Octet quark contents from SU(3) flavor symmetry

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Abstract – With the parametrization of parton distribution functions (PDFs) of the proton by Soffer et al., we extend the valence quark contents to other octet baryons by utilizing SU(3) flavor symmetry. We find the method practically useful. Fragmentation functions (FFs) are further obtained through the phenomenological Gribov-Lipatov relation at the $x \to 1$ region. Our results are compared with different models, and these different predictions can be discriminated by upcoming experiments.

Introduction. – A major property of the theory of strong interactions, i.e. quantum chromodynamics (QCD), is color confinement, i.e., quarks and gluons cannot be free but must be bounded inside hadrons. Due to the complicated non-perturbative effects of strong interaction, nowadays, it is still difficult to calculate baryon structure functions, in terms of parton distribution functions (PDFs), from the basic principle of QCD. One possible direction is lattice QCD, however, its calculation is largely constrained by the computational capability. Therefore, phenomenological models based on the spirit of QCD still play an important role in the studies of baryon structures.

Statistical models, providing intuitive appeal and physical simplicity, have made amazing success. Angelini and Pazzi first verified that valence quark distribution has a statistical behavior when the Bjorken variable $x$ is larger than 0.1. Utilizing a thermodynamical form as an input to the first-order QCD $Q^2$-evolution, they obtained a good fit at $5 < Q^2 < 100 \text{ GeV}^2$ [1]. Cleymans et al. then argued that Pauli principle should have effects on PDFs, and based on the MIT-bag model they got a statistical way to generate reasonable PDFs [2]. Along this way, several other models were proposed [3–12], where quarks follow Fermi-Dirac distribution and gluons obey Bose-Einstein statistics. For example, Mac and Ugaz [3] incorporated first-order QCD correction and Devanathan et al. [5] exhibited the scaling behavior. Afterwards, Bhalerao et al. [7] considered finite-size correction, and Trevisan et al. [8] introduced a confining potential and took gluon splitting into account.

Recently, Zhang et al. established a new and simple statistical model in terms of light-front kinematic variables and calculated the nucleon PDFs [12]. Besides, models based on other statistical principles were also studied. For instance, Zhang et al. [13] constructed a model using the principle of detailed balance, and the Gottfried sum they got is in surprising agreement with experiments. Singh and Upadhyay [14] extended this model to have spin considered with modifications. Further, Alberg and Henley [15] tracked the detailed balance model, and obtained PDFs for the proton as well as the pion.

BBS model, established by Bourrely, Buccella and Soffer [9–11], allows PDFs to be directly expressed in terms of $x$. By using 8 free parameters, the model can obtain all polarized and unpolarized PDFs of the proton, and it well fits to experimental data in a broad range of $x$ and $Q^2$. Extension of the model to other baryons is still in progress, but one of the limitations is in the determination of unknown parameters due to the currently relatively lack of relevant experiments. We stress that, SU(3) flavor symmetry [16] presents a kind of connection of quark distributions between octet baryons, and by using it, we get PDFs of all octet baryons from the BBS PDFs of the proton.

On the other hand, fragmentation function (FF), which describes the process of quark hadronization, is another basic quantity in QCD. One application of PDFs is to study the fragmentation function $D_q(z)$. At present, it will be very useful if there exists simple connections between them, so that one can predict the poorly known $D_q(z)$...
Table 1: PDFs of octet baryons in the quark-diquark model. The unit of $m_D$ ($D = V$ or $S$) is MeV, and $m_q = 330$ MeV for $u$, $d$ quarks, $m_q = 480$ MeV for $s$ quark.

