Intrinsic sea content of the ground state decuplet baryons in the extended chiral constituent quark model

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The intrinsic sea content in the ground state decuplet baryons is investigated employing an extended chiral constituent quark model, in which the wave functions of the baryons are taken to be superposition of the traditional qqq and the $qqqq\bar{q}$ higher Fock components. The probability amplitudes of corresponding pentaquark components are calculated using the widely employed $^3P_0$ model, which could lead to transition couplings between the qqq and the $qqqq\bar{q}$ components in the studied baryons. All the involved model parameters are taken to be the empirical values, and our numerical results show the total probabilities $\mathcal{P}_5^B$ of the pentaquark components in the decuplet baryons are close to each others, while $\mathcal{P}_5^B$ decreases with the increasing strangeness number of the baryon.

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I. INTRODUCTION

The quark model is one of the most successful models in hadronic physics. With an appropriate hyperfine interaction between quarks based on quantum chromodynamics (QCD), the constituent quark models (CQM) could explain fairly well the spectroscopy and static properties such as magnetic moment of the baryons and their excitations below 2 GeV [1–3], and the one-gluon-exchange model has also been successfully applied to the charm hadron sector [4,5], especially, the prediction of the charmonium spectrum in Ref. [5] is still a guideline for investigations on the hadron spectroscopy up to now. However, the deep inelastic scattering experiments have revealed that the intrinsic sea content of the nucleon should play important roles in the properties of nucleon [6–14], which cannot be depicted by the classic three-quark picture of CQM.

At the beginning of this century, several experimental measurements on the cross section of the polarized electron-nucleon scattering indicated that contributions of the strange quarks to the magnetic moment of proton should not be zero but a positive value, inconsistent with the predictions by lattice QCD and the widely employed meson cloud model [15–17]. Consequently, this surprising result triggered intensive theoretical investigations on the intrinsic sea content of the proton, using various of approaches. For example, Zou and Riska suggested that one had to consider the compact pentaquark components with strange quark-antiquark pairs as higher Fock components, in addition to the traditional three-quark component in the wave function of proton [18,19]. In the lowest strangeness pentaquark configuration with positive parity, the strange quark must be in its first orbitally excited state, which could lead to a positive strangeness magnetic moment of the proton, in agreement with the experiment data. Later, the model has been successfully applied to investigate the strangeness spin and form factors of the nucleon, and decay properties of baryon resonances such as $\Delta(1232)$, $N(1440)$, $\Lambda(1405)$, $N(1535)$, etc. [20–28].

Although several experimental measurements after 2009 have shown that the strangeness magnetic moment of the proton may be very small and negative [29,30], phenomenologically, there is no doubt that one has to consider the higher Fock components in the baryons' wave functions, whether as the compact multiquark states or the hadronic molecular ones. The key ingredient is the dynamical mechanism for the creation of quark-antiquark pairs in a tradition three-quark baryon state. In the extended chiral constituent quark model (EχCQM), tentatively, the widely used

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$^3P_0$ mechanism is employed [31]. The EχCQM could reproduce the sea flavor asymmetry $\int_0^1 \bar{d}(x) - \bar{u}(x) = 0.118 \pm 0.012$ in the proton very well [32], and describe the properties of the octet baryons, for instance, meson-baryon σ terms and the axial charges consistently [33–38]. One may note that the latest data on the sea flavor asymmetry in proton released by FNAL E906/SeaQuest Collaboration is $\int_{0.15}^{0.45} \bar{d}(x) - \bar{u}(x) = 0.0159 \pm 0.004$ [39], while in [32], the importance of the (very) low-x measurements is clearly shown, which renders the extraction of the extrapolated values in the whole range more reliable.

Consequently, in this work, we study the sea content of the ground state decuplet baryons, employing the EχCQM. The paper is organized as follows. In Sec. II, we briefly introduce the EχCQM, and give the wave functions of the possible pentaquark components in the decuplet baryons explicitly, the numerical results and discussions are given in Sec. III. Finally, we give a brief summary of present work in Sec. IV.

II. FRAMEWORK

Within the EχCQM, the wave functions of baryons (B) can be expressed in a general form as

$$|B\rangle = \frac{1}{\sqrt{\mathcal{N}}}\left(|qqq\rangle + \sum_{i_5,n_r,n_l,q} \mathcal{C}^q_{i_5,n_r,n_l}|qqq(q\bar{q}), i_5, n_r, n_l\rangle\right), \tag{1}$$

where the first term represents the wave functions for the traditional three-quark components of the baryons, while the second term denotes the wave functions for the compact pentaquark components with the sum over i_5 running over all the possible pentaquark configurations with a $q\bar{q}$ ($q = u, d, s$) pair that may form considerable higher Fock components in the baryons, n_r and n_l are the inner radial and orbital quantum numbers, $\mathcal{C}^q_{i_5,n_r,n_l}/\sqrt{\mathcal{N}} \equiv \mathcal{A}^q_{i_5,n_r,n_l}$ are the corresponding probability amplitudes for the pentaquark components with $\mathcal{N}$ being a normalization constant. Therefore, the total probability of the pentaquark components in a given baryon B can be calculated by

$$\mathcal{P}^B_5 = \sum_{i_5,n_r,n_l,q} \left(\mathcal{A}^q_{i_5,n_r,n_l}\right)^2. \tag{2}$$

The wave functions of the three-quark components for the decuplet baryons are taken to be the ones in the classic constituent quark model, and we show the wave functions and probability amplitudes in the following subsections, respectively.

A. Explicit wave functions for the pentaquark components

To form the positive parity and spin quantum number $J = 3/2$ of the ground state decuplet baryons, the inner orbital quantum numbers of the pentaquark components must be $l = 1$ or 3, while the pentaquark states with $n_l = 3$ are 500–800 MeV higher than the ones with $n_l = 1$. Analogous to the case for the octet baryons [31], here, only the pentaquark configurations with $n_l = 1$ and $n_r = 0$, and those with lower energies and stronger couplings to the three-quark components, are taken into account. Accordingly, the general form of the wave functions for the involved pentaquark components with the third component of spin being $+3/2$ is given by

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

where the coefficients $C^{[\cdots]}_{[\cdots][\cdots]}$ represent the CG coefficients of the S_4 permutation group, with $[\cdots]$ being the Yong tableaux. $|[211]^{\bar{k}}_C(a)\rangle$ and $|[11]_{C,\bar{q}}(b)\rangle$ are the color wave functions for the four-quark subsystem and the antiquark, $|I, I_3\rangle^{[F]^l_F}$ just represents the flavor wave function of the pentaquark states with an appropriate isospin quantum number, and the flavor symmetry of the four-quark subsystem being $[F]_F$, the explicit $|I, I_3\rangle^{[F]^l_F}$ for the presently studied baryons are shown in Appendix A. $|1, m\rangle^{[O]^i_\chi}$ and $|[S]^S_n, s_z\rangle$ are the orbital and spin symmetry of the four-quark subsystem, $|\bar{\chi}, \bar{s}_z\rangle$ is the spin wave function of the antiquark.

With respect to the four-quark subsystem, the Pauli principle requires that the orbital-flavor-spin-color wave function must be completely antisymmetric, since the color symmetry must be $[211]_C$, the coupling state of the orbital-flavor-spin is limited to $[31]_{\chi FS}$, so that the coupling between $[211]_C$ and $[31]_{\chi FS}$ reads

$$\begin{aligned}[1^4]_{C\chi FS} = \frac{1}{\sqrt{3}}\big(&[211]^1_C[31]^3_{\chi FS} - [211]^2_C[31]^2_{\chi FS}\\ &+ [211]^3_C[31]^1_{\chi FS}\big).\end{aligned} \tag{4}$$

As we have mentioned above, here, we take the inner orbital quantum number of the pentaquark configurations to be $n_l = 1$, considering the orbital quantum number of the antiquark state to be 1 or 0, the orbital symmetry of the four-quark subsystem can be the completely symmetric $[4]_\chi$ with all four quarks being in their ground states, and the mixing symmetric $[31]_\chi$ with one of the quarks being in its first orbitally excited state. Accordingly, the flavor-spin coupling symmetry should be $[4]_{FS}$, $[31]_{FS}$, $[22]_{FS}$, or $[211]_{FS}$, while one can easily get that the latter two do not couple to the three-quark components of the decuplet baryons whose flavor-spin state are the totally symmetric $[3]_{FS}$.

