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STRANGENESS AND CHIRAL SYMMETRY BREAKING

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The implications of chiral symmetry breaking and SU(3) symmetry breaking have been studied in the chiral constituent quark model (χCQM). The role of hidden strangeness component has been investigated for the scalar matrix elements of the nucleon with an emphasis on the meson-nucleon sigma terms. The χCQM is able to give a qualitative and quantitative description of the "quark sea" generation through chiral symmetry breaking. The significant contribution of the strangeness is consistent with the recent available experimental observations.

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The internal structure of the nucleon has been extensively studied over the past 40 or 50 years and it is still a big challenge to perform the calculations from the first principles of Quantum Chromodynamics (QCD). The measurements of polarized structure functions of proton in the deep inelastic scattering (DIS) experiments[1,2,3,4,5,6,7,8] provided the first evidence that the valence quarks of proton carry only a small fraction of its spin suggesting that they should be surrounded by an indistinct sea of quark-antiquark pairs. These observations were in contradiction with the predictions of Naive Quark Model (NQM)[9,10,11,12,13] which is able to provide a intuitive picture of the nucleon and successfully accounts for many of the low-energy properties of the hadrons in terms of the valence quarks.

Several interesting facts have also been revealed regarding the flavor distribution functions in the famous New Muon Collaboration[14,15] and E866 experiments[16,17,18] indicating that the flavor structure of the nucleon is not limited to u and d quarks only. The measured quark sea asymmetry of the unpolarized quarks in the nucleon established that the study of the structure of the nucleon is intrinsically a nonperturbative phenomena and is considered as one of the most active areas in the present day.

Recently, there have been indications of strangeness contribution in the exper-

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iments measuring electromagnetic form factors, for example, SAMPLE at MIT-Bates[19], G0 at JLab[20], A4 at MAMI[21] and HAPPEX at JLab[22,23]. These experiments have provided considerable insight on the role played by strange quarks when the nucleon interacts at high energies. On the other hand, a non-zero strangeness content in the nucleon y_N has been indicated in the context of low-energy experiments[24,25,26,27,28]. Even though there has been considerable progress in the past few years to estimate the strangeness matrix elements from the neutral current observables, there is no consensus regarding the various mechanisms which can contribute to y_N[29,30,31]. Since the strange quarks constitute purely sea degrees of freedom, the low-energy determination of the strangeness contribution to the nucleon would undoubtedly provide vital clues to the nonperturbative aspects of QCD.

Currently, there is enormous interest in determining the meson-nucleon sigma terms[25,26,27,28]. These are the fundamental parameters to test the chiral symmetry breaking (χSB) effects and thereby determine the scalar quark content of the baryons. The meson-nucleon sigma terms cannot be measured directly from experiments and are known to have intimate connection with the dynamics of the non-valence quarks. They are theoretically interesting because there is a discrepancy in the value derived from the meson-nucleon scattering experiments[32,33,34,35,36,37,38] and from the hadron spectroscopy[31,39]. The meson-nucleon sigma terms also provide restriction on the contribution of strangeness to the parameters measured in low-energy[40,41,42,43,44,45].

One of the most successful model which can yield an adequate description in this energy regime is the chiral constituent quark model (χCQM)[46,47,48]. The χCQM is not only successful in giving a satisfactory explanation of "proton spin crisis"[49,50,51,52,53], baryon magnetic moments[54,55] and hyperon $\beta-$decay parameters[56,57] but is also able to account for the violation of Gottfried Sum Rule[58,59,60] and Coleman-Glashow sum rule[54,55,61]. Recently, the comparatively large masses of the strange quarks has been reiterated in detail through SU(3) symmetry breaking[49,50,51,52,53,56,57] and the predictions are found to improve in the case of spin polarization functions and related parameters. In this context, it therefore becomes desirable to carry out a detailed analysis of the role played by chiral symmetry breaking and SU(3) symmetry breaking in understanding the dynamics of quark sea in the nonperturbative regime of QCD with an emphasis on the strangeness flavor distribution functions.

