NON-PERTURBATIVE QCD SPIN STUDIES[a]

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A whole class of non-perturbative QCD studies (*e.g.* the instanton models, chiral quark models, *etc.*) indicates that the effective degrees of freedom for the physics in the low $Q^2 \lesssim 1\, GeV^2$ region could be the constituent quarks (CQs) and internal Goldstone bosons (IGBs). This leads to a nucleon structure with the spin being carried by three constituent quark systems, each composed of a massive compact CQ surrounded by a $q\bar{q}$ sea perturbatively generated by the valence quark's IGB emissions. Such a CQ-system has a total angular momentum of 1/2 and a small anomalous magnetic moment, built up from a quark-spin polarization and a significant orbital motion in the quark sea. The distinctive phenomenological signal for such a non-perturbative structure is that the polarization of the sea-quarks differs from that of the antiquarks: $(\Delta_q)_{\rm sea} \neq \Delta_{\bar{q}}$: the sea-quarks are polarized negatively, $(\Delta_q)_{\rm sea} < 0$, while the antiquarks are not polarized, $\Delta_{\bar{q}} = 0$. This picture also suggests a negligibly small gluon polarization, $\Delta G \simeq 0$. All such features can be tested by experiments in the near future.

1 Introduction

The QCD gauge coupling is not small for the distance and energy scales involved in the structural study of hadrons composed of light u, d, and s quarks. Thus questions such as "what carries the proton spin?" will necessarily involve an understanding of non-perturbative QCD. Even if we were able to answer this spin question in term of percentages of the proton spin being carried by its component quarks and gluons, to explicate the mechanism that built up the final spin from these fundamental QCD degrees of freedom (DOF) is still a daunting task. For this we may ultimately rely on such approaches as lattice QCD calculations. But instead of such a head-on attack (and in order to have a simple physical understanding), it may well be useful to adopt a two-stage approach using an effective DOF description of the non-perturbative phenomena.

1.1 The two-stage approach

At the first stage, one tries to find the effective degrees of freedom for the strong interactions in this low Q^2 regime, in terms of which the physics description will be simple, intuitive, and phenomenologically correct. At the second stage, one then looks for the relation of these non-perturbative effective DOF and the QCD quarks and gluons.

An example of the non-perturbative DOF is the constituent quark of the non-relativistic quark model. The constituent quarks U, D, and S carry the same quantum numbers as the QCD Lagrangian quarks u, d, and s, but they have much greater mass values. It is well-known that the non-relativistic quark model correctly describes most of the static hadronic properties. The spectroscopy and baryon magnetic moments are well fitted[b] with CQ masses:

$$M_U \simeq M_D \equiv M_{U,D} \simeq 350\,MeV,\ M_S \simeq 500\,MeV \tag{1}$$

which are to be compared to the Lagrangian quark mass values (at $1\,GeV$) of

$$m_{u,d} \equiv \frac{m_u + m_d}{2} \simeq 6\,MeV, \quad m_s \simeq 150\,MeV. \tag{2}$$

Presumably the extra mass of the CQ results from some non-perturbative QCD interaction. Thus, at the second stage, one needs to work out the details showing how QCD can endow the light quarks with a sizable mass — yet retaining their simple Dirac magnetic moment structure, $\mu_Q = q_Q/2M_Q$. Later on we shall discuss examples of models (such as the chiral quark model and the instanton model) that can account for such entities.

The advantage of separating the non-perturbative study into two stages is that the effective DOF of the first stage provides us with a simple common language, which can facilitate and stimulate communications among the diverse groups investigating the nucleon structure problem, and which allows for simpler generalizations to the more difficult non-perturbative phenomena. Also, alternative approaches have many features in common at the first stage. (What differentiate them are the details and precise connection to the underlying QCD.) This two-stage approach should help us in making comparisons.

1.2 The naive quark sea

The non-relativistic quark model is often referred to as being the naive quark model (NQM). Relativistic corrections have not been taken into account, and it lacks a $q\bar{q}$ quark sea, which is expected in any quantum field theoretical description involving quarks.

The NQM gives a good description of the baryon magnetic moment (*i.e.* minimally affected by the quark sea). This has led to the belief that the NQM

[b]For a recent pedigogical review, see [1].

account of the quark contribution to the baryon spin should be reliable[c]. Thus the discrepancy between the NQM prediction for the neutron axial-vector constant $g_A = \Delta u - \Delta d = 5/3$ and the experimental value of $1.26 \simeq 5/4$ has generally been attributed to a possibly large relativistic correction[2,3]. But such a reduction depends on the details of the internal quark momentum distribution.