Therefore, the corresponding flavor symmetry of the four-quark subsystem can be $[4]_F$, $[31]_F$, $[22]_F$, or $[211]_F$, and spin symmetry can be $[4]_S$, $[31]_S$, and $[22]_S$, while for the sake of the flavor and spin symmetry for the three-quark of decuplet baryons being the totally symmetric ones $[3]_F$ and $[3]_S$, respectively, only the flavor symmetry $[4]_F$ and $[31]_F$ and the spin symmetry $[4]_S$ and $[31]_S$ could contribute. The corresponding obtained different orbital-flavor-spin configurations of the four-quark subsystem are shown in Table I, where the two flavor symmetries $[31]_{F_1}$ and $[31]_{F_2}$ denote the two flavor states for the configurations with only

TABLE I. The orbital-flavor-spin configurations for five-quark configurations that may exist as higher Fock components in ground decuplet baryons.

i_5	1	2	3	4	5
Config.	$[31]_\chi[4]_{FS}[4]_F[4]_S$	$[31]_\chi[31]_{FS}[31]_{F_1}[4]_S$	$[31]_\chi[31]_{FS}[31]_{F_2}[4]_S$	$[4]_\chi[31]_{FS}[31]_{F_1}[4]_S$	$[4]_\chi[31]_{FS}[31]_{F_2}[4]_S$
i_5	6	7	8	9	10
Config.	$[31]_\chi[4]_{FS}[31]_{F_1}[31]_S$	$[31]_\chi[4]_{FS}[31]_{F_2}[31]_S$	$[31]_\chi[31]_{FS}[31]_{F_1}[31]_S$	$[31]_\chi[31]_{FS}[31]_{F_2}[31]_S$	$[31]_\chi[31]_{FS}[4]_F[31]_S$
i_5	11	12	13		
Config.	$[4]_\chi[31]_{FS}[4]_F[31]_S$	$[4]_\chi[31]_{FS}[31]_{F_1}[31]_S$	$[4]_\chi[31]_{FS}[31]_{F_2}[31]_S$		

two quarks being the same flavor, those have been shown explicitly in Refs. [20,31].

The configurations in Table I can be categorized into two groups by the spin symmetry of the four-quark subsystems, namely, $i_5 = 1$–5 for $[4]_S$, and $i_5 = 6$–13 for $[31]_S$. The spin symmetry $[4]_S$ leads to total spin $S = 2$ for the four-quark subsystem, combining the inner quark orbital angular momentum with $n_l = 1$ of the five-quark system, it would result in the angular momentum $J = 1$, 2, and 3, while the total spin of $[31]_S$ is $S = 1$, which leads to the angular momentum $J = 0$, 1, and 2. To form the total spin 3/2 of the decuplet baryons, only $J = 1$ and 2 can contribute since the spin of the antiquark is 1/2. accordingly, hereafter we denote the cases of $J = 1$ and 2 by Sets I and II, respectively.

For instance, for the pentaquark configurations $i_5 = 1$–3, those with one quark being in its first orbitally excited state, the total angular momentum of the four-quark subsystem can be $J = 1$ and $J = 2$, the general wave function of these pentaquark configurations for the two different cases can be written as

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

and

$$|B,3/2\rangle^{\rm II}_{5q} = \sum_{ijkln}\sum_{ab}\sum_{J_z\bar{s}_z}\sum_{ms_z} C^{\frac{3}{2},\frac{3}{2}}_{2,J_z;\frac{1}{2},\bar{s}_z} C^{2,J_z}_{1,m;2,s_z} C^{[1^4]}_{[31]^k_{\chi FS};[211]^{\bar{k}}_C} C^{[31]^k_{\chi FS}}_{[O]^i_\chi;[FS]^j_{FS}} C^{[FS]^j_{FS}}_{[F]^l_F;[4]^n_S} C^{[2^3]_C}_{a,b} \left|[211]^{\bar{k}}_C(a)\right\rangle \times |[11]_{C,\bar{q}}(b)\rangle |I,I_3\rangle^{[F]^l_F} |1,m\rangle^{[O]^\chi_i} \left|[4]^n_S,s_z\right\rangle |\bar{\chi},\bar{s}_z\rangle \phi(\{\vec{r}_q\}), \tag{6}$$

respectively. The wave functions of all other configurations for Sets I and II can be obtained similarly.

B. The probability amplitudes of the pentaquark components

The other key ingredient in the wave function (1) is the probability amplitudes of the pentaquark components. As discussed in Sec. II A, we take the inner radial and orbital quantum numbers of the pentaquark components to be $n_r = 0$ and $n_l = 1$ in the present work, so hereafter we denote the corresponding coefficient as $\mathcal{C}^q_{i_5,n_r,n_l} \equiv \mathcal{C}^q_{i_5}$.

To determine $\mathcal{C}^q_{i_5}$ in a given baryon state explicitly, one has to evaluate the energy of corresponding pentaquark state, and its coupling to the three-quark component of the baryon, since $\mathcal{C}^q_{i_5}$ can be calculated by

$$\mathcal{C}^q_{i_5} = \frac{\langle qqq(q\bar{q}), i_5|\hat{T}|qqq\rangle}{M_B - E^q_{i_5}}, \tag{7}$$

where M_B is the physical mass of the baryon. The decuplet baryons' masses are taken to be the empirical values [40]

$$M_\Delta = 1232\,\text{MeV}, \quad M_{\Sigma^*} = 1385\,\text{MeV}, \quad M_{\Xi^*} = 1530\,\text{MeV}, \quad M_{\Omega^-} = 1672\,\text{MeV}. \tag{8}$$

In this work we employ the EχCQM developed in Ref. [31], in which the chiral constituent quark model [2] is applied to calculate the energy of the pentaquark state, and the widely used $^3P_0$ mechanism proposed in Refs. [41,42] is taken to estimate the transition coupling between the three- and five-quark components. The EχCQM has been given explicitly in Ref. [31], for completeness, here, we briefly introduce it.

In the chiral constituent quark model, the contact hyperfine interaction between quarks in a baryon, that leads to the mass splitting of the baryon states with the same quark content and inner radial and orbital quantum numbers but different flavor-color-spin configurations, is assumed to be via the goldstone-boson-exchange, which can be expressed as [2]

$$H_{\rm hyp} = -\sum_{i<j}\delta(r_{ij})\vec{\sigma}_i\cdot\vec{\sigma}_j\left[\sum_{a=1}^{3}V_\pi(r_{ij})\lambda^a_i\lambda^a_j + \sum_{a=4}^{7}V_K(r_{ij})\lambda^a_i\lambda^a_j + V_\eta(r_{ij})\lambda^8_i\lambda^8_j\right], \tag{9}$$

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 an M meson. Concerning the η-meson exchange, which should involve the light quark-antiquark pair exchange, and the strange quark-antiquark pair exchange. Since the coupling strength for meson exchange interactions in the chiral constituent quark model depends on the constituent quark masses, one may treat the former one as the same as π-meson exchange, namely,

$$V_{u\bar{u}}(r_{ij}) \equiv V_{d\bar{d}}(r_{ij}) \equiv V_\pi(r_{ij}), \tag{10}$$

and leave the latter one just as $V_{s\bar{s}}(r_{ij})$.

