Charm Antiquark and Charm Quark in the Nucleon

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We estimate the intrinsic charm contributions to the quark flavor and spin observables of the nucleon in the SU(4) quark meson fluctuation model. In this model, the charm or antiquark reside in the charmed mesons created by the nonperturbative quantum meson-fluctuation transitions. The intrinsic charm content in the proton, $2\bar{c}/\sum(q+\bar{q}) \approx 0.011 \pm 0.008$, is almost one order of magnitude smaller than the intrinsic strange content. The intrinsic charm helicity is also small and negative, $\Delta c \approx -(0.009 \pm 0.006)$. The fraction of the total quark helicity carried by the charm is $|\Delta c/\Delta \Sigma| \approx 0.021 \pm 0.014$. The ratio of the charm with positive helicity to that with negative helicity is $c_+/(c_-) = 35/67$. For the intrinsic strange component, one has $s_+/s_- \approx 7/13$. A detailed comparison of our predictions with data and other models or analyses is given. The intrinsic charm contribution to the Ellis-Jaffe sum rule is also discussed.

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1. Introduction

As suggested by many authors long time ago [1, 2], there are so called ‘intrinsic’ heavy quark components in the proton wave function. The intrinsic heavy quarks are created from the quantum fluctuations associated with the bound state hadron dynamics. They exist in the hadron over a long time independent of any external probe momentum transferred in the collision. The probability of finding the intrinsic heavy quarks in the hadron is completely determined by nonperturbative mechanisms. On the other hand, the extrinsic heavy quarks are created on a short time scale in association with a large transverse momentum reaction and their distributions can be derived from QCD bremsstrahlung and pair production processes, which lead to standard QCD evolution. The study of nonperturbative mechanism $gg \rightarrow q\bar{q}$ [4] shows that the intrinsic heavy quark contribution scales as $1/m_Q^2$, where $m_Q$ is the mass of the heavy quark, the probability of finding the intrinsic bottom is expected to be much smaller, hence we will only consider the intrinsic charm (IC) component, e.g. $|\bar{u}d\bar{c}\bar{c}|$, in the nucleon.

Many works on intrinsic charm are based on models of the nucleon (see e.g. MIT bag model [2], NJL model [3], meson cloud model [1, 5], instanton model [6, 7] and others [1, 3, 4, 5, 6, 7, 8] etc.) or combination of the IC hypothesis and analysing the existing DIS data on charm production to obtain some information of the intrinsic charm content (see e.g. [2, 3, 4, 5]). As pointed out in [4], that a non-perturbative IC component was unable to explain enhancement in the $e^+p$ neutral current cross section at HERA kinematics, but HERA data may provide a good test of the intrinsic charm if the charm component of $F_2$ is directly isolated and no new physics exists. Another discussion given in [12] suggested a nonsymmetric charm distribution, for which $\bar{c}$ is much harder than $c$, which may account for the HERA anomaly, a significant enhancement of cross sections at HERA at large $x$ and $Q^2$ [19, 20]. However, the most recent analysis given in [17], which includes both the perturbative photon-gluon fusion process and nonperturbative intrinsic charm contribution, found no conclusive evidence for the intrinsic charm and only provided an upper bound of around 0.4%. Therefore what is the effect of charm in the structure of the proton is still an open and interesting question. A comprehensive review on the nucleon sea, which includes light quark, intrinsic strange and charm, can be found in [3].

The chiral quark model or more precisely the quark meson fluctuation model (in SU(2) version) was first suggested in [2] to explain the sea flavor asymmetry, $d - \bar{u} > 0$. The model was extended to SU(3) without and with SU(3) symmetry breaking to describe the quark spin structure (see e.g. [23, 24, 25, 26, 27, 28] and references therein), and orbital structure (see e.g. [28] and references therein) of the nucleon. In this model, the nucleon structure is determined by its zeroth order valence quark configuration and all possible quantum fluctuations of the valence quark into a recoil quark and a meson. It provides a natural and nonperturbative explanation of a nonzero (intrinsic) strange sea and negative strange sea polarization through the quark-kaon fluctuation (e.g. $u \rightarrow s + K^+$). The results agree quite well with the data obtained in deep-inelastic scattering and other related experiments.

