Intrinsic charm content of the nucleon and charmness-nucleon sigma term

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In the extended chiral constituent quark model, the intrinsic $c\bar{c}$ content of the nucleon is investigated. The probabilities of the quark-antiquark components in the nucleon wave functions are calculated by taking the nucleon to be admixtures of three- and five-quark components, with the relevant transitions handled via the $^3P_0$ mechanism. Predictions for the probability of the $c\bar{c}$ in the nucleon wave function and the charmness-nucleon sigma term are presented. Our numerical results turn out to be consistent with the predictions from various other approaches reported in the literature.

I. INTRODUCTION

Intrinsic quark-antiquark content of the nucleon is a prediction of quantum chromodynamics (QCD). Recent papers have reviewed the ongoing, extensive theoretical and experimental efforts of the past four decades on the light and heavy quark-antiquark pairs in baryons; see, e.g., [1–3].

In the 1980s, Brodsky *et al.* [4,5] postulated the existence of the $|uudc\bar{c}\rangle$ components in the proton in order to account for the large cross section of charmness production in proton-proton collisions. They coined the term "intrinsic" to be distinguished from the extrinsic contributions arising from gluon splitting in perturbative QCD. The outcome of the developed light-cone formalism is known as the BHPS model (named after Brodsky-Hoyer-Peterson-Sakai [4]) and suggests a probability of $\mathcal{P}_N^{c\bar{c}} \approx 1\%$ for the intrinsic $c\bar{c}$ (IC) component in the proton. Following that pioneering work, various phenomenological approaches were developed to extract $\mathcal{P}_N^{c\bar{c}}$ from data, such as photon-gluon fusion [6–8], the meson cloud model [9], and global QCD analysis of parton distribution [10], leading to $\mathcal{P}_N^{c\bar{c}} \approx 0.3$–$1(\%)$. Pumplin *et al.* [11] removed some simplification assumptions of the BHPS model and evaluated the sensitivity of the hard-scattering data to the IC, concluding that the corresponding probability can range between zero and 3%. More recently Dulat *et al.* [12] analyzed the parton distribution function (PDF) of the proton based on the next-to-next-to-leading order (NNLO) approximation of perturbative QCD and included the combined H1 and ZEUS data [13], reaching the conclusion that the PDF uncertainties are just as large as the IC effects. In summary, the nucleon's IC remains elusive; however, several studies predict measurable effects of such

possible components in the ongoing and/or forthcoming experiments at the LHC [12,14–20] and RHIC [15,21,22].

Another important entity in this realm is the charmness-nucleon sigma term σ_{cN}, related to the explicit breaking of chiral symmetry. In recent years, a few lattice QCD (LQCD) results were made available by the ETM [23] and χQCD [24] Collaborations. It can also be extracted from another LQCD calculation performed by the MILC Collaboration [25]. The central values coming from those works lie in the range of 67–94 MeV, albeit with large uncertainties $\approx(30$–$50)\%$, making all results consistent with one another.

Phenomenologically, genuine higher Fock states in the baryons' wave functions constitute a pertinent nonperturbative source of the intrinsic $Q\bar{Q}$ components. In our recent works [26,27] we studied those components in baryons, with $Q \equiv u$, d, s, and the associated sigma terms. In the present work we extend our approach to the intrinsic $c\bar{c}$ content of the nucleon and the charmness-nucleon sigma term. Here we derive the wave functions for all possible quark-antiquark components in the nucleon, and calculate the corresponding probability amplitudes using the $^3P_0$ quark-antiquark creation model [28]. Also the resulting charmness-nucleon sigma term is evaluated.

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 the sigma terms relating them to the quark-antiquark pair probabilities. Numerical results for the probabilities of light, strange, and charm quark-antiquark pairs in the nucleon, as well as $\sigma_{\pi N}$, σ_{sN}, and σ_{cN}, are reported in Sec. III and compared to findings from other sources. Finally, Sec. IV contains a summary and conclusions.

II. THEORETICAL FRAME

The extended chiral constituent quark model on the light and strangeness components of baryons was developed in

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TABLE I. Categories (second row) and configurations (rows 3–8) for five-quark components.

