# Quark orbital angular momentum of ground-state octet baryons

Jing-Feng Li,[1] Cheng Chen,[2,3] Gang Li,[4,*] Chun-Sheng An,[1,†] Cheng-Rong Deng,[1,‡] and Ju-Jun Xie[2,3,5,§]
[1]*School of Physical Science and Technology, Southwest University, Chongqing 400715, China*
[2]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[3]*School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 101408, China*
[4]*College of Physics and Engineering, Qufu Normal University, Qufu 273165, China*
[5]*Lanzhou Center for Theoretical Physics, Key Laboratory of Theoretical Physics of Gansu Province, Lanzhou University, Lanzhou 730000, China*

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Here we study the quark orbital angular momentum of the ground octet baryons employing an extended chiral constituent quark model, within which the baryon wave functions are taken to be superposition of the traditional $qqq$ and the $qqqq\bar{q}$ higher Fock components. Coupling between the two configurations is estimated using the $^3P_0$ quark-antiquark creation mechanism, and the corresponding coupling strength is determined by fitting the sea flavor asymmetry of the nucleon. The obtained numerical results show that the quark angular momentum of the nucleon, $\Sigma$, $\Lambda$, and $\Xi$ hyperons, are in the range 0.10–0.30. In addition, the quark angular momentum of all the hyperons are a little bit smaller than that of the nucleon. And the octet baryons spin fractions taken by the intrinsic quark orbital angular momentum could be up to 60% in present model.

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## I. INTRODUCTION

In the traditional constituent quark models, the ground octet baryons are composed of three quarks that are in their $S$ wave, thus the total spin of the baryons are contributed from only the spin of their quark content, namely the $SU(2)$ mixed symmetric spin configuration of the three-quark system with total spin $S = 1/2$ should account for the total spin of corresponding baryons completely [1,2]. However, in the late 1980s, the famous European muon collaboration found that the quark spin could take only a small fraction of the proton spin [3,4], which raised up the proton spin crisis.

Since then intensively experimental measurements on the spin structure of proton have been taken [5–11], and, on the theoretical side, the spin decomposition of proton in gauge theory was proposed in Refs. [12–15]. Accordingly, contributions of the quarks, the gluons, and orbital angular momentum (OAM) to the total proton spin have been investigated by lattice QCD [16–23], chiral perturbation theory [24–27], as well as other theoretical approaches [28–39], for recent reviews on status of the experimental and theoretical investigations on nucleon spin structure, see Refs. [40–46].

Based on these previous theoretical studies, one may conclude that the intrinsic sea content in baryons should play important roles in the static properties of baryons. On the other hand, the experimentally observed sea flavor asymmetry of proton [47,48] also reveals the nonperturbative effects of the intrinsic sea content in baryons.

Constructively, the proton can be depicted by a meson-cloud picture that the proton is explained to be a neutron core surrounding by pion meson cloud. Furthermore, one can also consider effects of the $K\Lambda$, $K\Sigma$, and $\pi\Delta$ components in proton [49–52]. Within the meson cloud model, spin of proton could be directly decomposed into the spin and orbital angular momentum of quarks, since the meson clouds should be in their $P$-wave states relative to the baryon cores. And the sea flavor asymmetry may be described by the $\pi N$ and $\pi\Delta$ components with appropriate probabilities in proton. Within this picture, one can also explain the intrinsic strange-antistrange quark asymmetry in proton if the $K\Lambda$ and $K\Sigma$ components are taken into account [52]. Straightforwardly, the meson cloud picture for nucleon can be extended to the other octet baryons [53].

Alternatively, the extended chiral constituent quark model (E$\chi$CQM), in which the higher Fock components in the baryon's wave function are assumed to be compact pentaquark configurations, was proposed to study the strangeness magnetic moment [54], strangeness form factor [55], and strangeness spin of proton [32] and further developed to investigate the intrinsic sea content and meson-baryon sigma terms of the octet baryons [56–58]. In addition, the experimental data for decays of baryon resonances such as $\Delta(1232)$,

*gli@qfnu.edu.cn
†ancs@swu.edu.cn
‡crdeng@swu.edu.cn
§xiejujun@impcas.ac.cn

TABLE I. The orbital-flavor-spin configurations for the four-quark subsystem of the five-quark configurations those may exist as higher Fock components in ground octet baryons.

| | | | | | |
|---|---|---|---|---|---|
| $i$ | 1 | 2 | 3 | 4 | 5 |
| Config. | $[31]_\chi[4]_{FS}[22]_F[22]_S$ | $[31]_\chi[31]_{FS}[211]_F[22]_S$ | $[31]_\chi[31]_{FS}[31]_{F_1}[22]_S$ | $[31]_\chi[31]_{FS}[31]_{F_2}[22]_S$ | $[4]_\chi[31]_{FS}[211]_F[22]_S$ |
| $i$ | 6 | 7 | 8 | 9 | 10 |
| Config. | $[4]_\chi[31]_{FS}[31]_{F_1}[22]_S$ | $[4]_\chi[31]_{FS}[31]_{F_2}[22]_S$ | $[31]_\chi[4]_{FS}[31]_{F_1}[31]_S$ | $[31]_\chi[4]_{FS}[31]_{F_2}[31]_S$ | $[31]_\chi[31]_{FS}[211]_F[31]_S$ |
| $i$ | 11 | 12 | 13 | 14 | 15 |
| Config. | $[31]_\chi[31]_{FS}[22]_F[31]_S$ | $[31]_\chi[31]_{FS}[31]_{F_1}[31]_S$ | $[31]_\chi[31]_{FS}[31]_{F_2}[31]_S$ | $[4]_\chi[31]_{FS}[211]_F[31]_S$ | $[4]_\chi[31]_{FS}[22]_F[31]_S$ |
| $i$ | 16 | 17 | | | |
| Config. | $[4]_\chi[31]_{FS}[31]_{F_1}[31]_S$ | $[4]_\chi[31]_{FS}[31]_{F_2}[31]_S$ | | | |

