Proton spin problem and chiral constituent quark model

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Abstract

The non-relativistic quark model (NRQM) predictions of some spin and flavor parameters are in sharp conflict with the observations made from deep inelastic scattering experiments. For example, these experiments indicated that only 30% of the spin is carried by the valence quarks. Besides this, along with the observation $\bar{u} - \bar{d} \neq 0$ there are other spin and flavor dependent quantities which could not be explained by NRQM. These contradictions are referred to as "Proton spin problem". These issues get resolved, to some extent, in Chiral constituent quark model (xCQM) which incorporates the basic features of NRQM and chiral symmetry. The implications of the latest data pertaining to $\bar{u} - \bar{d}$ asymmetry and the spin polarization functions on the contributions of singlet Goldstone Boson η' within xCQM with configuration mixing for explaining the "proton spin problem" have been investigated. It is found that the present data favors smaller values of the coupling of singlet Goldstone Boson η' as compared to the corresponding contributions from π, K and η Goldstone bosons. It seems that a small non-zero value of the coupling of η' ($\zeta \neq 0$) is preferred over $\zeta = 0$ phenomenologically.

1. Introduction:

Understanding of QCD, the most valuable theory of strong interactions, in the low energy limits has been a challenging task, however, considerable progress has been achieved in this regime through the calculations of QCD using lattice techniques. The lattice guage theory calculations have given strong evidence for the *confinement* as well as existence of chiral symmetry breaking in the non-perturvative regime of QCD. This has given strong impetus to the formulation of the models such as chiral quark model, instanton model etc., for studying the low energy features of hadrons. One of the most enigmatic feature of the low energy hadron physics has been the remarkable success of the **non relativistic quark model** (**NRQM**), first introduced by Rujula, Georgi and Glashow [1] in explaining a large amount of hadron data.The NRQM, can now be considered as an intermediate phenomenological model that fits the experimental data and incorporates several of the key features of QCD. Based on every simple assumptions, such as, point like quarks carrying spin $\frac{1}{2}$, valence quark structure of hadrons, single quark transitions etc., the NRQM along with the color spin-spin forces has given a remarkable fit to the hadron spectroscopy data including some of the very subtle features of the data such as neutron charge radius, $N - \Delta$ mass difference, photohelicity amplitudes, baryon magnetic moments, etc.. The success of NRQM led Weinberg, Manohar and Georgi [2] to formulate **chiral constituentquark model** (χ**CQM**), which has strong linkage with QCD Lagrangian.

Europian Muon collaboration (EMC) in deep inelastic scattering (DIS) experiment [3], interestingly found that valence quarks of proton carry only about 30% of proton spin which is quite in contradiction with the predictions of NRQM. Viewed from the point of overwhaling success of NRQM in explaining hadronic data led many to christian the above problem as "*proton spin crisis*". The EMC observations were confirmed by several other experimental groups. Apart from the problem faced by NRQM with regard to spin structure of nucleon, the NRQM also faced problem regarding its flavor structure, for example, the strange quark content measured in the pion nucleon sigma ($\sigma_{\pi \mathrm{N}}$) term as well as the $\bar{u}-\bar{d}$ asymmetry measured in the DIS data. The contradictions observed in reference to spin and flavor structure of proton are referred to as "**PROTON SPIN PROBLEM**". The problem becomes more intriguing when one realizes that NRQM is able to give fairly good description of magnetic moments of octet baryons using the assumption that magnetic moments of valence quarks are proportional to the spin carried by them. Thus, finding appropriate spin and flavor structure of nucleon becomes important issue to be resolved.

2. NRQM and Proton spin problem: NRQM is based on the assumption that hadrons are made up of point like valence quarks carrying spin $\frac{1}{2}$, with baryons and mesons consisting of three quarks and quark-antiquark combinations, respectively. Quarks do not appear as free particles but are confined within color neutral i.e., color singlet states. These quarks are supposed to be interacting through confining potential, several of these have been used, the most popular being Coulombic+linear and the harmonic oscillator potential, the latter facilitating exact solutions. The color wavefunctions of mesons are: $|M\rangle = \frac{1}{\sqrt{3}}\left|q\bar{q}\right\rangle$, and that of baryons are: $|B\rangle = \frac{1}{\sqrt{6}}\left|q\,q\,q\right\rangle$. Taking into account all the degrees of freedom the baryon wavefunction can be factorized as: $\Psi_{3q} = \Psi_{\text{colour}} \times \Phi_{\text{flavor}} \times \chi_{\text{spin}}$.