Clearly one would identify the NQM quarks as the valence quarks. Therefore, the recent study of the hadron structure can be said to be primarily the study of the quark sea. But, the conventional expectation of the quark sea properties had been heavily influenced by perturbative QCD reasoning: Namely, the sea is pictured to result from the quark-pair production by gluons.

- The sea is supposed to have the same amount of $\bar{u}$ and $\bar{d}$, because gluon is flavor-independent, and u and d quarks have similar masses.
- The gluon coupling is such that quarks and antiquarks are expected to have the same polarization, (to the extend that masses can be ignored):

  $$(\Delta_q)_{\rm sea} = \Delta_{\bar{q}} \quad \text{or} \quad (\Delta_q)_{\rm sea} - \Delta_{\bar{q}} \equiv \left(\widetilde{\Delta q}\right)_{\rm sea} \simeq 0.$$

  Since $\widetilde{\Delta q}$ enters into the magnetic moment calculation, this possibility was thought to be helpful to account for the absence of a quark sea effect on the baryon moments.
- One part of the conventional expectation that is non-perturbative in character is the suggestion that OZI rule[4] should be applicable in general. Namely, not only we expect a suppression of $s\bar{s}$ in the vector channel (which explains, for example, the ideal mixing observed among the vector meson spectrum) but in other channels as well, *e.g.* in the scalar and axial vector channels: thus the suppression of the proton matrix elements of

  $$\langle p\,|\bar{s}s|\,p\rangle \simeq \langle p\,|\bar{s}\gamma_\mu\gamma_5 s|\,p\rangle \simeq 0.$$

  and the anticipation of a small pion-nucleon sigma term[5], and $\Delta s \simeq 0$[6].

All such conventional expectations have been called into question by experimental measurements.

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[c] Quark contribution Δq to the proton spin is the sum of quark and antiquark polarizations, $\Delta q = \Delta_q + \Delta_{\bar{q}}$, while the magnetic moment involves their difference $\widetilde{\Delta q} = \Delta_q - \Delta_{\bar{q}}$ — because antiquark has the opposite electric charge. In NQM there is no antiquark in the proton, hence $\widetilde{\Delta q} = \Delta q$ and the magnetic moment result directly probes the quark spin contributions Δq.

2 Experimental measurements

2.1 The proton spin structure

The interest in the proton spin problem has been high, ever since the discovery in the late 1980's by the European Muon Collaboration[7] that the Ellis-Jaffe sum rule[6] is violated by the experimental data from polarized deep inelastic scattering. It implies that the proton quark sea has a polarized strange quark component, $\Delta s \neq 0$. This is followed by more polarized DIS experiments, SMC at CERN[8], E142-3, E154-5 at SLAC[9], and HERME at DESY[10], which generally support the original EMC findings. Here we quote a typical set of phenomenological result as reported by SMC[11]:

$$\begin{aligned} (\Delta u)_{\rm expt} &= 0.82 \pm 0.02, \quad (\Delta d)_{\rm expt} = -0.43 \pm 0.02, \\ (\Delta s)_{\rm expt} &= -0.10 \pm 0.02, \quad (\Delta \Sigma)_{\rm expt} = 0.29 \pm 0.06, \end{aligned} \tag{3}$$

all evaluated at $Q^2 = 5\,GeV^2$. These results have been obtained with the assumption of flavor-SU(3) symmetry[6]. There are indications[d] that SU(3) breaking corrections might lower somewhat the magnitude of Δs. Here we note the main feature that they deviate significantly from the NQM prediction:

$$(\Delta u)_{\rm NQM} = \frac{4}{3}, \;\; (\Delta d)_{\rm NQM} = -\frac{1}{3}, \;\; (\Delta s)_{\rm NQM} = 0, \;\; (\Delta \Sigma)_{\rm NQM} = 1. \tag{4}$$

This comparison naturally leads one to the possible interpretation[e] of Eqs.(3) and (4) as indicating a negatively polarized quark sea. Namely, if we identify the NQM values as the polarization of the valence quarks, and the difference as due to the $q\bar{q}$ quark sea:

$$(\Delta q)_{\rm expt} = (\Delta q)_{\rm NQM} + (\Delta q)_{\rm sea} \quad \text{with} \quad (\Delta q)_{\rm sea} < 0. \tag{5}$$

The quark sea is polarized in the direction opposite to the proton spin.

2.2 The proton flavor structure

The spin puzzle is part of nucleon structure problem and should not be treated in isolation. There is by now a considerable amount of experimental data having bearing on the flavor structure of the proton.

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[d] This is indicated by models for SU(3) breaking[12] and by direct measurement[13].
[e] This interpretation implicitly assumes that the relativistic correction is not the principal reduction factor of the NQM values to the ones in (3). For example, the reduction $(5/3 \to 5/4)$ of g_A is attributed mainly to the depolarization effect of the quark sea.