$P_{11}(1440)$, $S_{11}(1535)$, $S_{11}(1650)$, $D_{13}(1520)$, and $D_{13}(1700)$ [59–64] can be also well reproduced by E$\chi$CQM. Very recently, the E$\chi$CQM has been applied to study the quark OAM of the proton and flavor-dependent axial charges of the ground-state octet baryons [65–67]. It is shown that the singlet axial charge $g_A^{(0)}$, the isovector axial charge $g_A^{(3)}$, and the $SU(3)$ octet axial charge $g_A^{(8)}$ of the octet baryons obtained in the E$\chi$CQM are consistent with predictions by lattice QCD and chiral perturbation theory if the model parameters are fixed by fitting the data for $\bar{d}-\bar{u}$ asymmetry of proton [48]. As an direct extension of Ref. [65], here we investigate the quark OAM of the ground octet baryons and analyze the spin decomposition of the corresponding baryons in the E$\chi$CQM.

The present paper is organized as follows. In Sec. II, we present the framework which includes the E$\chi$CQM and the formalism for calculations on the OAM in corresponding model, the explicit numerical results and discussions are given in Sec. III. Finally, we give a brief summary of present work in Sec. IV.

## II. FRAMEWORK

To investigate the quark orbital angular momentum of the ground octet baryons, here we employ the E$\chi$CQM, in which the wave functions of baryons can be expressed in a general form as:

$$|B\rangle = \frac{1}{\sqrt{\mathcal{N}}}\left[|qqq\rangle + \sum_i C_i^q |qqq(q\bar{q}), i\rangle\right], \qquad (1)$$

where the first term just represents the wave functions for the traditional three-quark components of the octet baryons, while the second term denotes the wave functions for the compact five-quark components, with the sum over $i$ runs over all the possible five-quark configurations with a $q\bar{q}$ ($q=u,d,s$) pair that may form considerable higher Fock components in the octet baryons. $C_i^q/\sqrt{\mathcal{N}}$ are the corresponding probability amplitudes for the five-quark components with $\mathcal{N}$ being a normalization constant. The 17 possible $qqq(q\bar{q})$ configurations with $i = 1\cdots 17$ are shown in Table I, where the flavor, spin, color, and orbital wave functions for the four-quark subsystem are denoted by the Young tableaux of the $S_4$ permutation group.

As we can see in Table I, spin-wave functions of the four-quark subsystem in configurations with $i=1\cdots 7$ are $[22]_S$, which leads to the total spin $S_4 = 0$ for the four-quark subsystem, and thus one only need to consider the combination of the quark (antiquark) OAM and spin of the antiquark to get the total spin of a given baryon. And a general form for the wave functions of these configurations can be expressed as

$$\begin{aligned}
&|B, i=1\cdots 7\rangle_{5q} \\
&= \sum_{ijkln}\sum_{ab}\sum_{m\bar{s}_z} C^{\frac{1}{2},\uparrow}_{1,m;\frac{1}{2},\bar{s}_z} C^{[1^4]}_{[31]^k_{\chi FS};[211]^{\bar{k}}_C} C^{[31]^k_{\chi FS}}_{[O]^i_\chi;[FS]^j_{FS}} C^{[FS]^j_{FS}}_{[F]^l_F;[22]^n_S} \\
&\times C^{[2^3]_C}_{a,b}\left|[211]^{\bar{k}}_C(a)\right\rangle|[11]_{C,\bar{q}}(b)\rangle|I,I_3\rangle^{[F]^l_F}|1,m\rangle^{[O]^i_\chi}\Big| \\
&\times [22]^n_S\Big\rangle|\bar{\chi},\bar{s}_z\rangle\phi(\{\vec{r}_q\}),
\end{aligned} \qquad (2)$$

with the coefficients $C^{[\cdots]}_{[\cdots][\cdots]}$ represent the CG coefficients of the $S_4$ permutation group and $C^{\frac{1}{2},\uparrow}_{1,m;\frac{1}{2},\bar{s}_z}$ the CG coefficients for the combination of the quark (antiquark) OAM and spin of the antiquark to form a spin $|1/2,+1/2\rangle$ baryon state. And the explicit flavor, orbital, spin, and color wave functions for the presently considered five-quark configurations have been given in Refs. [67].