Correspondingly, matrix elements of $H_{\rm hyp}$ in the pentaquark configurations listed in Table I can be calculated as follows:

$$\begin{aligned}\langle H_{\rm hyp}\rangle^q_{i_5} &= \langle qqq(q\bar{q}), i_5|H_{\rm hyp}|qqq(q\bar{q}), i_5\rangle \\ &= -6\sum_{njklm}\Bigg[\left(C^{[1^4]}_{[31]^n_i[211]_n}\right)^2 C^{[31]^n_i}_{[FS]^j_i[\chi]^l_i} C^{[31]^k_i}_{[FS]^j_i[\chi]^m_i}\times\Bigg(\big\langle[\chi]^l_i\big|V_\pi(r_{12})\big|[\chi]^m_i\big\rangle\big\langle[FS]^j_i\big|\vec{\sigma}_1\cdot\vec{\sigma}_2\sum_{a=1}^{3}\lambda^a_1\lambda^a_2\big|[FS]^k_i\big\rangle \\ &\quad+\big\langle[\chi]^l_i\big|V_K(r_{12})\big|[\chi]^m_i\big\rangle\big\langle[FS]^j_i\big|\vec{\sigma}_1\cdot\vec{\sigma}_2\sum_{a=4}^{7}\lambda^a_1\lambda^a_2\big|[FS]^k_i\big\rangle+\big\langle[\chi]^l_i\big|V_\eta(r_{12})\big|[\chi]^m_i\big\rangle\big\langle[FS]^j_i\big|\vec{\sigma}_1\cdot\vec{\sigma}_2\lambda^8_1\lambda^8_2\big|[FS]^k_i\big\rangle\Bigg)\Bigg].\end{aligned} \tag{11}$$

Calculations on the matrix elements $\langle[\chi]^l_i|V_M(r_{12})|[\chi]^m_i\rangle$ in Eq. (11) will lead to the following common factors:

$$P^M_{n_l} = \langle n_l m|\delta(r_{ij})V_M(r_{ij})|n_l m\rangle \tag{12}$$

with $|n_l m\rangle$ being the spatial wave function with orbital quantum number n_l. Here, we just take the empirical values for $P^M_{n_l}$ that could very well reproduce the spectroscopy of light and strange baryons [2]:

$$\begin{aligned}P^\pi_0 &= 29\,\text{MeV}, \quad P^K_0 = 20\,\text{MeV}, \quad P^{s\bar{s}}_0 = 14\,\text{MeV},\\ P^\pi_1 &= 45\,\text{MeV}, \quad P^K_1 = 30\,\text{MeV}, \quad P^{s\bar{s}}_1 = 20\,\text{MeV}.\end{aligned} \tag{13}$$

Then the energy $E^q_{i_5}$ for the five-quark configurations listed in Table I can be calculated by

$$E^q_{i_5} = E_0 + \langle H_{\rm hyp}\rangle^q_{i_5} + n^s_{i_5}\delta m, \tag{14}$$

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 δ_m and $n^s_{i_5}$ denote the constituent 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 δ_m are taken to be the empirical values [31]

$$E_0 = 2127\,\text{MeV}, \quad \delta_m = 120\,\text{MeV}, \tag{15}$$

and hereafter we use the following definition:

$$\Delta E^q_{i_5} = \langle H_{\rm hyp}\rangle^q_{i_5} + n^s_{i_5}\delta m. \tag{16}$$

Finally, the $^3P_0$ version of the transition coupling operator $\hat{T}$ in Eq. (7), as depicted in Fig. 1, can be written as [31]

$$\begin{aligned}\hat{T} = -\gamma\sum_{j=1,4}\mathcal{F}^{00}_{j,5}\mathcal{C}^{00}_{j,5}\mathcal{C}_{OFSC}\sum_m\langle 1,m;1,-m|00\rangle\\ \times\chi^{1,m}_{j,5}\mathcal{Y}^{1,-m}_{j,5}(\vec{p}_j-\vec{p}_5)b^\dagger(\vec{p}_j)d^\dagger(\vec{p}_5),\end{aligned} \tag{17}$$

where γ 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 $\mathcal{C}_{OFSC}$ is to calculate the overlap factor between the residual three-quark configuration in the five-quark component and the valence three-quark component, finally, $b^\dagger(\vec{p}_j)$, $d^\dagger(\vec{p}_5)$ are the quark and antiquark creation operators.

Similar to the case of calculations on the sea content of the octet baryons in Ref. [31], explicit calculations on the transition matrix elements $\langle qqq(q\bar{q}), i_5|\hat{T}|qqq\rangle$ between all the five-quark configurations shown in Table I and the qqq components in the presently studied decuplet baryons will result in a common factor $\mathcal{V}$, namely,

$$\langle qqq(q\bar{q}), i_{5q}|\hat{T}|qqq\rangle = \mathcal{T}^q_{i_5}\mathcal{V}. \tag{18}$$

The coefficient $\mathcal{T}^q_{i_5}$ is determined by the explicit color-orbital-flavor-spin symmetry of the corresponding five-quark configuration, and $\mathcal{V}$ depends on the $^3P_0$ transition coupling constant γ and parameters of explicit spatial wave functions determined by a given quark confinement potential. It is shown that if the quantity $\mathcal{V}$ is taken to be 570 ± 46 MeV or 697 ± 80 MeV, the latest data for the sea flavor asymmetry in proton that $\bar{d} - \bar{u} = 0.118 \pm 0.012$ can be well reproduced [37], so here, we just tentatively take these two values.

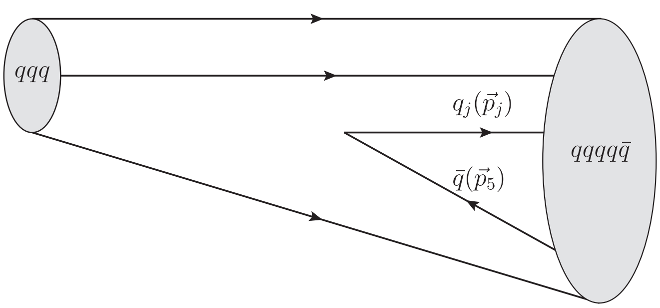

FIG. 1. Transition of $qqq \to qqqq\bar{q}$ caused by a quark-antiquark pair creation in a baryon via the $^3P_0$ mechanism.

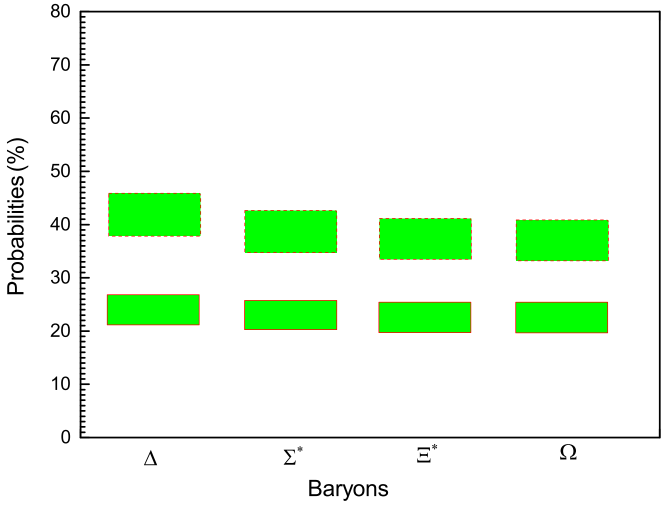

FIG. 2. Total probabilities of the pentaquark components in the decuplet baryons obtained by taking $\mathcal{V}$ to be 570 ± 46 MeV, the rectangles with solid and dashed borders are numerical results for Sets I and II, respectively, and the heights of the rectangles represent the uncertainties.

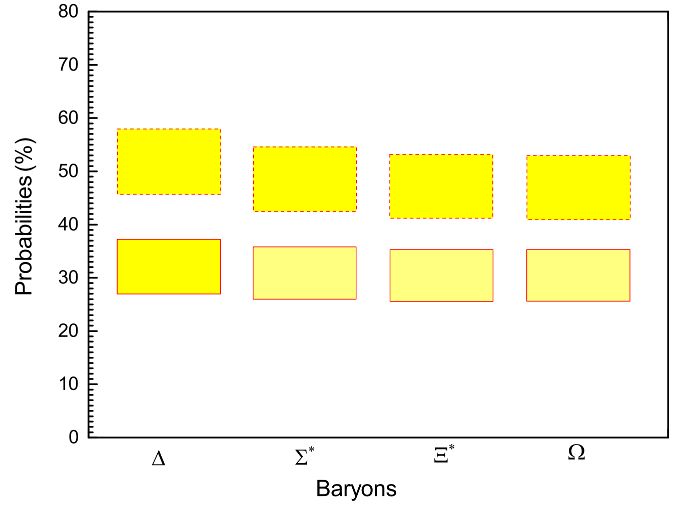

FIG. 3. Total probabilities of the pentaquark components in the decuplet baryons obtained by taking $\mathcal{V}$ to be 697 ± 80 MeV, conventions are the same as in Fig. 2.