i	Category/config. I/$[31]_X[22]_S$	i	Category/config. II/$[31]_X[31]_S$	i	Category/config. III/$[4]_X[22]_S$	i	Category/config. IV/$[4]_X[31]_S$
1	$[31]_X[4]_{FS}[22]_F[22]_S$	5	$[31]_X[4]_{FS}[31]^1_F[31]_S$	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	$[31]_X[4]_{FS}[31]^2_F[31]_S$	12	$[4]_X[31]_{FS}[31]^1_F[22]_S$	15	$[4]_X[31]_{FS}[22]_F[31]_S$
3	$[31]_X[31]_{FS}[31]^1_F[22]_S$	7	$[31]_X[31]_{FS}[211]_F[31]_S$	13	$[4]_X[31]_{FS}[31]^2_F[22]_S$	16	$[4]_X[31]_{FS}[31]^1_F[31]_S$
4	$[31]_X[31]_{FS}[31]^2_F[22]_S$	8	$[31]_X[31]_{FS}[22]_F[31]_S$			17	$[4]_X[31]_{FS}[31]^2_F[31]_S$
		9	$[31]_X[31]_{FS}[31]^1_F[31]_S$				
		10	$[31]_X[31]_{FS}[31]^2_F[31]_S$				

[26], and applied to the sigma terms of baryons in [27]. So, here we briefly present the main content of the formalism and extend it to the charm sector.

A. The extended chiral constituent quark model

In the extended chiral constituent quark model, the wave function for the nucleon reads

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

where the first term is the conventional wave function for the nucleon 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: $Q\bar{Q} \equiv u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$. Different possible orbital-flavor-spin-color configurations of the four-quark subsystems in the five-quark system, 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. As discussed explicitly in [26], here we only need to consider the five-quark configurations with $n_r = 0$ and $l = 1$; consequently, there are 17 different configurations which can be classified in four categories according to the orbital and spin wave functions of the four-quark subsystem; the corresponding configurations are listed in Table I, using the shorthand notation for Young tableaux. Note that the charmness configurations with flavor symmetry $[31]^1_F$ cannot form Fock components of the nucleon.

In Table II, we construct the explicit wave functions of the studied flavor configurations of the four-quark subsystem in the charmness components in the nucleon. To estimate the energies of the studied hidden charm pentaquark configurations, we employ the chiral constituent quark model developed in [26]. As discussed in that reference, all the configurations share the same energy, $E_0 = 2127$ MeV, if the difference between the constituent masses of charm and light quarks and the hyperfine interaction between quarks are not taken into account. Consequently, the energy E_i for the ith configuration reads

$$E_i = E_0 + 2\delta m + E_i^h, \quad (2)$$

where $\delta m = m_c - m_q$ is the constituent mass difference between charm and light quarks and E_i^h the energy caused by hyperfine interaction between quarks. To consider the hyperfine interaction between quarks, we employ the flavor-spin-dependent version in the chiral constituent quark model [29],

$$
\begin{aligned}
H_h = -\sum_{i<j} \vec{\sigma}_i \cdot \vec{\sigma}_j \Bigg[& \sum_{a=1}^{3} V_\pi(\vec{r}_{ij})\lambda_i^a \lambda_j^a + \sum_{a=4}^{7} V_K(\vec{r}_{ij})\lambda_i^a \lambda_j^a \\
& + V_\eta(\vec{r}_{ij})\lambda_i^8 \lambda_j^8 + \sum_{a=9}^{12} V_D(\vec{r}_{ij})\lambda_i^a \lambda_j^a \\
& + \sum_{a=13}^{14} V_{D_s}(\vec{r}_{ij})\lambda_i^a \lambda_j^a + V_{\eta_c}(\vec{r}_{ij})\lambda_i^{15}\lambda_j^{15} \Bigg],
\end{aligned}
\quad (3)
$$

where λ_i^a denotes the $SU(4)$ Gell-Mann matrix acting on the ith quark and $V_M(r_{ij})$ is the potential of the M meson-exchange interaction between the ith and jth quarks, as extensively discussed in [29,30]. Then, E_i^h is obtained by

TABLE II. Flavor wave functions of the charmness configurations studied here. Note that the full wave functions are obtained by multiplying each column by the corresponding normalization factor.

	$[22]_{F_1}$	$[22]_{F_2}$	$[31]^2_{F_1}$	$[31]^2_{F_2}$	$[31]^2_{F_3}$	$[211]_{F_1}$	$[211]_{F_2}$	$[211]_{F_3}$
$uudc$	2	0	0	6	0	2	0	0
$uucd$	2	0	2	2	0	-2	0	0
$dcuu$	2	0	-1	-4	-2	0	2	1
$cduu$	2	0	-1	-4	2	0	-2	-1
$duuc$	-1	-1	0	-3	-3	-1	-3	0
$uduc$	-1	1	0	-3	3	-1	3	0
$cudu$	-1	1	-1	5	-1	-1	-1	1
$ucdu$	-1	-1	-1	5	1	-1	1	-1
$cuud$	-1	-1	2	-1	-1	1	3	0
$ducu$	-1	1	-1	-1	-3	1	1	-1
$ucud$	-1	1	2	-1	1	1	-3	0
$udcu$	-1	-1	-1	-1	3	1	-1	1