While for the five-quark configurations with $i=8\cdots 17$ shown in Table I, the spin-wave function of the four-quark subsystem is $[31]_S$ which results in the total spin $S_4=1$ for the four-quark subsystem. Accordingly, we have to take into account the combination of the spin of both the four-quark and the antiquark and the quark (antiquark) OAM to get the total spin of the octet baryon. One should note that combination of the spin for four-quark subsystem $S_4 = 1$ and the quark OAM $L=1$ will lead to $J = L\oplus S_4 = 0$, 1 or 2, and the former two $J$ those could form the total spin $S_B = 1/2$ of the presently studied octet baryons, when combine to the spin of the antiquark $S_{\bar{q}} = 1/2$ are applicable. Hereafter, we denote these two cases of wave functions as Set I and Set II, respectively.

The general forms for wave functions of the five-quark configurations with $i=8\cdots 17$ in these two cases are then given by

$$\begin{aligned}
&|B, i=8\cdots 17\rangle^{\rm I}_{5q} \\
&= \sum_{ijkln}\sum_{ab}\sum_{ms_z} C^{00}_{1,m;1,s_z} C^{[1^4]}_{[31]^k_{\chi FS};[211]^{\bar{k}}_C} C^{[31]^k_{\chi FS}}_{[O]^\chi_i;[FS]^j_{FS}} C^{[FS]^j_{FS}}_{[F]^l_F;[31]^n_S} \\
&\times C^{[2^3]_C}_{a,b}\left|[211]^{\bar{k}}_C(a)\right\rangle|[11]_{C,\bar{q}}(b)\rangle|I,I_3\rangle^{[F]^l_F} \\
&\times |1,m\rangle^{[O]^i_\chi}\left|[31]^n_S, s_z\right\rangle|\bar{\chi},\bar{s}_z\rangle\phi(\{\vec{r}_q\}),
\end{aligned} \qquad (3)$$

and

$$|B, i = 8 \cdots 17\rangle_{5q}^{\mathrm{II}}$$
$$= \sum_{ijkln}\sum_{ab}\sum_{J_z\bar{s}_z}\sum_{ms_z} C^{\frac{1}{2},\frac{1}{2}}_{1,J_z;\frac{1}{2},\bar{s}_z} C^{1,J_z}_{1,m;1,s_z} C^{[1^4]}_{[31]^k_{\chi FS};[211]^{\bar{k}}_C} C^{[31]^k_{\chi FS}}_{[O]^i_\chi;[FS]^j_{FS}}$$
$$\times C^{[FS]^j_{FS}}_{[F]^l_F;[31]^n_S} C^{[2^3]_C}_{a,b} \big|[211]^{\bar{k}}_C(a)\big\rangle\big|[11]_{C,\bar{q}}(b)\big\rangle$$
$$\times |I, I_3\rangle^{[F]^l_F}|1, m\rangle^{[O]^\chi_i}\big|[31]^S_n, s_z\big\rangle|\bar{\chi}, \bar{s}_z\rangle\phi(\{\vec{r}_q\}). \tag{4}$$

Next we turn to the coefficients $C_i^q$ in Eq. (1). Generally, to get the probability amplitude for a five-quark component in a given baryon, one has to evaluate energy of the five-quark configuration $E_i^q$ and its coupling to the three-quark component in the corresponding baryon.

In present work, the energy $E_i^q$ for a given five-quark configuration is estimated using the chiral constituent quark model, within which the hyperfine interaction between quarks is [2]

$$H_{\mathrm{hyp}} = -\sum_{i<j}\delta(r_{ij})\vec{\sigma}_i\cdot\vec{\sigma}_j\left[\sum_{a=1}^{3}V_\pi(r_{ij})\lambda_i^a\lambda_j^a + \sum_{a=4}^{7}V_K(r_{ij})\lambda_i^a\lambda_j^a + V_\eta(r_{ij})\lambda_i^8\lambda_j^8\right], \tag{5}$$

where $\vec{\sigma}_{i(j)}$ and $\lambda^a_{i(j)}$ are the Pauli and flavor $SU(3)$ Gell-Mann matrices acting on the $i(j)$th quark and $V_M(r_{ij})$ denotes the potential for exchanging a $M$ meson. Calculations on the matrix elements $\langle qqq(q\bar{q}), i|H_{\mathrm{hyp}}|qqq(q\bar{q}), i\rangle$ will lead to the following common factors:

$$P_l^M = \langle lm|\delta(r_{ij})V_M(r_{ij})|lm\rangle, \tag{6}$$

with $|lm\rangle$ the spatial wave function with OAM quantum number $l$. Here we just take the empirical values for $P_l^M$ those could very well reproduce the spectroscopy of light and strange baryons [2]:

$$P_0^\pi = 29\ \mathrm{MeV},\ P_0^K = 20\ \mathrm{MeV},\ P_0^{s\bar{s}} = 14\ \mathrm{MeV},$$
$$P_1^\pi = 45\ \mathrm{MeV},\ P_1^K = 30\ \mathrm{MeV},\ P_1^{s\bar{s}} = 20\ \mathrm{MeV}. \tag{7}$$