The purpose of the present communication is to understand the implications of chiral symmetry breaking (χSB) for the scalar matrix elements of the nucleon within the χCQM. In particular, we would like to phenomenologically estimate the quantities affected by the hidden strangeness component in the nucleon, for example, strangeness content in the nucleon y_N and strangeness fraction f_s. Further, it would be significant to study the meson-nucleon sigma terms (σ_{KN}, $\sigma_{\eta N}$) which have not been observed experimentally and are expected to have large contributions from the quark sea. Furthermore, it would be interesting to understand the extent to which the strange quark mass contribute through the SU(3) symmetry breaking effects in understanding the nucleon properties.

For ready reference as well as to make the mss. more readable, we present the essentials of χCQM. The key to understand the structure of the nucleon, in the χCQM formalism[62,63,64,65], is the fluctuation process

$$q^{\pm} \rightarrow \mathrm{GB} + q^{'\mp} \rightarrow (q\bar{q}^{'}) + q^{'\mp}\,, \tag{1}$$

where GB represents the Goldstone boson and $q\bar{q}^{'} + q^{'}$ constitute the "quark sea"[49,50,51,52,53,62,63,64,65,66,67]. The effective Lagrangian describing the interaction between quarks and a nonet of GBs, can be expressed as

$$\mathcal{L} = g_8 \bar{\mathbf{q}} \left(\Phi + \zeta \frac{\eta'}{\sqrt{3}} I \right) \mathbf{q} = g_8 \bar{\mathbf{q}} \left(\Phi' \right) \mathbf{q}\,, \tag{2}$$

where $\zeta = g_1/g_8$, g_1 and g_8 are the coupling constants for the singlet and octet GBs, respectively, I is the 3×3 identity matrix. The parameter $a (= |g_8|^2)$ denotes the probability of chiral fluctuation $u(d) \rightarrow d(u) + \pi^{+(-)}$. The SU(3) symmetry breaking parameters α, β and ζ are introduced by considering $M_s > M_{u,d}$, $M_{K,\eta} > M_\pi$ and $M_{\eta'} > M_{K,\eta}$[62,63,64,65,66,67] and they respectively denote the probabilities of fluctuations $u(d) \rightarrow s + K^{-(0)}$, $u(d,s) \rightarrow u(d,s) + \eta$, and $u(d,s) \rightarrow u(d,s) + \eta^{'}$. These fluctuation parameters provide the basis to understand the extent to which the quark sea contributes to the structure of the nucleon.

The GB field can be expressed in terms of the quark contents of the GBs and their transition probabilities as

$$\Phi' = \begin{pmatrix} \phi_{uu} u\bar{u} + \phi_{ud} d\bar{d} + \phi_{us} s\bar{s} & \varphi_{ud} u\bar{d} & \varphi_{us} u\bar{s} \\ \varphi_{du} d\bar{u} & \phi_{du} u\bar{u} + \phi_{dd} d\bar{d} + \phi_{ds} s\bar{s} & \varphi_{ds} d\bar{s} \\ \varphi_{su} s\bar{u} & \phi_{sd} s\bar{d} & \phi_{su} u\bar{u} + \phi_{sd} d\bar{d} + \phi_{ss} s\bar{s} \end{pmatrix}, \tag{3}$$

where

$$\phi_{uu} = \phi_{dd} = \frac{1}{2} + \frac{\beta}{6} + \frac{\zeta}{3}\,, \qquad \phi_{ss} = \frac{2\beta}{3} + \frac{\zeta}{3}\,, \qquad \phi_{us} = \phi_{ds} = \phi_{su} = \phi_{sd} = -\frac{\beta}{3} + \frac{\zeta}{3}\,,$$
$$\phi_{du} = \phi_{ud} = -\frac{1}{2} + \frac{\beta}{6} + \frac{\zeta}{3}\,, \qquad \varphi_{ud} = \varphi_{du} = 1\,, \qquad \varphi_{us} = \varphi_{ds} = \varphi_{su} = \varphi_{sd} = \alpha\,. \tag{4}$$

The contributions of the quark sea coming from the fluctuation process in Eq. (1) can be calculated by substituting for every constituent quark $q \rightarrow \sum P_q q + |\psi(q)|^2$, where $\sum P_q$ is the transition probability of the emission of a GB from any of the q quark and $|\psi(q)|^2$ is the transition probability of the q quark.

