilities, whereas 5 of them have only $u\bar{u}$ and $d\bar{d}$ components, while the remaining 9 configurations are exclusively composed of $s\bar{s}$ pairs; see Table V. Accordingly, any configuration truncated set would alter not only the respective probabilities in light and/or strange sectors, but also would change their relative probabilities and, hence, y_N .

The strangeness-nucleon sigma term being proportional to y_N [Eq. (24)], σ_{sN} shows similar behaviors with respect to the probabilities of light and strange quark–antiquark pairs (Table II, last column). Moreover, while σ_{sN} per configuration stays between 7 and 9 MeV, the complete calculation with all 17 configurations leads to a value more than 3 times larger (Table II, last row).

TABLE II. Predictions for the nucleon strangeness content parameter y_N , $\sigma_{\pi N}$ and σ_{sN} (MeV), per configuration $i = 1, 17$ and per category I to IV.

i	Category	y_N	$\sigma_{\pi N}$	σ_{sN}
	(I) $[31]_X[22]_S$:			
1		0.006 (1)	33.4 (5.1)	5.5 (1.5)
2		0.002 (0)	33.2 (5.0)	2.2 (0.6)
3		0	33.0 (5.0)	0
4		0.002 (0)	33.1 (5.0)	1.6 (0.5)
	Category I	0.010 (1)	33.6 (5.2)	8.9 (2.5)
	(II) $[31]_X[31]_S$:			
5		0	33.0 (5.0)	0
6		0.004 (0)	33.3 (5.1)	3.8 (1.1)
7		0.002 (0)	33.1 (5.0)	2.0 (0.6)
8		0.001 (0)	33.1 (5.0)	1.1 (0.3)
9		0	33.0 (5.0)	0
10		0.001 (0)	33.0 (5.0)	0.5 (0.1)
	Category II	0.008 (1)	33.5 (5.1)	7.0 (2.0)
	(III) $[4]_X[22]_S$:			
11		0.006 (1)	33.4 (5.1)	5.2 (1.5)
12		0	33.0 (5.0)	0
13		0.004 (0)	33.3 (5.1)	4.0 (1.2)
	Category III	0.010 (1)	33.7 (5.2)	9.0 (2.6)
	(IV) $[4]_X[31]_S$:			
14		0.005 (1)	33.3 (5.1)	4.7 (1.4)
15		0.003 (0)	33.2 (5.0)	2.6 (0.8)
16		0	33.0 (5.0)	0
17		0.001 (0)	33.1 (5.0)	1.2 (0.3)
	Category IV	0.009 (1)	33.6 (5.2)	8.5 (2.5)
	All configurations	0.031(3)	35.2 (5.5)	30.5 (8.5)

The above two paragraphs allow establishing that any configuration truncated model will significantly underestimate both y_N and σ_{sN} . A similar conclusion was reached in our study [32] on the strangeness magnetic form factor of the proton, where the truncation effects were found to be even more drastic.

Given that the nucleon structure is dominated by the three-light-quark component, the pion-nucleon σ term shows much less sensitivity to the probabilities, leading to results per configuration or per category close to the final value (Table II, column 4). Actually, Eq. (25) puts $\sigma_{\pi N} \approx \hat{\sigma}$. Note that the nucleon expectation value of the purely octet operator $\hat{\sigma}$ is still under debate [16].

Hyperon σ terms are related to $\sigma_{\pi N}$ [Eqs. (27)–(30)], and taking $m_s/m_l \approx 27$, one obtains the following approximations, where $Y \equiv \Lambda, \Sigma$:

$$\begin{aligned} \sigma_{\pi Y} &\approx (2/3)\sigma_{\pi N}, & \sigma_{sY} &\approx 9\sigma_{\pi N}, & \sigma_{\pi \Xi} &\approx (1/3)\sigma_{\pi N}, \\ \sigma_{s\Xi} &\approx 18\sigma_{\pi N}. \end{aligned} \quad (31)$$

Accordingly, the hyperon sigma terms vary slightly from one configuration/category to another, as was discussed for $\sigma_{\pi N}$, so we do not show detailed results per configuration for hyperons but only summarize the numerical results per category in Table III.

The pion-hyperon σ terms per category turn out to be smaller than the final results, while the strangeness-baryon terms oscillate around the final value, with deviations staying within the uncertainties.