Then the energy $E_i^q$ for the five-quark configurations listed in Table I can be calculated by

$$E_i^q = E_0 + \langle qqq(q\bar{q}), i|H_{\mathrm{hyp}}|qqq(q\bar{q}), i\rangle + n_i^s\delta m, \tag{8}$$

where $E_0$ is a degenerated energy for all the studied configurations when the hyperfine interaction between quarks and the flavor $SU(3)$ breaking effects are not taken into account and $\delta_m$ and $n_i^s$ denote the mass difference of the light and strange quarks and number of strange quarks in the corresponding five-quark system, respectively. Here both $E_0$ and $\delta_m$ are taken to be the empirical values [56]:

$$E_0 = 2127\ \mathrm{MeV}, \quad \delta_m = 120\ \mathrm{MeV}. \tag{9}$$

To calculate the transition coupling matrix elements between the $qqq$ and $qqqq\bar{q}$ components, here we adopt a widely accepted $^3P_0$ quark-antiquark creation mechanism [68,69], which has been used to study the intrinsic sea content of nucleon [56]. Explicitly, as depicted in Fig. 1, the three initial quarks go as spectators, and a quark-antiquark pair with quantum number $J^P = 0^+$ is created in the vacuum and then form the final five-quark system. The operator for this kind of transition can be written as

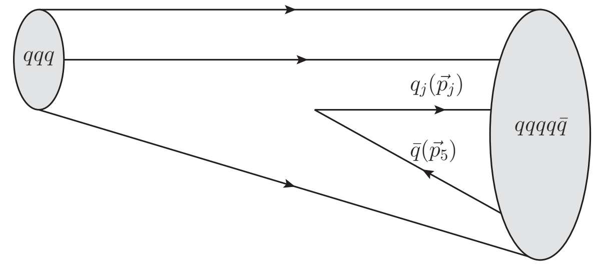


FIG. 1. Transition $qqq \to qqqq\bar{q}$ caused by a quark-antiquark pair creation in a baryon via the $^3P_0$ mechanism.

$$\hat{T} = -\gamma\sum_{j=1,4}\mathcal{F}^{00}_{j,5}\mathcal{C}^{00}_{j,5}\mathcal{C}_{\mathrm{OFSC}}\sum_m\langle 1, m; 1, -m|00\rangle \times\chi^{1,m}_{j,5}\mathcal{Y}^{1,-m}_{j,5}(\vec{p}_j - \vec{p}_5)b^\dagger(\vec{p}_j)d^\dagger(\vec{p}_5), \tag{10}$$

where $\gamma$ is an dimensionless transition coupling constant, $\mathcal{F}^{00}_{j,5}$ and $\mathcal{C}^{00}_{j,5}$ are the flavor and color singlet of the created quark-antiquark pair $q_j\bar{q}_5$, $\chi^{1,m}_{j,5}$ and $\mathcal{Y}^{1,-m}_{j,5}$ are the total spin $S_{q\bar{q}} = 1$ and relative orbital $P$ state of the created quark-antiquark system, the operator $\mathcal{C}_{\mathrm{OFSC}}$ is to calculate the overlap factor between the residual three-quark configuration in the five-quark component and the valence three-quark component, and, finally, $b^\dagger(\vec{p}_j)$, $d^\dagger(\vec{p}_5)$ are the quark and antiquark creation operators.

Then, one can calculate the probability amplitude for a five-quark configuration $|qqq(q\bar{q}), i\rangle$ in a given baryon $B$ by the following equation:

$$C_i^q = \frac{\langle qqq(q\bar{q}), i|\hat{T}|qqq\rangle}{M_B - E_i^q}, \tag{11}$$

here $M_B$ denote the physical mass of the baryon $B$ [70].

Explicit calculations on the transition matrix elements $\langle qqq(q\bar{q}), i|\hat{T}|qqq\rangle$ between all the five-quark configurations shown in Table I and the $qqq$ components in the presently studied octet baryons will result in a common factor $\mathcal{V}$, namely

$$\langle qqq(q\bar{q}), i|\hat{T}|qqq\rangle = \mathcal{T}_i\mathcal{V}, \tag{12}$$

the coefficient $\mathcal{T}_i$ can be obtained directly by the given wave function of the $i$th five-quark configuration and $\mathcal{V}$ depends on the $^3P_0$ transition coupling constant $\gamma$ and parameters of explicit spatial wave functions determined by a given quark confinement potential.

To reduce free model parameters, here we just fix $\mathcal{V}$ by fitting experimental data for the intrinsic sea flavor asymmetry of the proton [48],

$$I_a = \bar{d} - \bar{u} = \int_0^1[\bar{d}_p(x) - \bar{u}_p(x)]dx = 0.118 \pm 0.012. \tag{13}$$

