Phenomenological analysis of nucleon strangeness and meson-nucleon sigma terms

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Abstract

We calculate the nucleon strangeness $y_N$ in the chiral quark model and the meson cloud model. With the internal relation between the sigma term of $\pi N$ ($\sigma_{\pi N}$) and $y_N$, we present the results of $\sigma_{\pi N}$ in these two models. Our calculations show that $y_N$ from the chiral quark model is significant larger than that from the meson cloud model, whereas the difference of $\sigma_{\pi N}$ between the two models is relatively small. We also present the results of $\sigma_{KN}$ and $\sigma_{\eta N}$, which could be determined by $\sigma_{\pi N}$ and $y_N$ from their definition in the current algebra, and find that these two physical parameters are quite sensitive to $y_N$. The results indicate the necessity to restrict the parameters of the two models from more precision measurements.

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I. INTRODUCTION

The nucleon structure has received much attention for its abundant phenomena away from naive theoretical expectations. One of them is that the nucleon may contain a significant component of strange-antistrange ($s\bar{s}$) pairs. Recently, a strange-antistrange asymmetry \[1,2\] has been applied to explain the NuTeV anomaly \[3\], while the asymmetric strange-antistrange contribution from the chiral quark model \[4,5,6\] is predicted to be different from that in the meson cloud model \[7\]. Apart from possible high-energy experimental verifications, some parameters measured in low-energy hadron physics could provide an instructive restriction on the nucleon strangeness which is usually indicated by the ratio of the strange component over the light components, $y_N$. The first example of a large strange component in the nucleon was from the measurement of the pion-nucleon sigma term \(\sigma_{\pi N}\) \[8\] which is a fundamental parameter of low-energy hadron physics. The precise value of $\sigma_{\pi N}$ is of practical importance for numerous phenomenological applications. It provides a direct test of chiral symmetry breaking effects and effective quark models since this quantity is sensitive to the quark-antiquark sea contribution \[9\].

The $\sigma_{\pi N}$ can not be measured directly \[9,10\]. There are two ways discussed in the literatures to determine the value of $\sigma_{\pi N}$ experimentally. The combination $\hat{\sigma} = \sigma_{\pi N}(1-2y_N)$ which measures the strength of the matrix element $\langle p|\bar{u}u + \bar{d}d-2\bar{s}s|p\rangle$ can be related to the baryon mass differences in the SU(3) limit \[3\]. Thus the $\sigma_{\pi N}$ can be “measured” from an analysis of the baryon mass spectrum using chiral perturbation theory (ChPT) and information on the value of $y_N$. A value about 45 MeV was obtained in Refs.\[11,12\]. The other method is to relate the value of the scalar-isoscalar form factor $\sigma(t)$ at the point $t = 2m^2_\pi$ to the isospin-even pion-nucleon scattering amplitude by using dispersion relation and phase shifts \[13,14\]. Earlier analyses of the pion-nucleon scattering data by Koch \[13\] and Gasser et al. \[14\] gave for $\sigma(2m^2_\pi)$ a value about 60 MeV. Using $\sigma(2m^2_\pi)-\sigma(0) = 15$ MeV found by Gasser et al. \[14\], one obtains for $\sigma_{\pi N} \equiv \sigma(0)$ a value around 45 MeV which agrees with the value obtained from the baryon mass spectrum. Several updated analyses \[15,16\], however, tended to yield higher values for $\sigma(2m^2_\pi)$ in the range of $(70 \sim 90)$ MeV, which resulted in a value of $\sigma_{\pi N}$ much larger than earlier analyses. Meanwhile, recent lattice calculations gave a value in the range of $33 \sim 50$ MeV depending on the extrapolation ansatz \[17\] and $43 \sim 49$ MeV \[18\].