- The are more $\bar{d}$ than $\bar{u}$ in the proton: NMC[14] first discovered that the Gottfried sum rule[15] of l-N DIS was violated. This can be translated into the statement about the difference of antiquark density as $\bar{d}-\bar{u}=0.147\pm0.026$. That there are more $\bar{d}$ than $\bar{u}$ has also been confirmed by comparing data from pp with pn Drell-Yan processes, first by NA51 at CERN[16] and more recently by Fermilab E866[17].

- The presence of $s\bar{s}$ in the nucleon is not suppressed by the basic mechanism that generates the quark sea, even though it is reduced somewhat by the strange quark mass factor $M_S > M_{U,D}$. This point is illustrated by the contrasting phenomenological results of the pion-nucleon sigma term $\sigma_{\pi N}$ (which is the pion-nucleon scattering amplitude at a particular kinematic point[18]) and neutrino charm production[19]. An SU(3) analysis[5] of the $\sigma_{\pi N}$[20] (entirely similar to the Ellis-Jaffe calculation[6] of the flavor spin factors) suggests a surprisingly large fraction of strange quarks (strange quark and antiquark number divided by the sum of all quark numbers) in the nucleon $f_s \simeq 0.18$, which is reduced to about 0.10 by SU(3) breaking effects[21]. Neutrino charm production is also sensitive to the presence of strange quarks in the nucleon. However its phenomenological fits suggest [22] a ratio of $2\bar{s}/\left(\bar{u}+\bar{d}\right)\simeq 0.5$.

3 The chiral quark idea

Non-perturbative QCD has two prominent features: confinement and dynamic breaking of chiral symmetry. The key to understand both is the structure of QCD vacuum. The most detailed theoretical model, (*i.e.* covering most of the non-perturbative issues in a self-consistent way), has been the instanton approach of Diakonov, et al.[23], or the related work by Shuryak, et al.[24] At a more phenomenological level, there are also the various quark models based on Nambu-Jona-Lasinio interaction[25]. All these models share the feature of having a "chiral quark" effective theory based on the interaction among constituent quarks and some entities having the quantum numbers of Goldstone bosons[f]. Since the basic chiral quark idea is simpler to explain in the form as first formulated by Manohar and Georgi[26], this is the language we shall adopt in this presentation. Later on we shall comment on the possible problems of this version of the chiral quark model (χQM) and its common features with the instanton approach.

[f] In the instanton models, there are actually no free propagating 0^- states at all, they are just short-hands for $q\bar{q}$ loop effects: $\bar{q}q$ pairs "propagate" by leaping among states associated with instantons.

The chiral quark idea is based on the possibility that chiral symmetry breaking (χSB) takes place at a distance scale much smaller than the confinement radius: in terms of the energy scales, $\Lambda_{\chi \rm SB} \gg \Lambda_{\rm conf} \approx \Lambda_{\rm QCD}$ with $\Lambda_{\chi \rm SB} \simeq 1\,GeV$ vs $\Lambda_{\rm QCD} \simeq 0.1 - 0.2\,GeV$. As distance increases, the increased QCD coupling strength g will be such that the non-perturbative phenomenon of χSB is triggered around $\Lambda_{\chi \rm SB}^{-1}$, way before the hadron exterior $\Lambda_{\rm conf}^{-1}$. In this interior region, the QCD vacuum acquires a non-trivial structure with a $q\bar{q}$ condensate: $\langle \bar{q}\,(x)\, q\,(x)\rangle_0 \neq 0$, and pseudoscalar massless states, the Goldstone bosons, come into being[g]. Thus in the hadron interior, but not so small a distance that perturbative QCD is applicable, the effective DOF are the CQs and internal GBs.

- Constituent quarks: They are just the ordinary QCD quarks, but now propagating in the non-trivial QCD vacuum having $q\bar{q}$ condensate. The quarks pick up an extra mass through the interaction with the condensate:

$$M_{\rm Q} = m_{\rm q} + \frac{f}{\Lambda_{\chi \rm SB}^2} \langle \bar{q} q \rangle_0 + ... \qquad (6)$$

  If for example $M_{\rm Q}|_{m_{\rm q}=0} = f \langle \bar{q}q\rangle_0 / \Lambda_{\chi \rm SB}^2 + .. \simeq 350\,MeV$ we can reproduce CQ masses of Eq.(1). This mechanism of mass generation is very similar to that of the electroweak symmetry breaking, where the non-trivial vacuum corresponds to the presence the Higgs condensate and the generation of the (Lagrangian) masses for leptons and quarks. The fermions gaining masses through such a mechanism are compact objects having a size on the order of symmetry breaking scale. That the constituent quarks are compact (because of a small $\Lambda_{\chi \rm SB}^{-1} \ll \Lambda_{\rm conf}^{-1}$) is supported by the absence of any observed excited quark states[27]. This also implies that a CQ does not have an anomalous moment.

