Baryon magnetic moments in colored quark cluster model

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Abstract

Using the colored quark cluster model, we study magnetic moments of the octet baryons. We give the values of the magnetic moments of baryons $p$, $n$, $\Sigma^+$, $\Sigma^-$, $\Xi^0$, and $\Xi^-$. The results also show that the orbital motion has very significant effects on the spin and magnetic moments of those baryons and the strange component in the proton is very small.

PACS numbers: 12.39.-x, 13.40.Em, 14.20.-c
I. INTRODUCTION

It is clear now that the quark sea in nucleon has a nontrivial contribution. The EMC effects have indicated that only a small amount of nucleon spin is carried by quark, and that the strange sea quark in the proton may have a negative contribution to the nucleon spin \[1, 2, 3\]. Recently, both deep inelastic scattering and Drell-Yan experiments show that there exists flavor asymmetry of light quarks in the nucleon sea \[4, 5\]. Moreover, the parity-violating electron-nucleon experiments indicate that the strangeness electric form factor \(G_E(q^2)\) is negative while the strangeness magnetic form factor \(G_M(q^2)\) is positive \[6, 7, 8, 9\]. These issues mean that the constituent valence quark model (CVQM) cannot explain the complicated quark structure of baryons completely.

Beyond the CVQM, more interesting models about the substructure of baryons have been proposed. Such as quark-gluon hybrid model, diquark-quark model \[10\], various meson cloud model \[11, 12, 13, 14\], and so on. To investigate the possible strange component in nucleon, there have many theoretical approaches, such as the lattice QCD calculation \[15\], chiral perturbation and dispersion relation \[16\], GDP sum rule \[17\], \(K^+\Lambda\) meson cloud model \[13\], and various quark models \[18\] correlating the octet baryon magnetic moments by assuming SU(3) flavor symmetry \[19, 20\]. Most of the theoretical analyses and calculations have given a negative sign for magnetic form factor of proton. Ref. \[21\] has obtained a positive result, however, the positive contribution is believed being automatically included by a relativistic calculation \[14\].

More recently, a new colored quark cluster model (CQCM) has been proposed. In this model, the \(qqqq\bar{q}\) fluctuation tends to arrange itself into energetically more favorable states. Of the strange components, there is a unique \(uuds\bar{s}\) configuration which can give the right signs of the strange magnetic, electric and axial form factors \[22, 23\]. In this configuration, the \(\bar{s}\) is in the ground state and the \(uuds\) subsystem in the \(P\)-state. This configuration has the lowest energy of all configurations under the assumption that the hyperfine interaction between the quarks is spin dependent \[24\]. This configuration may also give an explanation to the excess of \(\bar{d}\) over \(\bar{u}\) \[5\]. Besides, the five-quark components of this configuration in the \(\Delta(1232)\) give a significant contribution to \(\Delta(1232) \rightarrow N\pi\) decay \[25\].

The purpose of this paper is to study the sea quark contributions to baryon magnetic moments. In Sec.II, we obtain a general formula of the magnetic moments of octet baryons.
by using the CQCM. In Sec.III we give our numerical results by fitting to experimental values of octet baryon magnetic moments. The results show that the theoretical values of those magnetic moments from the CQCM is better than those from the CVQM, and that the strange component in the nucleon is small or zero. In Sec.IV, we have compared our results with the already existed experiments and other theoretical analyses.

II. THE BARYON MAGNETIC MOMENT

We now discuss the magnetic moment of octet baryons. In the CQCM of Ref.[22], the positive parity demands that the four-quark subsystem is orbitally excited to P-shell with a spatial symmetry $[31]_X$. In order to give a colored singlet state the four-quark subsystem has the color state $[211]_C$ since the anti-quark is in the $[11]_C$ representation. The Ref.[22] also indicates that configuration $[4]_{FS}[22]_F[22]_S$ is outstanding for its energy is some 140-200MeV lower than any other configuration if the hyperfine interaction between the quarks is described both by the flavor and spin dependent hyperfine interaction $-C\sum_{i<j} \bar{\lambda}_i \cdot \bar{\lambda}_j \cdot \bar{\sigma}_i \cdot \bar{\sigma}_j$, where $C$ is a constant with the value $\sim 20-30$MeV. This hyperfine interaction has led to the empirical ordering of the baryon resonances[24]. The total wave function of the 5-q state with spin $+1/2$ is written as