| $q$  | $\Delta q$ | $m_V$ | $m_S$ |
|------|-------------|-------|-------|
| $p$  | $u = a_V/6 + a_S/2$ | $\Delta u = -\bar{a}_V/18 + a_S/2$ | 800 | 600 |
|      | $d = a_V/3$       | $\Delta d = -\bar{a}_V/9$       | 800 | 600 |
| $\Sigma^+$ | $u = a_V/6 + a_S/2$ | $\Delta u = -\bar{a}_V/18 + \bar{a}_S/2$ | 950 | 750 |
|      | $s = a_V/3$       | $\Delta s = -\bar{a}_V/9$       | 800 | 600 |
| $\Sigma^0$ | $u = a_V/12 + a_S/4$ | $\Delta u = -\bar{a}_V/36 + \bar{a}_S/4$ | 950 | 750 |
|      | $d = a_V/12 + a_S/4$ | $\Delta d = -\bar{a}_V/36 + \bar{a}_S/4$ | 950 | 750 |
|      | $s = a_S/3$       | $\Delta s = \bar{a}_S/3$       | 800 | 600 |
| $\Lambda^0$ | $u = a_V/4 + a_S/12$ | $\Delta u = -\bar{a}_V/12 + \bar{a}_S/12$ | 950 | 750 |
|      | $d = a_V/4 + a_S/12$ | $\Delta d = -\bar{a}_V/12 + \bar{a}_S/12$ | 950 | 750 |
|      | $s = a_S/3$       | $\Delta s = \bar{a}_S/3$       | 800 | 600 |
| $\Xi^-$  | $s = a_V/6 + a_S/2$ | $\Delta s = -\bar{a}_V/18 + \bar{a}_S/2$ | 950 | 750 |

from $q(x)$. One tentative attempt is the so-called Gribov-Lipatov relation [17], where

$$xq^h(x) = D_q^h(x),$$  \hspace{1cm} (1)

is suggested as a phenomenological approximate when $z(=x) \to 1$. Utilizing this relation, we get FF ratios, from our calculated PDF ratios, $u(x)/d(x)$ and $u(x)/s(x)$, for $p$ and $\Lambda$, at the $z \to 1$ region. Recently, Soffer et al. gave FFs out of the same statistical spirit, and they parameterized the free parameters for $p$ and $\Lambda$ directly from experimental data [18]. On the contrary, our results are based on SU(3) flavor symmetry.

The paper is organized as follows. First we briefly review the quark-diquark model, perturbative QCD (pQCD), and BBS model. Then we extend the BBS PDFs to octet baryons through SU(3) flavor symmetry, and compare results among different models.

Quark-diquark model. – SU(6) quark-diquark model, based on the SU(6) quark wave functions, was applied to nucleon structures when $x$ is large, first by Feynman [19]. In this model, when a valence quark of baryon is probed, we can reorganize the other two quarks as a mixture of a scalar diquark with spin 0 and an axial vector diquark with spin 1, denoted as $S$ and $V$, respectively.

Therefore, the unpolarized PDF is written as

$$q(x) = c_S^q a_S(x) + c_V^q a_V(x),$$  \hspace{1cm} (2)

where $c_S^q$ and $c_V^q$, the weight coefficients, can be determined from SU(6) quark-diquark wave functions, and their values are different for different baryons; $a_D(x)$ ($D = S, V$) represents the probability of finding the diquark in the state $D$, and when expressed in terms of light-cone wave function [20], is

$$a_D(x) \propto \int |d^2 \vec{k}_\perp| \varphi(x, \vec{k}_\perp)|^2,$$  \hspace{1cm} (3)

with normalization to 3 when integrated in $x \in [0, 1]$.

To calculate explicitly, we can use the Brodsky-Huang-Lepage (BHL) prescription for the light-cone wave function in momentum space,

$$\varphi(x, \vec{k}_\perp) \propto \exp \left\{ - \frac{1}{8a_D^2} \left[ \frac{m_q^2 + \vec{k}_\perp^2}{x} + \frac{m_D^2 + \vec{k}_\perp^2}{1 - x} \right] \right\},$$  \hspace{1cm} (4)

where $m_q$ and $m_D$ are masses of quarks and diquarks, respectively, and the parameter $a_D \approx 330$ MeV.

Similarly, for a polarized baryon, the PDF reads

$$\Delta q(x) = c_S^q \bar{a}_S(x) + c_V^q \bar{a}_V(x),$$  \hspace{1cm} (5)

$$\bar{a}_D(x) = \int |d^2 \vec{k}_\perp| \varphi(x, \vec{k}_\perp)^2 |W_D(x, \vec{k}_\perp)|,$$  \hspace{1cm} (6)

$$W_D(x, \vec{k}_\perp) = \frac{(k^+ + m_q)^2 - \vec{k}_\perp^2}{(k^+ + m_q)^2 + \vec{k}_\perp^2},$$  \hspace{1cm} (7)

where $k^+ = x \sqrt{(m_q^2 + \vec{k}_\perp^2)/x + (m_D^2 + \vec{k}_\perp^2)/(1 - x)}$.