In the present model, the $\bar{d}$-$\bar{u}$ asymmetry can be obtained by

$$\begin{aligned} I_a &= \bar{d} - \bar{u} \\ &= \frac{1}{\mathcal{N}}\Bigg\{\left(\frac{T_1^{l\bar{l}}}{M_p - E_1^l}\right)^2 + \left(\frac{T_{11}^{l\bar{l}}}{M_p - E_{11}^l}\right)^2 + \left(\frac{T_{15}^{l\bar{l}}}{M_p - E_{15}^l}\right)^2 \\ &\quad -\frac{1}{3}\Bigg[\left(\frac{T_3^{l\bar{l}}}{M_p - E_3^l}\right)^2 + \left(\frac{T_6^{l\bar{l}}}{M_p - E_6^l})\right)^2 + \left(\frac{T_8^{l\bar{l}}}{M_p - E_8^l}\right)^2 \\ &\quad +\left(\frac{T_{12}^{l\bar{l}}}{M_p - E_{12}^l}\right)^2 + \left(\frac{T_{16}^{l\bar{l}}}{M_p - E_{16}^l}\right)^2\Bigg]\Bigg\}, \end{aligned} \tag{14}$$

where $T_i^{l\bar{l}}$ denotes the transition coupling matrix element between the $i$th five-quark configuration in Table I with a light quark-antiquark pair $l\bar{l}$ and the three-quark component in proton:

$$T_i^{l\bar{l}} = \langle uud(l\bar{l}), i|\hat{T}|uud\rangle, \tag{15}$$

and $E_i^l$ is energy of the corresponding five-quark configuration with a light quark-antiquark pair.

Accordingly, the involved parameters in present model are the coupling strengths $P_l^M$ (six involved ones in total), the degenerated energy $E_0$ for all the five-quark configurations given in Table I, mass difference of the light and strange quark $\delta_m$, and the common factor $\mathcal{V}$ for the transition matrix elements $\langle\hat{T}\rangle$. As shown in Eqs. (7) and (9), the former eight parameters are taken to be the empirical values used in the literature. And by fitting the sea flavor asymmetry of proton in Eq. (13), one can get the following values of $\mathcal{V}$:

$$\mathcal{V}_{\rm I} = 570 \pm 46\ \text{MeV}, \tag{16}$$

$$\mathcal{V}_{\rm II} = 697 \pm 80\ \text{MeV}, \tag{17}$$

for the two different sets of wave functions using in present model, respectively.

Note that one could also consider the higher Fock components $qqq(q\bar{q})^2$ in the baryons. Energies of these kinds of components those can couple to the ground-state octet baryons may be about 600–900 MeV higher than the five-quark components, taking into account the two quark-antiquark pairs creations, a rough estimation shows that the probability amplitudes of the $qqq(q\bar{q})^2$ components are about 1/5 of those of the presently considered five-quark components.

Finally, within the E$\chi$CQM, the quark OAM of the octet baryons can be calculated by

$$L_f = \langle B|\hat{L}_{fz}|B\rangle = \frac{(C_i^q)^2\langle qqq(q\bar{q},i)|\hat{L}_{fz}|qqq(q\bar{q},i)\rangle}{\mathcal{N}}, \tag{18}$$

with the operator $\hat{L}_{fz}$ defined by

$$\hat{L}_{fz} = \sum_f(\hat{l}_f + \hat{l}_{\bar{f}})_z, \tag{19}$$

where $\hat{l}_f$ and $\hat{l}_{\bar{f}}$ are the OAM operators for the quark and antiquark with flavor $f$, respectively, and the sum runs over the flavors $u$, $d$, and $s$.

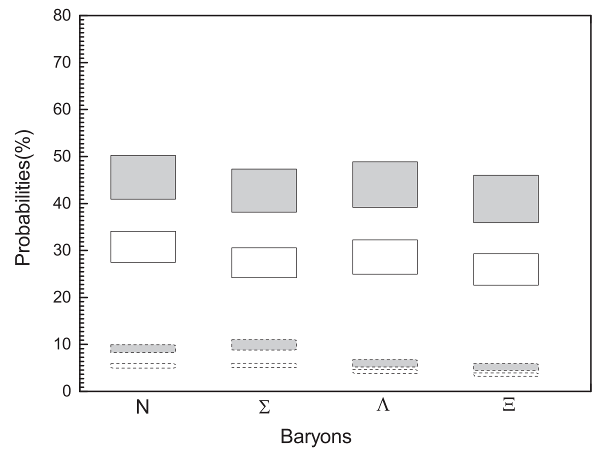


FIG. 2. The probabilities of the five-quark components in the octet baryons, the boxes filled by white and grey colors are results obtained in Sets I and II, respectively, and the boxes with solid line border are results for the five-quark components with a light quark-antiquark pair, while those with dash line border are results for the five-quark components with a strange quark-antiquark pair. The rectangle height shows the uncertainty.

## III. NUMERICAL RESULTS AND DISCUSSIONS

### A. The quark OAM of the octet baryons

Within the framework of the E$\chi$CQM as shown in Sec. II, one can calculate the probabilities of all the possible five-quark components in the octet baryons, here we show the probabilities of the five-quark components with light and strange quark-antiquark pairs in each octet baryon in Fig. 2. As discussed explicitly in Ref. [67], the obtained baryon wave functions in the both the Set I and Set II could result in the meson-baryon sigma terms consistent with the predictions by other theoretical approaches, although the probabilities for the five-quark components in the two sets are very different. And one may note that the upper limit of probabilities for the intrinsic five-quark components obtained in Set II of present model are larger than 50%, while these values are very close to those predicted in Refs. [71–73], where the model proposed by Brodsky *et al.* [74] was employed.