$$|B, +1/2 \rangle = A_5 \sum_{abcde} \sum_{Ms'_z} C^{[14]}_{JM} C^{[1]}_{JM, S_z} C^{[1]}_{F, M_s} C^{[31]}_{F, S' z} C^{[31]}_{S, S_z} C^{[FS]}_{F, S_z} \times [31]x_m(b)[F_d[S]_z(c)[211]C(a)\bar{\chi}_{s'_z}\varphi(\{r_i\}).$$

Here we use Weyl tableaux to represent the flavor, spin and color state wave function[26]. The capital $C$ with superscripts and subscripts denotes the Clebsch-Gordan(CG) coefficient. The $\bar{\chi}_{s'_z}$ is the spin state of the anti-quark and $\varphi(\{r_i\})$ a symmetric function of the coordinates of the 5-q system. $A_5$ denotes the amplitude of the 5-q component. For the mixed flavor symmetry representation $[22]_F$ of the $uuds$ system, two independent flavor wave functions are written as

$$|[22]_{F1} = \frac{1}{\sqrt{24}} [2 |uuds \rangle + 2 |uusd \rangle + 2 |dsuu \rangle + 2 |sduu \rangle - |duus \rangle - |udus \rangle - |sudu \rangle - |usdu \rangle - |suud \rangle - |dusu \rangle - |usud \rangle - |udsu \rangle].$$
\[ |[22]_F^2 \rangle = \frac{1}{\sqrt{8}} [ |udus \rangle + |sudu \rangle + |dusu \rangle + |usud \rangle \\
- |duus \rangle - |usdu \rangle - |suud \rangle - |udsu \rangle ] . \] (3)

And the two spin functions of \([22]_S\) can be obtained by the substitutions \(u \leftrightarrow \uparrow\) and \(d, s \leftrightarrow \downarrow\) with a proper normalization factor. Using 0 and 1 to denote the ground-state and \(P\)-state wave functions for the constituent quarks, the spatial wave functions of \([31]_X\) are

\[ |[31]_{X1} \rangle = \frac{1}{\sqrt{12}} [3 |0001 \rangle - |0010 \rangle - |0100 \rangle - |1000 \rangle] , \] (4)

\[ |[31]_{X2} \rangle = \frac{1}{\sqrt{6}} [2 |0010 \rangle - |0100 \rangle - |1000 \rangle] , \] (5)

\[ |[31]_{X3} \rangle = \frac{1}{\sqrt{2}} [ |0100 \rangle - |1000 \rangle] . \] (6)

From Ref.\([22]\) we know that the \([4]_{FS}[22]_F[22]_S\) configuration does not allow \(uudu\bar{u}\) in the proton. This is consistent with the observed excess of \(\bar{d}\) over \(\bar{u}\)\([5]\). The proton may also have an admixture with the flavor-spin symmetry \([4]_{FS}[31]_F[31]_S\), in which case no suppression exists. However, it is energetically less favorable. The empirical evidence for the large flavor asymmetry of the \(q\bar{q}\) components\([5]\) suggests that this configuration \([4]_{FS}[31]_F[31]_S\) should have a smaller probability than the favored one \([4]_{FS}[22]_F[22]_S\). We do not consider the meson cloud contribution here, and the quark wave function for proton may now be expressed as

\[ |p \rangle = A_3 |uud\rangle + A_{5d} |uudd\rangle + A_{5s} |uudss\rangle \] (7)

with the normalization condition \( |A_3|^2 + |A_{5d}|^2 + |A_{5s}|^2 = 1 \).