Based on these simple assumptions, NRQM has been applied successfully to huge amount of low energy hadronic data. In particular, Isgur *et. al.* [4], have shown that NRQM incorporating color spin-spin interaction is remarkably successful in this context. Some of the well known successes of NRQM are as follows:

◇ It is not only successful in explaining the flavor J^{PC} (spin parity-chrge conjugation), quantum number of hundreds of hadrons but is also able to give a fair descritpion of their masses, including mass splitting within the multiplet.

◇ Based on single quark transition rule, it is able to provide fairly satisfactory description of large number of strong decay of hadrons, electromagnetic decays, as well as their weak decays.

◇ It is able to provide a highly satisfying description of subtle features such as: Δ-N splitting, non-zero neutron charge radius, photohelicity amplitudes, magnetic moments of octet and decuplet of baryons, etc..

For the present purpose, the effect of color spin-spin forces in the proton wavefunction, referred to as configuration mixing, can be expressed as [5]

(2.1) $$|B\rangle_{\text{config}} = \cos\phi\,|56,\ 0^+\rangle_{N=0} + \sin\phi\left|70,\ 0^+\right\rangle_{N=2},$$

where

(2.2) $$|56,\ 0^+\rangle_{N=0} = \frac{1}{\sqrt{2}}\,(\varphi'\chi' + \varphi''\chi'')\,\psi^s,$$

(2.3) $$|70,\ 0^+\rangle_{N=2} = \frac{1}{2}[(\varphi' \chi'' + \varphi'' \chi')\psi'(0^+) + (\varphi' \chi' - \varphi'' \chi'')\psi''(0^+)],$$

The spin and unitary spin wavefunctions χ, φ' and φ'' for proton are

(2.4) $$\chi' = \frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow),\ \chi'' = \frac{1}{\sqrt{6}}(2\uparrow\uparrow\downarrow - \uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow),$$

(2.5) $$\varphi'_B = \frac{1}{\sqrt{2}}(\text{udu} - \text{duu}),\ \varphi''_B = \frac{1}{\sqrt{6}}(2\,\text{uud} - \text{udu} - \text{duu}).$$

In order to understand the proton spin problem, we have worked out in detail the spin and flavor structure of proton within NRQM with and without configuration mixing. The quark spin polarization is defined as[6]:

(2.6) $$\Delta \text{q} = q^+ - q^-,$$

where $q^{+(-)}$ is the number of q quarks with spin up (down). The sum of Δq's gives the total spin carried by the quarks, for example, ΔΣ=Δu+Δd+Δs, where ΔΣ is twice the spin of the proton. The spin structure for baryon is defined as

(2.7) $$\hat{B} \equiv \langle B | \mathbb{N} | B \rangle,$$

where $\mathbb{N}$ is the number operator corresponding to different quark flavor with spin up and spin down and is expressed as

(2.8) $$\mathbb{N} = n_{u^+}\ u^+ + n_{u^-}\ u^- + n_{d^+}\ d^+ + n_{d^-}\ d^- + n_{s^+}\ s^+ + n_{s^-}\ s^-,$$

with the coefficients of the $q^\pm$ giving the number of $q^\pm$ quarks. Using the above number operator, we can calculate for proton, the number of u quarks with spin up (u^+), for example, $u^+ = \langle 56, 0^+ | n_{u^+} | 56, 0^+\rangle$. As the operator does not affect the spatial part of the wavefunction, therefore, using Eq. (2.2), we can write

(2.8) $$u^+ = \frac{3}{2}\langle \chi' \varphi' + \chi'' \varphi'' |_{n_{u^+}} (3) | \chi' \varphi' + \chi'' \varphi'' \rangle.$$

Using the explicit form of χ and φ wavefunctions, one finds $u^+ = \frac{5}{3}$ for the case of proton, similarly, we can find u^-, d^+ and d^-, for example

(2.10) $$u^- = \frac{1}{3},\ d^+ = \frac{1}{3}.\ d^- = \frac{2}{3}.$$

Thus, using Eq. (2.6), the contribution by each of the quark flavors to the proton spin polarization can be written as:

(2.11) $\Delta\mathrm{u} = \frac{4}{3},\ \Delta\mathrm{d} = \frac{-1}{3},\ \Delta\mathrm{s} = 0.$