Straightforwardly, explicit calculations of the matrix elements Eqs. (11) and (18) using the wave functions in Set I lead to the results shown in Tables IV and V.

For the wave functions in Set II, the obtained energies $\Delta E_{i_5}^{q}$ are all the same as shown in these two tables since the orbital-spin interactions are not considered in the present work, while the transition coupling matrix elements have the following relations:

$$\left(\mathcal{T}_{i_5}^{q}\right)_{\rm II} = -\left(\mathcal{T}_{i_5}^{q}\right)_{\rm I}, \quad i_5 = 1\text{–}5, \tag{19}$$

$$\left(\mathcal{T}_{i_5}^{q}\right)_{\rm II} = -\sqrt{5}\left(\mathcal{T}_{i_5}^{q}\right)_{\rm I}, \quad i_5 = 6\text{–}13, \tag{20}$$

for the pentaquark configurations with four-quark spin symmetry $[4]_S$ and $[31]_S$, respectively. Therefore, one can expect that the Set II wave functions will lead to larger probabilities of the pentaquark components in the decuplet baryons.

III. NUMERICAL RESULTS AND DISCUSSIONS

A. The total probabilities of the pentaquark components in the decuplet baryons

As discussed in Sec. II, the parameters in the present employed EχCQM are: the six meson-exchange coupling strength $P_{n_l}^{M}$, the degenerated energy E_0, the difference between the constituent masses of light and strange quarks δm, and $\mathcal{V}$ in the transition coupling between the three- and five-quark components. Note that all these above model parameters have been fixed by various of experimental data.

With the matrix elements obtained in Tables IV and V, and empirical values for all the model parameters, we get the numerical results for total probabilities of the pentaquark components in the decuplet baryons shown in Figs. 2 and 3, by taking the parameter $\mathcal{V}$ to be 570 ± 46 MeV and 697 ± 80 MeV, respectively.

As we can see in Figs. 2 and 3, if one takes the same set of wave functions for the pentaquark components and the same value for $\mathcal{V}$, the obtained total probabilities $\mathcal{P}_5^B$ of the pentaquark components in Δ, Σ^*, Ξ^*, and Ω will be very close to each other, and $\mathcal{P}_5^B$ decreases with an increasing of the strangeness number of the baryon, this is very similar to the case of the octet baryons [38].

As shown in Fig. 2, taking $\mathcal{V} = 570 \pm 46$ MeV, and using the wave functions of Set I, one can get the central value $\mathcal{P}_5^B \approx 25\%$, which is about 10% lower than that for the octet baryons obtained in Refs. [31,38]. While the wave functions of Set II lead to the central value $\mathcal{P}_5^B \approx 40\%$, which is a little higher than that for the octet baryons. If one expects that the probabilities for pentaquark components in decuplet baryons are higher than those in octet baryons, then Set II wave functions will be more preferable.

Figure 3 shows similar results to Fig. 2, the wave functions of Set II result in larger $\mathcal{P}_5^B$ than those of Set I, this is in line with our expectations, as discussed in Sec. II B. Explicitly, the corresponding central values for $\mathcal{P}_5^B$ are ~30% and ~50% for Sets I and II, respectively, the former is still lower than $\mathcal{P}_5^B$ in the octet baryons, and the latter is comparable to the total probabilities of the pentaquark components in nucleon obtained by taking $\mathcal{V} = 697 \pm 80$ MeV.

B. Sea-quark flavor content in the decuplet baryons

Explicitly, it is very interesting to discuss the sea-quark flavor content in the decuplet baryons. Here, we show the numerical results of the probabilities for intrinsic sea contents $\bar{u}$, $\bar{d}$, and $\bar{s}$, and the sea flavor asymmetry $\bar{d} - \bar{u}$ and $\bar{u} + \bar{d} - 2\bar{s}$ obtained by taking $\mathcal{V} = 570 \pm 46$ MeV in Table II, and those obtained by taking $\mathcal{V} = 697 \pm 80$ MeV in Table III, respectively.

As shown in Tables II and III, probabilities for the $\bar{s}$ quark $\mathcal{P}_{\bar{s}}^B$ are smaller than those for the light antiquarks, this is because the pentaquark components with strange

TABLE II. Probabilities of sea content in the decuplet baryons with the model parameter $\mathcal{V} = 570 \pm 46$ MeV.

		Δ^{++}	Δ^{+}	Σ^{*+}	Σ^{*0}	Ξ^{*0}	Ω^{-}
Set I	$\bar{u}$	0.070 ± 0.009	0.087 ± 0.011	0.079 ± 0.010	0.092 ± 0.011	0.087 ± 0.011	0.095 ± 0.012
	$\bar{d}$	0.120 ± 0.015	0.103 ± 0.013	0.105 ± 0.013	0.092 ± 0.011	0.098 ± 0.012	0.095 ± 0.012
	$\bar{s}$	0.050 ± 0.006	0.050 ± 0.006	0.046 ± 0.006	0.046 ± 0.006	0.041 ± 0.005	0.036 ± 0.004
	$\bar{d} - \bar{u}$	0.049 ± 0.017	0.016 ± 0.017	0.025 ± 0.016	0	0.011 ± 0.016	0
	$\bar{u} + \bar{d} - 2\bar{s}$	0.090 ± 0.019	0.090 ± 0.019	0.092 ± 0.018	0.092 ± 0.018	0.103 ± 0.018	0.117 ± 0.018
Set II	$\bar{u}$	0.088 ± 0.008	0.146 ± 0.014	0.115 ± 0.012	0.160 ± 0.016	0.137 ± 0.014	0.156 ± 0.016
	$\bar{d}$	0.262 ± 0.025	0.204 ± 0.020	0.204 ± 0.021	0.160 ± 0.016	0.173 ± 0.018	0.156 ± 0.016
	$\bar{s}$	0.069 ± 0.007	0.069 ± 0.007	0.068 ± 0.007	0.068 ± 0.007	0.064 ± 0.007	0.059 ± 0.006
	$\bar{d} - \bar{u}$	0.175 ± 0.026	0.058 ± 0.024	0.090 ± 0.024	0	0.036 ± 0.023	0
	$\bar{u} + \bar{d} - 2\bar{s}$	0.211 ± 0.028	0.211 ± 0.026	0.184 ± 0.026	0.184 ± 0.025	0.182 ± 0.025	0.194 ± 0.024

quark-antiquark pairs should be several hundreds heavier than those with light quark-antiquark pairs. In addition, in Δ and Σ^* baryons, the transition coupling matrix elements between the strangeness components and the three-quark components are smaller than those for the pentaquark with light quark-antiquark pairs, as one can see in Tables IV and V, so the sea flavor asymmetry $\bar{u} + \bar{d} - 2\bar{s}$ in all the decuplet baryons are positive. And $\mathcal{P}^B_{\bar{s}}$ decreases with the increasing strangeness number of the baryons.

In addition, if one expects that $\mathcal{P}_5$ in decuplet baryons are larger than those in the octet baryons, namely, wave functions of Set II are preferable, then the antiquark sea flavor asymmetry $\bar{d} - \bar{u}$ in the Δ^{++} baryon will be in the range 0.15–0.26, while in any case, the presently obtained $\bar{d} - \bar{u}$ in the Δ^{+} baryon should be smaller than that in the proton, which takes the value 0.118 ± 0.012 [32,37]. For the sake of the $SU(2)$ isospin symmetry, values of the sea flavor asymmetry $\bar{d} - \bar{u}$ in Σ^{*0} and Ω^{-} hyperons are exactly zero.