Before proceeding further, we briefly discuss the calculation of the scalar matrix elements of the nucleon. The flavor structure of the nucleon is defined as[62,63,64,65]

$$\hat{N} \equiv \langle N | q\bar{q} | N \rangle, \tag{5}$$

where $|N\rangle$ is the nucleon wavefunction (detailed in Ref.[68]) and $q\bar{q}$ is the number operator for the scalar quark content measuring the sum of the quark and antiquark numbers

$$q\bar{q} = \sum_{q=u,d,s} (n_q q + n_{\bar{q}} \bar{q}) = n_u u + n_{\bar{u}} \bar{u} + n_d d + n_{\bar{d}} \bar{d} + n_s s + n_{\bar{s}} \bar{s}\,, \tag{6}$$

$n_{q(\bar{q})}$ being the number of $q(\bar{q})$ quarks. The modified flavor structure of proton after the inclusion of the effects of chiral fluctuations in the χCQM is expressed as

$$2P_u u + P_d d + 2|\psi(u)|^2 + |\psi(d)|^2\,, \tag{7}$$

where the total probability of no emission of GB from a q quark ($q = u,\ d,\ s$) can be calculated from the Lagrangian and is given by

$$P_q = 1 - \sum P_q, \tag{8}$$

with

$$\sum P_u = a(\phi_{uu}^2 + \phi_{ud}^2 + \phi_{us}^2 + \varphi_{ud}^2 + \varphi_{us}^2)\,, \tag{9}$$

$$\sum P_d = a(\phi_{du}^2 + \phi_{dd}^2 + \phi_{ds}^2 + \varphi_{du}^2 + \varphi_{ds}^2)\,, \tag{10}$$

$$\sum P_s = a\left(\phi_{su}^2 + \phi_{sd}^2 + \phi_{ss}^2 + \varphi_{su}^2 + \varphi_{sd}^2\right)\,, \tag{11}$$

$$\begin{aligned}|\psi(u)|^2 = a\big[&(2\phi_{uu}^2 + \phi_{ud}^2 + \phi_{us}^2 + \varphi_{ud}^2 + \varphi_{us}^2)u + \phi_{uu}^2\bar{u} \\ &+(\phi_{ud}^2 + \varphi_{ud}^2)(d+\bar{d}) + (\phi_{us}^2 + \varphi_{us}^2)(s+\bar{s})\big]\,,\end{aligned} \tag{12}$$

$$\begin{aligned}|\psi(d)|^2 = a\big[&(\phi_{du}^2 + 2\phi_{dd}^2 + \phi_{ds}^2 + \varphi_{du}^2 + \varphi_{ds}^2)d + \phi_{dd}^2\bar{d} \\ &+(\phi_{du}^2 + \varphi_{du}^2)(u+\bar{u}) + (\phi_{ds}^2 + \varphi_{ds}^2)(s+\bar{s})\big]\,,\end{aligned} \tag{13}$$

$$\begin{aligned}|\psi(s)|^2 = a\big[&\left(\phi_{su}^2 + \phi_{sd}^2 + 2\phi_{ss}^2 + \varphi_{su}^2 + \varphi_{sd}^2\right)s + \phi_{ss}^2\bar{s} \\ &+(\phi_{su}^2 + \varphi_{su}^2)(u+\bar{u}) + (\phi_{sd}^2 + \varphi_{sd}^2)(d+\bar{d})\big]\,.\end{aligned} \tag{14}$$