The nonperturbative sea quark effects have also been studied in baryons other than nucleons\([27]\). Taking the same consideration above for proton, we can write the wave functions of baryons \(p, n, \Sigma^+, \Sigma^-, \Xi^0, \) and \(\Xi^-\) in a general form as

\[ |B \rangle = A_3 |\alpha\alpha\beta\rangle + A_{5\beta} |\alpha\alpha\beta\bar{\beta}\rangle + A_{5\gamma} |\alpha\alpha\beta\gamma\rangle \] (8)

where the \(\alpha, \beta, \) and \(\gamma\) can be taken as \(d, u,\) and \(s\) quarks for neutron, \(u, s,\) and \(d\) for \(\Sigma^+,\) etc. The 5-q components only contain the configuration of \([4]_{FS}[22]_F[22]_S\) here and we use this representation throughout this paper. Because the \(\Sigma^0\) and \(\Lambda^0\) have three different valence quarks, we do not consider them here.
In the non-relativistic quark model, the magnetic moment contribution of quark to the proton magnetic moment is defined as the expectation value of the following operator

\[ \hat{\mu}_i = \frac{\hat{Q}_i}{2m_i}(\hat{l}_i + \hat{\sigma}_i), \quad i = u, d, s. \]  

(9)

Here \( \hat{Q}_i \) is the electrical charge operator, and \( m_i \) the constituent quark mass. In the naive quark model the proton consisting of two \( u \) quarks and one \( d \) quark, all in a relative S-wave. Using the \( SU_6^{sf} \supset SU_2^\sigma \times SU_3^f \) symmetrical wave function as an approximation, the magnetic moment contribution of the \( uud \) component in unit of nuclear magneton (n.m) is

\[ \langle uud | \sum_i \hat{\mu}_i | uud \rangle = \frac{4}{3} e_u \frac{m_p}{m_u} - \frac{1}{3} e_d \frac{m_p}{m_d}. \]  

(10)

where the \( e_u \) and \( e_d \) denote the electric charges of \( u \) quark and \( d \) quark respectively, and in the following \( e_q(e_{\bar{q}}) \) the corresponding quark(anti-quark) electric charge. \( m_u \) and \( m_d \) are the \( u \) and \( d \) quark mass, while \( m_p \) the mass of proton. And for baryon \( B = \alpha\alpha\beta \)

\[ \langle \alpha\alpha\beta | \sum_i \hat{\mu}_i | \alpha\alpha\beta \rangle = \frac{4}{3} e_\alpha \frac{m_p}{m_\alpha} - \frac{1}{3} e_\beta \frac{m_p}{m_\beta}. \]  

(11)

Within the 5-q components, the 4-q subsystem gives no spin contribution to the magnetic moment because symmetry \[22\] gives spin zero. But every quark in this subsystem has probability of being excited to P-state, which gives an orbital magnetic moment

\[ \mu_q^{(l)} = \left\langle qqqq\bar{q}, \frac{1}{2} \left| \hat{Q}_q \right| qqqq\bar{q}, \frac{1}{2} \right\rangle = \frac{e_q}{6} \frac{m_p}{m_q} P_{5q}. \]  

(12)

Here \( P_{5q} = |A_{5q}|^2 \) is the probability of 5-q components. The anti-quark in its ground state gives a magnetic contribution

\[ \mu_{\bar{q}} = \left\langle qqqq\bar{q}, \frac{1}{2} \left| \hat{Q}_{\bar{q}} \right| qqqq\bar{q}, \frac{1}{2} \right\rangle = -\frac{e_{\bar{q}}}{3} \frac{m_p}{m_{\bar{q}}} P_{5q}. \]  

(13)

Besides these diagonal contributions from quark spin and orbital motion, the transitions or non-diagonal matrix elements between the \( qqqq\bar{q} \) and \( qqq \) components may have some contributions, too. However, these non-diagonal contributions depend both on the explicit wave function model and the model for \( q\bar{q} \to \gamma \) vertices. Cases will be more complicated to take into account the confining interaction between the quarks that leads to bound state wave functions \[23\]. With a lot of unexplicit parameters, the results will be very ambiguous. So, for simplicity, we neglect the contributions of these transition matrix elements in this
paper. Then, by adding all the spin and orbital angular contributions to the magnetic moment, the total magnetic moment of polarized proton is

$$\mu_p = P_3\left(\frac{4}{3}e_u m_p - \frac{1}{3}e_d m_p\right) + P_{5d}(\sum_{q=u,u,d} \frac{e_q m_p}{6 m_q} - \frac{e_s m_p}{3 m_d}) + P_{5s}(\sum_{q=u,u,d,s} \frac{e_q m_p}{6 m_q} - \frac{e_s m_p}{3 m_s}).$$  \(14\)