Using Eq. (2.7), the spin structure for Eq. (2.1) is given as

(2.12) $\hat{p}_{\text{config}} = \cos^2\phi(\frac{5}{3}\ u^+ + \frac{1}{3}\ u^- + \frac{1}{3}\ d^+ + \frac{2}{3}\ d^-) +$
$+\sin^2\phi(\frac{4}{3}\ u^+ + \frac{2}{3}\ u^- + \frac{2}{3}\ d^+ + \frac{1}{3}\ d^-).$

The spin polarization functions are therefore given as

(2.13) $\Delta\mathrm{u}_{\text{val}} = \cos^2\phi[\frac{4}{3}] + \sin^2\phi[\frac{2}{3}],\ \Delta\mathrm{d}_{\text{val}} =$
$= \cos^2\phi[-\frac{1}{3}] + \sin^2\phi[\frac{1}{3}],\ \Delta\mathrm{s}_{\text{val}} = 0.$

The typical set of the phenomenological result for the quark spin polarizations, as found by EMC and other experiments, are as follows:

(2.14) Δu=0.85, Δd=-0.41, Δs=-0.07,

to be compared with the predictions of NRQM, for example

(2.15) Δu=1.33, Δd=-0.33, Δs=0,

where, the total polarization ΔΣ=Δu+Δd+Δs is normalizes to 1 in the case of NRQM. The total spin polarization, from Eq. (2.14), corresponds to ΔΣ=0.38, showing a good deal of disagreement with NRQM expectations.

Apart from the above mentioned inadequacy of NRQM, the problem of NRQM becomes more acute when one confronts it with some of the well known sum rules involving spin polarization functions having weak Q^2 dependecne and are derived rigorouslyfrom QCD using operator product expansion, renormalization group invariance and isospin conservation. For example, the Bjorken sum rule (BSR), relates the flavor non-singlet component (Δ_3), isovector axial current obtained using SU(3) flavor symmetry from the neutron β-decay (G_A / G_V) and the spin polarization functions of proton, is given as

(2.16) BSR: $\Delta_3 = G_A / G_V = \Delta\mathrm{u} - \Delta\mathrm{d}.$

Experimentally, the value of G_A / G_V is 1.267, to be compared with the NRQM value 1.66, again indicating the inadequacy of NRQM. Similarly, the Ellis-Jaffe sum rule (EJSR), relating the flavor non-singlet component (Δ_8) and the spin polarization functions, has the form

(2.17) EJSR: $\Delta_8 = \Delta u + \Delta d - 2\,\Delta s$.

If one assumes Δs=0, we get $\Delta\Sigma = \Delta_8$ which is observed to be strongly violated by data. This implies that there is a significant contribution to the proton spin by the polarized strange quark components in the sea. The measured value of the pion-nucleon sigma term $\sigma_{\pi N}$ suggests a surprisingly large fraction of strange quark. When SU(3) breaking effects are taken into account, the fraction f_s, defined as the strange quark and antiquark number divided by the sum of the quark numbers, if of the order of 0.10, indicating the failure of NRQM which predicts it to be zero.

Apart from the spin polarization functions, the valence quark structure of NRQM is inadequate to describe the flavor structure of the proton. For example, the Gottfried sum rule (GSR), in terms of antiquark densities as $\bar{u} - \bar{d} = -0.118 \pm 0.026$, indicates that the nucleon sea is quite asymmetric with respect to $\bar{u}$ and $\bar{d}$ quark contents. This is in contrast to the symmetric expectation from NRQM. These inadequacies of NRQM are to be referred as "PROTON SPIN PROBLEM". The situation is still further intriguing for NRQM's description of magnetic moments of octet baryons using the assumption that magnetic moments of valence quarks are proportional to the spin carried by them. Thus, finding the appropriate spin and flavor structure of the nucleon becomes an urgent issue to be resloved.

3. χCQM and emission of GB:

The chiral constituent quark model (χCQM), as formulated by Manohar and Georgi [2], has recently got good deal of attention [6, 7, 8, 9] as it is success - ful in not only explaining the "proton spin crisis" [3, 10, 11, 12] through the emission of a Goldstone boson (GB) but is also able to acount for the $\bar{u}-\bar{d}$ asymmetry [13, 14, 15], existence of significant strange quark content $\bar{s}$ in the nucleon, various quark flavor contributions to the proton spin [7], baryon magnetic moments [6, 7] and hyperon β-decay parameters etc..