In Ref. [43], sea contents in the decuplet baryons are studied employing the chiral constituent quark model in which the Goldstone bosons (GB) couple directly to the constituent quarks as

$$q^{\pm} \rightarrow GB + q'^{\mp} \rightarrow (q\bar{q}') + q'^{\mp}, \tag{21}$$

where $q\bar{q}' + q'$ constitutes the quark sea. The numerical results for the probability of $\bar{d}$ in Δ^{++} is 0.352, which is consistent with the presently obtained value using wave functions of Set II, and taking $\mathcal{V} = 697 \pm 80$ MeV, while the probabilities for $\bar{u}$ and $\bar{s}$ in [43] are larger than the presently obtained ones.

On the other hand, contributions of the sea contents to the spin of decuplet baryons and Dalitz decays of decuplet to octet baryons are investigated in Refs. [44,45], respectively, both of which show the importance of the sea contents in the decuplet baryons.

IV. SUMMARY

To summarize, we investigate the sea contents in the ground state decuplet baryons, employing the extended chiral constituent quark model, in which the hyperfine interactions between quarks are assumed to be via the GB exchange, and the $^3P_0$ mechanism is taken to study the transition couplings between the three- and five-quark components in a given baryon. All the model parameters are taken to be the empirical values, with the spectrum of baryon resonances below 2 GeV, and the sea flavor asymmetry $\bar{d} - \bar{u}$ in the proton could be well reproduced.

We present the numerical results for probabilities of the pentaquark components and the sea quark flavor contents $\bar{u}$, $\bar{d}$, and $\bar{s}$ in the decuplet baryons. It is shown that the total probabilities $\mathcal{P}^B_5$ of the pentaquark components in the decuplet baryons are close to each other, while $\mathcal{P}^B_5$ decreases with an increasing of strangeness number of the baryon. If one expects the probabilities of the pentaquark components to be larger than those in the octet baryons, namely, the wave functions in

TABLE III. Probabilities of sea content in the decuplet baryons, with the model parameter $\mathcal{V} = 697 \pm 80$ MeV.

		Δ^{++}	Δ^{+}	Σ^{*+}	Σ^{*0}	Ξ^{*0}	Ω^{-}
Set I	$\bar{u}$	0.094 ± 0.015	0.116 ± 0.018	0.107 ± 0.017	0.124 ± 0.020	0.117 ± 0.019	0.128 ± 0.021
	$\bar{d}$	0.160 ± 0.025	0.138 ± 0.022	0.141 ± 0.023	0.124 ± 0.020	0.131 ± 0.021	0.128 ± 0.021
	$\bar{s}$	0.067 ± 0.011	0.067 ± 0.011	0.062 ± 0.010	0.062 ± 0.010	0.055 ± 0.009	0.049 ± 0.008
	$\bar{d} - \bar{u}$	0.066 ± 0.029	0.022 ± 0.028	0.034 ± 0.029	0	0.014 ± 0.028	0
	$\bar{u} + \bar{d} - 2\bar{s}$	0.120 ± 0.033	0.120 ± 0.032	0.124 ± 0.032	0.124 ± 0.032	0.138 ± 0.031	0.158 ± 0.032
Set II	$\bar{u}$	0.108 ± 0.013	0.180 ± 0.021	0.144 ± 0.018	0.200 ± 0.025	0.173 ± 0.022	0.197 ± 0.025
	$\bar{d}$	0.325 ± 0.038	0.253 ± 0.030	0.257 ± 0.032	0.200 ± 0.025	0.218 ± 0.028	0.197 ± 0.025
	$\bar{s}$	0.086 ± 0.010	0.086 ± 0.010	0.085 ± 0.011	0.085 ± 0.011	0.080 ± 0.010	0.074 ± 0.010
	$\bar{d} - \bar{u}$	0.216 ± 0.040	0.072 ± 0.037	0.113 ± 0.037	0	0.045 ± 0.036	0
	$\bar{u} + \bar{d} - 2\bar{s}$	0.262 ± 0.043	0.262 ± 0.039	0.230 ± 0.040	0.230 ± 0.039	0.230 ± 0.038	0.245 ± 0.038

TABLE IV. Matrix elements $\mathcal{T}_{i_5}^{q}$ and $\Delta E_{i_5}^{q}$ for the pentaquark configurations with $q\bar{q} = u\bar{u}$ and $d\bar{d}$ using the wave functions in Set I. For each configuration with number i_5, the first row is the coupling $\mathcal{T}_{i_5}^{q}$, and the second row is ΔE_{i_5}.