- Internal Goldstone bosons: One of the direct consequence of spontaneous chiral symmetry breaking is that there will be massless pseudoscalar states. When propagating outside the confinement radius, they are the familiar light pseudoscalar octet mesons, π, K, and η. Here we are discussing Goldstone bosons in the hadron interior. To emphasize that they may well have different propagation properties, *e.g.* different effective masses (also see footnote 5), we call them the internal Goldstone bosons (IGB)

[g] For a textbook review of the strong interaction chiral symmetry, see, for example, [28].

What about the gluons? Of course, it is the QCD gluonic interaction that brings about the non-perturbative phenomena of chiral symmetry breaking and the generation of massless pseudoscalar bound $q\bar{q}$ Goldstone bosons. In the $Q^2 \lesssim 1\,GeV^2$ range, besides such "non-perturbative gluons", no perturbative gluons are expected to be an important factor. Namely, after χSB has taken place, the interaction should be dominated by that among the CQs and IGBs. In short, while the fundamental QCD interaction, in terms of quarks and gluons, is non-perturbative in the low energies, after separating out the non-perturbative effects of χSB, because CQs are so heavy the remanent interaction is again perturbative. [This is also *a posteriori* justified in χQM calculations.] In this way one can consider the following (tree diagram) mechanism for the quark sea generation through the perturbative emission of IGB by a valence quark Q:

$$Q_{\uparrow} \longrightarrow GB + Q'_{\downarrow} \longrightarrow Q + \bar{Q}' + Q'_{\downarrow} \tag{7}$$

The arrow indicates the quark helicity; no arrow means an unpolarized quark.

Whatever created by the quantum fluctuation, *e.g.* all quarks other than the original valence quarks in the NQM, is considered to be part of the sea. Thus all three final-state quarks in (7) are taken to be components of the quark sea.

3.1 Spin structure in the χQM

The axial γ_5 coupling of IGB to the constituent quark reduces, in the non-relativistic limit, to $(\vec{s}/M) \cdot \vec{p}$ where $\vec{s}$ and $\vec{p}$ are the spin and momentum operators, respectively. The one-pseudoscalar-meson-exchange between CQs has the same spin dependent $(\vec{s}_i/M_i) \cdot (\vec{s}_j/M_j)$ structure as that due to the one-gluon-exchange[29] — except that the overall color factor is replaced by some flavor coefficients. Thus all the successful account of the spin dependent features in the baryon spectrum by the gluonic exchange mechanism (*e.g.* the mass differences between Δ and N, between Σ and Λ etc.) can be taken over by the IGB exchange description. In fact, as shown by Glozman and Riska[30], the IGB scenario leads to a better spectroscopy: certain features on the level orderings in the higher mass strange baryon states can now be explained. Moreover, the mystery of why there is not a significant spin-orbit contribution can also be accounted for by this IGB exchange mechanism.

This same spin-dependence of the IGB-quark coupling also implies that the GB vertex will flip the helicity of the quark $Q_{\uparrow} \rightarrow Q'_{\downarrow}$ in the emission process (7). Furthermore, the final $Q + \bar{Q}'$ quarks in (7), being produced through the GB channel must have their spins add up to a spin-zero system, $2^{-1/2}\left(Q_\uparrow\bar{Q}'_\downarrow - Q_\downarrow\bar{Q}'_\uparrow\right)$.

- *Antiquarks are not polarized*[31] — Since the antiquarks in the sea must all be produced through such spin-zero mesons, the antiquarks in the quark sea are not polarized, $\Delta_{\bar{q}} = 0$ — the probability for finding an spin-up antiquark equals to that for an antiquark in the spin-down state.

- *Quark sea is negatively polarized* — Since both Q and $\bar{Q}'$ quarks are unpolarized, the polarization of the entire final state (the quark sea) must be given by the $Q'_\downarrow$ quark, which is opposite to the initial quark helicity state. This naturally leads to a negatively polarized sea, in qualitative agreement with phenomenological observation, as expressed in Eq.(5) so that $\Delta\Sigma = \Delta\Sigma_{\rm val} + \Delta\Sigma_{\rm sea}$ is less than one.