The PDFs of five baryons calculated from the quark-diquark model are listed in table 1 [21].

Perturbative QCD. – In pQCD, the quark distribution in the hadron $h$ satisfies the counting rule [22],

$$q_h(x) \propto (1 - x)^p, \hspace{1cm} p = 2n - 1 + 2\Delta S,$$  \hspace{1cm} (8)

where $n$ is the minimal number of spectator quarks, and $\Delta S = |S^2 - S_h^2|$ equals 0 and 1 for parallel and anti-parallel quark helicity with respect to the hadron [23].

Keeping to the next-to-leading order,

$$q_h^1(x) = \frac{\bar{A}_q}{B_\bar{q}} x^{-1/2} (1 - x)^3 + \frac{\bar{B}_q}{B_\bar{q}} x^{-1/2} (1 - x)^4,$$  \hspace{1cm} (9)

$$q_h^1(x) = \frac{\bar{C}_q}{B_\bar{q}} x^{-1/2} (1 - x)^5 + \frac{\bar{D}_q}{B_\bar{q}} x^{-1/2} (1 - x)^6,$$  \hspace{1cm} (10)

where $B_n = B(1/2, n + 1)$ is $\beta$-function. For each baryon, there are 5 constraints among 8 parameters [21], so
only 3 are left free. Parameters for all octet baryons are given in table 2.
A more brief form of pQCD (called brief pQCD hereafter), considering only the leading terms of quark helicity distribution, is expressed as [24]

\[ q_i^q(x) = \frac{\bar{A}_q}{\bar{B}_q} x^{-1/2} (1 - x)^3. \]

\[ q_i^q(x) = \frac{\bar{C}_q}{\bar{D}_q} x^{-1/2} (1 - x)^5. \]

For the nucleon, 4 constraints are given. They are (1) normalizations for \( q_i \), i.e., \( N_i = \bar{A}_q + \bar{C}_q \); and (2) the corresponding polarizations, i.e., \( \Delta q_i = \bar{A}_q - \bar{C}_q \). Parameters can be extracted through \( \Sigma = \Delta u + \Delta d + \Delta s \approx 0.3 \), and the Bjorken sum rule \( \Gamma^p - \Gamma^n = \frac{4}{9} g_A/g_V \approx 0.2 \), from polarized DIS experiments [25]. Besides, all octet baryons are related to each other by SU(3) flavor symmetry. So there is no free parameter in the brief pQCD. All parameters are listed in table 3.

**BBS model.** In the BBS statistical approach, the nucleon is assumed to be a massless parton gas in equilibrium at a temperature \( T \). The parton distribution \( p(x) \), at an input energy scale \( Q_0^2 \), can be written as

\[ p(x, Q_0^2) \propto [e^{x - X_{0p}}/2 \pm 1]^{-1}, \]

where “+” is for fermions (quarks and antiquarks) and “−” for bosons (gluons). \( X_{0p} \) is the thermodynamical potential of parton \( p \), and \( \bar{x} \) is the universal temperature.

PDFs for \( u, d \) quarks of helicity \( h \), are [9]

\[ xq^h(x, Q_0^2) = \frac{AX_0^{bh}x^b}{e^{x - X_{0p}/2} + 1} + \frac{\bar{A}_b^b}{e^x + 1}, \]

\[ x\bar{q}^h(x, Q_0^2) = \frac{\bar{A}(X_{0q}^{bh})^{-1}2e^{\bar{x}b}}{e^{x + X_{0q}/2} + 1} + \frac{\bar{A}_b^b}{e^x + 1}. \]

where we have \( q_i = q_i^+ + q_i^- \), \( \Delta q_i = q_i^+ - q_i^- \). From a next-to-leading-order fit of a selection of 233 data points at \( Q_0^2 = 4 \text{ GeV}^2 \), parameters for the proton were determined,

\[ \bar{x} = 0.099, \quad b = 0.40962, \quad \bar{b} = 0.25347, \]

\[ A = 1.74938, \quad \bar{A} = 0.08318, \quad \bar{A} = 1.90801, \]

\[ X_{od} = 0.30174, \quad X_{od}^+ = 0.22775, \]

\[ X_{ou}^+ = 0.46128, \quad X_{ou}^- = 0.29766. \]