i_5	Δ	Σ^*	Ξ^*	Ω^-
1	$\frac{5\sqrt{6}}{36}$	$\frac{\sqrt{30}}{18}$	$\frac{\sqrt{10}}{12}$	$\frac{\sqrt{15}}{18}$
	$-\frac{1}{3}(16P_0^\pi + 8P_1^\pi)$	$\delta m - \frac{1}{3}(8P_0^\pi + 4P_1^\pi + 8P_0^K + 4P_1^K)$	$2\delta m - \frac{1}{9}(8P_0^\pi + 4P_1^\pi + 32P_0^K + 16P_1^K + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	$3\delta m - \frac{1}{3}(8P_0^K + 4P_1^K + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$
2	$-\frac{\sqrt{15}}{18}$	$-\frac{\sqrt{15}}{27}$	$-\frac{\sqrt{15}}{18}$	$-\frac{\sqrt{30}}{18}$
	$-\frac{1}{3}(4P_0^\pi - 4P_1^\pi)$	$\delta m - \frac{1}{27}(82P_0^\pi + 26P_1^\pi - 46P_0^K - 62P_1^K)$	$2\delta m - \frac{1}{27}(26P_0^\pi + 10P_1^\pi - 16P_0^K - 56P_1^K + 26P_0^{s\bar{s}} + 10P_1^{s\bar{s}})$	$3\delta m + \frac{1}{27}(46P_0^K + 62P_1^K - 82P_0^{s\bar{s}} - 26P_1^{s\bar{s}})$
3	0	$-\frac{\sqrt{30}}{27}$	$-\frac{\sqrt{10}}{18}$	0
	–	$\delta m + \frac{1}{27}(14P_0^\pi + 40P_1^\pi - 50P_0^K - 4P_1^K)$	$2\delta m + \frac{1}{27}(36P_0^\pi + 36P_1^\pi - 44P_0^K + 8P_1^K - 28P_0^{s\bar{s}} - 8P_1^{s\bar{s}})$	–
4	$\frac{5\sqrt{6}}{36}$	$\frac{5\sqrt{6}}{54}$	$\frac{5\sqrt{6}}{36}$	$\frac{5\sqrt{3}}{18}$
	0	$\delta m - 4P_0^\pi + 4P_0^K$	$2\delta m - \frac{1}{3}(4P_0^\pi - 8P_0^K + 4P_0^{s\bar{s}})$	$3\delta m + 4P_0^K - 4P_0^{s\bar{s}}$
5	0	$\frac{5\sqrt{3}}{27}$	$\frac{5}{18}$	0
	–	$\delta m + 2P_0^\pi - 2P_0^K$	$2\delta m + \frac{1}{3}(8P_0^\pi - 4P_0^K - 4P_0^{s\bar{s}})$	–
6	$\frac{\sqrt{6}}{36}$	$\frac{\sqrt{6}}{54}$	$\frac{\sqrt{6}}{36}$	$\frac{\sqrt{3}}{18}$
	$-\frac{1}{9}(128P_0^\pi + 64P_1^\pi)$	$\delta m - \frac{1}{9}(24P_0^\pi + 12P_1^\pi + 104P_0^K + 52P_1^K)$	$2\delta m - \frac{1}{9}(8P_0^\pi + 4P_1^\pi + 112P_0^K + 56P_1^K + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	$3\delta m - \frac{1}{9}(104P_0^K + 52P_1^K + 24P_0^{s\bar{s}} + 12P_1^{s\bar{s}})$
7	0	$\frac{\sqrt{3}}{27}$	$\frac{1}{18}$	0
	–	$\delta m - \frac{1}{9}(84P_0^\pi + 42P_1^\pi + 44P_0^K + 22P_1^K)$	$2\delta m - \frac{1}{9}(48P_0^\pi + 24P_1^\pi + 72P_0^K + 36P_1^K + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	–
8	$\frac{\sqrt{2}}{18}$	$\frac{\sqrt{2}}{27}$	$\frac{\sqrt{2}}{18}$	$\frac{1}{9}$
	$-\frac{1}{27}(148P_0^\pi - 4P_1^\pi)$	$\delta m - \frac{1}{81}(71P_0^\pi - 59P_1^\pi + 373P_0^K + 47P_1^K)$	$2\delta m - \frac{1}{81}(13P_0^\pi - 25P_1^\pi + 418P_0^K + 38P_1^K + 13P_0^{s\bar{s}} - 25P_1^{s\bar{s}})$	$3\delta m - \frac{1}{81}(373P_0^K + 47P_1^K + 71P_0^{s\bar{s}} - 59P_1^{s\bar{s}})$
9	0	$\frac{2}{27}$	$\frac{\sqrt{3}}{27}$	0
	–	$\delta m - \frac{1}{162}(595P_0^\pi + 41P_1^\pi + 293P_0^K - 65P_1^K)$	$2\delta m - \frac{1}{81}(180P_0^\pi + 36P_1^\pi + 235P_0^K - 31P_1^K + 29P_0^{s\bar{s}} - 17P_1^{s\bar{s}})$	–
10	$-\frac{\sqrt{5}}{18}$	$-\frac{1}{9}$	$-\frac{\sqrt{3}}{18}$	$-\frac{\sqrt{2}}{18}$
	$\frac{8}{3}P_1^\pi$	$\delta m + \frac{1}{3}(4P_1^\pi + 4P_1^K)$	$2\delta m + \frac{1}{9}(4P_1^\pi + 16P_1^K + 4P_1^{s\bar{s}})$	$3\delta m + \frac{1}{3}(4P_1^K + 4P_1^{s\bar{s}})$
11	$\frac{5\sqrt{2}}{36}$	$\frac{\sqrt{10}}{18}$	$\frac{\sqrt{30}}{36}$	$\frac{\sqrt{5}}{18}$
	$\frac{8}{3}P_0^\pi$	$\delta m + \frac{1}{3}(4P_0^\pi + 4P_0^K)$	$2\delta m + \frac{1}{9}(4P_0^\pi + 16P_0^K + 4P_0^{s\bar{s}})$	$3\delta m + \frac{1}{3}(4P_0^K + 4P_0^{s\bar{s}})$
12	$-\frac{\sqrt{5}}{18}$	$-\frac{\sqrt{5}}{27}$	$-\frac{\sqrt{5}}{18}$	$-\frac{\sqrt{10}}{18}$
	$-\frac{16}{3}P_0^\pi$	$\delta m - \frac{1}{27}(4P_0^\pi + 140P_0^K)$	$2\delta m + \frac{1}{27}(4P_0^\pi - 152P_0^K + 4P_0^{s\bar{s}})$	$3\delta m - \frac{1}{27}(140P_0^K + 4P_0^{s\bar{s}})$
13	0	$-\frac{\sqrt{10}}{27}$	$-\frac{\sqrt{30}}{54}$	0
	–	$\delta m - \frac{1}{27}(106P_0^\pi + 38P_0^K)$	$2\delta m - \frac{1}{27}(72P_0^\pi + 68P_0^K + 4P_0^{s\bar{s}})$	–

TABLE V. Matrix elements $\mathcal{T}_{i_5}^{q}$ and $\Delta E_{i_5}^{q}$ for the pentaquark configurations with $q\bar{q} = s\bar{s}$ using the wave functions in Set I. Conventions are the same as those in Table IV.

i	Δ	Σ^*	Ξ^*	Ω^-
1	$\frac{\sqrt{30}}{36}$	$\frac{\sqrt{15}}{18}$	$\frac{\sqrt{10}}{12}$	$\frac{\sqrt{30}}{18}$
	$2\delta m - \frac{1}{3}(8P_0^{\pi} + 4P_1^{\pi} + 8P_0^{K} + 4P_1^{K})$	$3\delta m - \frac{1}{9}(8P_0^{\pi} + 4P_1^{\pi} + 32P_0^{K} + 16P_1^{K} + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	$4\delta m - \frac{1}{3}(8P_0^{K} + 4P_1^{K} + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	$5\delta m - \frac{1}{3}(16P_0^{s\bar{s}} + 8P_1^{s\bar{s}})$
2	$\frac{\sqrt{15}}{18}$	$\frac{\sqrt{10}}{18}$	$\frac{\sqrt{5}}{18}$	0
	$2\delta m - \frac{1}{27}(82P_0^{\pi} + 26P_1^{\pi} - 46P_0^{K} - 62P_1^{K})$	$3\delta m - \frac{1}{27}(26P_0^{\pi} + 10P_1^{\pi} - 16P_0^{K} - 56P_1^{K} + 26P_0^{s\bar{s}} + 10P_1^{s\bar{s}})$	$4\delta m + \frac{1}{27}(46P_0^{K} + 62P_1^{K} - 82P_0^{s\bar{s}} - 26P_1^{s\bar{s}})$	–
3	0	0	0	0
	–	–	–	–
4	$-\frac{5\sqrt{6}}{36}$	$-\frac{5}{18}$	$-\frac{5\sqrt{2}}{36}$	0
	$2\delta m - 4P_0^{\pi} + 4P_0^{K}$	$3\delta m - \frac{1}{3}(4P_0^{\pi} - 8P_0^{K} + 4P_0^{s\bar{s}})$	$4\delta m + 4P_0^{K} - 4P_0^{s\bar{s}}$	–
5	0	0	0	0
	–	–	–	–
6	$-\frac{\sqrt{6}}{36}$	$-\frac{1}{18}$	$-\frac{\sqrt{2}}{36}$	0
	$2\delta m - \frac{1}{9}(24P_0^{\pi} + 12P_1^{\pi} + 104P_0^{K} + 52P_1^{K})$	$3\delta m - \frac{1}{9}(8P_0^{\pi} + 4P_1^{\pi} + 112P_0^{K} + 56P_1^{K} + 8P_0^{s\bar{s}} + 4P_1^{s\bar{s}})$	$4\delta m - \frac{1}{9}(104P_0^{K} + 52P_1^{K} + 24P_0^{s\bar{s}} + 12P_1^{s\bar{s}})$	–
7	0	0	0	0
	–	–	–	–
8	$-\frac{\sqrt{2}}{18}$	$-\frac{\sqrt{3}}{27}$	$-\frac{\sqrt{6}}{54}$	0
	$2\delta m - \frac{1}{81}(71P_0^{\pi} - 59P_1^{\pi} + 373P_0^{K} + 47P_1^{K})$	$3\delta m - \frac{1}{81}(13P_0^{\pi} - 25P_1^{\pi} + 418P_0^{K} + 38P_1^{K} + 13P_0^{s\bar{s}} - 25P_1^{s\bar{s}})$	$4\delta m - \frac{1}{81}(373P_0^{K} + 47P_1^{K} + 71P_0^{s\bar{s}} - 59P_1^{s\bar{s}})$	
9	0	0	0	0
	–	–	–	–
10	$-\frac{1}{18}$	$-\frac{\sqrt{2}}{18}$	$-\frac{\sqrt{3}}{18}$	$-\frac{1}{9}$
	$2\delta m + \frac{1}{3}(4P_1^{\pi} + 4P_1^{K})$	$3\delta m + \frac{1}{9}(4P_1^{\pi} + 16P_1^{K} + 4P_1^{s\bar{s}})$	$4\delta m + \frac{1}{3}(4P_1^{K} + 4P_1^{s\bar{s}})$	$5\delta m + \frac{8}{3}P_1^{s\bar{s}}$
11	$\frac{\sqrt{10}}{36}$	$\frac{\sqrt{5}}{18}$	$\frac{\sqrt{30}}{36}$	$\frac{\sqrt{10}}{18}$
	$2\delta m + \frac{1}{3}(4P_0^{\pi} + 4P_0^{K})$	$3\delta m + \frac{1}{9}(4P_0^{\pi} + 16P_0^{K} + 4P_0^{s\bar{s}})$	$4\delta m + \frac{1}{3}(4P_0^{K} + 4P_0^{s\bar{s}})$	$5\delta m + \frac{8}{3}P_0^{s\bar{s}}$
12	$\frac{\sqrt{5}}{18}$	$\frac{\sqrt{30}}{54}$	$\frac{\sqrt{15}}{54}$	0
	$2\delta m - \frac{1}{27}(4P_0^{\pi} + 140P_0^{K})$	$3\delta m + \frac{1}{27}(4P_0^{\pi} - 152P_0^{K} + 4P_0^{s\bar{s}})$	$4\delta m - \frac{1}{27}(140P_0^{K} + 4P_0^{s\bar{s}})$	–
13	0	0	0	0
	–	–	–	–