$$E_i^h = \langle QQQ(Q\bar{Q}), i, 0, 1 | H_h | QQQ(Q\bar{Q}), i, 0, 1 \rangle$$

$$= -6 \sum_{njklm} \left[(C_{[31]_i^n[211]_n}^{[1^4]})^2 C_{[\mathcal{FS}]_i^j[\mathcal{X}]_i^l}^{[31]_i^n} C_{[\mathcal{FS}]_i^k[\mathcal{X}]_i^m}^{[31]_i^n} \right.$$

$$\times \left(\langle [\mathcal{X}]_i^l | V_\pi(r_{12}) | [\mathcal{X}]_i^m \rangle \langle [\mathcal{FS}]_i^j | \vec{\sigma}_1 \cdot \vec{\sigma}_2 \sum_{a=1}^{3} \lambda_1^a \lambda_2^a | [\mathcal{FS}]_i^k \rangle \right.$$

$$+ \langle [\mathcal{X}]_i^l | V_K(\vec{r}_{12}) | [\mathcal{X}]_i^m \rangle \langle [\mathcal{FS}]_i^j | \vec{\sigma}_1 \cdot \vec{\sigma}_2 \sum_{a=4}^{7} \lambda_1^a \lambda_2^a | [\mathcal{FS}]_i^k \rangle$$

$$+ \langle [\mathcal{X}]_i^l | V_\eta(\vec{r}_{12}) | [\mathcal{X}]_i^m \rangle \langle [\mathcal{FS}]_i^j | \vec{\sigma}_1 \cdot \vec{\sigma}_2 \lambda_1^8 \lambda_2^8 | [\mathcal{FS}]_i^k \rangle$$

$$+ \langle [\mathcal{X}]_i^l | V_D(\vec{r}_{12}) | [\mathcal{X}]_i^m \rangle \langle [\mathcal{FS}]_i^j | \vec{\sigma}_1 \cdot \vec{\sigma}_2 \sum_{a=9}^{12} \lambda_1^a \lambda_2^a | [\mathcal{FS}]_i^k \rangle$$

$$+ \langle [\mathcal{X}]_i^l | V_{D_s}(\vec{r}_{12}) | [\mathcal{X}]_i^m \rangle \langle [\mathcal{FS}]_i^j | \vec{\sigma}_1 \cdot \vec{\sigma}_2 \sum_{a=13}^{14} \lambda_1^a \lambda_2^a | [\mathcal{FS}]_i^k \rangle$$

$$\left. \left. + \langle [\mathcal{X}]_i^l | V_{\eta_c}(\vec{r}_{12}) | [\mathcal{X}]_i^m \rangle \langle [\mathcal{FS}]_i^j | \vec{\sigma}_1 \cdot \vec{\sigma}_2 \lambda_1^{15} \lambda_2^{15} | [\mathcal{FS}]_i^k \rangle \right) \right],$$

$$(4)$$

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. $C_{[31]_i^n[211]_n}^{[1^4]}$, $C_{[\mathcal{FS}]_i^j[\mathcal{X}]_i^l}^{[31]_i^n}$, and $C_{[\mathcal{FS}]_i^k[\mathcal{X}]_i^m}^{[31]_i^n}$ are the S_4 Clebsch-Gordan coefficients.

On the other hand, we have to consider the $SU(4)$ flavor symmetry breaking effects because of the large difference between the light and charm quark constituent masses. As introduced in [31], these effects can be calculated by using the following flavor-dependent Hamiltonian,

$$H_{sb} = -\sum_{i=1}^{4} \frac{m_c - m_q}{2 m_q} \left\{ \frac{p_i^2}{m_c} + \frac{p_{\bar{c}}^2}{m_c} \right\} \delta_{ic}, \quad (5)$$

where δ_{ic} is a flavor-dependent operator with eigenvalue 1 for the charm quark and 0 for the light quark. Here m_q is the constituent mass of the light quark.