Using the wave functions shown in Eqs. (2), (3), and (4) with explicit $C_i^q$ calculated by Eq. (11), one can directly calculate the quark OAM of the octet baryons by Eq. (18). The corresponding numerical results for $L_u$, $L_d$, and $L_s$ of the proton, $\Sigma^+$, $\Sigma^0$, $\Lambda$, and $\Xi^0$ baryons are presented in Table II. And the flavor-dependent quark OAM of neutron, $\Sigma^-$ and $\Xi^-$ can be obtained directly using the $SU(2)$ isospin symmetry, which yields

$$L_{u(d)}(n) = L_{d(u)}(p)\,,\quad L_s(n) = L_s(p), \tag{20}$$

$$L_{u(d)}(\Sigma^-) = L_{d(u)}(\Sigma^+)\,,\quad L_s(\Sigma^-) = L_s(\Sigma^+), \tag{21}$$

$$L_{u(d)}(\Xi^-) = L_{d(u)}(\Xi^0)\,,\quad L_s(\Xi^-) = L_s(\Xi^0). \tag{22}$$

And in Fig. 3, we depict the presently obtained total quark OAM $L_q$ of all flavors compared to the results predicted by lattice QCD [20], unquenched quark model [38], and light cone constituent quark model [39].

TABLE II. The quark OAM of the octet baryons. The upper and lower panels denoted by Set I and Set II are the numerical results obtained using the two sets of wave functions, respectively.

| | | $p$ | $\Sigma^+$ | $\Sigma^0$ | $\Lambda$ | $\Xi^0$ |
|---|---|---|---|---|---|---|
| | $L_u$ | 0.080(09) | 0.063(07) | 0.050(06) | 0.049(06) | 0.041(05) |
| Set I | $L_d$ | 0.063(07) | 0.037(04) | 0.050(06) | 0.049(06) | 0.031(03) |
| | $L_s$ | 0.014(02) | 0.029(03) | 0.029(03) | 0.040(05) | 0.055(06) |
| | $L_u$ | 0.136(15) | 0.114(13) | 0.091(10) | 0.089(10) | 0.078(09) |
| Set II | $L_d$ | 0.105(11) | 0.068(09) | 0.091(10) | 0.089(10) | 0.065(08) |
| | $L_s$ | 0.026(04) | 0.060(08) | 0.060(08) | 0.067(08) | 0.085(11) |

Since all the valence quarks in the octet baryons are in their $S$ wave, the quark OAM should be only contributed from the five-quark higher Fock components of baryons. Therefore, the quark OAM should be sensitive to the probabilities of the five-quark components. Therefore, as we can see in Table II, the results for the quark OAM obtained in Set II model are about 1.5–2 times of those in Set I model. On the other hand, in Set I, the five-quark configurations with $i = 8 \cdots 17$ do not contribute to the quark OAM of proton, as discussed in Ref. [65], but it is not true for Set II. Consequently, the relationship between the flavor sea asymmetry and total quark OAM of proton in Set II is

$$L_q \approx 9/4 I_a, \tag{23}$$

instead of the $\sim 4/3 I_a$ in Set I obtained in Ref. [65].

For the nucleon, in both Sets I and II, the up and down quarks OAM are comparable to each other, this is very different from the lattice QCD predictions in Ref. [20], where the obtained light quark OAM are $L_u = -0.107(40)$ and $L_d = 0.247(38)$, while the total quark OAM of all flavors in Ref. [20] is in the same range of the presently obtained results, as shown in Fig. 3. In addition, the presently obtained total quark OAM is in consistent with the predictions by unquenched quark model [38] and light cone constituent quark model [39].

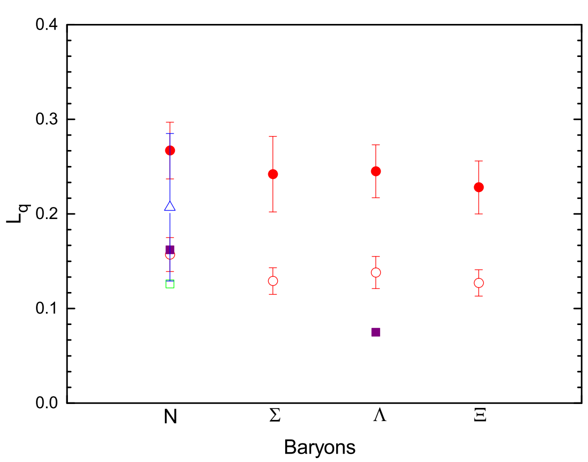


FIG. 3. The total quark OAM of all flavors for the octet baryons. The present results in Sets I and II are shown by (red) hollow and solid circles, respectively. And the (blue) triangle, (purple) solid square, and (green) hollow square are results predicted by lattice QCD [20], unquenched quark model [38], and light cone constituent quark model [39], respectively.

For the other octet baryons, the light quarks OAM of the hyperons are smaller than that of nucleon, while the strange quark OAM of hyperons are 2–4 times of that of nucleon. Obviously, this is because of the more strange quark contents in hyperons than in nucleon. In Ref. [38], the total quark OAM of $\Lambda$ was studied employing the unquenched quark model by considering the effects of the quark-antiquark pairs created via the $^3P_0$ mechanism, and the predicted $L_q$ of $\Lambda$ hyperon is 0.075, that is, smaller than the presently obtained results in both Sets I and II.

