Is Nucleon Spin Structure Inconsistent with Constituent Quark Model?

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A qualitative QCD analysis and a quantitative model calculation are given to show that the constituent quark model remains a good approximation even with the nucleon spin structure revealed in polarized deep inelastic scattering taking into account.

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I. INTRODUCTION

Hadron structure studies might be traced back to Fermi-Yang [1] and Sakata models [2]. Gell-Mann [3] and Zweig [4] proposed the quark model of hadrons. Lepton-nucleon deep inelastic scattering (DIS) [5] verified the quark structure of hadrons. However the quark revealed in DIS is found to be different from the quark as a carrier of SU(3) symmetry in Gell-Mann-Zweig model. The former is almost a free particle, the later is strongly bounded. Even though this lead Feynman [6] to call the quark detected in DIS as parton, such qualitatively different behavior of quark didn’t hurt the hadron structure studies in both directions. On the contrary, phenomenological success of SU(6) quark model in explaining the hadron properties and the evidence obtained in DIS for the existence of quark inside hadrons worked together and motivated the development of a new strong interaction theory, the quantum chromodynamics (QCD) [7]. The asymptotic freedom and confinement properties of QCD fitted perfectly weak interaction parton picture revealed in DIS and the fact that no free quark was discovered in all intensive experimental searches. The weak interacting high energy process can be calculated and tested due to asymptotic freedom of QCD and gave strong support to this new strong interaction theory. However the hadron structure and low energy hadron interactions are hard to be calculated due to confinement. Lattice QCD is promising to find low energy solution but still suffers numerical uncertainty for the time being. Various QCD models developed under this condition. Different models emphasize different effective degree of freedom inspired by QCD properties [8]. Among them, constituent quark model is the most successful one in explaining hadron properties [9] and hadron interactions [10]; and gives the most popular intuitive picture of hadron internal structure.

The most striking feature of constituent quark model is that it gives a very simple but quite successful explanation of the baryon spin and magnetic moment by means of effective constituent quark masses. Once again, one meets the qualitatively different behaviors of quark, i.e., the constituent quark mass needed in the hadron spectroscopy is much larger than the current quark mass revealed in high energy processes. This lead Weinberg to ask “why do quarks behave like bare Dirac particles” [11]; and the relation between constituent quark and current quark is a holy grail in hadron physics. In the (1s)\(^3\) pure valence nonrelativistic constituent quark model, the nucleon spin is solely carried by quark spin, the orbital angular momentum is zero because quarks are assumed to be in the lowest s-wave (1s) state. The nucleon magnetic moment is also solely contributed by quark spin magnetic moments. In 1988, EMC group [12] measured the polarization asymmetry of polarized \(\mu\)-proton deep inelastic scattering and extracted the proton spin structure function which showed that quark spin contributes only a small amount of the proton spin. Constituent quark model has been challenged by this surprising result and lead to the proton spin crisis. Many models and mechanisms have been invoked to explain why quark spin contribution is suppressed and how to supply angular momentum to compensate the missing spin of nucleon [13]. After ten years intensive studies both experimentally and theoretically, the prevailing view point seems to be that the nucleon spin structure discovered in DIS is inconsistent with constituent quark model. Only a minority [14] keeps the view point that quark spin is primarily responsible for generating the nucleon spin because in the valence quark region the polarization asymmetry confirmed the constituent quark model prediction. The sea quark component neglected as an approximation in pure valence quark model plays a vital role in suppressing the quark spin contribution \(\Delta q\) extracted from DIS.

This report stands by the minority through both a qualitative QCD analysis and a quantitative model calculation. In section II, the difference between the quark spin sum \(\Delta \Sigma\) of the constituent quark model and the \(\Delta q\) measured in DIS is explained. In section III, the duality of nucleon spin structure is explained. In section IV, QCD relations of baryon spin, magnetic moment, and tensor charge are derived and discussed. A constituent quark model with valence-sea quark component mixing is shown to be able to reconcile the difference between the quark spin sum \(\Delta \Sigma\) and \(\Delta q\) and fit other baryon properties as well in section V. The discussions and conclusions are put in section VI.
II. THE DIFFERENCE BETWEEN THE QUARK SPIN SUM $\Delta \Sigma$ OF THE CONSTITUENT QUARK MODEL AND THE QUARK SPIN CONTRIBUTION $\Delta q$ MEASURED IN DIS

For a constituent quark model, the quark spin sum of proton (in general baryon) at rest can be expressed as

$$\Delta \Sigma = \sum_i \int d^3k \left( q_i^+ \left( \vec{k} \right) - q_i^- \left( \vec{k} \right) + \overline{T}_i^+ \left( \vec{k} \right) - \overline{T}_i^- \left( \vec{k} \right) \right)$$

$$= \sum_i \left( q_i^+ - q_i^- + \overline{T}_i - \overline{T}_i \right),$$

(1)

where $q_i^\pm \left( \overline{T}_i^\pm \right)$ means quark (antiquark) of flavor $i$ with spin parallel or antiparallel to the baryon spin. $\vec{k}$ is used to show the momentum distribution.