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 $\hat{T}$,

$$\hat{T} = -\gamma \sum_j \mathcal{F}_{j,5}^{00} \mathcal{C}_{j,5}^{00} C_{\text{OFSC}} \sum_m \langle 1, m; 1, -m | 00 \rangle \chi_{j,5}^{1,m}$$

$$\times \mathcal{Y}_{j,5}^{1,-m}(\vec{p}_j - \vec{p}_5) b^\dagger(\vec{p}_j) d^\dagger(\vec{p}_5), \quad (6)$$

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 quark-antiquark pairs in the nucleon and the normalization factor read, respectively,

$$\mathcal{P}^{Q\bar{Q}} = \frac{1}{\mathcal{N}} \sum_{i=1}^{17} \left[\left(\frac{T_i^{Q\bar{Q}}}{M_N - E_i^{Q\bar{Q}}} \right)^2 \right], \quad (7)$$

$$\mathcal{N} \equiv 1 + \sum_{i=1}^{17} \mathcal{N}_i = 1 + \sum_{i=1}^{17} \sum_{Q\bar{Q}} \left[\left(\frac{T_i^{Q\bar{Q}}}{M_B - E_i^{Q\bar{Q}}} \right)^2 \right], \quad (8)$$

where the first term in Eq. (8) is due to the valence three-quark state, while the second term comes from the five-quark mixtures.

To derive the explicit wave functions of the five-quark components with light quark-antiquark pairs in the nucleon, we construct the wave functions for $u\bar{u}$ and $d\bar{d}$ components of the 17 different flavor-spin configurations to form the isospin state $|\frac{1}{2}, \frac{1}{2}\rangle$. The five-quark components with $s\bar{s}$ and $c\bar{c}$ pairs form the nucleon isospin naturally since those pairs do not contribute to isospin. Accordingly, starting from Eq. (7), the light quark-antiquark pairs ($u\bar{u}$ and $d\bar{d}$) probabilities for the nucleon in terms of the five-quark probabilities per configuration [$P_N(i), i = 1$–17] are combined [27] with the relevant squared Clebsch-Gordan coefficients in $SU(2)$ isospin space. For the $s\bar{s}$ and $c\bar{c}$ components, the probabilities $\mathcal{P}_N^{s\bar{s}}$ and $\mathcal{P}_N^{c\bar{c}}$ are obtained by summing up linearly the relevant nonvanishing contributions, $P_N^{s\bar{s}}(i)$ and $P_N^{c\bar{c}}(i)$ (i = 1, 17), respectively.

B. Sigma terms

Here we proceed in line with Ref. [27], where explicit expressions for the pion- and strangeness-baryon sigma terms were given as a function of quark-antiquark pair probabilities. Accordingly, the charmness-nucleon σ term is defined as follows:

$$\sigma_{c_N} = m_c \langle N | c\bar{c} | N \rangle, \quad (9)$$

which can be related to $\sigma_{\pi N}$,

$$\sigma_{cN} = \frac{m_c}{m_l} \frac{\langle N | c\bar{c} | N \rangle}{\langle N | u\bar{u} + d\bar{d} | N \rangle} \sigma_{\pi N} \quad (10)$$

$$= \frac{m_c}{m_l} \frac{2\mathcal{P}_N^{c\bar{c}}}{3 + 2(\mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}})} \sigma_{\pi N}, \quad (11)$$

where

$$\sigma_{\pi N} = \frac{\hat{\sigma}}{1 - 2(\langle N | s\bar{s} | N \rangle / \langle N | u\bar{u} + d\bar{d} | N \rangle)} \quad (12)$$

$$= \frac{3 + 2(\mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}})}{3 + 2(\mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}} - 2\mathcal{P}_N^{s\bar{s}})} \hat{\sigma}, \qquad (13)$$

with $m_l \equiv (m_u + m_d)/2$ the average current mass of the up and down quarks; m_s and m_c the current mass of the strange and charm quarks, respectively; and $\hat{\sigma}$ the nucleon expectation value of the purely octet operator.

III. RESULTS AND DISCUSSION

First we present the model parameters. As documented in [32], the input parameters of the model for $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ are taken from the literature. The newly introduced ones concern the charm quark, namely, its mass and the hyperfine interaction strength between the light and charm quarks. For the former one, we use the empirical value $m_c = 1275(25)$ MeV given in PDG [33], and the latter one is taken from Ref. [30].

The only source of uncertainty in the probabilities, presented in Sec. III A, comes from a common factor of the matrix elements of the transitions between three- and five-quark components and was found [26] to be $V = 570 \pm 46$ MeV, by successfully fitting the experimental data for the proton flavor asymmetry $\bar{d} - \bar{u} \equiv \mathcal{P}_p^{d\bar{d}} - \mathcal{P}_p^{u\bar{u}} = 0.118 \pm 0.012$ [34]. By introducing the five-quark

components with the charm quark-antiquark pairs and fitting the same data point, we get the new extracted value $V = 572 \pm 47$ MeV, which differs by 0.4% from the previous one. For the σ-terms two additional entities contribute to the uncertainties [27], namely, the nonsinglet component $\hat{\sigma} = 33(5)$ MeV, as extracted within chiral perturbation theory [35] and the PDG masses ratio [33] $m_s/m_l = 27.5(1.0)$. Accordingly, compared to our previous studies [26,27] only one parameter was slightly readjusted in the frame of the present work.