In this paper, we present a theoretical calculation of the nucleon strangeness $y_N$ using the chiral quark model (CQM) and the meson cloud model (MCM) which both have been applied to the study of the nucleon structure extensively. These models provide different mechanism to incorporate the meson degree of freedom in the nucleon and the contributions from different mesons can be easily recognized. In order to get a relatively accurate estimation on the value of $y_N$, we calculate the contributions to the non-perturbative sea from various
mesons. Then, we use \( y_N \) as an input to calculate the result of \( \sigma_{\pi N} \). Moreover, we present the results of \( \sigma_{KN} \) and \( \sigma_{\eta N} \) which can be easily derived from \( \sigma_{\pi N} \) and \( y_N \).

The paper is organized as follows. The definition of the sigma terms and the internal relation between the nucleon sigma terms (\( \sigma_{\pi N}, \sigma_{KN} \) and \( \sigma_{\eta N} \)) and \( y_N \) are given in Section II. The basic formalism in the CQM and MCM used to obtain the non-perturbative strange quark component is presented in Sections III and IV, respectively. Numerical results are given in Section V and the last section is reserved for a summary.

II. THE SIGMA TERMS AND THE RELATION BETWEEN \( y_N \) AND \( \sigma_{\pi N} \)

The pion-nucleon sigma term is defined as \[9, 10\]

\[
\sigma_{\pi N} = \hat{m} \langle N|\bar{u}u + \bar{d}d|N \rangle,
\]

where terms proportional to \( (m_u - m_d) \langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N \rangle \) have been neglected, and \( \hat{m} = \frac{1}{2}(m_u + m_d) \) is the average value of current quark masses of the \( u \) and \( d \) quarks. The scalar operator \( \bar{q}q \) measures the sum of the quark and antiquark numbers \[8\], thus \( \sigma_{\pi N} \) is the contribution to the nucleon mass from the \( u \) and \( d \) quarks having a mass of \( \hat{m} \). Algebraically, \( \sigma_{\pi N} \) can be written in the form of

\[
\sigma_{\pi N} = \hat{m} \frac{\langle p|\bar{u}u + \bar{d}d - 2\bar{s}s|p \rangle}{1 - 2y_N} = \frac{\hat{\sigma}}{1 - 2y_N},
\]

where

\[
\hat{\sigma} = \hat{m} \langle p|\bar{u}u + \bar{d}d - 2\bar{s}s|p \rangle,
\]

and

\[
y_N = \frac{\langle p|\bar{s}s|p \rangle}{\langle p|\bar{u}u + \bar{d}d|p \rangle}
\]

represents the strangeness content of the nucleon.

Moreover, \( \sigma_{KN} \) and \( \sigma_{\eta N} \) can be defined in the same way as \[19\]

\[
\sigma_{KN}^u \equiv \frac{\hat{m} + m_s}{2} \langle p|\bar{u}u + \bar{s}s|p \rangle, \\
\sigma_{KN}^d \equiv \frac{\hat{m} + m_s}{2} \langle p|\bar{d}d + \bar{s}s|p \rangle, \\
\sigma_{KN}^{I=0} \equiv \frac{\sigma_{KN}^u + \sigma_{KN}^d}{2}, \\
\sigma_{\eta N} \equiv \frac{1}{3} \langle p|\hat{m}(\bar{u}u + \bar{d}d) + 2m_s\bar{s}s|p \rangle.
\]
The $\sigma_{KN}$ and $\sigma_{\eta N}$ can be expressed in term of $\sigma_{\pi N}$ and $y_N$,

$$\sigma_{KN}^{I=0} = \sigma_{\pi N}(1 + 2y_N) \frac{\hat{m} + m_s}{4\hat{m}} = \frac{13}{2} \sigma_{\pi N}(1 + 2y_N), \quad (6)$$

$$\sigma_{\eta N} = \sigma_{\pi N} \frac{\hat{m} + 2y_N m_s}{3\hat{m}} = \frac{1 + 50y_N}{3} \sigma_{\pi N} \quad (7)$$

where the quark mass ratio $m_s/\hat{m} \simeq 25 \[20]$ has been used.