In terms of the transition probabilities, the 'averaged' integrals of the quark distribution functions are expressed as

$$u - \bar{u} = 2\,, \qquad d - \bar{d} = 1\,, \qquad s - \bar{s} = 0\,, \tag{15}$$

where the antiquark distribution functions are

$$\begin{aligned}\bar{u} &= a(2\phi_{uu}^2 + \phi_{du}^2 + \varphi_{du}^2)\,, \\ \bar{d} &= a(2\phi_{ud}^2 + 2\varphi_{ud}^2 + \phi_{dd}^2)\,, \\ \bar{s} &= a(2\phi_{us}^2 + 2\varphi_{us}^2 + \phi_{ds}^2 + \varphi_{ds}^2)\,.\end{aligned} \tag{16}$$

The pion-nucleon sigma term ($\sigma_{\pi N}$) affected by the contributions of the quark sea is expressed as

$$\sigma_{\pi N} = \hat{m}\langle N|\bar{u}u + \bar{d}d|N\rangle = \hat{m}\left(3 + 6a\left(\phi_{uu}^2 + \phi_{ud}^2 + \varphi_{ud}^2\right)\right)\,, \tag{17}$$

where $\hat{m} = \frac{(m_u+m_d)}{2}$ is the average value of current u and d quark masses evaluated at fixed gauge coupling and $q\bar{q}$ is the scalar quark content[69]. Since $\sigma_{\pi N}$ provides restriction on the contribution of strange quarks in the nucleon, it can be rewritten in terms of the strangeness content in nucleon y_N as

$$\sigma_{\pi N} = \hat{m}\frac{\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle}{1-2y_N} = \frac{\hat{\sigma}}{1-2y_N}\,, \tag{18}$$

where we have defined

$$\hat{\sigma} = \hat{m}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle = \hat{m}(3 + 6a(\phi_{uu}^2 + \phi_{ud}^2 + \varphi_{ud}^2 - 2\phi_{us}^2 - 2\varphi_{us}^2))\,, \tag{19}$$

and

$$y_N = \frac{\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle} = \frac{2a(\phi_{us}^2 + \varphi_{us}^2)}{1 + 2a(\phi_{uu}^2 + \phi_{ud}^2 + \phi_{us}^2 + \varphi_{ud}^2 + \varphi_{us}^2)}\,. \tag{20}$$

Since $\sigma_{\pi N}$ is related to the hadron mass spectrum as well as the quark mass ratio, therefore, following Ref.[39], we can express $\hat{\sigma}$ as

$$\hat{\sigma} = -\frac{3(M_\Xi - M_\Lambda)}{(1 - \frac{m_s}{\hat{m}})}\,, \tag{21}$$

where M_Ξ and M_Λ are the baryon masses. The latest accepted quark mass ratio $\frac{m_s}{\hat{m}}$ has the value 22-30[70].

It is also important to define the strangeness fraction of the nucleon which is related to the strangeness content in nucleon y_N as

$$f_s = \frac{\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d + \bar{s}s|N\rangle} = \frac{y_N}{1-y_N}\,. \tag{22}$$

This can further be rewritten in terms of $\sigma_{\pi N}$ and $\hat{\sigma}$ and is expressed as

$$f_s = \frac{\sigma_{\pi N} - \hat{\sigma}}{3\sigma_{\pi N} - \hat{\sigma}}\,. \tag{23}$$

Another important parameter which is completely determined from the strangeness content in nucleon y_N and the mass ratio is the strangeness sigma term

$$\sigma_s = m_s\langle N|\bar{s}s|N\rangle = \frac{1}{2}y_N\frac{m_s}{\hat{m}}\sigma_{\pi N}\,. \tag{24}$$

According to NQM, the valence quark structure of the nucleon does not involve strange quarks. The validity of OZI rule[71,72,73,74,75] in this case would imply $y_N = f_s = 0$ or $\hat{\sigma} = \sigma_{\pi N}$. For $\frac{m_s}{\hat{m}} = 22$, the value of $\sigma_{\pi N}$ comes out to be close to 28 MeV. However, the most recent analysis of experimental data gives higher values of $\sigma_{\pi N}$ which points towards a significant strangeness content in the nucleon.