In this section, we report our numerical results for the probabilities of the quark-antiquark components in the nucleon and the relevant sigma terms, followed by comparisons to findings by other authors.

A. Numerical results

Table III embodies our numerical results. In columns 3 to 5 the quark-antiquark pair probabilities in the nucleon per configuration are given for light, strange, and charm components, respectively. The sum of the five quark-antiquark probabilities are reported in column 6. The pion-, strangeness-, and charmness-sigma terms are given in columns 7 to 9, respectively.

Note that the numerical results for the light and strange quark-antiquark pairs (columns 3–4 and 7–8), reported in

TABLE III. Predictions for probabilities of different five-quark configurations for the nucleon, with $\mathcal{P}_N^{q\bar{q}} = \mathcal{P}_N^{u\bar{u}} + \mathcal{P}_N^{d\bar{d}}$, $\mathcal{P}_N^{Q\bar{Q}} = \mathcal{P}_N^{q\bar{q}} + \mathcal{P}_N^{s\bar{s}} + \mathcal{P}_N^{c\bar{c}}$, and pion-, strangeness-, and charmness-nucleon sigma terms.

i	Category	$\mathcal{P}_N^{q\bar{q}}$ (%)	$\mathcal{P}_N^{s\bar{s}}$ (%)	$\mathcal{P}_N^{c\bar{c}}$ (%)	$\mathcal{P}_N^{Q\bar{Q}}$ (%)	$\sigma_{\pi N}$ (MeV)	σ_{sN} (MeV)	σ_{cN} (MeV)
	(I) $[31]_X[22]_S$:							
1		14.58 (1.50)	0.98 (10)	0.04 (0)	15.60 (1.60)	33.4 (5.1)	5.5 (1.5)	3.0 (8)
2		0	0.36 (4)	0.03 (1)	0.39 (4)	33.2 (5.0)	2.2 (6)	2.7 (7)
3		1.64 (17)	0	0	1.64 (17)	33.0 (5.0)	0	0
4		0	0.26 (3)	0.03 (1)	0.29 (3)	33.1 (5.0)	1.6 (5)	2.6 (7)
	Category I	16.22 (1.66)	1.60 (16)	0.10 (1)	17.92 (1.83)	33.6 (5.2)	8.9 (2.5)	7.8 (2.1)
	(II) $[31]_X[31]_S$:							
5		7.27 (75)	0	0	7.27 (75)	33.0 (5.0)	0	0
6		0	0.63 (6)	0.04 (0)	0.67 (6)	33.3 (5.1)	3.8 (1.1)	3.2 (9)
7		0	0.32 (4)	0.03 (1)	0.36 (3)	33.1 (5.0)	2.0 (6)	2.6 (7)
8		0.61 (6)	0.18 (2)	0.02 (0)	0.81 (8)	33.1 (5.0)	1.1 (3)	1.5 (4)
9		0.47 (5)	0	0	0.47 (5)	33.0 (5.0)	0	0
10		0	0.08 (1)	0.01 (0)	0.09 (1)	33.0 (5.0)	0.5 (1)	0.8 (2)
	Category II	8.33 (0.86)	1.21 (13)	0.10 (1)	9.64 (98)	33.5 (5.1)	7.0 (2.0)	7.8 (2.1)
	(III) $[4]_X[22]_S$:							
11		0	0.85 (9)	0.09 (1)	0.94 (10)	33.4 (5.1)	5.2 (1.5)	7.2 (2.0)
12		4.13 (42)	0	0	4.13 (42)	33.0 (5.0)	0	0
13		0	0.65 (7)	0.09(1)	0.74 (8)	33.3 (5.1)	4.0(1.2)	7.0 (1.9)
	Category III	4.13 (42)	1.50 (16)	0.18 (2)	5.81 (60)	33.7 (5.2)	9.0 (2.6)	14.0 (3.8)
	(IV) $[4]_X[31]_S$:							
14		0	0.77 (8)	0.09 (1)	0.86 (9)	33.3 (5.1)	4.7 (1.4)	7.1 (2.0)
15		1.49 (16)	0.44 (5)	0.06 (1)	1.99 (21)	33.2 (5.0)	2.6 (8)	4.5 (1.2)
16		1.18 (12)	0	0	1.18 (12)	33.0 (5.0)	0	0
17		0	0.19 (2)	0.03 (1)	0.22 (2)	33.1 (5.1)	1.1 (3)	2.2 (6)
	Category IV	2.67 (28)	1.40 (15)	0.18 (2)	4.25 (44)	33.6 (5.2)	8.5 (2.5)	13.8 (3.8)
	All configurations	31.35 (3.21)	5.71 (59)	0.56 (6)	37.62 (3.85)	35.2 (5.5)	30.5 (8.5)	39.3 (10.3)

[27] for $V = 570 \pm 46$ MeV, are given here with the updated value for V and allow us to make clear the relative weight of the $c\bar{c}$ component and the discussion on the sigma terms at the end of this section.