The “quark flavor fraction” in a nucleon, $f_q$, was defined by Cheng and Li $[21, 22]$,

$$f_q = \frac{\langle p|\overline{q}q|p\rangle}{\langle p|\overline{u}u + \overline{d}d + \overline{s}s|p\rangle} = \frac{q + \overline{q}}{3 + 2(\overline{u} + d + \overline{s})}, \quad (8)$$

where $q$ and $\overline{q}$ in the proton matrix elements $\langle p|\overline{q}q|p\rangle$ are the quark and antiquark field operators, and in the last term they stand for the quark and antiquark numbers in the nucleon. Thus, one can express $y_N$ in term of quark and antiquark numbers in the nucleon and the strange quark fraction $f_s$,

$$y_N = \frac{2\pi}{3 + 2(\overline{u} + d)} \quad (9)$$

and

$$y_N = \frac{f_s}{1 - f_s}. \quad (10)$$

It is worth pointing out that the quark and antiquark numbers in Eqs. (8) and (10) are the total numbers in the nucleon.

As discussed in the Introduction, we need to calculate $y_N$ directly in the two models, which will avoid discussing the much more complicated case about the matrix elements with mass parameters and reduce the model dependence of calculation since the quantity calculated is a ratio. For the $\hat{\sigma}$ part, it was normally adopted as $\hat{\sigma} \simeq 26$ MeV in leading order in the ChPT $[9]$, while a larger value $\hat{\sigma} = 33 \pm 5$ MeV was obtained by Gasser and Leutwyler $[11]$ in $O(m_q^{3/2})$ calculation. Borasoy and Meißner $[12]$ analyzed the octet baryon masses in the heavy baryon framework of ChPT to order $O(m_q^2)$ and obtained $\hat{\sigma} = 36 \pm 7$ MeV. In this paper, we will perform calculation with $\hat{\sigma} = 26$ MeV and 36 MeV respectively, and compare the effects on the sigma terms.

III. CHIRAL QUARK MODEL

The chiral quark model which was first formulated by Manohar and Georgi $[23]$ describes successfully the nucleon properties in the scale range from $\Lambda_{QCD}$ ($0.2 \sim 0.3$ GeV) to $\Lambda_{\chi_{SB}}$ ($\sim 1$ GeV). The dominant interaction is the coupling among constituent (dressed) quarks and Goldstone bosons (GBs), while the gluon effect is expected to be small. This model has
been employed in the study of flavor asymmetry in the nucleon sea and the proton spin problem by introducing SU(3) breaking and U(1) breaking effects.

The effective Lagrangian describing interaction between quarks and the nonet of GBs can be expressed as

\[ L_I = g_8 \bar{q} \Phi q + g_1 \frac{\eta'}{\sqrt{3}} q = g_8 \left( \Phi + \frac{\eta'}{\sqrt{3}} I \right) q , \]  

(11)

where \( \zeta = g_1/g_8 \), \( g_1 \) and \( g_8 \) are coupling constants for the singlet and octet GBs, respectively, and \( I \) is the 3 \times 3 identity matrix. The GB field which includes the octet and the singlet GBs is written as

\[ L_I = g_8 \bar{q} \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\beta \eta'}{\sqrt{6}} + \frac{\zeta \eta'}{\sqrt{3}} & \pi^+ & \alpha K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\beta \eta'}{\sqrt{6}} + \frac{\zeta \eta'}{\sqrt{3}} & \alpha K^0 \\ \alpha K^- & \alpha K^+ & -\frac{\beta \eta'}{\sqrt{6}} + \frac{\zeta \eta'}{\sqrt{3}} \end{pmatrix} q . \]

(12)