Considering the asymmetry, PDFs for \( s, \bar{s} \) quarks [11] are formulated as

\[ xs^h(x, Q_0^2) = \frac{AX_0^{bh}x^b}{e^{x - X_{0s}/2} + 1} \ln(1 + e^{kX_{0s}/2}) \]

\[ + \frac{\bar{A}_b^b}{e^x + 1}, \]

\[ x\bar{s}^h(x, Q_0^2) = \frac{\bar{A}(X_{0q}^{bh})^{-1}2e^{\bar{x}b}}{e^{x + X_{0q}/2} + 1} \ln(1 + e^{-kX_{0q}/2}) \]

\[ + \frac{\bar{A}_b^b}{e^x + 1}. \]

For the proton, the parameters are,

\[ X_{0s} = 0.08101, \quad X_{0s} = 0.2029, \]

\[ b_s = 0.25035, \quad \bar{A}_s = 0.05762. \]

From the above expressions and by utilizing SU(3) flavor symmetry (table 4), we get PDFs for all octet baryons as shown in figs. 1 to 5.

**Fragmentation functions.** Fragmentation function for \( u, d, s \) quarks, given by Soffer and Bourrely [18], is of the form

\[ D_q^B(x, Q_0^2) = \frac{A_q^B X_q^B x^b}{e^{x - X_q^B/2} + 1}, \]

### Table 2: Parameters for PDFs of octet baryons in pQCD.

| \( q \) | \( q_2 \) | \( \bar{A}_{q_1} \) | \( \bar{B}_{q_1} \) | \( \bar{C}_{q_1} \) | \( \bar{D}_{q_1} \) | \( \bar{A}_{q_2} \) | \( \bar{B}_{q_2} \) | \( \bar{C}_{q_2} \) | \( \bar{D}_{q_2} \) |
|---|---|---|---|---|---|---|---|---|---|
| \( p \) | \( u \) | \( d \) | 5.0 | -3.61 | 3.0 | -2.40 | 1.0 | -0.74 | 2.0 | -1.27 |
| \( \Sigma^+ \) | \( u \) | \( s \) | 5.0 | -3.61 | 3.0 | -2.40 | 1.0 | -0.74 | 2.0 | -1.27 |
| \( \Sigma^0 \) | \( u(d) \) | \( s \) | 2.0 | -1.34 | 2.0 | -1.67 | 0.8 | -0.54 | 2.0 | -1.27 |
| \( \Lambda^0 \) | \( s \) | \( u(d) \) | 2.0 | -1.2 | 2.0 | -1.8 | 1.0 | -0.6 | 2.0 | -1.40 |
| \( \Xi^- \) | \( s \) | \( d \) | 5.0 | -3.61 | 3.0 | -2.40 | 1.0 | -0.74 | 2.0 | -1.27 |

### Table 3: Parameters for PDFs of octet baryons in the brief pQCD.

| \( q_1 \) | \( q_2 \) | \( R_A \) | \( \Delta q_1 \) | \( \Delta q_2 \) | \( \bar{A}_{q_1} \) | \( \bar{C}_{q_1} \) | \( \bar{A}_{q_2} \) | \( \bar{C}_{q_2} \) |
|---|---|---|---|---|---|---|---|---|
| \( p \) | \( u \) | \( d \) | 5 | 0.75 | -0.45 | 1.375 | 0.625 | 0.275 | 0.725 |
| \( \Sigma^+ \) | \( u \) | \( s \) | 5 | 0.75 | -0.45 | 1.375 | 0.625 | 0.275 | 0.725 |
| \( \Sigma^0 \) | \( u(d) \) | \( s \) | 5/2 | 0.375 | -0.45 | 0.6875 | 0.3125 | 0.275 | 0.725 |
| \( \Lambda^0 \) | \( s \) | \( u(d) \) | 2 | 0.65 | -0.175 | 0.825 | 0.175 | 0.4125 | 0.5875 |
| \( \Xi^- \) | \( s \) | \( d \) | 5 | 0.75 | -0.45 | 1.375 | 0.625 | 0.275 | 0.725 |
Table 4: PDFs of octet baryons from SU(3) flavor symmetry.