As reported in Table III, out of the 17 five-quark configurations in the nucleon, only 3 of them contribute to all the light, $s\bar{s}$, and $c\bar{c}$ pair probabilities, whereas 5 of them have only $u\bar{u}$ and/or $d\bar{d}$ components, while the remaining 9 configurations are exclusively composed of $s\bar{s}$ and $c\bar{c}$ pairs.

In the light quark-antiquark sector, the five-quark probability is dominated by the first category, where the total spin of the four-quark subsystem is zero. Within that category, the configuration $n°$ gives the largest contribution and corresponds to the configuration with the lowest energy and largest coupling to the three-quark component.

In the case of $\mathcal{P}_N^{s\bar{s}}$, the four categories have comparable contributions, though the first one gives the highest probability, where the total spin of the four-quark subsystem is $S = 1$ and the total angular momentum is $J = 0$.

Finally, for $\mathcal{P}_N^{c\bar{c}}$, the last two categories contribute almost equally, but with larger probabilities than the first two. While category III corresponds to the four-quark subsystem $J = 0$, in category IV the total spin of the four-quark subsystem should be $S_{[31]} = 1$ and $J = S_4 \oplus L_{\bar{q}} = 0$.

With respect to the sigma terms, the pion-nucleon σ term of every configuration is ≈ 33.6 MeV, very close to the complete calculation with all 17 configurations leading to ≈ 35 MeV. But the strangeness- and charmness-nucleon sigma terms per configuration are about a factor of 4 to more than 1 order of magnitude smaller than the total of all configurations. Accordingly, any configuration-truncated model will significantly underestimate both σ_{sN} and σ_{cN}, leading to confusing results.

B. Discussion and comparisons to previous results

Probabilities and sigma terms related to the light and strange quark-antiquark sector were presented and discussed in our previous study [27]. Therein, the determined probabilities came out compatible with those reported within the generalized BHPS approach [36] and the meson cloud model [37]. Also the sigma terms related to the light and strange quark-antiquark sector turned out to be in good agreement with results coming from various approaches, namely, chiral Lagrangian [38], chiral perturbation theory [39], and LQCD [40]. In this section we hence concentrate on the charm issues.

1. Quark-antiquark probabilities in the nucleon

In Table IV probabilities for the $c\bar{c}$ pairs in the nucleon are reported.

As mentioned in the Introduction, the first calculations embodying intrinsic $c\bar{c}$ were performed by Brodsky *et al.* [4] within the light-cone Fock space framework, by

TABLE IV. Predictions for the probability of $c\bar{c}$ in the nucleon.

Reference	Approach	$\mathcal{P}_N^{c\bar{c}}$ (%)
Present work	$E\chi$CQM	0.6(1)
Brodsky *et al.* [4]	Light cone	≈ 1
Hoffmann and Moore [6]	PGF-NLO	0.31
Harris *et al.* [7]	PGF-NLO	0.86(60)
Martin *et al.* [8]	NNLO	0.3
Steffens *et al.* [9]	Meson cloud	≈ 0.4
Dulat *et al.* [12]	PQCD-NNLO	≤ 2
Jimenez-Delgado [10]	PDF	0.3–0.4; ≈ 1

introducing the hypothesis that $P_N^{c\bar{c}}$ could be around 1%. Hoffmann and Moore [6] investigated the matter within a photon-gluon fusion (PGF) model at NLO and also took into account the quark and target mass contributions to the charm cross section, finding a smaller probability: $P_N^{c\bar{c}} = 0.31\%$. Harris *et al.* [7] extended that work interpreting the EMC charm production data [41] by calculating next-to-leading order and generalizing it for both extrinsic and intrinsic contributions to the charm structure function and found an intrinsic charm probability of $(0.86 \pm 0.60)\%$. Steffens *et al.* [9] used a more extended database for the charm structure function, including the very low-x region measurements by the H1 [42] and ZEUS [43] collaborations. The authors performed a consistent interpolation between the two asymptotic regions of massless evolution at large Q^2 and the PGF, finding a slight preference for $P_N^{c\bar{c}} \approx 0.4\%$. Later Martin *et al.* [8], using very extensive data coming from some 40 data sets released between 1989 and 2008, updated the parton distribution functions determined from global analysis of hard-scattering data up to NNLO and found $P_N^{c\bar{c}} = 0.3\%$. In a recent work, Jimenez-Delgado *et al.* [10] reported the results of a new global QCD analysis of PDFs, concentrating on the momentum fraction carried by the intrinsic charm quarks in terms of the Feynman-x,