Further, we can calculate the sigma terms corresponding to the strange mesons. For example, the kaon-nucleon sigma term can be expressed in terms of the scalar quark content and $\sigma_{\pi N}$ as

$$\sigma_{KN} = \frac{\sigma_{KN}^u + \sigma_{KN}^d}{2} = \frac{\hat{m} + m_s}{2}\langle N|\bar{u}u + \bar{d}d + 2\bar{s}s|N\rangle = \frac{\hat{m} + m_s}{4\hat{m}}(2\sigma_{\pi N} - \hat{\sigma})\,, \tag{25}$$

where $\sigma^u_{KN} = \frac{\hat{m}+m_s}{2}\langle N|\bar{u}u + \bar{s}s|N\rangle$ and $\sigma^d_{KN} = \frac{\hat{m}+m_s}{2}\langle N|\bar{d}d + \bar{s}s|N\rangle$. Similarly, the η-nucleon sigma term can be expressed as

$$\sigma_{\eta N} = \frac{1}{3}\langle N|\hat{m}(\bar{u}u + \bar{d}d) + 2m_s\bar{s}s|N\rangle = \frac{1}{3}\hat{\sigma} + \frac{2(m_s+\hat{m})}{3\hat{m}}y_N\sigma_{\pi N}\,. \qquad (26)$$

In Table 1, we have presented the results of our calculations in χCQM pertaining to the scalar matrix elements which are affected by the strangeness content of the nucleon as well as the quantities which are affected by the quark mass ratio as well as the strangeness content, for example, $\hat{\sigma}$, σ_s, $\sigma_{\pi N}$, σ_{KN}, and $\sigma_{\eta N}$. For the sake of comparison, we have also given the corresponding quantities in NQM and the available phenomenological values. To understand the implications of the strange quark mass and SU(3) symmetry breaking, we have presented the results with and without SU(3) symmetry breaking. A closer look at the expressions of these quantities reveals that the constant factors represent the NQM results which do not include the effects of chiral symmetry breaking. On the other hand, the factors with transition probability a represent the contribution from the "quark sea" in general (with or without SU(3) symmetry breaking). As discussed earlier, the terms α, β and ζ give the SU(3) symmetry breaking effects. In the present case, we have considered $a = 0.12$, $\zeta = -0.15$, $\alpha = \beta = 0.45$ for the SU(3) symmetry breaking case whereas under the SU(3) symmetric assumption we have taken $\alpha = \beta = -\zeta = 1$. Since the σ terms are characterized by the parameters of χCQM as well as the light quark mass ratio, we have used the same set of parameters for χCQM as discussed above and for $\frac{m_s}{\hat{m}}$, we have used the most widely accepted value $\frac{m_s}{\hat{m}} = 22$ from the range $22-30$[70].

From the Table one finds that the present result for the strangeness content in the nucleon y_N and strangeness fraction of the nucleon f_s looks to be in agreement with the most recent phenomenological results available which the NQM is unable to explain. The non-zero values for y_N and f_s in the present case indicate that the chiral symmetry breaking is essential to understand the significant role played by the quark sea. It is also clear from the table that, in general, the quantities involving the strange quark content are very sensitive to SU(3) symmetry breaking. For example, the values of the strangeness dependent quantities y_N and f_s change to a large extent when compared for the SU(3) symmetric and SU(3) symmetry breaking case. The results for other quantities which do not have strangeness contribution are not much different for both the cases. The SU(3) symmetric results for y_N and f_s are $\sim 5-6$ times higher than the SU(3) symmetry breaking case. Such a large value cannot be justified which is also in agreement with the observations of other authors[29,30,62,63,64,65].