### B. The spin decomposition of the octet baryons

It is also very interesting to investigate the spin decomposition of the octet baryons. In present model, the spin and OAM of gluons are not involved, and, accordingly, one can decompose the octet baryons spin by

$$S_B = 1/2 = \sum_f \left[(\Delta f^{\text{val}} + \Delta f^{\text{sea}})/2 + L_f^{\text{sea}}\right], \tag{24}$$

where $\Delta f^{\text{val}}/2$ and $\Delta f^{\text{sea}}/2$ are the flavor-dependent valence and intrinsic sea quarks spin, respectively, and $L_f^{\text{sea}}$ the intrinsic sea quark OAM which should be the same as those numerical results shown in Table II, and the sum over $f$ runs over the three flavors $u$, $d$, and $s$. We present our numerical results of Sets I and II obtained by limiting the sea flavor asymmetry in proton to be the experimentally measured central value $I_a = \bar{d} - \bar{u} = 0.118$ [48] in Table III, compared to the results in the traditional three-quark constituent quark model.

As shown in Table III, in the traditional three-quark constituent quark model, only spin of the valence up and down quarks contribute to the nucleon spin. While in the presently employed E$\chi$CQM, spin of the valence and intrinsic sea quarks contribute $\sim$63% and 6% of the nucleon spin, respectively, and the nucleon spin arisen from the intrinsic sea quark OAM is 31%, if the wave functions of Set I are adopted. This is in good agreement with the results in Ref. [38] obtained by the unquenched quark model. While if we use the wave functions of Set II, then the nucleon spin contributed from the valence quark spin is 46%, and the intrinsic sea quark spin and OAM should contribute 1% and 53% to the nucleon spin, respectively. In addition, if the uncertainty in present model caused by fitting the sea flavor asymmetry data are taken

TABLE III. Spin decomposition of the octet baryons. The three panels from left to right denoted by traditional three-quark CQM, E$\chi$CQM Set I, and E$\chi$CQM Set II are results in the traditional three-quark constituent quark model and the presently obtained results in Sets I and II, respectively. The last three rows denoted by $\mathcal{C}_\Delta^{\rm val}$, $\mathcal{C}_\Delta^{\rm sea}$, $\mathcal{C}_\Delta^{\Sigma}$, and $\mathcal{C}_L^{\rm sea}$ are baryon spin fractions carried by the valence quark spin, intrinsic sea quark spin, total (valence and sea) quark spin and intrinsic sea quark OAM, respectively, in unit of %.

| | Traditional three-quark CQM | | | | | E$\chi$CQM Set I | | | | | E$\chi$CQM Set II | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $p$ | $\Sigma^+$ | $\Sigma^0$ | $\Lambda$ | $\Xi^0$ | $p$ | $\Sigma^+$ | $\Sigma^0$ | $\Lambda$ | $\Xi^0$ | $p$ | $\Sigma^+$ | $\Sigma^0$ | $\Lambda$ | $\Xi^0$ |
| $\Delta u^{\rm val}$ | 4/3 | 4/3 | 2/3 | 0 | −1/3 | 0.839 | 0.883 | 0.442 | 0 | −0.233 | 0.606 | 0.638 | 0.319 | 0 | −0.177 |
| $\Delta d^{\rm val}$ | −1/3 | 0 | 2/3 | 0 | 0 | −0.210 | 0 | 0.442 | 0 | 0 | −0.152 | 0 | 0.319 | 0 | 0 |
| $\Delta s^{\rm val}$ | 0 | −1/3 | −1/3 | −1/3 | 4/3 | 0 | −0.221 | −0.221 | 0.671 | 0.933 | 0 | −0.160 | −0.160 | 0.497 | 0.708 |
| $\Delta u^{\rm sea}$ | 0 | 0 | 0 | 0 | 0 | 0.044 | 0.039 | 0.031 | 0.026 | 0.018 | 0.104 | 0.124 | 0.029 | −0.020 | −0.017 |
| $\Delta d^{\rm sea}$ | 0 | 0 | 0 | 0 | 0 | −0.003 | 0.023 | 0.031 | 0.026 | 0.030 | −0.073 | −0.066 | 0.029 | −0.020 | −0.059 |
| $\Delta s^{\rm sea}$ | 0 | 0 | 0 | 0 | 0 | 0.015 | 0.016 | 0.016 | 0.003 | −0.003 | −0.020 | −0.020 | −0.020 | 0.054 | 0.090 |
| $L_u^{\rm sea}$ | 0 | 0 | 0 | 0 | 0 | 0.080 | 0.063 | 0.050 | 0.049 | 0.041 | 0.136 | 0.114 | 0.091 | 0.089 | 0.078 |
| $L_d^{\rm sea}$ | 0 | 0 | 0 | 0 | 0 | 0.063 | 0.037 | 0.050 | 0.049 | 0.031 | 0.105 | 0.068 | 0.091 | 0.089 | 0.065 |
| $L_s^{\rm sea}$ | 0 | 0 | 0 | 0 | 0 | 0.014 | 0.029 | 0.029 | 0.040 | 0.055 | 0.026 | 0.060 | 0.060 | 0.067 | 0.085 |
| $\mathcal{C}_\Delta^{\rm val}$ (%) | 100 | 100 | 100 | 100 | 100 | 63 | 66 | 66 | 67 | 70 | 46 | 48 | 48 | 50 | 53 |
| $\mathcal{C}_\Delta^{\rm sea}$ (%) | 0 | 0 | 0 | 0 | 0 | 6 | 8 | 8 | 5 | 5 | 1 | 4 | 4 | 1 | 1 |
| $\mathcal{C}_\Delta^{\Sigma}$ (%) | 100 | 100 | 100 | 100 | 100 | 69 | 74 | 74 | 72 | 75 | 47 | 52 | 52 | 51 | 54 |
| $\mathcal{C}_L^{\rm sea}$ (%) | 0 | 0 | 0 | 0 | 0 | 31 | 26 | 26 | 28 | 25 | 53 | 48 | 48 | 49 | 46 |