In Table IV, we compare our results with recent findings by other authors. Note that, wherever appropriate, using statistical and systematic uncertainties reported in those

papers, we give $\delta = \sqrt{\delta_{\text{stat}}^2 + \delta_{\text{sys}}^2}$.

Semke and Lutz [12] determined the sigma terms via a relativistic chiral Lagrangian and large- N_c sum rules at $N^3\text{LO}$, using different LQCD data as input. That work also led to the small value for y_N and to σ terms compatible with our results, though within 2σ for the largest discrepancies, i.e., $\sigma_{s\Lambda}$, $\sigma_{\pi\Sigma}$, and $\sigma_{\pi\Xi}$. By considering the finite volume effects, Lutz and collaborators [13] improved significantly the relativistic chiral Lagrangian approach. The 12 free parameters of the model were successfully extracted by fitting about 220 data points reported by six different LQCD groups. It is worth noting that a full estimate of the systematic uncertainties in that approach requires investigating the corrections to the large- N_c sum rules... a task not yet performed. Hence, the uncertainties turn out to be rather small (Table IV). The most striking feature due to the finite volume effects is the large value obtained for σ_{sN} , which falls in the large ranges determined by BMW and QCDSF-UKQCD groups but is not consistent with findings from other predictions quoted in Table IV.

Ren and collaborators [14,15] performed studies within the extended-on-mass-shell renormalization scheme in the baryon chiral perturbation theory up to $N^3\text{LO}$. The earlier

 TABLE III. Predictions per category for the σ terms of the octet baryons (MeV).

Category	N		Λ		Σ		Ξ	
	$\sigma_{\pi N}$	σ_{sN}	$\sigma_{\pi\Lambda}$	$\sigma_{s\Lambda}$	$\sigma_{\pi\Sigma}$	$\sigma_{s\Sigma}$	$\sigma_{\pi\Xi}$	$\sigma_{s\Xi}$
I	33.6 ± 5.2	8.9 ± 2.5	22.9 ± 3.6	283 ± 51	22.1 ± 3.4	292 ± 54	12.2 ± 2.0	562 ± 101
II	33.5 ± 5.1	7.0 ± 2.0	22.6 ± 3.5	301 ± 56	22.8 ± 3.5	299 ± 56	11.8 ± 1.9	582 ± 109
III	33.7 ± 5.2	9.0 ± 2.6	22.7 ± 3.5	313 ± 60	23.3 ± 3.4	307 ± 58	12.0 ± 1.9	614 ± 116
IV	33.6 ± 5.2	8.5 ± 2.5	22.9 ± 3.6	309 ± 59	22.5 ± 3.5	311 ± 59	12.2 ± 2.0	609 ± 115
All	35.2 ± 5.5	30.5 ± 8.5	25.0 ± 4.1	297 ± 55	24.5 ± 4.0	301 ± 57	14.8 ± 2.6	564 ± 102

TABLE IV. Predictions for the $\sigma_{\pi B}$ and σ_{sB} of the octet baryons (MeV).

Reference (Collaboration)	Approach	y_N	$\sigma_{\pi N}$	σ_{sN}	$\sigma_{\pi\Lambda}$	$\sigma_{s\Lambda}$	$\sigma_{\pi\Sigma}$	$\sigma_{s\Sigma}$	$\sigma_{\pi\Xi}$	$\sigma_{s\Xi}$
Present work	E χ CQM	0.03 ± 0.00	35 ± 5	30 ± 8	25 ± 4	297 ± 55	24 ± 4	301 ± 57	15 ± 3	564 ± 102
Semke-Lutz [12]	χ Lagrangian	0.05 ± 0.04	32 ± 2	22 ± 20	22 ± 2	214 ± 24	15 ± 2	292 ± 19	9 ± 2	414 ± 35
Lutz <i>et al.</i> [13]	χ Lagrangian		39 ± 1	84 ± 3	23 ± 1	230 ± 3	18 ± 1	355 ± 5	6 ± 1	368 ± 8
Ren <i>et al.</i> [14]	χ PT	0.24 ± 0.12	43 ± 6	126 ± 59	19 ± 7	269 ± 70	18 ± 6	296 ± 54	4 ± 3	397 ± 60
Ren <i>et al.</i> [15]	χ PT	*	55 ± 1	27 ± 27	32 ± 2	185 ± 29	34 ± 3	210 ± 49	16 ± 2	333 ± 28
Alarcon <i>et al.</i> [16]	χ PT	0.02 ± 0.16	59 ± 7	16 ± 100						
Bali <i>et al.</i> [21] (QCDSF)	LQCD	< 0.14	38 ± 12	12 ± 28						
Durr <i>et al.</i> [22] (BMW)	LQCD	0.20 ± 0.17	39 ± 13	67 ± 58	29 ± 8	180 ± 68	28 ± 11	245 ± 68	16 ± 6	312 ± 82
Horsley <i>et al.</i> [23] (QCDSF-UKQCD)	LQCD	0.18 ± 0.17	31 ± 5	71 ± 68	24 ± 5	247 ± 77	21 ± 5	336 ± 77	16 ± 5	468 ± 69
Alexandrou <i>et al.</i> [24] (ETM)	LQCD	0.13 ± 0.05	37 ± 25	28 ± 13						