From Eq.(8), we obtain the general form of the magnetic moment for the six baryons as

$$\mu_B = P_3\left(\frac{4}{3}e_\alpha m_p - \frac{1}{3}e_\beta m_p\right) + P_{5\beta}(\sum_{q=\alpha,\alpha,\beta,\beta} \frac{e_q m_p}{6 m_q} - \frac{e_\gamma m_p}{3 m_\beta}) + P_{5\gamma}(\sum_{q=\alpha,\alpha,\beta,\gamma} \frac{e_q m_p}{6 m_q} - \frac{e_\gamma m_p}{3 m_\gamma}),$$  \(15\)

with the normalization condition $P_3 + P_{5\beta} + P_{5\gamma} = 1$.

### III. THE GLOBAL FIT AND RESULTS

The Eq.(15) means that the baryon magnetic moments depend on the quark masses and the probabilities of those 5-q components. To reduce the number of these parameters, we assume that those $P_3$ are equal for the six baryons, i.e., $P_3^n = P_3^p = P_3^{\Sigma^+} = P_3^{\Sigma^-} = P_3^{\Xi^0} = P_3^{\Xi^-}$, and we hold the same assumption for $P_{5\beta}$ and $P_{5\gamma}$. As in Ref.[20], we use a fit method to discuss these parameters. In order to reduce these parameters further, we take $m_u = m_d$, $m_q = m_\bar{q}$. As a result, we see that the six baryon magnetic moments from Eq.(15) contain only four parameters now, i.e., $m_u$, $m_s$, $P_{5\beta}$, and $P_{5\gamma}$. To give the concrete values of these parameters, we consider the relatively simple but commonly used method, namely, to minimize the following function[20]:

$$\chi^2 = \sum_{k=1}^{m} \frac{(T_k - E_k)^2}{\sigma_k^2},$$  \(16\)

where $E_k$ is the measured value, and $T_k$ the corresponding theoretical value. $m$, the number of the baryons, is six here. The error $\sigma_k^2$ is taken to be the addition of a theoretical error and experimental error in quadrature as in Ref.[20]. The theoretical error comes from a comparison of the sum rule

$$\mu(n) - \mu(p) + \mu(\Sigma^+) - \mu(\Xi^0) + \mu(\Xi^-) - \mu(\Sigma^-) = 0$$  \(17\)

with experimental data. The left hand of this equation is actually $-0.49 \pm 0.03$ n.m. If the errors are equally shared among the six baryons, the theoretical error may be $0.49/6 \sim 0.08$ n.m. In Table[II], we list the experimental data from PDG[29].
we firstly examine the value of $P_{5\gamma}$ given in Ref.\[23\]. In that work, an analysis for the preferred configuration $[4]_{FS}[22]_{F}[22]_{S}$ shows that the qualitative features of empirical strangeness form factors may be described with a 15% admixture of $uuds\bar{s}$ in the proton. Fixing the $P_{5\gamma}$ with this value and taking only the $P_{5\beta}$ as variable, the minimum of $\chi^2$ happens at $P_{5\beta} = 0.13$, ie, the probability of $uudd\bar{d}$ in proton is 0.13. We express the minimum of $\chi^2$ as $\chi^2_m = 18.07$ is not better than that from the CVQM. The fitting results of the CVQM ($P_{5\alpha} = P_{5\beta} = 0$) are showed in the Table I with quark masses being $m_u = 344.03\text{MeV}$ and $m_s = 544.76\text{MeV}$.

Then, we take both the probabilities of 5-q components $P_{5\beta}$ and $P_{5\gamma}$ as variables to minimize the Eq.(16). And we find that there are two areas where the minimum can occur: the 3-q component or the 5-q component dominant in the baryons. As we know, however, the CVQM has success in low-lying baryon spectroscopy and magnetic moment. The probabilities of non-perturbative sea-quarks may not be very large. So, we only consider the case that the probabilities of 5-q components are small.