The quark spin contribution $\Delta q$ measured in DIS is defined as

$$\left\langle PS \left| \int d^3x \overline{\psi} \gamma_\mu \gamma_5 \psi \right| PS \right\rangle = S_\mu \cdot \Delta q,$$

(2)

where $S_\mu$ is the proton polarization vector, $\int d^3x \overline{\psi} \gamma_\mu \gamma_5 \psi$ is the quark axial vector current. For the parton model in the infinite momentum frame

$$\Delta q = \sum_i \int dx \left( q_i^+ (x) - q_i^- (x) + \overline{T}_i (x) - \overline{T}_i (x) \right),$$

(3)

where $q_i^\pm (x) \left( \overline{T}_i^\pm (x) \right)$ is the probability of finding a quark (antiquark) with fraction $x$ of the proton momentum and polarization parallel or antiparallel to the proton spin. Even though the expressions (1) and (3) are similar, the physical meaning is not the same in general. To show the difference, let’s express the quark axial vector current operator in terms of Pauli spin

$$\int d^3x \overline{\psi} \gamma^\mu \gamma^5 \psi = \sum_{i\lambda\lambda'} \int d^3k \chi_{i\lambda}^\dagger \sigma \cdot \overline{k} \chi_{i'\lambda'} \left( a_{i\lambda}^{+} a_{i'\lambda'} - b_{i\lambda}^{+} b_{i'\lambda'} \right)$$

$$- \sum_{i\lambda\lambda'} \int d^3k \chi_{i\lambda}^\dagger \sigma \cdot \overline{k} \chi_{i'\lambda'} \left( a_{i\lambda}^{+} a_{i'\lambda'} - b_{i\lambda}^{+} b_{i'\lambda'} \right)$$

$$+ \sum_{i\lambda\lambda'} \int d^3k \chi_{i\lambda}^\dagger \sigma \cdot \overline{k} \chi_{i'\lambda'} a_{i\lambda} b_{i'\lambda'} + h.c. \right).$$

(4)

In getting this expression an expansion

$$\psi_i (x) = (2\pi)^{-3} \sum_\lambda \int d^3k \left( a_{i\lambda}^{+} u_{i\lambda} e^{i\overline{k} \cdot x} + b_{i\lambda}^{+} v_{i\lambda} e^{-i\overline{k} \cdot x} \right)$$

(5)

has been used. Here $a_{i\lambda}^{+} \left( b_{i\lambda}^{+} \right)$ is quark (antiquark) of flavor $i$ creation operator with momentum $\overline{k}$ and polarization $\lambda$ in Heisenberg representation. $u_{i\lambda}, v_{i\lambda}$ are usual Dirac spinors, $\chi_{i\lambda}$ is Pauli spinor. Flavor spinor wavefunction is omitted in Eq.(5). $k_0 \left( \overline{k} \right)$ and $m_i$ are energy (momentum) and mass of quarks. We can’t identify the $a_{i\lambda}^{+} \left( b_{i\lambda}^{+} \right)$ with the constituent quark and antiquark creation operators. However Eq.(4) shows at least that for any realistic proton state, the matrix element of the quark axial vector current operator, usually called the quark spin contribution to the nucleon spin, is not solely due to Pauli spin contribution (the first term in Eq.(4)), but also a contribution from quark orbital motion (the second term in Eq.(4)). Only in special cases, such as for static quark model (all quark momentum $\overline{k}$ is assumed to be zero), the second terms does not contribute. Another case is the parton model in the infinite momentum frame where $k_{\perp}/k_0$ is negligible and therefore the second term does not contribute either. However it should be noted that it is the matrix element of the axial vector current operator evolved to be the helicity difference in Eq.(3) which should be compared to the matrix element of the whole axial vector current operator in Eq.(4) for a proton at rest rather than the matrix element of the first term in Eq.(4). The Pauli spin itself is not a Lorentz invariant quantity as had been pointed out by Ma [13].
In addition, pure valence quark configuration is an approximation. Sea quark component should be considered even for a constituent quark model from a general view point of Fock space expansion. After including the valence and sea quark components mixing in the model Fock space, the third term of Eq.(4) (pair creation and annihilation term) will also contribute to the \(\Delta q\) defined in Eq.(2). This would make the quark spin sum \(\Delta \Sigma\) deviating from the quark spin contribution \(\Delta q\) further. This effect has rarely been calculated in quark model approach [16]. It will be shown in a valence-sea quark mixing model calculation (see section V) that this is an important correction to \(\Delta q\) even for a 15% sea quark component mixing.

Neglecting the antiquark and the pair creation (annihilation) term and assuming the quark moment distribution of nucleon ground state to be spherically symmetric, Eq.(4) reduces to the Melosh rotation result discussed by Ma [15].

To sum up, the quark spin sum \(\Delta \Sigma\) of a constituent quark model should not be identified with the quark spin contribution \(\Delta q\) measured in DIS. The fact that \(\Delta q\) discovered in DIS is much smaller (see next section) than the constituent quark spin sum \(\Delta \Sigma\) has not proved yet that the nucleon spin structure is inconsistent with the constituent quark model.

### III. DUALITY OF NUCLEON SPIN STRUCTURE

After ten years intensive theoretical and experimental studies, now the world average of quark spin contribution to the proton spin is [17]

\[
\Delta q (3 \text{GeV}^2) = \Delta u + \Delta d + \Delta s = 0.82(1) - 0.44(1) - 0.11(1) = 0.27(4), \quad (6)
\]

We have explained in section II that there is not really a serious contradiction between the DIS measurement and the constituent quark model picture, even though for example, a pure valence nonrelativistic constituent quark model gives

\[
\Delta u = \frac{4}{3}, \quad \Delta d = -\frac{1}{3}, \quad \Delta s = 0, \quad \Delta \Sigma = 1. \quad (7)
\]

Because \(\Delta q\) and \(\Delta \Sigma\) are not the same matrix element of proton.