- *Quark sea has a positive orbital angular momentum*[32] — Angular momentum conservation in the reaction $Q_\uparrow \to GB + Q'_\downarrow$ requires that $\left[GB,\ Q'_\downarrow\right]$ be in the relative P-wave state, $\langle l_z\rangle = +1$, in order to compensate the $Q_\uparrow \to Q'_\downarrow$ quark helicity flip $\delta\sigma = -2$,

$$\frac{1}{2}\Delta\Sigma_{\rm sea} + \langle L_z\rangle = 0 \tag{8}$$

- *The proton spin is built up from quark spins and orbital motion in the quark sea* — Combining Eq.(8) and $\Delta\Sigma_{\rm val} = 1$, we see that the proton spin sum ($\equiv 1$) is composed of quark spin and orbital angular momentum:

$$\Delta\Sigma + 2\langle L_z\rangle = 1. \tag{9}$$

Many authors have suggested the possibility of proton spin receiving a significant contribution from the orbital angular momentum[33]. However, most of such schemes have $\langle L_z\rangle$ arising from the valence quarks in higher orbital states (so called configuration mixing). In contrast, the present discussion concerns the orbital angular momentum in the quark sea. To make this distinction clearer, it may be helpful to consider the valence CQ and the sea it generates together as a "*constituent quark system*". What we suggest here is that, even though the sea has a depolarization effect, it is compensated by its positive orbital motion — so that the whole CQ-system remains to be a spin $\frac{1}{2}$ entity. Proton's three CQ-systems themselves, however, remain in the relative S-wave state, *i.e.* not in any significant relative orbital motion.

3.2 Magnetic moments in the χQM

The quark sea will also contribute to the baryon magnetic moment $\mu_{\rm B} = \mu^{\rm B}_{\rm val} + \left(\mu^{\rm B}_{\rm sea}\right)$. Because $(\Delta_q)_{\rm sea} - \Delta_{\bar{q}} = \left(\widetilde{\Delta q}\right)_{\rm sea} \neq 0$, it is puzzling why the NQM can yield a good account of the baryon magnetic moments even when the sea is strongly polarized. The answer is that, because the spin polarization and orbital angular momentum have opposite signs, Eq.(8), their magnetic moment contributions also tend to cancel [32]:

$$\left(\mu^{\rm B}_{\rm sea}\right) = \mu^{\rm B}_{\rm spin} + \mu^{\rm B}_{\rm orb} \simeq 0. \tag{10}$$

This is indicated in a non-relativistic calculation. While the non-relativistic approximation is useful in giving us a simple intuitive physical picture, the relativistic field-theoretical loop calculation will automatically include both the spin and orbital contributions. It yields an anomalous magnetic moment for the constituent quark system. The claimed cancellation in (10) simply means that the anomalous moment due to the chiral field is particularly small. This is in agreement with the explicit calculations by Dicus et al.[34] and by Brekke[35].

Thus we see that even though the quark sea has a strong depolarization effect, the constituent quark system still has spin $\frac{1}{2}$ with an approximate Dirac moment. This explains the reason why NQM can yield a good account of the baryon magnetic moments even though its spin content predictions has been found to be incomplete.

The anomalous moment is small, but measurable. It has been shown[35] that the NQM fit of the baryon moments can be considerably improved by giving quarks small anomalous moments and the fit supplemented by exchange current contributions, which arise naturally in the χQM.

3.3 Flavor structure in the χQM

Here we make the brief comment that the chiral quark approach can naturally account for the observed proton flavor puzzles: $\bar{d} \gg \bar{u}$ and a significant $\bar{s}$.

- In the χQM the valence u quark, through the intermediate state of IGB, is more likely to produce $\bar{d}$, and valence d tends to produce $\bar{u}$. While $u \to \pi^+ d \to u\bar{d}d$ and $u \to K^+ s \to u\bar{s}s$ are allowed, the $u \to \pi^- q^{5/3}$ or $K^- q^{5/3} \to \bar{u}$.... processes cannot take place because there does not exit a $q^{5/3}$ quark having a 5/3 charge. This naturally leads a proton quark sea having more $\bar{d}$ than $\bar{u}$ because there are two valence u quarks and only one valence d. (This effect is diluted somewhat by $q \to \pi^0 q$, $\eta^0 q$ which produce equal amount of $\bar{d}$ and $\bar{u}$.)

- While there is a tendency for $u \nrightarrow \bar{u}...$ and $d \nrightarrow \bar{d}...$ both valence u and d can produce $\bar{s}$. If one could ignore the effect of $M_S > M_{U,D}$, there would be more strange than non-strange antiquarks: $\bar{s} > \bar{d}$, $\bar{u}$ in the quark sea[36]. The M_S suppression effect is not expected to be overwhelming because constituent mass difference is considerably smaller than current quark mass differences, $(M_S/M_{U,D}) \ll (m_s/m_{u,d})$, and because of non-vanishing internal momentum $\langle k^2 \rangle \neq 0$.