The mathematical minimum of $\chi$ is $\chi^2_m = 13.36$ with $P_{5\gamma} = 0$ and $P_{5\beta} = 0.08$, which is inconsistent with the observed excess of $\bar{d}$ over $\bar{u}$ in proton with $\bar{d} − \bar{u} = 0.12$. Considering this excess, the best fitting result is $\chi^2_m = 14.57$, with $P_{5\gamma} = 0$, $P_{5\beta} = 0.12$. In this case, we obtain the magnetic moments of baryons labelled as CQCM in Table II. The corresponding quark masses are $m_u = 300.84\text{MeV}$ and $m_s = 463.74\text{MeV}$. The $\chi^2_m$ as a function of $P_{5\beta}$ with $P_{5\gamma} = 0$ is presented on Fig.1. And we find, if $P_{5\gamma}$ is not zero and to ensure the $\chi^2_m$ less than that deduced from the naive quark model, the value of $P_{5\gamma}$ needs to be less than 10%. This means that the the probability of strange component in the proton cannot be more than 10%. On Fig.2 we plot $\chi^2_m$ as function of $P_{5\gamma}$ at some fixed points of $P_{5\beta}$. Both form Fig.1 and Fig.2 we can see that the up limit of the probability $P_{5\gamma}$ is about 14%, ie, the probability of the $uudd\bar{d}$ may not be more than 14% in proton.

In Table II, the theoretical errors are computed as $E − T)/E$, where $E$ is the experimental magnetic moment value, and $T$, the corresponding theoretical value. From the Table II, we can see, except the error of the neutron, that all errors given by the CQCM are less than 9%, which is much better than those given by the CVQM. Besides, adding the theoretical errors in quadrature we get $\sigma^2_{CQCM} = 0.046$, so small than $\sigma^2_{CVQM} = 0.12$.

The early EMC experiment results of quark spin contributions to the proton are very rough. The missing spin in this experiment may come from the gluon polarizations, or
TABLE I: Magnetic moments (in unit of nucleon magnetic moment) of the six baryons. The total
errors are given by adding to the experimental error a theoretical error 0.08 in quadrature. The
theoretical results including and not including the sea quark contributions are listed in the lines of
CQCM and CVQM respectively.

|      | p  | n  | Σ⁺  | Σ⁻  | Ξ⁰  | Ξ⁻  |
|------|----|----|-----|-----|-----|-----|
| exp  | 2.793 | -1.913 | 2.458 | -1.160 | -1.250 | -0.651 |
| error| 0   | 0   | 0.01 | 0.025 | 0.014 | 0.0025 |
| total error| 0.08 | 0.08 | 0.0806 | 0.0838 | 0.0812 | 0.08 |
| CVQM | 2.727 | -1.818 | 2.616 | -1.021 | -1.372 | -0.462 |
| error| -0.0235 | -0.0794 | 0.0641 | -0.120 | 0.0972 | -0.290 |
| CQCM | 2.745 | -1.705 | 2.668 | -1.118 | -1.261 | -0.597 |
| error| -0.0173 | -0.174 | 0.0849 | -0.0361 | 0.00950 | -0.0837 |

\( \chi_{m}^{2} \)

FIG. 1: The minimum of quantity \( \chi^{2} \) vs the
probability of \( \alpha\alpha\beta\bar{\beta} \) in case of \( P_{5\gamma} = 0 \).
When \( P_{5\beta} > 0.14 \), the \( \chi_{m}^{2} \) will be large than
the value from the naive quark model, which
corresponds to the point of \( P_{5\beta} = 0 \).
FIG. 2: The $\chi^2_m$ as a function of the probability of $\alpha\alpha\beta\gamma\bar{\gamma}$ component at several fixed points of $P_{5\beta}$. Only the $P_{5\beta}$ is less than 0.14 and the $P_{5\gamma}$ is less than 0.10, can make the $\chi^2_m$ be small than the value from naive quark model.

orbitangular momentum of quarks and gluon. But how large they are is still an open question. In the non-relative quark model, there is no room for gluons. In the CQCM model with only 12% of $uudd\bar{d}$ in the proton, the spin contributions from quark spin and orbital angular moment are $\Delta u = \frac{4}{3}P_3 = 1.173$, $\Delta d = -\frac{1}{3}$, and $\Delta l = \frac{4}{3}P_{5d} = 0.16$. Their sum is equal to 1, which is guarantied by the wave function Eq.(I) to give the total spin of proton. And we see that the orbital angular moment contributes a lot.