Recently, it has been shown that configuration mixing generated by spin-spin forces [1, 4, 16], known to be compatible with the χCQM [17, 18, 19], improves the predictions regarding the quark distribution functions and the spin polarization functions [20]. Further, χCQM with configuration mixing (henceforth to be referred as $\chi\text{CQM}_{\text{config}}$) when coupled with the quark sea polarization and orbital angular momentum (Cheng-Li mechanism [21]) as well as "confinement effects" is able to give an exellent fit for the violation of Coleman Glashow sum rule [22].

The scope of χCQM, as developed by Weinberg, Manohar and Georgi [2], was extended by Cheng and Li [6] to resolve the "proton spin problem" [23]. They realized that the key to understand the problem lies in generating an appropriate quark sea in the proton through the chiral symmetry breaking mechanism. They considered the following chiral fluctuations for the quark sea generation through the emission of Goldstone boson (GB) by a given valence quark $q^{\pm}$

(3.1) $$q_{\pm} \to \text{GB}^{0} + q'_{\mp} \to \left(\text{q}\bar{\text{q}}'\right) + q'_{\mp},$$

where the superscript – indicates the helicity of the quark. The $\text{q}\bar{\text{q}}'$ and $q'_{\mp}$ represent the "sea" associated with the quark $q_{\pm}$. The production of the $\text{q}\bar{\text{q}}'$ pair is shown in Figure 3.1 In the SU(3) symmetric model, they demonstrated that this picture can account for the observed spin and flavor structure in the nucleon in terms of two parameters: the probability of the above fluctuation of the pion GB to be controlled by the parameter a and the ratio of singlet and octet coupling ζ. The agreement of Cheng and Li improves further when symmetry breaking effects, attributed to the difference between strange and non-strange quarks, are taken into considerations.

It is not difficult to understand the success of χCQM in resolving the "proton spin problem' in terms of its basic tenets. The depolarization of the valence quarks can be understood from Eq. (3.1). Since both the q and $\bar{q}'$ quarks of the "quark sea" in the equation are unpolarized, the polarization of the entire quark sea must be given by the $q'_{\mp}$, which is opposite to the initial quark helicity state. This naturally leads to a negatively polarized sea and is in qualitative agree - ment with the phenomenological observation that the entire spin is not carried by the valence quarks and is less than one. The negatively polarized seaq makes

$$\Delta\Sigma = \Delta\Sigma_{\text{val}} + \Delta\Sigma_{\text{sea}} \tag{3.2}$$

less than one as observed in the DIS experiments.

To understand the proton flavor structure in χCQM, it can be seen that the valence u quark more likely produces $\bar{d}$ whereas the valence d quark tends to produce $\bar{u}$ through the intermediate state of GBs, for example, $u \to \pi^+ d \to u \bar{d} d$ and $d \to \pi^- u \to d \bar{u} u$. This naturally leads to a proton "quark sea" having more $\bar{d}$ than $\bar{u}$ because there are two valence u quarks and only one valence d quark. This accounts for the $\bar{u} - \bar{d}$ asymmetry as measured by the deviation from the GSR and by the cross section difference of the Drell-Yan process on proton and neutron targets. As both u and d quarks can produce $\bar{s}$, we have a significant strange quark content f_s, as indicated by the value of the pion nucleon sigma term.

In recent work, Cheng and Li [21] have discussed in detail the reason why NRQM is able to give a reasonably good description of baryon magnetic moments without satisfying the data pertaining to the spin polarization functions. In this context, they have shown that this longstanding puzzle can be resolved if, apart from the contribution of the sea polarization, the intermediate GBs also have angular momentum and therefore contribute to the magnetic moments as well. Interestingly, they found that there is a significant cancellation between the sea polarization and the orbital angular momentum of the GBs, giving the magnetic moments in terms of the valence constituent quarks alone. To make the χCQM, which is SU(3) symmetric, more realistic, one can add a singlet of η' to the octet of the GB. The Lagrangian is now U(1) symmetric, however, such a symmetry is not observed in nature. To incluid the broken U(1) symmetry, the η' boson should come with a coupling constant g_8 for the other octet GBs. This is realised by adding the SU(3) scalar interaction $\mathcal{L} = g_1 \bar{q} \frac{\eta'}{\sqrt{3}} q$ to the Lagrangian, where g_1 is the coupling constant for the η' bosons. Thus, the effective Lagrangian describing interaction between quarks and nonet of GBs (consisting of octet and singlet) can be expressed as

$$\mathcal{L} = g_8 \bar{q} \Phi q + g_1 \bar{q} \frac{\eta'}{\sqrt{3}} q = g_8 \bar{q}\left(\Phi + \zeta \frac{\eta'}{\sqrt{3}} I\right) q, \tag{3.3}$$

where $\zeta = g_1 / g_8$, g_1 and g_8 are the coupling constants for the singlet and octet GBs, respectively, I is a 3⊗3 identity matrix and