|          | $u_v^B$ | $d_v^B$ | $s_v^B$ | $u_v^B$ | $d^B$ | $s^B$ |
|----------|---------|---------|---------|---------|-------|-------|
| p        | $u_v$   | $d_v$   | $s - \bar{s}$ | $\bar{u}$ | $d$   | $\bar{s}$ |
| $\Sigma^+$ | $u_v$   | $s - \bar{s}$ | $\bar{u}$ | $\bar{s}$ | $\bar{d}$ |
| $\Sigma^0$ | $(u_v + s - \bar{s})/2$ | $(u_v + s - \bar{s})/2$ | $d_v$ | $(\bar{u} + \bar{s})/2$ | $(\bar{u} + \bar{s})/2$ | $d$ |
| $\Lambda^0$ | $(u_v + 4d_v)/6$ | $(u_v + 4d_v)/6$ | $(2u_v - d_v)/3$ | $(\bar{u} + \bar{s})/2$ | $(\bar{u} + \bar{s})/2$ | $d$ |
| $\Xi^-$   | $s - \bar{s}$ | $d_v$ | $u_v$ | $\bar{s}$ | $\bar{d}$ | $\bar{u}$ |

Fig. 1: (a) $\Delta u(x)/u(x)$, (b) $\Delta d(x)/d(x)$, (c) $d(x)/u(x)$ for the proton. The full, dotted, dashed, and thick full lines are results for quark-diquark model, brief pQCD model, pQCD model, and BBS model, respectively.

Fig. 2: (a) $\Delta u(x)/u(x)$, (b) $\Delta s(x)/s(x)$, (c) $u(x)/s(x)$ for $\Lambda$. The full, dotted, dashed, and thick full lines are results for quark-diquark model, brief pQCD model, pQCD model, and SU(3)-extended BBS model, respectively.

Fig. 3: (a) $\Delta u(x)/u(x)$, (b) $\Delta s(x)/s(x)$, (c) $s(x)/u(x)$ for $\Sigma^+$. Models are identical to those in fig. 2.

where $X_q^B$ is the potential related to the fragmentation process $q \to B$. They then determine the parameters as [18]

$A_u^\Lambda = A_d^\Lambda = 0.428, \quad b = 0.200, \quad \bar{x} = 0.099,\nA_u^p = A_d^p = 0.264, \quad A_s^p = 1.168, \quad A_s^\Lambda = 1.094,\nX_u^p = 0.648, \quad X_s^p = 0.247,\nX_u^\Lambda = 0.296, \quad X_s^\Lambda = 0.476,$

where the input energy scale was fixed at $Q_0 = 0.632$ GeV, and the yielded $\chi^2 = 227.5$ for 206 experimental points.

Comparisons between models. – We calculate PDFs as a function of $x$ for models mentioned above, and our extension of BBS model based on SU(3) flavor symmetry is compared with them. Comparisons are shown in figs. 1–5.

Below we discuss physical issues at the $x \to 1$ region.
In fig. 1, we illustrate $\Delta u(x)/u(x)$ of the proton. We can see that quark-diquark model, pQCD model, and brief pQCD model all give $\Delta u(x)/u(x) \rightarrow 1$ when $x \rightarrow 1$, that is, the proton is completely positively polarized. However, BBS model gives a different result of 0.779. Figure 1 also shows $\Delta d(x)/d(x), d_{s}(x)/s(x)$ for the proton. For $\Delta d(x)/d(x)$, pQCD model and brief pQCD model give $\Delta d(x)/d(x) \rightarrow 1$ when $x \rightarrow 1$, while quark-diquark model and BBS model predict negative values. For $d_{s}(x)/s(x)$, the prediction of BBS model is close to those from pQCD and brief pQCD models, while the result of quark-diquark model is different from that of other models, i.e., it gives a larger value when $x \rightarrow 0$ and approaches to 0 when $x \rightarrow 1$.