Set II are favored, then the sea flavor asymmetry $\bar{d} - \bar{u}$ in Δ^{++} will be 0.15–0.26, which is larger than that in the proton [32]. And the pentaquark components with strange quark-antiquark pairs take smaller probabilities than those with light quark-antiquark pairs.

Finally, there is no experimental data for the sea flavor content in the decuplet baryons available up to now, but it has been shown that the intrinsic sea content plays crucial roles in the structure and properties of the nucleon [46–52], one can expect that contributions of the sea content to properties of the other octet baryons and the decuplet baryons should be more significant. Therefore, we look forward to corresponding measurements in the future, which could certainly enrich our understanding of the structure of hadrons, and provide us more information on the origin of the intrinsic sea content in baryons.

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APPENDIX A: FLAVOR DECOMPOSITIONS OF FIVE-QUARK COMPONENTS IN THE DECUPLET BARYONS

In each five-quark configuration, $[v]_F$ is the flavor wave function of the four-quark subsystem, one can get the flavor wave function of the five-quark system by combining $[v]_F$ and antiquark flavor wave function $|\bar{q}\rangle$. Here, we give the explicit flavor decompositions for all the possible five-quark configurations in the decuplet baryons.

1. Δ baryons

For the Δ^{++} baryon, whose isospin wave function is $|\frac{3}{2},\frac{3}{2}\rangle_I$, the configurations with $[v]_F=[4]_F$, both the light and strange quark-antiquark pairs survive. Then the four-quark subsystem should couple with the antiquark as

$$\left|\frac{3}{2},\frac{3}{2}\right\rangle_I^{[4]_F} = \sqrt{\frac{4}{5}}\left|u^4_{[4]_F}\right\rangle\otimes|\bar{u}\rangle+\sqrt{\frac{1}{5}}\left|u^3d_{[4]_F}\right\rangle\otimes|\bar{d}\rangle, \quad \text{(A1)}$$

$$\left|\frac{3}{2},\frac{3}{2}\right\rangle_I^{[4]_F} = \left|u^3s_{[4]_F}\right\rangle\otimes|\bar{s}\rangle. \quad \text{(A2)}$$

For the configurations with $[v]_F=[31]_{F_1}$, the quark-antiquark pairs can be $d\bar{d}$ and $s\bar{s}$. And the corresponding isospin wave function of the Δ^{++} baryon is

$$\left|\frac{3}{2},\frac{3}{2}\right\rangle_I^{[31]_{F_1}} = -\left|u^3d_{[31]_{F_1}}\right\rangle\otimes|\bar{d}\rangle, \quad \text{(A3)}$$

$$\left|\frac{3}{2},\frac{3}{2}\right\rangle_I^{[31]_{F_1}} = \left|u^3s_{[31]_{F_1}}\right\rangle\otimes|\bar{s}\rangle. \quad \text{(A4)}$$

For the five-quark components in the Δ^+ baryon, the isospin wave function is $|\frac{3}{2},\frac{1}{2}\rangle_I$,

$$\left|\frac{3}{2},\frac{1}{2}\right\rangle_I^{[4]_F} = \sqrt{\frac{3}{5}}\left|u^3d_{[4]_F}\right\rangle\otimes|\bar{u}\rangle+\sqrt{\frac{2}{5}}\left|u^2d^2_{[4]_F}\right\rangle\otimes|\bar{d}\rangle, \quad \text{(A5)}$$

$$\left|\frac{3}{2},\frac{1}{2}\right\rangle_I^{[4]_F} = \left|u^2ds_{[4]_F}\right\rangle\otimes|\bar{s}\rangle. \quad \text{(A6)}$$

For the configurations with $[v]_F=[31]_{F_1}$, the quark-antiquark pairs can be $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$.

$$\left|\frac{3}{2},\frac{1}{2}\right\rangle_I^{[31]_{F_1}} = \sqrt{\frac{1}{3}}\left|u^3d_{[31]_{F_1}}\right\rangle\otimes|\bar{u}\rangle-\sqrt{\frac{2}{3}}\left|u^2d^2_{[31]_{F_1}}\right\rangle\otimes|\bar{d}\rangle, \quad \text{(A7)}$$

$$\left|\frac{3}{2},\frac{1}{2}\right\rangle_I^{[31]_{F_1}} = \left|u^2ds_{[31]_{F_1}}\right\rangle\otimes|\bar{s}\rangle. \quad \text{(A8)}$$

Considering the isospin $SU(2)$ symmetry, one can obtain the flavor decomposition

$$\left|\frac{3}{2},-\frac{1}{2}\right\rangle_I^{[4]_F} = \sqrt{\frac{2}{5}}\left|u^2d^2_{[4]_F}\right\rangle\otimes|\bar{u}\rangle+\sqrt{\frac{3}{5}}\left|ud^3_{[4]_F}\right\rangle\otimes|\bar{d}\rangle, \quad \text{(A9)}$$

$$\left|\frac{3}{2},-\frac{1}{2}\right\rangle_I^{[4]_F} = \left|ud^2s_{[4]_F}\right\rangle\otimes|\bar{s}\rangle, \quad \text{(A10)}$$

$$\left|\frac{3}{2},-\frac{1}{2}\right\rangle_I^{[31]_{F_1}} = \sqrt{\frac{2}{3}}\left|u^2d^2_{[31]_{F_1}}\right\rangle\otimes|\bar{u}\rangle-\sqrt{\frac{1}{3}}\left|ud^3_{[31]_{F_1}}\right\rangle\otimes|\bar{d}\rangle, \quad \text{(A11)}$$

$$\left|\frac{3}{2},-\frac{1}{2}\right\rangle_I^{[31]_{F_1}} = \left|ud^2s_{[31]_{F_1}}\right\rangle\otimes|\bar{s}\rangle, \quad \text{(A12)}$$

for the five-quark components in the Δ^0 baryon, and

$$\left|\frac{3}{2},-\frac{3}{2}\right\rangle_I^{[4]_F} = \sqrt{\frac{1}{5}}\left|ud^3_{[4]_F}\right\rangle\otimes|\bar{u}\rangle+\sqrt{\frac{4}{5}}\left|d^4_{[4]_F}\right\rangle\otimes|\bar{d}\rangle, \quad \text{(A13)}$$

$$\left|\frac{3}{2},-\frac{3}{2}\right\rangle_I^{[4]_F} = \left|d^3s_{[4]_F}\right\rangle\otimes|\bar{s}\rangle, \quad \text{(A14)}$$

$$\left|\frac{3}{2},-\frac{3}{2}\right\rangle_I^{[31]_{F_1}} = \left|ud^3_{[31]_{F_1}}\right\rangle\otimes|\bar{u}\rangle, \quad \text{(A15)}$$

$$\left|\frac{3}{2},-\frac{3}{2}\right\rangle_I^{[31]_{F_1}} = \left|d^3s_{[31]_{F_1}}\right\rangle\otimes|\bar{s}\rangle, \quad \text{(A16)}$$

for the five-quark components in the Δ^- baryon, respectively.