$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix}. \tag{3.4}$$

The GB field which includes the octet and the singlet GBs is written as

(3.5)

$$\Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \beta \frac{\eta}{\sqrt{6}} + \zeta \frac{\eta'}{\sqrt{3}} & \pi^+ & \alpha K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \beta \frac{\eta}{\sqrt{6}} + \zeta \frac{\eta'}{\sqrt{3}} & \alpha K^0 \\ \alpha K^- & \alpha \overline{K}^0 & -\beta \frac{2\eta}{\sqrt{6}} + \zeta \frac{\eta'}{\sqrt{3}} \end{pmatrix}$$

SU(3) symmetry breaking is introduced by considering $M_s > M_{u,d}$ as well as by considering the masses of GBs to be nondegenerate $(M_{K,\eta} > M_\pi)$ [8, 9, 21], whereas the axial U(1) breaking is introduced by $M_{\eta'} > M_{K,\eta}$ [6, 8, 9, 21]. The parameter $a(= |g_8|^2)$ denotes the transition probability of chiral fluctuation of the splittings $u(d) \to d(u) + \pi^{+(-)}$, whereas $\alpha^2 a$, $\beta^2 a$ and $\zeta^2 a$, respectively denote the probabilities of transitions of $u(d) \to s + K^{-(0)}$, $u(d, s) \to u(d, s) + \eta$, and $u(d, s) \to u(d, s) + \eta'$.

Recently, it has been pointed out that the new measurement of both the $\bar{u}/\bar{d}$ asymmetry as well as $\bar{u} - \bar{d}$ asymmetry by the NuSea Collaboration [14] may not require substantial contribution of η' [9]. As the contribution of η' not only has important implications for the χCQM but also has deeper significance for axial U(1) anomaly as well as nonperturbative aspects of QCD including the effects of gluon anomaly on the spin polarizations [24], it therefore becomes interesting to understand the extent to which its contribution is needed in the χCQM to fit the data pertaining to the "proton spin problem".

The puspose of the present communication is to phenomenologically estimate the contribution of η' GB by carrying out a fine grained analysis of "proton spin problem" within $\chi\text{CQM}_{\text{config}}$ which also includes the implications of the latest E866 data. Further, it would be interesting to fine tune the contribution of η', expressed through the parameter ζ, by studying its implications on spin polarization functions and quark distribution functions.

The details of χCQM$_{\text{config}}$ have already been discussed in Ref. [20], however to facilitate the discussion as well as for the sake of readability of the manuscript, some essential details of χCQM with configuration mixing have been presented in the sequel. As has already been discussed that spin-spin forces generate configuration mixing [1, 4, 16] which effectively leads to modification of the spin polarization functions [20]. The most general configuration mixing in the case of octet barayons [4, 16, 25] can be expressed as

(3.6) $$|B\rangle = (|56, 0^+\rangle_{N=0} \cos\theta + |56, 0^+\rangle_{N=2} \sin\theta) \cos\phi + (|70, 0^+\rangle_{N=2} \cos\theta' + |70, 2^+\rangle_{N=2} \sin\theta') \sin\phi,$$

where ϕ represents the $|56\rangle - |70\rangle$ mixing, θ and θ' respectively correspond to the mixing among $|56, 0^+\rangle_{N=0} - |56, 0^+\rangle_{N=2}$ states and $|70, 0^+\rangle_{N=2} - |70, 2^+\rangle_{N=2}$ states. For the present purpose, it is adequate [16, 20, 26] to consider the mixing only between $(|56, 0^+\rangle_{N=0}$ and $70, 0^+\rangle_{N=2}$ states and the corresponding "mixed" octet of baryons is expressed as