Based on earlier encouraging result [27], we suggested an SU(4) version of quark-meson fluctuation model and predicted a nonzero intrinsic charm in the proton [29]. In the SU(4) version, charm or anti-charm quarks re-
side in the charmed mesons which are created by non-
perturbative quantum quark-meson fluctuations such as
\( u \rightarrow c + D^0 \). These charm or anti-charm quarks are es-
sentially intrinsic components of the hadron.

The main motivations of extending to SU(4) version are: 1) There is no physical reason to forbid the fluctua-
tion from a light quark to a charmed quark and charmed
meson. Hence it is interesting to investigate what are the
changes of the SU(3) predictions after including the
charm or anticharm contributions. 2) According to the
symmetric GIM model \( [3] \), one should deal with the
weak axial current in the framework of SU(4) symme-
try. It implies that the charm quark should play some
role in determining the spin, flavor and orbital structure
of the nucleon. Therefore it is natural and reasonable
to extend the SU(3) version to SU(4) by including the
charm and anticharm contributions.

In this paper, we will discuss the effect of the IC con-
tribution to the flavor and spin observables of the pro-
ton in the SU(4) quark meson fluctuation model with
symmetry-breaking. The analytic and numerical results
of the flavor and spin contents for each quark flavor
are compared with the existing data and other model results or
analyses. The intrinsic charm contribution to the Ellis-
Jaffe sum rule is also discussed.

2. SU(4) model with symmetry breaking

In the framework of SU(4) quark model, there are six-
teen pseudoscalar mesons, a 15-plet and a singlet. In this
paper, the contribution of the SU(4) singlet will be ne-
glected. It is easy to show that the effective Lagrangian
describing interaction between quarks and the mesons in
the SU(4) case is

\[
L_I = g_{15} \bar{q} \left( \begin{array}{cccc}
G^0_u & \pi^+ & \sqrt{2} K^+ & \sqrt{2} D^0 \\
\pi^- & G^0_d & \sqrt{2} K^0 & \sqrt{2} D^+ \\
\sqrt{2} K^- & \sqrt{2} K^0 & G^0_0 & \sqrt{2} D^- \\
\sqrt{2} D^0 & \sqrt{2} D^+ & \sqrt{2} D^- & G^0_s \\
\end{array} \right) q.
\]

where \( D^+ = (\bar{c}d) \), \( D^- = (\bar{d}c) \), \( D^0 = (\bar{c}u) \), \( d^0 = (\bar{u}c) \), \( D^+ = (\bar{c}s) \), and \( D^- = (\bar{s}c) \). The neutral charge compo-
ents \( G^0_u(d) \) and \( G^0_{s,c} \) are defined as

\[
G^0_{u(d)} = \frac{1}{\sqrt{2}} \eta_0 \epsilon^\eta_0 \sqrt{\zeta} / \epsilon \epsilon^\epsilon / 16
\]
(2)

\[
G^0_s = -\eta_0 \epsilon^\eta_0 \sqrt{2} \epsilon / 3 \epsilon^\epsilon / 16
\]
(3)

\[
G^0_c = -\eta_0 \epsilon^\eta_0 \sqrt{2} \epsilon / 3 \epsilon^\epsilon / 16
\]
with

\[
\eta_0 = (u\bar{u} - d\bar{d}) / \sqrt{2}, \quad \eta_0 = (u\bar{u} + d\bar{d} - 2s\bar{s}) / \sqrt{6},
\]

\[
\eta_0 = (u\bar{u} + d\bar{d} + s\bar{s}) / \sqrt{3}, \quad \eta_0 = (c\bar{c}).
\]

Similar to the SU(3) case, we define \( a \equiv |g_{15}|^2 \), which de-
notes the transition probability of splitting \( u(d) \rightarrow d(u) +
\pi^+(-) \). Hence \( a, \epsilon_0 \), and \( \zeta \) are denoted by the proba-
bilities of splittings \( u(d) \rightarrow s + K^-(0), \ u(d) \rightarrow u(d) + \eta^0, \ u(d) \rightarrow d(u) + \eta^0 \) and \( u(d) \rightarrow c + D^0(D^-) \) respectively. If the splitting probability is dominated by the mass effects, we expect \( 0 < \epsilon_0 < \zeta \eta < \epsilon \approx \epsilon_0 < 1 \).