However one question should be answered that where does the proton get additional angular momentum if one follows the QCD view point where quark axial vector current is only part of the source of the proton spin. Proton, as a QCD system, its angular momentum is in general consisted of [18]

\[
\vec{J}_{QCD} = \vec{S}_q + \vec{L}_q + \vec{S}_g + \vec{L}_g
\]

\[
= \frac{1}{2} \int d^3x \psi^\dagger \vec{\Sigma} \psi + \int d^3x \psi^\dagger \vec{E} \times \vec{A} + \int d^3x E_i \vec{r} \times \vec{\partial} A_i. \quad (8)
\]

In a constituent quark model, the explicit gluon degree of freedom is usually neglected and its effect is included in the quark interaction term. Therefore only quark orbital angular momentum \(\vec{L}_q\) will be able to contribute additional angular momentum to proton spin besides the quark axial vector current operator \(\vec{S}_q\) in the constituent quark model space. Let’s also express the quark orbital angular momentum \(\vec{L}_q\) in terms of Pauli spinor,

\[
\vec{L}_q = \sum_{i\lambda} \int d^3k \left( a^\dagger_{i k \lambda} i \overrightarrow{\partial} k \times \vec{k} a_{i k \lambda} + b^\dagger_{i k \lambda} i \overrightarrow{\partial} k \times \vec{k} b_{i k \lambda} \right)
\]

\[
+ \frac{1}{2} \sum_{\lambda \lambda'} \int d^3k \chi^\dagger_{i k \lambda} \frac{\vec{\sigma} \cdot \vec{k}}{k_0 (k_0 + m)} \chi_{i k \lambda'} \left( a^\dagger_{i k \lambda} a_{i k \lambda'} - b^\dagger_{i k \lambda} b_{i k \lambda'} \right)
\]

\[
- \sum_{i \lambda \lambda'} \int d^3k \chi^\dagger_{i k \lambda} \frac{i \vec{\sigma} \times \vec{k}}{2k_0} \chi_{i k \lambda'} b^\dagger_{i k \lambda} a^\dagger_{i k \lambda'} + h.c.. \quad (9)
\]
It is interesting to note that the second and third term in Eq.(4) and (9) cancel with each other exactly. We have

$$\vec{S}_q + \vec{L}_q = \vec{S}^{NR}_q + \vec{L}^{NR}_q$$

$$= \frac{1}{2}\sum_{i\lambda\lambda'}\int d^3k \chi_\lambda^\dagger \vec{\sigma} \chi_{\lambda'} \left( a^\dagger_{i\lambda\lambda'} \sigma_{-} i \vec{k} \times \vec{k} a_{i\lambda\lambda'} - b^\dagger_{i\lambda\lambda'} b_{i\lambda\lambda'} \right)$$

$$+ \sum_{i\lambda}\int d^3k \left( a^\dagger_{i\lambda\lambda} \partial_k \times \vec{k} a_{i\lambda\lambda} + b^\dagger_{i\lambda\lambda} i \vec{k} \times b_{i\lambda\lambda} \right).$$

(10)

where $\vec{S}^{NR}_q$, $\vec{L}^{NR}_q$ represent the first term in Eq.(4) and (9). We call them nonrelativistic quark spin and nonrelativistic quark orbital angular momentum because they can be related to the constituent quark model spin and orbital angular momentum if we make an assumption that the quark (antiquark) creation operator $a^\dagger_{ks}$ $(b^\dagger_{ks})$ can be directly related to the effective constituent quark degree of freedom (see section V). Eq.(10) tells us that there are two equivalent decompositions of the proton spin, either in terms of the relativistic $\vec{S}_q$ and $\vec{L}_q$ directly derived from QCD Lagrangian, or in terms of the nonrelativistic quark spin $\vec{S}^{NR}_q$ and orbital angular momentum $\vec{L}^{NR}_q$. Under the assumption that the Heisenberg operators used in Eq.(5) can be related to the constituent quark degree of freedom, then in a pure s-wave nonrelativistic constituent quark model we would have the picture that the nucleon spin can either attributed solely to constituent quark spin $\vec{S}^{NR}_q$ and orbital angular momentum $\vec{L}^{NR}_q$ would not contribute (we have this picture already more than twenty years); or attributed to the relativistic quark spin $\vec{S}_q$ which is reduced due to the orbital motion of quarks and the sea quark pair creation (annihilation) process (see section V), and the relativistic angular momentum $\vec{L}_q$ will contribute compensation terms to make the total proton spin unchanged even for a pure s-wave constituent quark model state. We call this the duality of nucleon spin structure. The above discussion is obviously also true for other baryons.

IV. QCD RELATIONS AMONG BARYON SPIN, MAGNETIC MOMENT, AND TENSOR CHARGE

Now let’s turn to baryon magnetic moment

$$\mu_B = \langle B \left| \vec{\mu}_B \right| 3 \rangle B$$

$$= \langle B \left| \sum_i \frac{Q_i}{2} \int d^3x \psi_i^\dagger \left( \vec{x} \times \vec{\sigma} \right) \psi_i \right| B \rangle.$$  

(11)