The SU(3) symmetry breaking is introduced by considering \( m_s > m_{u,d} \) and the masses of GBs to be non-degenerate (\( M_{K,\eta} > M_{\pi} \)), whereas the axial U(1) breaking is introduced by \( M_{\eta'} > M_{K,\eta} \). These effects are expressed in Eq. (12) by suppression factors \( \beta \) (for \( \eta \)), \( \alpha \) (for \( K \)), and \( \zeta \) (for \( \eta' \)) which deviate from 1, the value for the symmetric limit. These values are generally fixed by the experimental data of the light antiquark asymmetry and quark spin component. The probabilities of chiral fluctuations \( u(d) \rightarrow d(u) + \pi^+(\pi^-) \), \( u(d) \rightarrow s + K^+(K^0) \), \( u(d,s) \rightarrow u(d,s) + \eta \), and \( u(d,s) \rightarrow u(d,s) + \eta' \) are proportional to \( a(=|g_8|^2) \), \( \alpha^2a \), \( \beta^2a \) and \( \zeta^2a \), respectively. The antiquark numbers calculated using the effective Lagrangian Eq. (12) are

\[ \pi = \frac{1}{12} [(2\zeta + \beta + 1)^2 + 20]a , \]
\[ \bar{d} = \frac{1}{12} [(2\zeta + \beta - 1)^2 + 32]a , \]
\[ \bar{s} = \frac{1}{3} [(\zeta - \beta)^2 + 9\alpha^2]a . \]  

(13)

Another method to introduce the symmetry breaking effects is to calculate directly the different fluctuations. The antiquark distribution functions are given by

\[ \bar{q}_k(x) = \int \frac{dy_1}{y_1} \frac{dy_2}{y_2} V_{K/\delta}(\frac{x}{y_1}) P_{\delta j/i}(\frac{y_2}{y_1}) g_i(y_2) , \]

(14)

where \( V_{K/\delta}(x) \) is the antiquark \( \bar{k} \) distribution function in a Gladstone Boson \( \delta \). \( P_{\delta j/i}(y) \) is the splitting function giving the probability for a parent quark \( i \) to split into a quark \( j \) with the light-cone momentum fraction \( y \) and transverse momentum \( k_{\perp} \), and a spectator GB (\( \delta = \pi, K, \eta \)) with the light-cone momentum fraction \( 1 - y \) and transverse momentum \( k_{\perp} \),

\[ P_{\delta j/i}(y) = \frac{1}{8\pi^2} \frac{g_A m_i}{f} \int dk_{\perp}^2 \frac{(m_j - m_i y)^2 + k_{\perp}^2}{y^2(1-y)[m_i^2 - M_{\delta j}^2]^2} , \]  

(15)
and

\[ P_{\delta j/i}(y) = P_{j\delta/i}(1 - y). \]  \hspace{1cm} (16)

In Eq. (15), \( m_i \) and \( m_j \) are the masses of the \( i, j \)-constituent quarks, \( \bar{m} = (m_i + m_j)/2 \) is the average mass of the constituent quarks, and \( m_\delta \) is the mass of the GB. \( M^2_{j\delta} \) is the invariant mass squared of the final state,

\[ M^2_{j\delta} = \frac{m^2_j + k^2_1}{y} + \frac{m^2_\delta + k^2_1}{1 - y}. \]  \hspace{1cm} (17)

The antiquark numbers can be obtained by integrating \( q(x) \) given by Eq. (14) over \( x \),

\[
\begin{align*}
\bar{u} &= \frac{7}{4} \langle P_\pi^+ \rangle + \frac{1}{12} \langle P_\eta \rangle + \frac{1}{3} \langle P_{\eta'} \rangle, \\
\bar{d} &= \frac{11}{4} \langle P_\pi^+ \rangle + \frac{1}{12} \langle P_\eta \rangle + \frac{1}{3} \langle P_{\eta'} \rangle, \\
\bar{s} &= 3 \langle P_K^+ \rangle + \frac{4}{3} \langle P_\eta \rangle + \frac{1}{3} \langle P_{\eta'} \rangle,
\end{align*}
\]  \hspace{1cm} (18)

where \( \langle P_\delta \rangle \equiv \langle P_{\delta j/i} \rangle = \langle P_{j\delta/i} \rangle \) is the first moment of splitting functions \[29\]. The contributions from \( \eta' \) meson are included in Eq. (18) in order to compare with results from Eq. (13).