(3.7) $$|B\rangle \equiv |8, \tfrac{1^+}{2}\rangle = \cos\phi\, |56, 0^+\rangle_{N=0} + \sin\phi\, |70, 2^+\rangle_{N=2},$$

for details of the spin, isospin ans spatial parts of the wavefunction, we refer the reader to reference [5]. To study the variation of the χCQM parameters and the role of ζ in obtaining the fit, one needs to formulate the experimentally measurable quantities having implications for these parameters as well as dependent on the unpolarized quark distribution functions and the spin polarization functions. We first calculate the spin polarizations and the related quantities which are affected by the "mixed" nucleon. The spin structure of a nucleon is defined as [6, 8, 9]

(3.8) $$\hat{B} \equiv \langle B | N | B \rangle,$$

where $|B\rangle$ is the nucleon wavefunction defined in Eq. (3.7) and N is the number operator given by

(3.9) $$N = n_{u^+}\ u^+ + n_{u^-}\ u^- + n_{d^+}\ d^+ + n_{d^-}\ d^- + n_{s^+}\ s^+ + n_{s^-}\ s-,$$

where $n_{q_\pm}$ are the number of $q_\pm$ quarks. The spin structure of the "mixed" nucleon, defined through the Eq.(3.7), is given by

(3.10) $$\left\langle 8, \tfrac{1^+}{2} \,\middle|\, N \,\middle|\, 8, \tfrac{1^+}{2} \right\rangle = \cos^2\phi \,\langle 56,\ 0^+ | \,N\, | 56,\ 0^+\rangle + \\ + \sin^2\phi\,\langle 70,\ 0^+ \,|N|\, 70,\ 0^+\rangle\,.$$

The contribution to the proton spin in $\chi\text{CQM}_{\text{config}}$, given by the spin polarizations defined as $\Delta q = q^+ - q^-$, can be written as

(3.11) $$\Delta u = \cos^2\phi[\tfrac{4}{3} - \tfrac{a}{3}\,(7 + 4\,\alpha^2 + \tfrac{4}{3}\,\beta^2 + \tfrac{8}{3}\,\zeta^2)] \\ +\sin^2\phi[\tfrac{2}{3} - \tfrac{a}{3}\,(5 + 2\,\alpha^2 + \tfrac{2}{3}\,\beta^2 + \tfrac{4}{3}\,\zeta^2)]\,,$$

(3.12) $$\Delta d = \cos^2\phi[-\tfrac{1}{3} - \tfrac{a}{3}\,(2 - \alpha^2 - \tfrac{1}{3}\,\beta^2 - \tfrac{2}{3}\,\zeta^2)] \\ +\sin^2\phi[\tfrac{1}{3} - \tfrac{a}{3}\,(4 + \alpha^2 + \tfrac{1}{3}\,\beta^2 + \tfrac{2}{3}\,\zeta^2)]\,,$$

(3.13) $$\Delta s = -a\alpha^2\,.$$

After having formulated the spin polarizations of various quarks, we consider several measured quantities which are expressed in terms of the above mentioned spin polarization functions. The quantities usually calculated in the χCQM are the flavor non-singlet components Δ_3 and Δ_8, obtained from the neutron β-decy and the weak decays of hyperons respectively. These can be related to Bjorken sum rule [27] and Ellis-Jaffe sum rule [28] as

(3.14) $$\text{BSR:}\quad \Delta_3 = \Delta u - \Delta d,$$

(3.15) $$\text{EJSR:}\quad \Delta_8 = \Delta u + \Delta d - 2\,\Delta s\,.$$

Another quantity which is usually evaluated is the flavor singlet component of the total quark spin content defined as

(3.16) $$2\,\Delta\Sigma = \Delta_0 = \Delta u + \Delta d + \Delta s\,.$$

Apart from the above mentioned spin polarization we have also considered the quark distribution functions which have implications for ζ as well as for other χCQM parameters. For example, the antiquark flavor contents of the "quark sea" can be expressed as [6, 8, 9]

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

and

(3.18) $$u - \bar{u} = 2,\, d - \bar{d} = 1,\, s - \bar{s} = 0.$$

The Gottfried sum rule [15] is expressed as

(3.19) $$I_G = \frac{1}{3} + \frac{2}{3}\int_0^1 \left[\bar{u}(x) - \bar{d}(x)\right] dx = 0.254 \pm 0.005.$$

In terms of the symmetry breaking parameters a, β and ζ, this deviation is given as