A closer examination of the results reveals several interesting points. We find that the σ terms increase by taking lower values of the quark mass ratio but it has been argued that the possibility of readjusting the quark mass ratio to get higher value of σ term is ruled out[76]. For $\sigma_{\pi N}$, the value of χCQM with SU(3) symmetry can give a value in the higher range by adopting a larger value of $\hat{\sigma}$ however, as has been shown in our earlier work, SU(3) symmetry does not give a satisfactory description of quark sea asymmetry and spin related quantities. Also, the σ_{KN} and $\sigma_{\eta N}$ become strangely large for the SU(3) symmetric case which confirms that SU(3) symmetry breaking effects should be taken into account. A refinement in the analysis of $\pi - N$ scattering giving higher values of $\sigma_{\pi N}$ would not only strengthen the mechanism of chiral symmetry breaking generating the appropriate amount of strangeness in the nucleon but would also justify the consequences of SU(3) symmetry breaking mechanism. The σ_{KN} and $\sigma_{\eta N}$ terms are found to be quite sensitive to y_N.

The effects of external effects like external magnetic and external gravitational field can easily be incorporated into the calculations of χCQM. Without getting into the details, our results show that the effects of magnetic field and gravitational field contribute towards χSB in the opposite directions. This is in agreement with the results in Ref.[77]. The chiral symmetry is broken by the presence of magnetic field whereas the presence of gravitational field tends to restore chiral symmetry. This leads to a very small overall contribution and the exact order of magnitude can be estimated in a more detailed calculation.

Future DAΦNE experiments[78] will allow a determination of KN sigma terms and hence could restrict the model parameters and provide better knowledge of strangeness content of the nucleon. Further, it would be interesting to find out the role of strangeness content in the nucleon in the hyperon-antihyperon production in heavy ion collisions.

To summarize, the χCQM is able to phenomenologically estimate the quantities having implications for chiral symmetry breaking. In particular, it provides a fairly good description of the scalar matrix elements having implications for hidden strangeness component in the nucleon, for example, the strangeness content in the nucleon y_N and strangeness fraction of the nucleon f_s. The non-zero values for y_N and f_s indicate that the chiral symmetry breaking is essential to understand the significant role of non-valence quarks in the nucleon structure. The significant contribution of the strangeness is consistent with the recent available experimental results which justify that chiral symmetry breaking and SU(3) symmetry breaking play an important role in understanding the flavor structure of the nucleon.

The calculations have also been extended to predict the meson-nucleon sigma terms (σ_{KN} and $\sigma_{\eta N}$). The future DAΦNE experiments to determine KN sigma terms could restrict the model parameters and provide better knowledge of strangeness content of the nucleon. The role of strangeness content in the nucleon would also have important implications for the hyperon-antihyperon production in the heavy ion collisions.

In conclusion, we would like to state that chiral symmetry breaking is the key to understand the hidden strangeness content of the nucleon. In the nonperturbative regime of QCD, constituent quarks and the weakly interacting Goldstone bosons constitute the appropriate degrees of freedom at the leading order.

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Table 1. The χCQM results for the scalar matrix elements of the nucleon and the meson-nucleon sigma terms.

Quantity	Phenomenology	NQM[9,10,11,12,13]	χCQM with SU(3) symmetry	χCQM with SU(3) symmetry breaking
$\langle N\|\bar{u}u\|N\rangle$	...	≤ 2	2.41	2.44
$\langle N\|\bar{d}d\|N\rangle$	...	≤ 1	1.75	1.68
$\langle N\|\bar{s}s\|N\rangle$	...	0.0	1.08	0.18
y_N	0.11 ± 0.07[29,30]	0.0	0.26	0.044
f_s	0.10 ± 0.06[24]	0.0	0.21	0.042
$\hat{\sigma}$	...	28.57	28.57	28.57
σ_s	...	0	168.71	15.12
$\sigma_{\pi N}$	...	28.57	59.25	31.32
σ_{KN}	...	164.29	517.04	195.90
$\sigma_{\eta N}$	...	9.52	244.70	30.60

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