4 Chiral QM calculations

Bjorken[37] was the first to suggest that the chiral quark idea may be relevant to a solution of the proton flavor and spin puzzles. Eichten, Hinchliffe and Quigg[38] carried out the non-relativistic quark model calculation (as well as the chiral field calculations of the x and Q^2 distributions). Cheng and Li[36] have proposed to work with a χQM including not only the octet GBs but also the singlet η' meson, with a broken $U(3) \rightarrow SU(3) \times U(1)$ symmetry. In the leading N_c^{-1} expansion (N_c is the number of colors), there are nine Goldstone bosons, but the concomitant U(3) symmetry must be broken by higher order N_c^{-1} corrections (so as to account for the presence of axial anomaly). This is implemented by allowing for distinctive couplings f_1 ($\neq f_8$) for the singlet GB.

The phenomenology at the SU(3) symmetric level suggests a negative ratio f_1/f_8[36]. Since the fit is not very sensitive to precise value, we shall simply fix it at $f_1 = -f_8$. In this way, there left only one parameter to adjust. This is the transition probability $a \propto |f_8|^2$ for the emission process $u \rightarrow \pi^+ d$ and its SU(3) equivalents. The model calculation results are shown in the third columns of Tables 1 and 2. At the next stage we can include the broken SU(3) effects of $M_S > M_{U,D}$, or equivalently $m_{K,\eta} > m_\pi$, by introducing suppression factors for strange-quark containing GB amplitudes [39,40]. To see whether our approach has the qualitatively correct phenomenological features, we will limit the number of extra parameters to one by applying a common factor of $\left[\langle k^2 \rangle + m_{GB}^2\right]^{-1}$ for each GB amplitude. The results from the two parameter, a and $\langle k^2 \rangle$, calculation[40] are shown in the last columns of Tables 1 and 2. We also recall that the same model can give a good account of the magnetic moment data as well as the baryon spectroscopy.

These calculations have not included relativistic corrections [3]. Relativistic reduction of the spin fractions is likely to improve the agreement, but to include this, more parameters would be needed.

SPIN	pheno. values	χQM	
		SU_3	br'n SU_3
Δu	0.82 ± 0.02	0.78	0.85
Δd	-0.43 ± 0.02	-0.33	-0.40
Δs	-0.10 ± 0.02 $(\downarrow ?)$	-0.11	-0.07
$\Delta\Sigma$	0.29 ± 0.06	0.34	0.38
$\Delta_{\bar{u}},\ \Delta_{\bar{d}}$	0.01 ± 0.07	0	0
g_A	1.257 ± 0.03	1.12	1.25
F/D	0.575 ± 0.016	2/3	0.57

Table 1. Comparison of χQM spin structure results with phenomenological values. The third column corresponds to the SU(3) symmetric result with a single parameter $a = 0.12$, while the fourth column for the broken SU(3) result with two parameters: $a = 0.15$ and $\langle k^2 \rangle = 350\, MeV^2$. The quark contributions to the proton spin $(\Delta q, \Delta_{\bar{q}})$ are from an SU(3) symmetric analysis by SMC[11,13]. The Δs magnitude may be reduced when broken SU(3) effect is taken into account (see footnote 3). Hence the symbol $(\downarrow ?)$ behind the stated value. F/D is the ratio of SU(3) reduced matrix elements for the axial currents.

FLAVOR	pheno. values	χQM	
		SU_3	br'n SU_3
$\bar{d} - \bar{u}$	0.147 ± 0.026	0.15	0.15
$\sigma_{\pi N} : f_s$	$0.18 \stackrel{m_s}{\to} 0.10$	0.19	0.09
$2\bar{s}/\left(\bar{u} + \bar{d}\right)$	$\simeq 0.5$	1.86	0.6

Table 2. Comparison of χQM flavor structure results with phenomenological values. Exactly the same parameters have been used as in Table 1. The $\bar{u} - \bar{d}$ difference is from NMC measurement which is supported by more recent E866 data, although the central value is somewhat lower. The strange quark fraction f_s is deduced from pion-nucleon sigma term with both SU(3) symmetric and breaking values given, while the antiquark ratio in the last row is from structure function fits based primarily on the CCFR data on neutrino charm production.

At this stage the calculated densities are understood to be averaged over all x. [See further discussion in the next Section.] Since this is non-perturbative model calculation, the results are for $Q^2 \lesssim 1\, GeV^2$. But the comparison with the experimental data measured at $Q^2 \simeq 5\, GeV^2$ is still valid because experimentally it is known that the Q^2 variation is small in going from 1 to 5 GeV^2. Putting it another way, if we had been calculating the distribution functions, they would be the "initial distributions" at $Q^2 \approx 1\,GeV^2$, from which the higher Q^2 distributions can be deduced by performing the pQCD calculations.