An exponential form factor is usually introduced in the calculation,

\[ g_A = g'_A \exp \left[ -\frac{m^2_i - M^2_{j\delta}}{4\Lambda^2_\delta} \right], \]  \hspace{1cm} (19)

with \( g'_A = 1 \) following the large \( N_c \) argument \[30\]. The cutoff parameter \( \Lambda_\delta \) which can be determined by fitting the Gottfried sum rule was taken to be \( \Lambda_\delta = \Lambda_\pi = 1500 \text{ MeV} \) in \[29\]. Recently, this method was used to calculate the strange-antistrange asymmetry \[5\] in which \( \Lambda_K = (900 \sim 1100) \text{ MeV} \) is adopted. The dependence of numerical calculations on \( \Lambda_\delta \) is studied by taking \( \Lambda_\delta = 1100 \text{ MeV} \) and \( 1500 \text{ MeV} \). The mass parameters are taken to be \( m_u = m_d = 330 \text{ MeV}, m_s = 480 \text{ MeV}, m_{\pi \pm} = m_{\pi^0} = 140 \text{ MeV}, m_{K^+} = m_{K^0} = 495 \text{ MeV}, m_\eta = 548 \text{ MeV} \) and \( m_{\eta'} = 958 \text{ MeV} \).

IV. MESON CLOUD MODEL

The meson cloud model is very successful in explaining many non-perturbative properties of the nucleon \[31, 32, 33, 34, 35, 36\]. In the meson cloud model, the nucleon can be viewed as a bare nucleon (core) plus a series of baryon-meson Fock states which result from the nucleon fluctuating into a baryon plus a meson \( N \rightarrow BM \) (a bare core surrounded by a meson cloud). The physical nucleon wave function is composed of various baryon-meson Fock states

\[ |N \rangle = \sqrt{Z} |N \rangle_{\text{bare}} + \sum_{BM} \int \mathrm{d}y \mathrm{d}^2k_\perp \Psi_{BM}(y, k_\perp^2) |B(y, k_\perp), M(1 - y, -k_\perp) \rangle, \]  \hspace{1cm} (20)
where $Z$ is the wave function renormalization constant, and $\Psi_{BM}(y, k_\perp^2)$ is the probability amplitude for finding a physical nucleon in a state consisting of a baryon $B$ with longitudinal moment fraction $y$ and transverse momentum $k_\perp$, and a meson $M$ with longitudinal moment fraction $1 - y$ and transverse momentum $-k_\perp$.

The model assumes that the life-time of a virtual baryon-meson Fock state is much longer than the interaction time in deep inelastic scattering (DIS) or Drell-Yan processes, thus the quark and anti-quark in the virtual baryon-meson Fock states can contribute to the parton distribution of the nucleon. The quark distribution $q(x)$ in the nucleon is given by

$$q(x) = Zq_{\text{bare}}(x) + \delta q(x), \quad (21)$$

where $q_{\text{bare}}$ and $\delta q$ are the contributions from the bare nucleon and the meson and baryon cloud.