*See the text.

work [14] led to $y_N = 0.24 \pm 0.12$, $\sigma_{\pi N} = 43 \pm 6$ MeV and $\sigma_{sN} = 126 \pm 59$ MeV. In the latest work [15], adopting a more selective and restricted LQCD data set, $\sigma_{\pi N}$ increases slightly, while σ_{sN} drops down to 27 ± 27 and, hence, y_N gets reduced by roughly a factor of 5, close enough to our value.

Alarcon and collaborators in a recent calculation [16], based on the Lorentz covariant chiral perturbation theory at $\mathcal{O}(p^3)$ taking $\sigma_{\pi N} = 59 \pm 7$ MeV [35], obtained $y_N = 0.02 \pm 0.16$ and $\sigma_{sN} = 16 \pm 100$ MeV, both consistent with our results, albeit with large uncertainties.

Lattice quantum chromodynamics (LQCD) approaches have put forward predictions for the σ terms. Here, we limit ourselves to a few recent ones; rather exhaustive references can be found in, e.g., Refs. [15,16]. Bali and collaborators [21], studying nucleon mass data with quark flavors $N_f = 2$, put an upper limit on y_N (< 0.14). Durr [22] and Horsley [23] and collaborators extended the study to $N_f = 2 + 1$, and reported results for y_N and σ_{sN} with large uncertainties. Alexandrou and collaborators [24,36] performed calculations using $N_f = 2 + 1 + 1$ flavors of maximally twisted mass fermions. Though the y_N is rather large, σ_{sN} turns out to endorse our value.

A general trend in the LQCD calculation is that the systematic errors are substantially larger than the statistical one(s). Detailed investigations of the systematic errors in the computation of the sigma terms and y_N were reported in Refs. [24,36], quantifying contributions from various sources, namely, the chiral extrapolation, the excited states contamination and the discretization. Note that therein, y_N was obtained directly by a ratio of three point function, while other LQCD works for $N_f = 2 + 1$ provide indirect determination of that quantity [18,22,23]. As reported in Ref. [36], computing directly the ratio of the matrix element allows avoiding any assumptions on the domain of validity of effective field theory relations which is based on SU(2) or SU(3) chiral perturbation expansion and sometimes known only at leading order accuracy. Figure 2 in

Ref. [36] is instructive regarding the interplay among y_N , $\sigma_{\pi N}$, σ_{sN} and $\hat{\sigma}$.

Finally, with respect to the hyperon σ terms, predictions from various approaches (columns 6–11 in Table IV) result in values compatible with each other, albeit with rather large uncertainties on the strangeness-hyperon terms (except for the chiral Lagrangian [12,13] findings).

IV. SUMMARY AND CONCLUSIONS

In the present work, we investigated the σ terms of the ground-state octet baryons, employing the recently developed extended chiral constituent quark model, within which the baryons are considered as admixtures of three- and five-quark states. Probabilities of the five-quark components were calculated using the 3P_0 transition operator. The set of adjustable parameters in our approach were given in a previous work [31] dedicated to the flavor asymmetry of the nucleon sea $\bar{d} - \bar{u}$. That set was used in a subsequent paper [32] and allowed us to predicting successfully the strangeness magnetic form factor of the proton. In the present work we kept with the same set of parameters to put forward predictions for the ground-state baryon octet sigma terms.