Use the same Fourier expansion (5), we obtain

$$\vec{\mu}_B = \sum_i \sum_{\lambda \lambda'} \int d^3k \frac{Q_i}{2k_0} \left( a^\dagger_{i\lambda\lambda} \sigma_{-} \vec{k} a_{i\lambda\lambda} - b^\dagger_{i\lambda\lambda} b_{i\lambda\lambda} \right)$$

$$+ \sum_i \sum_{\lambda \lambda'} \int d^3k \frac{Q_i}{2k_0} \chi_\lambda^\dagger \chi_{\lambda'} \left( a^\dagger_{i\lambda\lambda} a_{i\lambda\lambda} + b^\dagger_{i\lambda\lambda} b_{i\lambda\lambda} \right)$$

$$- \sum_i \sum_{\lambda \lambda'} \int d^3k \frac{Q_i}{2k_0} \chi_\lambda^\dagger \frac{\vec{\sigma} \cdot \vec{k}}{2k_0 (k_0 + m_i)} i \vec{k} \chi_{\lambda'} \left( a^\dagger_{i\lambda\lambda} a_{i\lambda\lambda} + b^\dagger_{i\lambda\lambda} b_{i\lambda\lambda} \right)$$

$$- \sum_i \sum_{\lambda \lambda'} \int d^3k \frac{Q_i}{2k_0} \frac{\vec{k}}{2k_0 (k_0 + m_i)} a^\dagger_{i\lambda\lambda} b^\dagger_{i\lambda\lambda} + h.c.$$ 

$$+ \sum_i \sum_{\lambda \lambda'} \int d^3k \frac{Q_i}{2k_0} \left( a^\dagger_{i\lambda\lambda} \sigma_{-} \vec{k} b_{i\lambda\lambda} + \vec{\sigma} \cdot \vec{k} \chi_\lambda \left( m_i \sigma + \frac{\vec{\sigma} \cdot \vec{k}}{k_0 + m_i} \sigma \times k \right) \chi_{\lambda'} + h.c. \right).$$ 

(12)

Use the expression (4) and (9) for $\vec{S}_q$ and $\vec{L}_q$, Eq.(12) can be reexpressed as
\[ \bar{\mu}_B = \sum_i \int d^3k \frac{Q_i}{k_0} \left( \vec{S}_{ik} - \vec{S}_{\mu i} \right) + \int d^3k \frac{Q_q}{2k_0} \left( \vec{L}_{ik} - \vec{L}_{\mu i} \right) \]

+ pair creation and annihilation terms.

Here

\[ \vec{S}_{ik} = \frac{1}{2} \sum_{\lambda \lambda'} \chi_\lambda^\dagger \left( \vec{\sigma} - \frac{\vec{\sigma} \cdot \vec{k}}{k_0 (k_0 + m_i)} \right) \chi_{\lambda'} a_{ik \lambda}^\dagger a_{ik \lambda'}^\dagger \]

\[ \vec{S}_{\mu i} = -\frac{1}{2} \sum_{\lambda \lambda'} \chi_\lambda^\dagger \left( \vec{\sigma} - \frac{\vec{\sigma} \cdot \vec{k}}{k_0 (k_0 + m_i)} \right) \chi_{\lambda'} b_{ik \lambda}^\dagger b_{ik \lambda'}^\dagger \]

\[ \vec{L}_{ik} = \sum_{\lambda} a_{ik \lambda}^\dagger i \partial \vec{k} \cdot \vec{a} - \frac{1}{2} \sum_{\lambda \lambda'} \frac{\vec{\sigma} \cdot \vec{k}}{k_0 (k_0 + m_i)} \chi_{\lambda'} a_{ik \lambda}^\dagger a_{ik \lambda'}^\dagger \]

\[ \vec{L}_{\mu i} = \sum_{\lambda} b_{ik \lambda}^\dagger i \partial \vec{k} \cdot \vec{b} - \frac{1}{2} \sum_{\lambda \lambda'} \frac{\vec{\sigma} \cdot \vec{k}}{k_0 (k_0 + m_i)} \chi_{\lambda'} b_{ik \lambda}^\dagger b_{ik \lambda'}^\dagger \]

If we restrict our discussion on the baryon ground states, it is plausible to approximate the \( k_0 \) by its average \( \langle k_0 \rangle \) and take \( \langle k_0 \rangle \) as effective quark mass \( m_{\text{eff}} \), we would have

\[ \bar{\mu}_B = \sum_i \frac{Q_i}{m_{\text{eff}}} \left( \vec{S}_i - \vec{S}_0 \right) + \sum_i \frac{Q_i}{2m_{\text{eff}}^2} \left( \vec{L}_i - \vec{L}_0 \right) \]

+ pair creation and annihilation terms,

where \( \vec{S}_i = \int d^3k \vec{S}_i(\vec{k}) \) and \( \vec{L}_i = \int d^3k \vec{L}_i(\vec{k}) \). Eq.(15), after neglecting the pair terms, is quite similar to the constituent quark model calculation. Suppose a baryon ground state in Eq.(11) can be expressed by a Fock state of quark degree of freedom (see Eq.(28)), the average is over all Fock components and all quark energy. This average quark energy can be expressed by a Fock state of quark degree of freedom (see Eq.(28)), the average is over all quark states in Eq.(11) can be expressed by a Fock state of quark degree of freedom (see Eq.(28)), the average is over all Fock components and all quark energy. This average quark energy \( \langle k_0 \rangle \) bounded in a baryon plays the role of the constituent quark mass, which explains why the constituent quark mass is much heavier than the current quark mass. However we have discussed before that it is not the relativistic spin \( \vec{S}_q \) and orbital angular momentum \( \vec{L}_q \) but the nonrelativistic \( \vec{S}_{q NR} \) and \( \vec{L}_{q NR} \) which are closely related to the operators used in constituent quark model calculations. In order to obtain the relation between baryon magnetic moments and the nonrelativistic spin \( \vec{S}_{q NR} \) and orbital angular momentum \( \vec{L}_{q NR} \), we need another operator — the tensor operator \( \int d^3x \psi^\dagger \sigma_{\mu \nu} \psi \) which was emphasized recently by MIT group [20]. Its matrix element in a proton state is

\[ \left\langle PS \bigg| \int d^3x \bar{\psi} \sigma_{\mu \nu} \psi \bigg| PS \right\rangle = \delta q \bar{\psi} (PS) \sigma_{\mu \nu} u (PS), \]