5 Discussion

These simple calculations seem to bolster the idea that CQ and internal GB as effective DOF can yield an adequate description of the principal features of the proton's spin/flavor structure. This provides the supporting reason as why the simple constituent quark model works. The massive but compact constituent valence quarks are surrounded by a quark sea, which is perturbatively generated by IGB emissions.

The advantage of working with such effective DOF description is that it is simple enough so that generalization to more complicated and difficult physical situations will be possible. Chiral quark model has already been applied by Troshin and Tyurin to hadron scattering, in particular in their attempt to calculate the single spin asymmetries in pp and $p\bar{p}$ collisions[41].

As we have already mentioned, this chiral effective description is shared by a number of non-perturbative approaches: instanton[23,24,42], quark model with NJL interaction[25], chiral bag model[43] and skyrmion model[44]. Some of them, because further approximation, (*e.g.* skyrmion model of baryon being the large-N_c approximation of QCD), may lead to a phenomenology somewhat different from that discussed above. For example, the skyrmion model has the prediction of $\Delta\Sigma = 0$[45].

5.1 The instanton approach

As we have emphasized, the main feature in the chiral quark approach is the dynamical chiral symmetry breaking, leading to a non-trivial QCD vacuum inside the hadron. Not surprisingly the most complete model is the one that has the most worked-out mechanism of chiral symmetry breaking. This is the instanton approach.

Instantons are classical Euclidean solutions of QCD[46]. Physically one may think of them as patches of intense gluon field fluctuations in spacetime (because they are $\sim g^{-1}$) that arise from tunnelling among different classical QCD vacua[47]. Attempts to understand the hadron structure by assuming an instanton dominance in non-pQCD phenomena were made at the earliest stage of instanton research[48]. The recent study has been greatly stimulated by the discovery, first through phenomenological study of correlations[24], and then by variational principle calculation[23], that large instanton effects are suppressed. The infrared problem is now under control.

Starting from the only dimensional parameter in QCD, namely $\Lambda_{\rm QCD}$, the two basic characteristic length scales of the instanton vacuum can be obtained through variational calculation: the average distance between neighboring instantons $\bar{R} \simeq 1\,fm$, and their average mean square radius $\bar{\rho} \simeq 0.35\,fm$. This in turn allows one to deduce quantities such as $M_Q|_{m_q=0} \simeq 350\,MeV$ and $\langle \bar{q}q \rangle_0 \simeq -(250\,MeV)^3$, *etc.* We remark that these two scales $(\bar{R}, \bar{\rho})$ essentially replaced the two scales of $(\Lambda_{\rm conf}, \Lambda_{\chi \rm SB})$ in the simple χQM.

The study of the equation of motion for light quarks propagating in the instanton field shows the existence of fermionic "zero modes", *i.e.* quarks localized around instanton. A well defined procedure[49] then leads one to conclude that there are quark pair condensate in the ground state: $\langle \bar{q}q \rangle_0 \neq 0$, hence, a spontaneously broken chiral symmetry. Furthermore, 't Hooft has shown that (for the three light flavor case) an effective six-quark interaction, in the determinantal form, is induced,

$$\mathcal{H}_G = \det_{i,j} \left[\bar{q}_{iR} q_{jL} + h.c. \right] \tag{11}$$

where the flavor indices $i, j = 1, 2, 3$. Because this term is symmetric under $SU_L(3) \times SU_R(3)$ but not under $U_A(1)$ it will give a mass to the singlet would-be-Goldstone boson, thus solving the axial $U_A(1)$ problem[47].

Instanton-induced quark-interaction is qualitatively similar to that of the chiral quark. Forte, Dorokhov, and Kochelev[50,42] have pointed out that just as the GB-quark coupling, the instanton induced quark interaction flips the quark chirality. The 't Hooft interaction (11) implies that an instanton absorbs a left-handed quark of each flavor and emits a right-handed quark of each flavor, $\bar{u}_R u_L \bar{d}_R d_L \bar{s}_R s_L$. This produces a negatively polarized quark sea, and (in the equal mass limit) a proton flavor structure of $\bar{s} > \bar{d} > \bar{u}$.