The determination of the strangeness content of the nucleon, the y_N parameter, the extraction of the strangeness-nucleon sigma term, σ_{sN} , and of the $\sigma_{\pi N}$ are among the crucial issues in this realm, going beyond the hadron physics and were found to be important in topics such as dark matter in WIMP-nucleon [24,37] or neutralino-nucleon [38] cross sections, and in neutron matter [39].

Our full calculation gives $y_N = 0.031 \pm 0.003$, $\sigma_{sN} = 30 \pm 8$ MeV, and $\sigma_{\pi N} = 35 \pm 5$ MeV. So, the small value for y_N fulfills partially the OZI rule, in agreement with results from the chiral Lagrangian [12,13] and chiral perturbation approaches [15,16]. LQCD calculations [21–24] give larger central values but with roughly 40% to 100% uncertainties. For σ_{sN} our result is consistent with values reported within chiral Lagrangian [12] and the LQCD from the ETM Collaboration [24]. Other LQCD

works discussed in the present paper led to too large uncertainties for significant comparisons. It is worth noting that our value for σ_{sN} is very close to that determined in Ref. [111] as the value at which the ϕ -meson mass-peak shift in nuclear matter would undergo a sign change. Accordingly, the expected accurate enough data [40] on that effect would put significant constraints on σ_{sN} . Finally for $\sigma_{\pi N}$, our finding is compatible with various calculations based on the chiral Lagrangian [12,13], χ PT [14], and LQCD [21–24].

Within 2σ , the pion-hyperon sigma term ($\sigma_{\pi\Lambda}$, $\sigma_{\pi\Sigma}$, $\sigma_{\pi\Xi}$) predictions from all the approaches quoted in Table IV come out in comparable ranges. This is not fully the case for $\sigma_{s\Lambda}$, $\sigma_{s\Sigma}$, and $\sigma_{s\Xi}$; the main disagreements with our values being with results coming from a χ PT [14] and (partially) with a LQCD approach [22].

In summary, the general trend is a convergence among predictions by different approaches, within the reported uncertainties. However, to achieve conclusive numerical results, several challenging issues deserve further

investigation, such as the large number of unknown low-energy constants appearing at $\mathcal{O}(p^4)$ in the χ PT approaches [16], dominant systematic errors in the LQCD calculations [41], and the chiral Lagrangian approaches [12,13], as well as the separation of contributions from the three-quark and five-quark components in the baryons within the chiral constituent quark formalism.

Finally, we emphasize the sizable sensitivities of y_N and σ_{sN} to the five-quark configurations set in our approach, showing that any truncated set will lead to significant deviations from the predictions obtained by the full calculation embodying all 17 five-quark configurations.

ACKNOWLEDGMENTS

This work is partly supported by the National Natural Science Foundation of China under Grant No. 11205164 and the Fundamental Research Funds for the Central Universities under Grants No. XDJK2015C150 and No. SWU115020.

APPENDIX: PROBABILITIES OF THE QUARK-ANTIQUARK COMPONENTS IN THE GROUND-STATE OCTET BARYONS

TABLE V. Predictions for probabilities of different five-quark configurations for the nucleon and Λ (in %), with $\mathcal{P}_B^{q\bar{q}} = \mathcal{P}_B^{u\bar{u}} + \mathcal{P}_B^{d\bar{d}}$, $\mathcal{P}_B^{Q\bar{Q}} = \mathcal{P}_B^{q\bar{q}} + \mathcal{P}_B^{s\bar{s}}$.