IV. DISCUSSIONS AND CONCLUSION

To find the effective degrees of freedom is at the first stage for studying baryon’s structure. The above numerical results have indicated that the non-perturbative effects of strangeness component in the nucleon are small. The strangeness content of the nucleon is purely a sea quark effect and therefor is a clean and important window to look into the nucleon internal structure and dynamics. The magnetic moment contribution of strange quark to nucleon is equal to the measured strange form factor at $Q^2 = 0$. The empirical value of strange form factor $G_M^S(Q^2 = 0.1) = 0.37 \pm 0.20 \pm 0.26 \pm 0.15$ can not give a compelling
evidence for nonzero strange quark effects of proton owing to the wide uncertainties\cite{6}. The experiment at Mainz with result $G_E^s + 0.106G_M^s = 0.071 \pm 0.036$ at $Q^2 = 0.108(\text{GeV}/c)^2$\cite{8} and the G0 experiment at Jefferson Lab\cite{9} may indicate nonzero $G_E^s$ and $G_M^s$. Because these experiments are carried out all in some special $Q^2$, the results are still very ambiguous when exploited to $Q^2 = 0$. For the strange electric form factor of the proton, the recent empirical value is $G_E^s(Q^2 = 0.1) = -0.038 \pm 0.042_{\text{(stat)}} \pm 0.010_{\text{(syst)}}$, which is really consistent with zero\cite{30}. A recent lattice result show that the strange electric form factor is $G_E^s(Q^2 = 0.1) = -0.009 \pm 0.005 \pm 0.003 \pm 0.027$\cite{31}. These may indicate that the pairs of strange and anti-strange quarks popping out of the sea cancel each other so effectively, that they have almost zero contributions to the proton’s magnetic moment, charge, or mass. This agrees with our numerical results. A very recent analysis of the complete world set of parity-violating electron scattering data also gives a result that the strange form factors are consistent with zero. Further more, recent experiments show that the strangeness contribution to the proton spin is very small\cite{32}. 

Besides, we like to note that there is another difference between the CQCM and the $K^+\Lambda$ meson cloud model, apart form the sign of the strangeness magnetic moment of proton. In the $K^+\Lambda$ model, the $s$ quark normalized to the probability $P_{K^+\Lambda}$ of the $K^+\Lambda$ configuration yields a fractional contribution $\Delta S_s = -\frac{1}{3}P_{K^+\Lambda}$ to the proton spin. Although the $K^+$, composed of $u\bar{s}$ quarks in valence quark model, is unpolarized, other mechanism may yield $\bar{s}$ quark polarized parallel to the initial proton spin\cite{33}. These results contradict the colored quark cluster model in which only the $\bar{s}$ quark give a negative contribution to the proton spin, while the $s$ quark is unpolarized because the spin symmetry of subsystem is $[22]_s$. Unfortunately, it is unable to measure the polarization of single quark experimentally nowadays. More deeply theoretical analyses are needed.

In the end, the observed non-perturbative quark sea in the nucleon leads us to reexamine the low lying baryon magnetic moments. We have deduced these magnetic moments in the CQCM and have give a discussion of the possible strange component in the nucleon. We see that the origin of the anomalous moments of quarks discussed in many works\cite{34} may be from the sea quark contributions, that the probability of strange component $uuds\bar{s}$ in the proton is less than 10% and the probability of $uudd\bar{d}$ less than 14%, and that the orbital motion has very significant effects on the spin and magnetic moment in the non-relative CQCM. Whether there has polarization and about its sign of strange quark in the proton
is still under debate. Our numerical results favor the non polarization of strange sea quark in the proton.

We hope future experiments will give us more clues of sea quarks in these baryons.

Acknowledgments

We are grateful to Prof. B. S. Zou for useful discussion.

This work was supported by Chinese Academy of Sciences Knowledge Innovation Project (KJCX2-SW-No16;KJCX2-SW-No2), National Natural Science Foundation of China(10435080;10575123).

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