where \( u (PS) \) is the Dirac spinor of proton and \( \sigma_{\mu \nu} = \frac{i}{2} (\gamma_{\mu} \gamma_{\nu} - \gamma_{\nu} \gamma_{\mu}) \), \( \delta q \) is called the tensor charge of proton (in general tensor charge of baryon). The spatial component of \( \sigma_{\mu \nu} \) is \( \Sigma_k = \frac{1}{2} \epsilon_{ijk} \sigma_{ij} \). Use the expansion (5) again, we obtain

\[ \delta q = \int d^3x \bar{\psi} \sum_{\lambda} \psi \]

\[ = \sum_i \sum_{\lambda} \int d^3k \chi_\lambda^\dagger \left( \frac{m}{k_0} \vec{\sigma} + \frac{\vec{\sigma} \cdot \vec{k}}{k_0 (k_0 + m_i)} i \vec{\sigma} \times \vec{k} \right) \chi_{\lambda'} \left( a_{ik \lambda}^\dagger a_{ik \lambda'}^\dagger + b_{ik \lambda}^\dagger b_{ik \lambda'}^\dagger \right) \]

\[ - \sum_i \sum_{\lambda} \int d^3k \frac{\vec{k}}{k_0} a_{ik \lambda}^\dagger b_{ik \lambda}^\dagger + h.c. \]

\[ = \sum_i \sum_{\lambda} \int d^3k \chi_\lambda^\dagger \left( \frac{\vec{\sigma} \cdot \vec{k}}{k_0 (k_0 + m_i)} \right) \chi_{\lambda'} \left( a_{ik \lambda}^\dagger a_{ik \lambda'} + b_{ik \lambda}^\dagger b_{ik \lambda'} \right) \]

\[ - \sum_i \sum_{\lambda} \int d^3k \frac{\vec{k}}{k_0} a_{ik \lambda}^\dagger b_{ik \lambda}^\dagger + h.c. \]
Under the same approximation as mentioned above for Eq.(4), i.e., neglecting the antiquark and the pair creation (annihilation) term and assuming the quark momentum distribution of nucleon ground state to be spherically symmetric, the second expression of Eq.(17) reduces to the Melosh rotation result discussed by I. Schmidt and J. Soffer \[20\].

From Eq.(10), (12)-(15) and (17), we obtain

\[
\vec{\mu}_B = \sum_i \frac{Q_i}{m_i^{eff}} \left( \begin{1}\right) \left( \begin{2}_{NR} \begin{3}_{\tau} \right)+ \sum_i \frac{Q_i}{2m_i^{eff}} \left( \begin{4}_{NR} \begin{5}_{\tau} \right) - \sum_i \frac{Q_i}{2m_i^{eff}} \frac{1}{2} \delta q_i \\
- \sum_i \sum_i \frac{Q_i}{2m_i^{eff}} \int d^3 k \left( \begin{6}\begin{7} \right) \right) \left( \begin{8}\begin{9} \right) + h.c.
- \sum_i \sum_i \frac{Q_i}{2m_i^{eff}} \int d^3 k \left( \begin{10}\begin{11} \right) \right) \left( \begin{12}\begin{13} \right) + h.c.
= \sum_i \frac{Q_i}{m_i^{eff}} \left( \begin{14}\begin{15} \right)+ \sum_i \frac{Q_i}{m_i^{eff}} \left( \begin{16}\begin{17} \right) \left( \begin{18}\begin{19} \right) + 1 \frac{1}{2} \delta q_i \\
- \sum_i \sum_i \frac{Q_i}{2m_i^{eff}} \int d^3 k \left( \begin{20}\begin{21} \right) \right) \left( \begin{22}\begin{23} \right) + h.c.
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Therefore the Karl-Sehgal relations of the octet baryon magnetic moments upgraded by Cheng and Li [21] should be upgraded further

\[
\begin{align*}
\mu_p &= \frac{2e}{3m_u} W_u - \frac{e}{3m_d} W_d - \frac{e}{3m_s} W_s, \\
\mu_n &= -\frac{e}{3m_d} W_u - \frac{2e}{3m_u} W_d - \frac{e}{m_s} W_s, \\
\mu_{\Sigma^+} &= \frac{2e}{3m_u} W_u - \frac{e}{3m_s} W_d + \frac{e}{3m_d} W_s, \\
\mu_{\Sigma^-} &= -\frac{e}{3m_d} W_u - \frac{e}{3m_s} W_d + \frac{2e}{3m_u} W_s, \\
\mu_{\Xi^0} &= -\frac{e}{3m_u} W_u + \frac{2e}{3m_u} W_d + \frac{e}{3m_d} W_s, \\
\mu_{\Xi^-} &= -\frac{e}{3m_u} W_u - \frac{e}{3m_u} W_d + \frac{2e}{3m_u} W_s, \\
\mu_{\Lambda} &= 1 - \frac{e}{3m_u} (W_u + 4W_d + W_s), \\
\mu_{\Lambda\Xi^0} &= -\frac{1}{2\sqrt{3}} \left( \frac{2e}{3m_u} - \frac{e}{3m_d} \right) (W_u - 2W_d + W_s).
\end{align*}
\]

where

\[
W_i = \frac{1}{2} \left( \frac{1 + m_i}{m_i^{\text{eff}}} \right) \left( \Delta_i^{NR} - \Delta_i^R - \frac{1}{2} \delta q_i \right)
= \frac{1}{2} \left( \frac{1 - \frac{m_i}{2 (m_i^{\text{eff}} + m_i)}}{m_i^{\text{eff}} + m_i} \right) \left( \Delta_i - \Delta_i + \frac{1}{2} \frac{m_i^{\text{eff}}}{m_i^{\text{eff}} + m_i} \delta q_i \right)
\]

and the effective quark mass \( m_i^{\text{eff}} \) has been written directly by constituent quark mass \( m_u, m_d \) and \( m_s \). It should be noted that these relations are now based on QCD but with the following approximation

\[
k_0 \text{ approximated by } \langle k_0 \rangle = m_i^{\text{eff}}.
\]

Pair creation terms neglected.