Figure 2 gives the results of $\Lambda$. As is shown, for $\Delta u(x)/u(x)$, SU(3)-extended BBS model gives much smaller prediction than the other models, while for $\Delta s(x)/s(x)$ and $u(x)/s(x)$, predictions are close to each other. Such result means that our extension of BBS model through SU(3) flavor symmetry is reasonable in the studies of baryon structures.

The comparisons for other baryons are also obtained. In figs. 3 and 4, we make comparisons for $\Sigma^{+}$ and $\Sigma^{0}$. We can see that in SU(3)-extended BBS model, $\Delta u(x)/u(x)$ approaches to 0.7–0.8 when $x \rightarrow 1$, allowing partly negative polarization of $u$ quark, contrary to the result of 1 from the other three models. Then as for $\Delta s(x)/s(x)$, SU(3)-extended BBS model and quark-diquark model give results around $-0.5$, against the positive value given by pQCD and brief pQCD. And as for $s_{s}(x)/s_{s}(x)$, pQCD, brief pQCD and SU(3)-extended BBS models give a similarly positive value, while quark-diquark model predicts zero.

Figure 5 presents results of $\Xi^{-}$. The behaviors for $\Delta s_{x}(x)/s_{x}(x)$ and $\Delta d_{x}(x)/d_{x}(x)$ are very similar to those of $\Delta u(x)/u(x)$ and $\Delta s_{x}(x)/s_{x}(x)$ in fig. 3, respectively. And as for $d_{x}(x)/s_{x}(x)$, it is shown that quark-diquark model get a slightly different behavior from that of the other models.

The results of $n$, $\Sigma^{-}$ and $\Sigma^{0}$ are not presented here, because they can be easily obtained from $p$, $\Sigma^{+}$ and $\Xi^{-}$, respectively, according to $u$-$d$ isospin symmetry. For examples, $u^{n}(x) = d^{p}(x)$ and $d^{-}\left(x\right) = u^{\Xi^{-}}(x)$.

One can also use other phenomenological parameterizations to study octet-baryon PDFs from SU(3) relations, and in ref. [16] two sets of octet-baryon PDFs were obtained from polarized PDFs parameterizations of the proton.

Besides, our calculation of quark fragmentation functions also gives predictive results. According to our BBS-based model and the Gribov-Lipatov relation, we get $D_{u}^{A}(z)/D_{d}^{A}(z) \rightarrow 6.252$, and $D_{s}^{A}(z)/D_{s}^{A}(z) \rightarrow 1.648$ when $z \rightarrow 1$. But in the statistical approach in ref. [18], the calculation gives $D_{u}^{A}(z)/D_{d}^{A}(z) \rightarrow 25.217$. We can see that the difference is very large both for the proton and $\Lambda$. We can also compare with AKK (Albino-Kniehl-Kramer) phenomenological parameterization [26] of the proton and $\Lambda$ fragmentation functions, and the calculation results are both 0 corresponding to the above two quantities. Thus further discriminations between different predictions are needed by experiments.

Finally, we would like to estimate the effect introduced by SU(3) breaking and Melosh-Wigner rotation [27] to the SU(3)-extended BBS model. In the quark-diquark model, this effect comes from different masses of $u$, $d$ and $s$.
and the correction is roughly estimated to be of about 10%. We therefore expect that such effect may bring about the same size correction in the SU(3)-extended BBS model. It means that our results are qualitatively reasonable, with some freedom to improve quantitatively when more data are available.

**Conclusion.** – In this paper, we calculate parton distribution functions (PDFs) of octet baryons through SU(3) flavor symmetry, starting from PDFs of the proton in the BBS statistical model. We make comparisons among different models, and find that our combination of the BBS statistical model and SU(3) flavor symmetry is an optional way to explore hadron structures. We also calculate the fragmentation function (FF) ratios, $D_u^C(z)/D_s^C(z)$ and $D_u^A(z)/D_s^A(z)$, at the $z \to 1$ region, based on the phenomenological Gribov-Lipatov relation. The results are compared with those from predictions of other models. We find our results are reasonable and the method can be extended to the studies of baryon structures.

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