$$\langle x \rangle_{c+\bar{c}} = \int_0^1 x[c(x) + \bar{c}(x)]dx, \qquad (14)$$

which is related to the $c\bar{c}$ content of the nucleon by

$$\mathcal{P}_N^{c\bar{c}} = \int_0^1 c(x)dx = \int_0^1 \bar{c}(x)dx. \qquad (15)$$

Note that in the BHPS model the predictions [1] at the input scale $Q_0 = m_c = 1.3$ GeV, are $\langle x \rangle_{c+\bar{c}} = 0.57\%$ and $\mathcal{P}_N^{c\bar{c}} = 1\%$. Jimenez-Delgado *et al.* [10] analyzed a large set of data with $\langle x \rangle_{c+\bar{c}}$ in the range of 0 to $\approx 0.6\%$. Fitting only the EMC data, they obtained $\mathcal{P}_N^{c\bar{c}} = 0.3$–$0.4\%$, while excluding the old EMC data led to $\langle x \rangle_{c+\bar{c}} = 0.5\%$, a value close to the BHPS prediction. The minimization approach in the former work raised a debate [44,45] emphasizing the need for more precise data.

TABLE V. Predictions for the sigma terms $\sigma_{\pi N}$, σ_{sN}, and σ_{cN} of the nucleon.

Reference (collaboration)	Approach	$\sigma_{\pi N}$ (MeV)	σ_{sN} (MeV)	σ_{cN} (MeV)
Present work	EχCQM	35(6)	30(8)	39(10)
Abdel-Rehim et al. [23] (ETM)	LQCD	37(7)	41(8)	79(22)
Gong et al. [24] (χQCD)	LQCD		33(6)	94(31)
Freeman and Toussaint [25] (MILC)	LQCD		39(8)	67(32)

Then, a global conclusion on the probability of the intrinsic $c\bar{c}$ component in the nucleon is that its value would be in the range of 0.3 to 1% and our result, 0.6%, falls in that range.

However, as briefly discussed below, the genuine $c\bar{c}$ component is predicted to play a significant role in the forthcoming measurements using high energy beams at CERN/LHC, BNL/RHIC, etc.

Actually, it is well established that the heavy quarks produced in line with perturbative QCD carry small longitudinal momentum, while the intrinsic heavy constituents transport the largest fraction of the momentum of the hadron. Accordingly, to probe the intrinsic charm in the nucleon, various guidelines were elaborated.

Brodsky et al. [14] proposed a fixed target experiment for the LHC 7 TeV beam, allowing precise enough measurements of the rapidity distribution of open- or hidden-charm hadrons at $\sqrt{s_{NN}} = 115$ GeV, accessing the domain of high x_F, knowing that [4,46] the intrinsic quark-antiquark possible manifestations should be looked for roughly in the range $0.2 \leq x_F \leq 0.8$.

Kniehl et al. [16] employed the general-mass variable-flavor-number scheme at NLO to study the inclusive production of the D meson, $pp \rightarrow D^{\circ}X$, at the LHC and found that the production cross sections at $\sqrt{s_{NN}} = 7$ TeV and large values of rapidity are sensitive to a nonperturbative component of the charm PDF for $\mathcal{P}_N^{c\bar{c}} = 3.5\%$.

Bednyakov et al. [17] reported results for the $pp \rightarrow \gamma cX$ differential cross section at $\sqrt{s} = 8$ TeV. Calculations come from the radiatively generated charm PDF (CTEQ66), the sealike PDF (CTEQ66c4), and the BHPS PDF (CTEQ66c2), also for $\mathcal{P}_N^{c\bar{c}} = 3.5\%$, and found that the IC manifestation could be measured with both the ATLAS and CMS detectors.

Bailas and Goncalves [18] studied, within various models, the impact of the IC on the rapidity and transverse momentum distribution in the Z-boson production in proton-proton collisions at the LHC, and showed that the $Z + c$ cross section is significantly sensitive to the presence of the IC.

Finally, the relevance of the CEBAF-12 GeV and FAIR-PANDA facilities to study the multiquark dynamics in baryons was also underlined [47].