The contribution $\delta q(x)$ can be calculated via a convolution between the fluctuation function which describes the microscopic process $N \rightarrow BM$, and the quark (anti-quark) distribution of hadrons in the Fock states $|BM\rangle$,

$$\delta q(x) = \sum_{MB} \left[ \int_x^1 \frac{dy}{y} f_{MB}(y) q_M(x/y) + \int_x^1 \frac{dy}{y} f_{BM}(y) q_B(x/y) \right] \quad (22)$$

where $q_M$ and $q_B$ are the quark distributions in the cloud meson and baryon respectively and $f_{BM}$ and $f_{MB}$ are the splitting functions,

$$f_{BM}(y) = \int_0^\infty |\Psi_{BM}(y, k_\perp^2)|^2 d^2k_\perp. \quad (23)$$

with the relation

$$f_{MB}(y) = f_{BM}(1 - y). \quad (24)$$

The anti-quark numbers needed in this study can be obtained by integrating the anti-quark distribution given by Eq. (22) over $x$. The time-ordered perturbation theory (TOPT) in the infinite momentum frame (IMF) is employed to calculate the splitting functions \cite{36,35,36}

$$f_{BM}(y) = \frac{1}{4\pi^2} \frac{m_Nm_B}{y(1 - y)} |G_M(y, k_\perp^2)|^2 |V_{\text{IMF}}|^2, \quad (25)$$

where

$$M_{BM}^2(y, k_\perp^2) = \frac{m_B^2 + k_\perp^2}{y} + \frac{m_M^2 + k_\perp^2}{1 - y} \quad (26)$$

is the invariant mass squared of the final state, and $G_M(y, k_\perp^2)$ is a phenomenological vertex form factor \cite{35,36,36},

$$G_M(y, k_\perp^2) = \exp \left[ \frac{m_N^2 - M_{BM}^2(y, k_\perp^2)}{2\Lambda_M^2} \right]. \quad (27)$$
A unique cutoff parameter \( \Lambda_M = 880 \text{ MeV} \) was taken in the calculation.

The Fock states considered include \(|N\pi\rangle\), \(|N\rho\rangle\), \(|N\omega\rangle\), \(|\Delta\pi\rangle\), \(|\Delta\rho\rangle\), \(|\Lambda K\rangle\), \(|\Lambda K^*\rangle\), \(|\Sigma K\rangle\), and \(|\Sigma K^*\rangle\). The vertex function \( V_{IMF}^\lambda(y, k_2^2) \) depends on the effective interaction Lagrangian that describes the fluctuation process \( N \rightarrow BM \). From the meson exchange model for hadron production \([36]\), we have

\[
L_1 = ig\bar{N}\gamma_5\pi B, \\
L_2 = f\bar{N}\partial_\mu\pi\Delta^\mu + \text{h.c.}, \\
L_3 = g\bar{N}\gamma_\mu\partial_\mu\Delta_\nu B(\partial^\nu\theta^\nu - \partial^\nu\theta^\nu), \\
L_4 = if\bar{N}\gamma_5\gamma_\mu\Delta_\nu(\partial^\nu\theta^\nu - \partial^\nu\theta^\nu) + \text{h.c.},
\]

(28)

where \( N \) and \( B = \Lambda, \Sigma \) are spin-1/2 fields, \( \Delta \) a spin-3/2 field of Rarita-Schwinger form (\( \Delta \) baryon), \( \pi \) a pseudoscalar field (\( \pi \) and \( K \)), and \( \theta \) a vector field (\( \rho, \omega \) and \( K^* \)). The coupling constants for various fluctuations are taken to be \([36, 37]\)

\[
g_{NN\pi}^2/4\pi = 13.6, \\
g_{NN\rho}^2/4\pi = 0.84, \\
g_{NN\omega}^2/4\pi = 8.1, \\
f_{N\Delta\pi}^2/4\pi = 12.3 \text{ GeV}^{-2}, \\
f_{N\Delta\rho}^2/4\pi = 34.5 \text{ GeV}^{-2}, \\
g_{N\Lambda K} = -13.98, \\
g_{N\Lambda K^*} = -5.63, \\
g_{N\Sigma K} = 2.69, \\
g_{N\Sigma K^*} = -3.25, \\
f_{N\Sigma K} = 2.09 \text{ GeV}^{-1}.
\]

(29)