An approximated relation between the nonrelativistic spin \( S_i^{NR} \), axial vector current and tensor current operators can be obtained as well. From Eq. (10), (14), and (17), neglecting the pair creation and annihilation terms we have

\[
\tilde{S}_q^{NR} = \sum_i \frac{1}{1 + \langle k_0 \rangle} \left( \tilde{S}_i + \tilde{S}_T + \frac{1}{2} \tilde{\delta q}_i + \tilde{\delta q}_T \right)
\]

where

\[
\tilde{\delta q}_T = - \sum_{\lambda \lambda'} \int d^3 k' \chi_{1}^\dagger \left( \frac{m}{k_0} \sigma + \frac{\bar{\sigma} \cdot \bar{k}}{k_0 (k_0 + m_i)} i \bar{\sigma} \times \bar{k} \right) \chi_{\lambda} b_{i, \lambda}^\dagger b_{i^k, \lambda}.
\]

Under further approximations mentioned for Eq. (4) and (17), i.e., in the pure valence quark and spherically symmetric momentum distribution approximation, by means of the second expression of \( \tilde{\delta q} \) in Eq. (17), one can obtain another relation between nonrelativistic spin sum \( \Delta \Sigma \), axial charge \( \Delta q \) and tensor charge \( \delta q \) of proton discussed by I. Schmidt, J. Soffer, Ma and He [22] which reads as \( \Delta \Sigma + \Delta q = 2\delta q \).
V. A VALENCE-SEA MIXING CONSTITUENT QUARK MODEL CALCULATION

Constituent quark model is the most successful one in low energy hadron physics. Even for the polarization asymmetry in the valence region in DIS, the constituent quark model still gave a historical successful prediction [4]. The OZI rule violation and the nucleon spin structure studies do remind us that pure valence configuration is an approximation and the sea quark components should be taken into account. From a general view point of Fock space expansion, a baryon should be described by

$$|B⟩_α = C_0 |q^3⟩_α + \sum C_i |q^iq^i⟩_α + \cdots$$ (28)

where the higher Fock components have been omitted. Chiral quark model leads to a similar description of baryons, where $q\bar{q}$ is replaced by a Goldstone boson (pseudo-scalar meson) [28]. Because we can’t do a nonperturbative QCD calculation to check what we have discussed so far, a valence-sea quark mixing constituent quark model calculation has been done under these inspirations [23]. The model Hilbert space is assumed to be consisted of pure valence component $q^3$ and all possible combinations compatible with the quantum number of a baryon with colorless s-wave octet and decuplet $q^3$ combined with $q\bar{q}$ having pseudo-scalar quantum numbers. To meet the positive parity condition of the ground octet and decuplet baryons, the relative motion between $q^3$ and $q\bar{q}$ centers is assumed to be in $p$-wave. The internal wavefunction of $q^3$ and $q\bar{q}$ and the relative motion wavefunction are all assumed to be a Gaussian one with a common size parameter $b$ for simplicity of the numerical calculation. The model Hamiltonian is almost the same as those of the Isgur model [9] except that a $q\bar{q}$ pair creation and annihilation interaction term has been included to mix the $q^3$ and $q^3q\bar{q}$ components.

$$H = \sum_i \left( m_i + \frac{q^2}{2m_i} \right) + \sum_{i<j} \left( V_{ij}^G + V_{ij}^{\prime G} \right) + \sum_{i<j} \left( V_{i,i'j,j} + V_{i,i',j,j}^{\prime} \right),$$

$$V_{ij}^c = -a_c\vec{\lambda}_i \cdot \vec{\lambda}_j \bar{r}_{ij}^2,$$

$$V_{ij}^{G^a} = \alpha_s \frac{\vec{\lambda}_i \cdot \vec{\lambda}_j}{4} \left( \frac{1}{r_{ij}} - \frac{\pi}{2} \left( \frac{1}{m_i^2} + \frac{1}{m_j^2} + \frac{2\vec{\sigma}_i \cdot \vec{\sigma}_j}{3m_im_j} \right) \delta (\bar{r}_{ij}) + \cdots \right),$$

$$V_{ij}^{G^a} = \alpha_s \frac{\vec{\lambda}_i \cdot \vec{\lambda}_j}{2} \left( \frac{1}{3} + \frac{\vec{f}_i \cdot \vec{f}_j}{2} \right) \left( \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{2} \right) \left( \frac{2}{3} \frac{1}{m_i + m_j} \right) \delta (\bar{r}_{ij}),$$

$$V_{i,i',j,j} = i\alpha_s \frac{\vec{\lambda}_i \cdot \vec{\lambda}_j}{4} \frac{1}{2r_{ij}} \left( \left( \frac{1}{m_i + m_j} \right) \vec{\sigma}_j + \frac{i\vec{\sigma}_j \times \vec{\sigma}_j}{m_i} \right) \cdot \frac{\vec{r}_{ij}}{r_{ij}^2} - \frac{2\vec{\sigma}_j \cdot \vec{\sigma}_j}{m_i},$$ (29)

where $\vec{\lambda}_i$ and $\vec{f}_i$ are the $SU_3$ ($\vec{S}U_3$) Gell-Mann operators, the $V_{ij}^{G^a}$, $V_{ij}^{G^a}$ and $V_{i,i',j,j}$ correspond to the following diagrams of Fig.1 respectively, i.e., we use an effective one gluon exchange to derive the quark interactions except the confinement part which is introduced phenomenologically. The other symbols have their usual meaning.