2. Sigma terms

Compared to $\sigma_{\pi N}$ and, to a lesser extent to σ_{sN}, for the charmness-nucleon sigma term fewer results are available,

coming from lattice QCD results as given in Table V. Note that, wherever appropriate, using statistical and systematic uncertainties reported in those papers, we give

$$\delta = \sqrt{\delta_{\text{stat}}^2 + \delta_{\text{sys}}^2}.$$

The most recent results were released by the ETM Collaboration [23], employing improved methods for the disconnected quark loops to determining $\sigma_{\pi N}$, σ_{sN}, and σ_{cN}. Comparing our results to those of the latter work, we note that the outcomes for $\sigma_{\pi N}$ and σ_{sN} are in agreement within 1σ (for a comprehensive discussion with extractions of these latter terms by other authors, see [27]). Our value for σ_{cN} is compatible with the ETM result within 2σ. This is also the case for the strangeness content of the nucleon y_N, for which they get 0.075(16) compared to our approach's value 0.031(3). The same quantity for the charmless content of the nucleon within the present work is $y_N^c = 0.004(1)$, but to our knowledge no other value was reported in the literature for that entity.

The χQCD Collaboration [24] investigated the $Q\bar{Q}$ components within a dynamical LQCD with overlap valence quarks on a $2 + 1$ flavors domain-wall fermion gauge configuration. They performed calculations for the strange and charm quark-antiquark contributions and determined both σ_{sN} and σ_{cN}. For the strangeness sigma term the agreement between their result and ours is perfect, while for σ_{cN} the two findings are compatible with each other within less than 2σ.

The MILC Collaboration [25] applied a hybrid method to the large library of improved staggered gauge configurations to calculate both matrix elements $\langle N|s\bar{s}|N\rangle = 0.44 \pm 0.08(\text{stat}) \pm 0.05$ and $\langle N|c\bar{c}|N\rangle = 0.058 \pm 0.027(\text{stat})$. Using for the masses the values quoted by the authors, $m_s = 89.0$ MeV and $m_c = 1.2$ GeV, we report in Table V the corresponding sigma terms. Here also we find good agreement with our results for σ_{sN} and σ_{cN} within 1σ.

IV. SUMMARY AND CONCLUSIONS

Our recent works [26,27] and the present study, performed within the extended chiral quark approach, constitute a thorough investigation of the genuine quark-antiquark pairs in the nucleon. Quark-antiquark pair creation was calculated via the $^3P_0$ mechanism [28]. All possible five-quark configurations that may form higher Fock components of the nucleon were taken into account, and it was shown that any configuration-truncated calculation will lead to unrealistic results.

This coherent and comprehensive set of results allowed us to predict the probabilities of the $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ pairs in the nucleon as well as the associated sigma terms $\sigma_{\pi N}$, σ_{sN}, and σ_{cN}. The model uncertainties are about 10%, mainly due to the only fitted parameter on the proton flavor asymmetry $\bar{d} - \bar{u} = 0.118(12)$ [34]. All other parameters were taken from the literature [32].

Extensive comparisons with the outcomes of other approaches, reported in [26,27] and the present paper, led in general to compatibility of the obtained results with those found in the literature. To our knowledge, the present approach is the only available one putting forward predictions for all the above mentioned entities within a single approach and set of input parameters.

The predicted probabilities of the five-quark components with light, strange, and charm quark-antiquark pairs in the nucleon wave function turned out to be (in %) $P_N^{q\bar{q}} = 31.3(3.2)$, $P_N^{s\bar{s}} = 5.7$ (6), and $P_N^{c\bar{c}} = 0.6(1)$, respectively, adding up to $P_N^{Q\bar{Q}} = 37.6$ (3.8). As reported in [26] and Sec. III B 1, our findings are compatible with results released by several authors.

Here, three observations are in order: (i) the intrinsic five-quark states represent a significant part of the nucleon wave function, (ii) the probability of charm-anticharm pairs is rather tiny, and (iii) there is no nonambiguous experimental evidence for the existence of heavy quark-antiquark pairs in the nonperturbative regime. However, as discussed in Sec. III B 1, the present state of the art in experimental high-energy physics allows us to anticipate crucial measurements at the LHC and RHIC [14–22]. Also empirical determination of the intrinsic charm through PDF analysis with heavy quarks is likely to shed valuable light on those issues; see, e.g., [48,49] and references therein.

In parallel, LQCD calculations are producing results for the charmless-nucleon sigma term [23–25]. Here also our determination of that entity is compatible with the LQCD findings. Refinements in the latter approach, expected to reduce the presently large uncertainties, will certainly offer a better understanding of the underlying mechanisms with respect to the role, if any, played by the charmness in the nucleon.

Those efforts will hopefully lead to uncovering the puzzle of possible charm components in the nucleon.

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