V. NUMERICAL RESULTS AND DISCUSSION

Strange quark numbers from contributions of different mesons are presented in Table 1. The first row is the CQM calculation under SU(3) symmetry assumption (i.e. \( \alpha = \beta = 1 \) and with \( a = 0.10 \) and \( \zeta = -1.2 \) according to \([21]\)). The second and third rows are the results when the SU(3) symmetry breaking effects are included using the parameters of \( \alpha \) and \( \beta \) given in \([28]\). The U(1) breaking parameter \( \zeta \) was set in order to give an overall description of the data as illustrated in \([38]\). In the next two rows, the results from the second method of introducing the symmetry break effects in the CQM by calculating the fluctuation probability with different cutoff values are given (see Eq. \((18)\)). The last row is the calculations from the MCM. It can be found from Table 1 that for the CQM calculations the ratio of the contributions from \( K \) and \( \eta + \eta' \) depends strongly on the parameters measuring the SU(3) breaking effects. For the second method introducing symmetry breaking effects in the CQM calculation, the strange quark number is very sensitive to the cutoff parameter \( \Lambda_\delta \). The contribution from the \( K \) meson calculated in the MCM is \( 3 \sim 10 \) times smaller than that
TABLE I: Strange quark number from different mesons

|     | $\bar{\pi}$ | $K$ | $\eta + \eta'$ | $K^*$ | sum  |
|-----|--------------|-----|----------------|------|------|
| CQM($\alpha = \beta = 1.0, \zeta = -1.2$) | 0.30 | 0.16 | -              | 0.46 |
| CQM($\alpha = 0.4, \beta = 0.7, \zeta = -0.65$) | 0.048 | 0.061 | -              | 0.11 |
| CQM($\alpha = \beta = 0.45, \zeta = -0.1$) | 0.061 | 0.031 | -              | 0.092 |
| CQM($\Lambda_\delta = 1500$ MeV) | 0.17 | 0.030 | -              | 0.20 |
| CQM($\Lambda_\delta = 1100$ MeV) | 0.092 | 0.016 | -              | 0.11 |
| MCM   | 0.016 | -      | 0.026         | 0.042 |

in the CQM with symmetry breaking effects. Though the contribution from the $K^*$ meson compensates to some extent, one can conclude that this two models give very different results for the magnitude of the non-perturbative strange sea. The $\eta$ and $\eta'$ mesons play an important role in the CQM calculation, while their contributions are negligible in the MCM calculation as their coupling constants are usually taken to be zero in this model.

The results for $\sigma_{\pi N}$ are presented in Table II with indexes 1 and 2 referring to the calculations adopting $\hat{\sigma} = 26$ MeV and 36 MeV respectively. For the CQM calculations with SU(3) symmetry being held, the larger value of $\hat{\sigma}$ yields $\sigma_{\pi N} = 67.8$ MeV which is comparable with recent analyses of $55 \sim 75$ MeV [15, 16]. If the SU(3) symmetry breaking effects are included, the strange quark number becomes much smaller and $\sigma_{\pi N}$ decreases by $24 \sim 28$ MeV depending on the method of introducing the SU(3) symmetry breaking effects, which gives a value for $\sigma_{\pi N}$ close to the earlier analyses of $45$ MeV [13, 14]. With the smaller value of $\hat{\sigma}$ the results for $\sigma_{\pi N}$ with the symmetry breaking effects are smaller than the earlier analyses of $45$ MeV [13, 14] by about 15 MeV. The two methods of introducing the breaking effects in the CQM are consistent with each other, and almost have the same impact on the $\sigma_{\pi N}$. For the calculations in the MCM, the fluctuation probability of $K^*$ is at the same level as $K$. Consequently adding vector meson $K^*$ will double the strange quark number, which changes the calculations of $f_s$ and $y_N$ dramatically. However, the value obtained for the $\sigma_{\pi N}$ remains quite small. Comparing the two model results, one can find that the strange quark number from the CQM with the symmetry breaking effects is $2 \sim 5$ times larger than that form the MCM, but the difference of $\sigma_{\pi N}$ from the two models is relatively small (less than 20 per cents).