The model parameters, $u, d$ quark mass $m$, $s$ quark mass $m_s$, quark gluon coupling constant $\alpha_s$, $q^3$ quark core baryon size $b$, and confinement strength $a_c$, are fixed by an overall fit to the ground state octet and decuplet baryon properties.

Table I goes here.
Table II goes here.
Table III goes here.
Table IV goes here.
Table V goes here.
The entry is the amplitude of the individual component. The total sea quark component is about 15%. It is an example of our model wave functions of ground state baryons.

Table II summarize our model predictions and the model parameters. These results show that it is possible to have a valence and sea quark mixing model which can describe, with the commonly accepted quark model parameters, the ground state octet and decuplet baryon properties as good as the successful pure valence quark model. Furthermore, the proton charge radius is reproduced as well. A too small proton charge radius has been a long standing problem of the constituent quark model. The first excited states are higher than 2 GeV. This is consistent with the fact that there is no pentaquark states observed below 2 GeV.
The spin content of the proton is listed in Table III, where the matrix element of the axial vector current operator (4) in a spin up proton state is decomposed into particle number conserved components $q^3 \leftrightarrow q^3, q^3 \tilde{q} \leftrightarrow q^3 \tilde{q}$ and particle number nonconserved components $q^3 \leftrightarrow q^3 \tilde{q}$. In doing this calculation, the quark (antiquark) operator $a_{iks} (b_{iks})$ in Eq. (4) has been identified with the constituent quark (antiquark) degree of freedom. This is a model assumption and is usual for quark model calculations. The second column lists the axial charge of the pure valence configuration $q^3$, there the relativistic correction (second term in Eq. (4)) and the normalization factor ($-0.923)^2$ have been included. The sum $\Delta u + \Delta d + \Delta s = 0.773 - 0.193 + 0 = 0.580$ of the $q^3$ configuration divided by the normalization factor gives $0.580 / (-0.923)^2 = 0.681$ which shows even for a pure $q^3$ configuration the axial charge $\Delta q$ is already different from the spin sum $\Delta \Sigma = 1$ due to the relativistic correction. The fourth column lists the axial charge of the $q^3 \tilde{q}$ configuration. The sea quark contribution can’t be separated due to quark antisymmetrization. Antiquark contribution (which has not been listed in Table III) is quite small. This is the same as the chiral quark model result obtained by Cheng and Li [23]. The main reduction is due to $q^3 \leftrightarrow q^3 \tilde{q}$ transition term. Physically it is similar to the generalized Sullivan processes discussed by Hwang et al [14] and makes our model different from the chiral quark model [23]. The sum of the three terms listed in column 5 is quite close to the world average value $\Delta q$ listed in column 6 and the lattice QCD results listed in column 7 [25, 26].

Tensor charge has been calculated by the operator in Eq. (17). It has the relativistic correction and pair creation (annihilation) correction too. Again, it is reduced due to relativistic correction and pair creation and annihilation term, but the effect is small for the tensor charge in comparison with those for the axial charge. Up to now tensor charge has not been measured. Fortunately a lattice QCD calculation has just been published [27]. Even though their axial charge $\Delta q$ does not match the experimental results as well as that of Dong, Lagae, and Liu [26]. It might still show our model tensor charge is close to the reality [27].

Even though the spin structure of barons is complicated than the naive pure valence quark model, the magnetic moments of baryons are fitted as well as the naive ones. These results show that the nucleon spin structure information obtained in polarized DIS is possible to be described in a constituent quark model. Of course, the sea quark components should be taken into account. However, to fit the DIS measured nucleon spin structure, only about 15% sea quark component is needed. This means the naive pure valence quark model is a reasonable approximation. We would like to emphasize that we are certainly not pretend to claim having a good nucleon model. On the contrary, our model is a rough one, many points should be improved, and many points should be checked. The aim to show this model results is to pass a message that constituent quark model result obtained by Cheng and Li [23]. The sea quark contribution can’t be separated due to quark antisymmetrization. Antiquark contribution (which has not been listed in table III) is quite small. This is the same as the chiral quark model result obtained by Cheng and Li [23]. The sum $\Delta u + \Delta d + \Delta s = 0.773 - 0.193 + 0 = 0.580$ of the $q^3$ configuration divided by the normalization factor gives $0.580 / (-0.923)^2 = 0.681$ which shows even for a pure $q^3$ configuration the axial charge $\Delta q$ is already different from the spin sum $\Delta \Sigma = 1$ due to the relativistic correction. The fourth column lists the axial charge of the $q^3 \tilde{q}$ configuration. The sea quark contribution can’t be separated due to quark antisymmetrization. Antiquark contribution (which has not been listed in Table III) is quite small. This is the same as the chiral quark model result obtained by Cheng and Li [23]. The sum of the three terms listed in column 5 is quite close to the world average value $\Delta q$ listed in column 6 and the lattice QCD results listed in column 7 [25, 26].

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VI. DISCUSSIONS AND CONCLUSIONS

Deep inelastic scattering detects the inner structure of nucleon directly and played vital role in establishing the quark model of hadrons. Constituent quark model is the most successful one in explaining the hadron properties. Polarized lepton-nucleon deep inelastic scattering reveals the spin structure of nucleon. Whether or not nucleon spin structure is consistent with the constituent quark model is controversial still.