(3.20) $$[I_G - \tfrac{1}{3}] = \frac{2}{3}[\frac{a}{3}\,(2\zeta + \beta - 3)].$$

Similarly, $\bar{u}/\bar{d}$ [14, 29] measured through the ratio of muon pair production cross sections σ_{pp} and σ_{pn}, is expressed in the present case as follows

(3.21) $$\bar{u}/\bar{d} = \frac{(2\zeta + \beta + 1)^2 + 20}{(2\zeta + \beta - 1)^2 + 32}.$$

Some of the important quantities depending on the quark distribution functions which are usually discussed in the literature are as follows

(3.22) $$f_q = \frac{q + \bar{q}}{[\Sigma_q (q + \bar{q})]},\ f_3 = f_u - f_d,\ f_8 = f_u + f_d - 2\, f_s.$$

The χCQM$_{\text{config}}$ involves five parameters: a, α, β, ζ and ϕ. Before carrying out the detailed analysis involving quantities which are dependent on ζ, to begin with we have fixed some of the χCQM parameters. The mixing angle ϕ is fixed from the consideration of neutron charge radius [16, 25, 30]. It has been shown [6, 9] that to fix the violation on Gottfried sum rule [15], we have to consider the relation

(3.23) $$\bar{u} - \bar{d} = \frac{a}{3}\,(2\zeta + \beta - 3),$$

which constraints the parameters a, ζ and β when the data pertaining to $\bar{u} - \bar{d}$ asymmetry [14] is used.

4. Results and Discussions:

The parameters α and β suppress the emission of K and η as compared to that of pions as these strange quark carrying GBs are more massive than the pions. However, because of the very small mass difference between them, the suppression factors α and β are taken to be equal. In Table 1, we summarize the input parameters and their values.

In Table 2, we have presented the various spin dependent phenomenological quantities which are affected by the variation of the symmetry breaking parameters. In the Table, to highlightthe particular values of a and ζ, we have presented the results for their different values. A general look at the Table shows that the results for all the quantities affected by the inclusion of ζ get improved in the right direction for lower values of ζ. In fact, for the case of $a = 0.13$ and $\zeta = -0.10$, we are able to get a perfect fit for Δ_3 and Δ_8.

Further, the results corresponding to quark distribution functions having implifications for the symmetry breaking parameters have been presented in Table 3. In general both for $\zeta = 0$ and $\zeta = -0.10$, we are able to obtain an excellent fit, however in the case of $\bar{u} - \bar{d}$, $\bar{u} / \bar{d}$ and f_3 / f_8, the non-zero (small) value of ζ gives a better fit that $\zeta = 0$. A closer scrutiny of the table reveals several interesting points. Δ_3 and Δ_8 from Table 2 as well as f_3 / f_8 from Table 3 perhaps suggest that a small non-zero value of ζ gives a better fit than the zero value of ζ. In the case of $\Delta\Sigma$ (Table 2), it seems that ζ=0 is a preferred value. However, as has been discussed earlier in χCQM [31] that the flavor singlet component of the spin of proton $\Delta\Sigma$ receives contributions from various sources such as gluon polarization and gluon angular momentum, therefore, we cannot conclude that $\zeta = 0$ is preferred over $\zeta \neq 0$. In this context, we would like to mention that the above contribution of η' is in agreement with the experimental value of $\Delta\Sigma$ in case we consider the contribution of the effects of gluon polarization and gluon angular momentum through gluon anomaly [31]. The results corresponding to small values of ζ including $\zeta = 0$ clearly show better overlap with the data after the latest $\bar{u} - \bar{d}$ asymmetry measurement [14]. In the χCQM, it is difficult to think of a mechanism wherein the contribution of η' or the ninth GB becomes zero. However, a small value of ζ looks to be in order from phenomenological considerations pertaining to the different GBs. For example, in case we consider the coupling of the GB corresponding to the pion, K, η an η' mesons being inversely proportional to the square of their respective masses, we find that their couplings are of the order $a\alpha^2 \sim 0.02$, $a\beta^2 \sim 0.02$ and $a\zeta^2 \sim 0.001$, for $a \sim 0.13$ which strangely agrees with our values obtained through the fit. These findings are also in agreement with the suggestions of Cheng and Li [6] who have advocated that the η' contribution corresponds to the non-planar contributions in the $1/N_c$ expansion.