i	Category	$P_p^{u\bar{u}}$	$P_p^{d\bar{d}}$	$P_N^{q\bar{q}}$	$P_N^{s\bar{s}}$	$P_N^{Q\bar{Q}}$	$P_\Lambda^{q\bar{q}}$	$P_\Lambda^{s\bar{s}}$	$P_\Lambda^{Q\bar{Q}}$
	(I) $[31]_X[22]_S$:								
1		0	14.6 (1.5)	14.6 (1.5)	1.0 (0.1)	15.6 (1.5)	11.3 (1.2)	0	11.3 (1.2)
2		0	0	0	0.3 (0.1)	0.3 (0.1)	0.3 (0.0)	0.3 (1)	0.6 (0.1)
3		1.1 (0.1)	0.5 (0.1)	1.6 (0.2)	0	1.6 (0.2)	0	0	0
4		0	0	0	0.3 (0.1)	0.3 (0.1)	1.4 (0.1)	0.6 (0.1)	2.0 (0.3)
	Category I	1.1 (0.1)	15.1 (1.5)	16.2 (1.6)	1.7 (0.2)	17.9 (0.8)	13.0 (1.4)	0.9 (0.2)	13.9 (1.6)
	(II) $[31]_X[31]_S$:								
5		4.8 (0.5)	2.4 (0.2)	7.2 (0.7)	0	7.2 (0.7)	0	0	0
6		0	0	0	0.6 (0.1)	0.6 (0.1)	5.1 (0.5)	1.3 (0.2)	6.4 (0.7)
7		0	0	0	0.3 (0.1)	0.3 (0.1)	0.3 (0.0)	0.2 (0.1)	0.5 (0.1)
8		0	0.6 (0.1)	0.6 (0.1)	0.2 (0.0)	0.8 (0.1)	1.0 (0.1)	0	1.0 (0.1)
9		0.3 (0.0)	0.2 (0.0)	0.5 (0.1)	0	0.5 (0.1)	0	0	0
10		0	0	0	0.1 (0.0)	0.1 (0.0)	0.4 (0)	0.2 (0)	0.6 (0.1)
	Category II	5.1 (0.5)	3.2 (0.3)	8.3 (0.8)	1.2 (0.1)	9.5 (1.0)	6.8 (0.6)	1.7 (0.2)	8.5 (0.9)
	(III) $[4]_X[22]_S$:								
11		0	0	0	0.9 (0.1)	0.9 (0.1)	0.6 (0.1)	0.6 (0.1)	1.2 (0.1)
12		2.7 (0.3)	1.4 (0.1)	4.1 (0.4)	0	4.1 (0.4)	0	0	0
13		0	0	0	0.7 (0.1)	0.7 (0.1)	3.6 (0.4)	1.5 (0.2)	5.1 (0.6)
	Category III	2.7 (0.3)	1.4 (0.1)	4.1 (0.4)	1.6 (0.2)	5.7 (0.6)	4.2 (0.4)	2.1 (0.2)	6.3(0.7)
	(IV) $[4]_X[31]_S$:								
14		0	0	0	0.8 (0.1)	0.8 (0.1)	1.5 (0.1)	0.6 (0.1)	2.1 (0.2)
15		0	1.5 (0.2)	1.5 (0.2)	0.4 (0.1)	1.9 (0.2)	2.4 (0.3)	0	2.4 (0.3)
16		0.8 (0.1)	0.4 (0.0)	1.2 (0.1)	0	1.2 (0.1)	0	0	0
17		0	0	0	0.2 (0.0)	0.2 (0.0)	1.0 (0.1)	0.4 (0.1)	1.4 (0.2)
	Category IV	0.8 (0.1)	1.9 (0.2)	2.7 (0.3)	1.4 (0.1)	4.1 (0.4)	4.9 (0.5)	1.0 (0.1)	5.9 (0.6)
	All configurations	9.7 (1.0)	21.6 (2.2)	31.3 (3.2)	5.8 (0.6)	37.1 (3.8)	28.9 (3.1)	5.7 (0.6)	34.6 (3.7)

TABLE VI. Same as Table V, but for Σ and Ξ hyperons (in %).