5.2 Alternative approaches

If different theories yield similar effective DOF descriptions, how do we differentiate them apart? We can do so by the following considerations:

Theoretical consideration: We give two illustrative examples: (i) The meson cloud model[51], at one level, is very similar to the chiral quark model: in both cases the pseudoscalar mesons play a central role. In the cloud model, the IGBs of χQM are replaced by the physical pseudoscalar mesons exterior to the nucleon. In DIS processes the lepton probe scatters off the meson cloud surrounding the target nucleon (the Sullivan mechanism[52]). But, it still has to be worked out why the long-distance feature of the pion cloud surrounding the nucleon should have such a pronounced effect on the DIS which should probe the interior of the target. (ii) The χQM as formulated by Manohar and Georgi[26] appears to have two sets of pseudoscalars: The GBs appearing in the effective Lagrangian as independent DOF, as well as another set of bound $\bar{Q}Q$ pseudoscalar states. On the other hands, the chiral effective Lagrangian from the instanton approach does not have an explicit kinetic energy term for GBs: there is no propagating GB in the instanton effective theory (footnote 5).

Consideration of model details: Even though different theories can result in similar effective structure at the quark model level, they may very well differ when more detailed phenomenology is examined. (i) An obvious example is that while several theories may give the same densities, when averaged over all x as discussed in Sec.4. Different theories have different distributions. Thus the distribution from chiral effective theory having propagating GBs will be different from theories such as instanton theory, where IGBs are just short-hand for $\bar{q}q$ loop effects[h]. (ii) While the singlet and octet coupling ratio f_1/f_8 in the χQM calculations is an arbitrary parameter. The instanton determinantal interaction suggests that it should be negative[55] (an effect directly related to the singlet meson gaining a mass even in the chiral limit). This is in accord with the phenomenology as shown in Sec.4.

Clearly much work need to be done in filling out the details of the model predictions which should then be checked by experimental measurement.

5.3 The gluonic contribution

The proton spin problem is often discussed in the context of percentage of the spin being carried by quark spin $\Delta\Sigma$, gluon spin ΔG[56] and the orbital angular momentum contributions:

$$\frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle = \frac{1}{2}. \tag{12}$$

How is our χQM conclusion, valid for $Q^2 \lesssim 1\,GeV^2$, related to such an expression at the higher Q^2 region? As we have emphasized, the constituent quarks are just the ordinary quarks propagating in the range of $Q^2 \lesssim 1\,GeV^2$. In the same manner, one would expect the non-perturbative gluons of the low Q^2 range to be the starting point for ΔG to evolve to higher Q^2 as prescribed by pQCD. The χQM suggests:

$$\frac{1}{2}\Delta\Sigma + \langle L_z \rangle = \frac{1}{2}, \quad \Delta G = 0. \tag{13}$$

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[h] The instanton theory can apparently produce quark distributions in general agreement[53] with those extracted from phenomenology[54].

About one-third of proton spin resides in the quark constituents while about two-thirds in the orbital angular momentum of the quark sea. There is no ΔG in the low energy regime. Namely, the non-perturbative gluons which bring about χSB and confinement are not polarized. Thus one would expect a negligibly small ΔG even for the higher Q^2 region. This is consistent with the experimental observation of the a very weak Q^2-dependence in $\Delta\Sigma$, which is determined by the $\Delta G\left(Q^2\right)$ contribution via the axial anomaly equation.

5.4 Concluding remarks

The nucleon spin/flavor structure, from the pQCD perspective, has been thought as being puzzling. This naturally suggests that the non-pQCD in the low energy $Q^2 \lesssim 1\,GeV^2$ region as being the source for this non-trivial structure. In this presentation we have concentrated on the possibility of using the effective DOF of constituent quarks and internal Goldstone bosons for a simple description of the non-perturbative phenomena. This gives the initial distributions which are to be evolved to the higher Q^2 ranges through pQCD equations.

The chiral quark model is able to provide us with an unified account for the main features of the observed nucleon spin and flavor structure. The simple picture is that nucleon is composed of three CQ systems which are the valence quarks being surrounded by their quark sea. The sea is generated perturbatively through the IGB emissions. The u valence system has a significant $\bar{d}$ and $\bar{s}$ components and the d valence system has a significant $\bar{u}$ and $\bar{s}$, with the would-be-large strange component being counterbalanced by mass suppression factor. The quark sea has a strong negative spin polarization which is compensated by a significant orbital motion so that each CQ system has spin 1/2 and a small anomalous magnetic moment. While its property of

$$(\Delta\Sigma)_{\text{sea}} = -2\left\langle L_z\right\rangle \simeq -2/3 \tag{14}$$

is compatible with the known spin and magnetic data, its prediction of no antiquark polarization, and a negligibly small gluonic polarization,

$$\Delta_{\bar{q}} = 0, \quad \text{and} \quad \Delta G \simeq 0 \tag{15}$$

can be checked by future experimental measurements, in particular the various spin programs at HERA[57], RHIC[58], and COMPASS[59].

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