The main messages of this report are:

1. In a truncated Fock space of a baryon with only effective quark degree of freedom, baryon spin operator can be decomposed in two equivalent ways

$$\vec{F} = \vec{S}^{NR} + \vec{L}^{NR} = \vec{S} + \vec{L}$$

(30)

$\vec{S}^{NR}$ and $\vec{L}^{NR}$ are the quark spin and orbital angular momentum operators used in the nonrelativistic constituent quark model, while $\vec{S}$ and $\vec{L}$ are the quark spin (i.e., axial vector current operator) and orbital angular momentum operators derived from QCD Lagrangian.

2. The axial charge $\Delta q$ extracted from the polarized lepton-proton deep inelastic scattering is related to the matrix element of $\vec{S}$ in a polarized proton and should not be identified to the constituent quark model spin sum $\Delta \Sigma$ which is related to the matrix element of $\vec{S}^{NR}$.

3. Constituent quark model, after mixing a small amount (15%) of sea quark components, is able to describe the fact that $\Delta q \sim \frac{1}{3} \Delta \Sigma$. The reduction of $\Delta q$ is due to relativistic correction and the transition matrix element

$$\langle q^3 | \vec{S} | q^3 \bar{q} \bar{q} \rangle.$$
4. The successful relation between magnetic moments and spins of baryons first obtained from constituent quark model are a robust relation. Even though it should be upgraded, the main feature of the Sehgal-Karl-Cheng-Li relations and the good fitting of baryon magnetic moments remain there even though the nucleon spin structure is complicated as revealed in polarized DIS.

5. The quantitative fit of baryon properties reported here, especially the axial charge $\Delta q$ and tensor charge $\delta q$ of proton, is model dependent. The main messages mentioned above are not a model one except the numerical values of $\langle q^3 \bar{q} | q^3 q \bar{q} \rangle$. This transition matrix element contribution to the axial charge $\Delta q$ might be a quark model version of the gluon contribution discussed in perturbative QCD calculation. Of course this point is tentative and further studies are needed.

The nucleon structure is certainly more complicated than the naive constituent quark model. However constituent quark model is a good approximation. The nucleon spin structure discovered in polarized deep inelastic scattering invites the improvement of constituent quark model, but does not invalidate it.

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Fig. 1 quark interaction diagrams

### TABLE I. proton model wave function

| $q^3$ | $N\eta$ | $N\pi$ | $\Delta\pi$ | $N\eta'$ | $\Lambda K$ | $\Sigma K$ | $\Sigma^* K$ |
|-------|---------|---------|-------------|---------|-------------|-------------|--------------|
| $-0.923$ | $0.044$ | $0.232$ | $-0.252$ | $0.065$ | $0.109$ | $-0.036$ | $-0.106$ |

### TABLE II. masses and magnetic moments of the baryon octect and decuplet.

$m = 330(\text{MeV}), m_s = 564(\text{MeV}), b = 0.61(\text{fm}), a_s = 1.46, a_c = 48.2(\text{MeV fm}^{-2})$

|       | p     | n     | $\Lambda$ | $\Sigma^+$ | $\Sigma^-$ | $\Xi^0$ | $\Xi^-$ | $\Delta$ | $\Sigma^*$ | $\Xi^*$ | $\Omega$ |
|-------|-------|-------|-----------|------------|------------|--------|--------|---------|------------|--------|---------|
| Theor. | M(MeV) | 939   | 1116      | 1193       | 1346       | 1232   | 1370   | 1523    | 1659       |        |         |
|       | E1(MeV) | 2203  | 2323      | 2306       | 2409       | 2288   | 2306   | 2450    | 2638       |        |         |
|       | $\mu(\mu N)$ | 2.780 | $-1.818$ | $-0.522$  | 2.652      | $-1.072$ | $-1.300$ | $-0.412$ |             |        |         |
|       | $\sqrt{(r^2)(fm)}$ | 0.802 | 0.124     |            |            |        |        |         |             |        |         |
| Exp.  | M(MeV) | 939   | 1116      | 1189       | 1315       | 1232   | 1385   | 1530    | 1672       |        |         |
|       | $\mu(\mu N)$ | 2.793 | $-1.913$ | $-0.613$  | 2.458      | $-1.160$ | $-1.250$ | $-0.651$ |             |        |         |
|       | $\sqrt{(r^2)(fm)}$ | 0.836 | 0.34      |            |            |        |        |         |             |        |         |

### TABLE III. The spin content and tensor charge of proton

|       | $q^3$ | $q^3 - q^3\bar{q}$ | $q^4\bar{q} - q^4\bar{q}$ | sum | exp. | lattice $[26]$ | lattice $[27]$ |
|-------|-------|---------------------|-----------------------------|-----|-----|----------------|----------------|
| $\Delta u$ | 0.773 | $-0.125$            | 0.100                       | 0.75 | 0.81 | 0.79(11)       | 0.638(54)      |
| $\Delta d$ | $-0.193$ | $-0.249$            | $-0.041$                    | $-0.48$ | $-0.44$ | $-0.42(11)$   | $-0.347(46)$   |
| $\Delta s$ | 0 | $-0.064$            | $-0.002$                    | $-0.07$ | $-0.10$ | $-0.12(1)$ | $-0.109(30)$   |
| $\delta u$ | 0.955 | $-0.123$            | 0.127                       | 0.959 |       | 0.839(60)     |                |
| $\delta d$ | $-0.239$ | $-0.061$            | $-0.047$                    | $-0.347$ |       | $-0.231(55)$ |                |
| $\delta s$ | 0 | $-0.022$            | $-0.002$                    | $-0.024$ |       | $-0.046(34)$ |                |
$V_{ij}^{G_0}$

$V_{ij}^{Ga}$