into account, then contributions from the quark OAM to the nucleon spin could be up to 60%.

Compared to the experimental data, i.e., the measured negative value for spin of strange quark in proton $\Delta s$, and the proton spin fraction carried by quark spin $\Sigma = 0.33(10)$ [5–11], one may conclude that the present Set II of wave functions should be more favorable than Set I, although the value $\mathcal{C}_\Delta^{\Sigma} = 47\%$ for the quark spin fraction of proton obtained in Set II model is still larger than experimental data.

The presently obtained quark spin fraction of the proton in the Set II model is very close to the numerical result 0.46 predicted in Ref. [34] with contributions of only the one-body axial current. It's shown that the simple additive constituent quark model should violate the partial conservation of the axial current condition [75,76], so one has to take into account contributions of two-body axial exchange currents, which could deduce the one-body axial current result by ∼40% [34], and the obtained quark spin fraction of proton including contributions from total currents is consistent with the experimental data.

In Ref. [36], the authors employed a relativistic constituent quark model and took into account the one-gluon-exchange effects and the pion cloud contributions, which resulted in that the quark OAM could contribute about 62% to the nucleon spin. This value is close to the presently obtained upper limit for the quark OAM in the Set II model.

For the other octet baryons, as shown in Table III, the baryon spin arisen from the intrinsic sea quark spin should be less than 10%, while contributions of the intrinsic sea quark OAM to the baryon spin are about 25–28% and 46–49% using the wave functions of Set I and Set II, respectively. And one should note that the contributions of the valence quark to spin of $\Sigma$, $\Lambda$, and $\Xi$ hyperons in the present Set I model are 66%, 67%, and 70%, respectively, while in Set II model, the corresponding contributions are 48%, 50%, and 53%, respectively.

In Refs. [77,78], the quark spin contribution to the total angular momentum of flavor octet and decuplet ground-state baryons are studied using a spin-flavor symmetry based parametrization method of quantum chromodynamics. The results for the quark spin fraction of the ground-state octet baryons in Ref. [77] is 0.35(12), and the value obtained in Ref. [78] is 0.41(12), which values are in general consistent with the presently obtained results.

In Ref. [79], the MIT bag model with corrections from the one-gluon-exchange and meson-cloud effects were employed to evaluate the octet baryons spin fractions carried by the valence quarks, and the obtained results were 42.6%, 58.9%, and 65.2% for the $\Sigma$, $\Lambda$ and $\Xi$ hyperons, respectively. And in a very recent paper [80], the quark spin content of $SU(3)$ light and singly heavy baryons were investigated using a pion mean-field approach or the chiral quark-soliton model, flavor decomposition of the axial charges of the baryons were studied explicitly, the numerical results of the singlet axial charge for nucleon are comparable with the present results in Set II model, within $1\sigma$, while those for the other octet baryons are smaller than the present results. And it is predicted that the composite quark spin should contribute about 44%, 46%, 42%, and 41% to spin of nucleon, $\Sigma$, $\Lambda$, and $\Xi$, respectively, these values are also close to the present results in Set II.

## IV. SUMMARY

To summarize, in present work, we investigate the quark orbital angular momentum of the ground octet baryons employing the extended chiral constituent quark model, in which the compact pentaquark higher Fock components in baryons are taken into account. The probabilities of the higher Fock components are determined by fitting the data for the sea flavor asymmetry of the proton.

In present model, there are two sets of wave functions for the pentaquark higher Fock components in the ground octet baryons. These two sets of wave functions could yield very different probability amplitudes of the pentaquark components, as well different quark orbital angular momentum of the octet baryons. Our numerical results show that the quark angular momentum of the nucleon should be about 0.15–0.3, namely the quark angular momentum could contribute 30–60% to the nucleon spin. And the contributions of the intrinsic sea quark spin to the nucleon spin are not large.

For the $\Lambda$, $\Sigma$, and $\Xi$ hyperons, it is very similar to the nucleon, the spin of the intrinsic sea quark contributes less than 10% to their total spin. And the obtained quark angular momentum are in the range 0.10–0.28, which are a little smaller than that of the nucleon. And the corresponding total spin arisen from the quark orbital angular momentum is about ∼25–50%.

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