i	Category	$P_{\Sigma^+}^{u\bar{u}}$	$P_{\Sigma^+}^{d\bar{d}}$	$P_{\Sigma}^{q\bar{q}}$	$P_{\Sigma}^{s\bar{s}}$	$P_{\Sigma}^{Q\bar{Q}}$	$P_{\Xi^0}^{u\bar{u}}$	$P_{\Xi^0}^{d\bar{d}}$	$P_{\Xi}^{q\bar{q}}$	$P_{\Xi}^{s\bar{s}}$	$P_{\Xi}^{Q\bar{Q}}$
	(I) $[31]_X[22]_S$:										
1		0	6.7 (0.7)	6.7 (0.7)	2.0 (0.2)	8.7 (1.0)	5.4 (0.6)	2.7 (0.3)	8.0 (0.9)	0	8.0 (0.9)
2		0	1.0 (0.1)	1.0 (0.1)	0	1.0 (0.1)	0	0.9 (0.1)	1.0 (0.1)	0	1.0 (0.1)
3		1.3 (0.1)	0.4 (0.0)	1.7 (0.2)	0.4 (0.1)	2.1 (0.2)	0.7 (0.1)	0.3 (0.0)	1.0 (0.1)	0.9 (0.1)	1.9 (0.2)
4		0	0.1 (0)	0.1 (0)	0	0.1 (0.0)	0	0.2 (0.0)	0.2 (0.0)	0	0.2 (0.0)
	Category I	1.3 (0.1)	8.2 (0.9)	9.5 (1.0)	2.4 (0.3)	11.9 (1.2)	6.1 (0.7)	4.1 (0.4)	10.2 (1.1)	0.9 (0.1)	11.1 (1.1)
	(II) $[31]_X[31]_S$:										
5		4.1 (0.4)	1.4 (0.1)	5.5 (0.6)	0.9 (0.1)	6.4 (0.7)	1.8 (0.2)	0.9 (0.1)	2.7 (0.3)	1.6 (0.2)	4.3 (0.5)
6		0	0.3 (0.1)	0.3 (0.1)	0	0.3 (0.1)	0	0.6 (0.1)	0.6 (0.1)	0	0.6 (0.1)
7		0	0.8 (0.1)	0.8 (0.1)	0	0.8 (0.1)	0	0.8 (0.1)	0.8 (0.1)	0	0.8 (0.1)
8		0	0.4 (0.0)	0.4 (0.0)	0.5 (0.1)	0.9 (0.0)	0.7 (0.1)	0.4 (0.0)	1.1 (0.1)	0	1.1 (0.1)
9		0.4 (0.0)	0.1 (0.0)	0.5 (0.1)	0.1 (0)	0.6 (0.1)	0.2 (0.0)	0.1 (0.0)	0.3 (0.1)	0.3 (0.0)	0.6 (0.1)
10		0	0.0 (0.0)	0.0 (0.0)	0	0.0 (0.0)	0	0.1 (0.0)	0.1 (0.0)	0	0.1 (0.0)
	Category II	4.5 (0.3)	3.0 (0.3)	7.5 (0.8)	1.5 (0.1)	9.0 (1.0)	2.7 (0.3)	2.9 (0.3)	5.6 (0.6)	1.9 (0.3)	7.5 (1.0)
	(III) $[4]_X[22]_S$:										
11		0	2.2 (0.2)	2.2 (0.2)	0	2.2 (0.2)	0	2.1 (0.2)	2.1 (0.2)	0	2.1 (0.2)
12		3.2 (0.4)	1.1 (0.1)	4.3 (0.5)	1.1 (0.2)	5.4 (0.6)	1.7 (0.2)	0.9 (0.1)	2.6 (0.3)	2.2 (0.2)	4.8 (0.5)
13		0	0.2 (0)	0.2 (0.0)	0	0.2 (0.1)	0	0.5 (0.1)	0.5 (0.1)	0	0.5 (0.1)
	Category III	3.2 (0.4)	3.5 (0.4)	6.7 (0.7)	1.1 (0.2)	7.8 (0.7)	1.7 (0.2)	3.5 (0.4)	5.2 (0.6)	2.2 (0.2)	7.4 (0.7)
	(IV) $[4]_X[31]_S$:										
14		0	0	0	0	0	0	1.7 (0.2)	1.7 (0.2)	0	1.7 (0.2)
15		0	1.0 (0.1)	1.0 (0.1)	1.1 (0.1)	2.1 (0.2)	1.9 (0.2)	0.9 (0.1)	2.8 (0.3)	0	2.8 (0.3)
16		1.0 (0.1)	0.3 (0.0)	1.3 (0.1)	0.3 (0.1)	1.6 (0.2)	0.5 (0.1)	0.3 (0.0)	0.8 (0.1)	0.6 (0.1)	1.4 (0.2)
17		0	0.1 (0.0)	0.1 (0.0)	0	0.1 (0.0)	0	0.1 (0.0)	0.1 (0.0)	0	0.1 (0.0)
	Category IV	1.0 (0.1)	1.4 (0.1)	2.4 (0.3)	1.4 (0.1)	3.8 (0.4)	2.4 (0.3)	3.0 (0.3)	5.4 (0.6)	0.6 (0.1)	6.0 (0.6)
	All configurations	10.0 (1.1)	16.1 (1.7)	26.1 (2.8)	6.4 (0.7)	32.5 (3.5)	12.9 (1.4)	13.5 (1.5)	26.4 (2.9)	5.6 (0.6)	32.0 (3.5)

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