The results for $\sigma_{K N}$ and $\sigma_{\eta N}$ are presented in Table III. The calculations for the $\sigma_{K N}$ and $\sigma_{\eta N}$ are more sensitive to $y_N$ than that for the $\sigma_{\pi N}$. From Table III one can find that the CQM calculations for the $\sigma_{K N}$ and $\sigma_{\eta N}$ with the SU(3) breaking effects are about 2 and 4 $\sim 8$ times smaller than that when the effects are not included. The MCM calculations for $\sigma_{K N}$ and $\sigma_{\eta N}$ are about 10% and 50% smaller that the smallest results from the CQM while
two models, as discussed above, may give comparable results for the $\sigma_{\pi N}$.

There are much less calculations for the $\sigma_{KN}$ and $\sigma_{\eta N}$ than for the $\sigma_{\pi N}$. A theoretical study based on the lattice QCD calculation gave $\sigma_{KN} = 362 \pm 13$ MeV \cite{39} and an analysis using
the Nambu-Jona-Lasinio model predicated $\sigma_{KN} = 425$ MeV (with an error of 10 $\sim$ 15\%) \cite{40}. A calculation using the perturbative chiral quark model gave $\sigma_{KN} = 312 \pm 37$ MeV and $\sigma_{\eta N} = 72 \pm 16$ MeV \cite{19}. Our calculations using the CQM with symmetry breaking effects are comparable with these results, while the results from the MCM are considerably smaller than these results. Future DAΦNE experiments \cite{41} will allow for a determination of the $KN$ sigma terms and hence give a more narrow range of the nucleon strangeness.

The antiquark numbers given by Eqs. (13) and (18) in the CQM and the antiquark distribution given by Eq. (22) in the MCM come from non-perturbative effects. The contributions from the process of gluons perturbatively splitting into quark-antiquark pairs need to be treated carefully, although any effect associated with gluon is expected to be small in the CQM. In several recent studies of $x$ dependence of the sea quark distributions in the MCM,
this effect was included by using a phenomenal parameterization for the symmetric nucleon sea in the bare nucleon \([42, 43]\). However, the perturbative quark distributions are divergent as \(x \to 0\), thus the quark and antiquark numbers from gluon perturbatively splitting can not be estimated using the same method. Further investigations are highly needed in order to include these perturbative contributions.

VI. SUMMARY

We calculated the nucleon strangeness \(y_N\) in the chiral quark model and the meson cloud model, and used \(y_N\) as a parameter to evaluate the the nucleon sigma terms (\(\sigma_{\pi N}, \sigma_{KN}\) and \(\sigma_{\eta N}\)). Our calculations show that \(y_N\) from the CQM is much larger than that from the MCM, while the difference for \(\sigma_{\pi N}\) between the two models is relatively small. The results indicate that adopting a larger value of \(\hat{\sigma}\) from higher order calculations in ChPT can give a value of \(\sigma_{\pi N}\) comparable with the earlier analyses. The only value that could be comparable to the recent analyses using the \(\pi N\) scattering data that gave a value in the range of 55 ~ 75 MeV is the result from the CQM with SU(3) symmetry. This picture, however, was not a good description of light flavor antiquark asymmetry and the quark spin component. Meanwhile, the results of \(\sigma_{KN}\) and \(\sigma_{\eta N}\) become strangely large with symmetry being held, which confirms that the SU(3) symmetry breaking effects should be considered. The higher value of \(\sigma_{\pi N}\) from recent analyses of pion-nucleon scattering data needs to be re-considered carefully. Another important conclusion is that both \(\sigma_{KN}\) and \(\sigma_{\eta N}\) are quite sensitive to \(y_N\). Thus, more exact values of them determined from the future experiments could restrict the model parameters and provide a better knowledge of the strangeness content of the nucleon.

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