2. Σ* baryons

For the Σ^{*+} baryon, the isospin wave function is $|1,1\rangle_I$. In the five-quark configurations with $[v]_F=[4]_F$, both the light and strange quark-antiquark pairs survive. The corresponding flavor decompositions are

$$|1,1\rangle_I^{[4]_F} = \sqrt{\frac{3}{4}}\left|u^3s_{[4]_F}\right\rangle\otimes|\bar{u}\rangle+\sqrt{\frac{1}{4}}\left|u^2ds_{[4]_F}\right\rangle\otimes|\bar{d}\rangle, \quad \text{(A17)}$$

$$|1,1\rangle_I^{[4]_F} = \left|u^2s^2_{[4]_F}\right\rangle\otimes|\bar{s}\rangle, \quad \text{(A18)}$$

respectively.

For the configurations with $[v]_F=[31]_{F_1}$, in the present case, flavor decompositions of the $uuss\bar{s}$ configuration and the five-quark configurations with light quark antiquark pair are the same as the configurations with $[v]_F=[4]_F$.

Finally, the configurations with $[v]_F = [31]_{F_2}$ rule out the strangeness five-quark component in Σ^{*+}, only the $uudsd\bar{d}$ component exists. The flavor decomposition reads

$$|1,1\rangle_I^{[31]_{F_2}} = -\left|u^2ds_{[31]_{F_2}}\right\rangle \otimes |\bar{d}\rangle. \quad \text{(A19)}$$

Considering the isospin $SU(2)$ symmetry, one can obtain the flavor decomposition

$$|1,0\rangle_I^{[4]_F} = \sqrt{\frac{1}{2}}\left|u^2ds_{[4]_F}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{1}{2}}\left|ud^2s_{[4]_F}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A20)}$$

$$|1,0\rangle_I^{[4]_F} = \left|uds^2_{[4]_F}\right\rangle \otimes |\bar{s}\rangle, \quad \text{(A21)}$$

$$|1,0\rangle_I^{[31]_{F_1}} = \sqrt{\frac{1}{2}}\left|u^2ds_{[31]_{F_1}}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{1}{2}}\left|ud^2s_{[31]_{F_1}}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A22)}$$

$$|1,0\rangle_I^{[31]_{F_1}} = \left|uds^2_{[31]_{F_1}}\right\rangle \otimes |\bar{s}\rangle, \quad \text{(A23)}$$

$$|1,0\rangle_I^{[31]_{F_2}} = \sqrt{\frac{1}{2}}\left|u^2ds_{[31]_{F_2}}\right\rangle \otimes |\bar{u}\rangle - \sqrt{\frac{1}{2}}\left|ud^2s_{[31]_{F_2}}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A24)}$$

for the five-quark components in the Σ^{*0} baryon, and

$$|1,-1\rangle_I^{[4]_F} = \sqrt{\frac{1}{4}}\left|ud^2s_{[4]_F}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{3}{4}}\left|d^3s_{[4]_F}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A25)}$$

$$|1,-1\rangle_I^{[4]_F} = \left|d^2s^2_{[4]_F}\right\rangle \otimes |\bar{s}\rangle, \quad \text{(A26)}$$

$$|1,-1\rangle_I^{[31]_{F_1}} = \sqrt{\frac{1}{4}}\left|ud^2s_{[31]_{F_1}}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{3}{4}}\left|d^3s_{[31]_{F_1}}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A27)}$$

$$|1,-1\rangle_I^{[31]_{F_1}} = \left|d^2s^2_{[31]_{F_1}}\right\rangle \otimes |\bar{s}\rangle, \quad \text{(A28)}$$

$$|1,-1\rangle_I^{[31]_{F_2}} = \left|ud^2s_{[31]_{F_2}}\right\rangle \otimes |\bar{u}\rangle, \quad \text{(A29)}$$

for the five-quark components in the Σ^{*-} baryon, respectively.

3. Ξ^* baryons

The isospin wave function of the Ξ^{*0} baryon is $|\frac{1}{2},\frac{1}{2}\rangle_I$. Accordingly, for the configurations with $[v]_F = [4]_F$, both the five-quark components with light and strange quark-antiquark pairs can exist. Accordingly, the flavor decompositions are

$$\left|\frac{1}{2},\frac{1}{2}\right\rangle_I^{[4]_F} = \sqrt{\frac{2}{3}}\left|u^2s^2_{[4]_F}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{1}{3}}\left|uds^2_{[4]_F}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A30)}$$

$$\left|\frac{1}{2},\frac{1}{2}\right\rangle_I^{[4]_F} = \left|us^3_{[4]_F}\right\rangle \otimes |\bar{s}\rangle, \quad \text{(A31)}$$

respectively.

For the configurations with $[v]_F = [31]_{F_1}$, in the present case, flavor decompositions of the $ussss\bar{s}$ configuration and the five-quark configurations with light quark antiquark pair are the same as the configurations with $[v]_F = [4]_F$.

For the configurations with $[v]_F = [31]_{F_2}$, we only have to consider the light five-quark components, which should be

$$\left|\frac{1}{2},\frac{1}{2}\right\rangle_I^{[31]_{F_2}} = -\left|uds^2_{[31]_{F_2}}\right\rangle \otimes |\bar{d}\rangle. \quad \text{(A32)}$$

The flavor decompositions of the five-quark components in the Ξ^{*-} baryon can be obtained by considering the $SU(2)$ isospin symmetry as

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle_I^{[4]_F} = \sqrt{\frac{1}{3}}\left|uds^2_{[4]_F}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{2}{3}}\left|d^2s^2_{[4]_F}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A33)}$$

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle_I^{[4]_F} = \left|ds^3_{[4]_F}\right\rangle \otimes |\bar{s}\rangle, \quad \text{(A34)}$$

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle_I^{[31]_{F_1}} = \sqrt{\frac{1}{3}}\left|uds^2_{[31]_{F_1}}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{2}{3}}\left|d^2s^2_{[31]_{F_1}}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A35)}$$

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle_I^{[31]_{F_1}} = \left|ds^3_{[31]_{F_1}}\right\rangle \otimes |\bar{s}\rangle, \quad \text{(A36)}$$

$$\left|\frac{1}{2},-\frac{1}{2}\right\rangle_I^{[31]_{F_2}} = \left|uds^2_{[31]_{F_2}}\right\rangle \otimes |\bar{u}\rangle. \quad \text{(A37)}$$

4. Ω^- baryon

The isospin wave function of the Ω^- baryon is $|0,0\rangle_I$. Accordingly, for the configurations with $[v]_F = [4]_F$, both the five-quark components with light and strange quark-antiquark pairs can exist:

$$|0,0\rangle_I^{[4]_F} = \sqrt{\frac{1}{2}}\left|us^3_{[4]_F}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{1}{2}}\left|d^3s_{[4]_F}\right\rangle \otimes |\bar{d}\rangle, \quad \text{(A38)}$$

$$|0,0\rangle_I^{[4]_F} = \left|s^4_{[4]_F}\right\rangle \otimes |\bar{s}\rangle. \quad \text{(A39)}$$

For the five-quark configurations with $[v]_F = [31]_{F_1}$, only the ones with light quark-antiquark pairs exist in Ω^- baryon, and the flavor decomposition is

$$|0,0\rangle_I^{[31]_{F_1}} = \sqrt{\frac{1}{2}}\left|us^3_{[31]_{F_1}}\right\rangle \otimes |\bar{u}\rangle + \sqrt{\frac{1}{2}}\left|ds^3_{[31]_{F_1}}\right\rangle \otimes |\bar{d}\rangle. \quad \text{(A40)}$$

APPENDIX B: THE MATRIX ELEMENTS $\mathcal{T}^q_{i_5}$ AND $\Delta E^q_{i_5}$ FOR THE PENTAQUARK CONFIGURATIONS

Here, we show the matrix elements $\mathcal{T}^q_{i_5}$ and $\Delta E^q_{i_5}$ for the pentaquark configurations with $q\bar{q} = u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ using the wave functions in Set I in Tables IV–V.

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