To summarize, we have investigated in detail the implications of the latest data pertaining to $\bar{u} - \bar{d}$ asymmetry and the spin polarization functions on the singlet Goldstone Boson η' within χCQM with configuration mixing for explaining the "proton spin problem". We find that the lower values of ζ are preferred over the higher values. Specifically, in the case of Δ_3, Δ_8, $\bar{u} - \bar{d}$, $\bar{u}/\bar{d}$ and f_3/f_8, it seems that the small non-zero value of ζ is preferred over $\zeta = 0$.

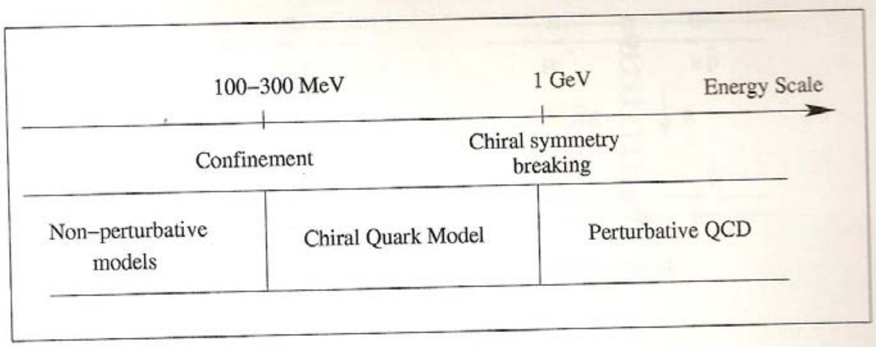

Figure 1. The energy scale in which χCQM works.

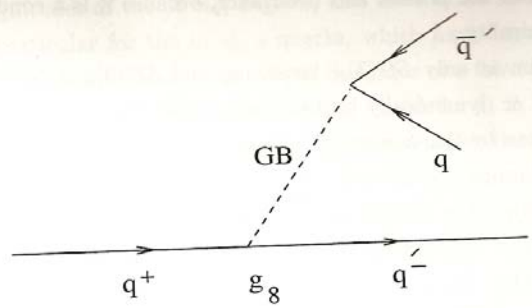

Figure 3.1: Production of a $q\bar{q}$ pair via a Goldstone Boson emission.

Parameter →	ϕ	a	α	β	ζ
Value	20°	0.1	0.4	0.7	$-0.3-\beta/2$
□	20°	0.13	0.4	0.4	$0.15-\beta/2$
□	20°	$0.345/(3-\beta)$	0.4	0.4	0

Table 1: Input parameters and their values used in the analysis.

"" Parameter	"Data"	χCQM$_{config}$			""	
		$a=0.1$ $\zeta=-0.65$	$a=0.14$ $\zeta=0$	$a=0.13$ $\zeta=-0.10$		
Δu	0.85 ± 0.05 [10]	0.95	0.91	0.91	□	□
Δd	-0.41 ± 0.05[10]	−0.31	− 0.35	− 0.36		
Δs	-0.07 ± 0.05[10]	−0.02	− 0.02	− 0.02		
Δ_3	1.267 ± 0.0035[32]	1.27	1.26	1.27		
Δ_8	$0.58 \pm .025$[32]	0.67	0.60	0.59		
$\Delta\Sigma$	$0.19 \pm .025$[32]	0.31	0.27	0.28		

Table 2: The phenomenological values of the spin polarizations and

dependent parameters.

"" Parameter	Data "	χCQM$_{\text{config}}$		
		$a = 0.1$ $\zeta = -0.65$	$a = 0.14$ $\zeta = 0$	$a = 0.13$ $\zeta = -0.10$
$\bar{u}$	. –	0.168	0.25	0.23
$\bar{d}$	–	0.288	0.366	0.35
$\bar{u} - \bar{d}$	-0.118 ± 0.015 [14]	0.108	0.07	0.07
$\bar{u} / \bar{d}$	0.67 ± 0.06 [14]	-0.108	-0.116	-0.117
I_G	$0.254 \pm .005$	0.58	0.68	0.67
f_u	–	0.253	0.255	0.255
f_d	–	0.655	0.677	0.675
f_s	0.10 ± 0.06 [33]	0.442	0.470	0.466
f_3	–	0.061	0.039	0.039
f_8	–	0.213	0.207	0.209
f_3 / f_8	0.21 ± 0.05 [6]	0.975	1.07	1.06
		0.22	0.19	0.20

Table 3 : The quark flavor distribution functions and dependent parameters

Null

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