It implies that the probability of emitting heavier me-
son such as \( D \) from light quarks is smaller than that of
emitting the lighter mesons such as \( K, \eta, \eta' \), etc.

- The quark contents of the \( \eta \) and \( \eta' \) shown in
Eqs.(5) and (6) imply that they are actually \( \eta_0 \) and
\( \eta_1 \). Hence the octet-singlet mixing is neglected in
our description.

- We have shown in \( [27] \) that a better SU(3) descrip-
tion can be achieved by taking \( a, \epsilon \), and \( \zeta \) as
one possible option in the numerical calculation, i.e. neglect
the singlet contribution from the beginning. In this case, the
number of independent parameters would be only
three: \( \alpha \), \( \epsilon \), and \( \epsilon_0 \). Since our analytical formulae
are not restricted to this approximation, we can also
discuss \( \zeta \neq 0 \) case (see discussion in section 4
below).

- It should be noted that the definition of \( G^0_{u(d)} \) in
SU(4) case is different from that in the SU(3) case.
Besides an additional charm term, \( -\eta_0 \epsilon^\epsilon / 16 \), the
coefficient of \( \eta_0 \) term is changed. For \( G^0_\epsilon \), even the
coefficient of \( \eta_0 \) term is also changed. Therefore,
the SU(4) formalism cannot be reduced to SU(3) simply
by taking \( \epsilon_0 \rightarrow 0 \) only [see later discussion on
Eqs. (15) and (16)]. The \( G^0_\epsilon \) is completely new
in the SU(4) version.

- As pointed out in the original chiral quark model
\( [22, 23, 24, 25, 26, 27] \), the nucleon properties are defined in the scale range between \( \Lambda_{QCD} \ (\sim 0.2 - 0.3 \text{ GeV}) \) and \( \Lambda_{\chi_B} \ (\sim 1 \text{ GeV}) \), where the
spontaneous breaking of chiral symmetry leads to
the existence of Goldstone bosons. In the quark meson fluctuation model (SU(3) in \[28\] and SU(4) in this paper), we will assume all calculated quantities are also defined in the same scale range \([0.2\ \text{GeV}^2 < \mu^2 < 1.0\ \text{GeV}^2]\). At this \(\mu^2\) range, the sea content should be dominated by the intrinsic component created by nonperturbative mechanism, quark-meson fluctuation, \([29\] and the extrinsic sea component is expected to be small.

- We note that in our formalism, only the integrated flavor content \(q(Q^2) = \int_0^1 dx q(x,Q^2)\) and helicity content \(\Delta q(Q^2) = \int_0^1 dx \Delta q(x,Q^2)\) are discussed. To make brief of the formalism, we will omit the all quantum fluctuations of a valence quark \(q\) of finding a quark or antiquark component is expected to be small.

In addition to the allowed fluctuations discussed in the SU(3) case, a valence quark is now allowed to split up or fluctuate to a recoil charm quark and a charmed meson. For example, a valence u-quark with spin-up, the allowed fluctuations are

\[
\begin{align*}
    u_\uparrow & \to d_\uparrow + \pi^+, \quad u_\uparrow \to s_\uparrow + K^+, \quad u_\uparrow \to u_\uparrow + G_u^0, \\
    d_\uparrow & \to c_\uparrow + \bar{D}^0, \\
    s_\uparrow & \to u_\uparrow.
\end{align*}
\]

Similarly, one can list the allowed fluctuations for \( u_\downarrow, \ d_\uparrow, \ d_\downarrow, \ s_\uparrow, \) and \( s_\downarrow. \) Since we are only interested in the spin-flavor structure of the nucleon (or other non-charmed hadrons), which does not have valence charm quark, hence the fluctuations from a valence charm quark will not be discussed.

The spin-up and spin-down quark or antiquark contents in the proton, up to first order of the quantum fluctuation, can be written as (a detail SU(3) version see e.g. \[28\]),

\[
    n_p(q_\uparrow, \text{or} \ q_\downarrow) = \sum_{q=u,d,s,c} \sum_{\alpha=q,\bar{q}} n_p^{(0)}(q_\alpha) P_{q_\alpha}(q_\uparrow, \text{or} \ q_\downarrow),
\]

where \( q = u,d,s,c \) and \( n_p^{(0)}(q_\uparrow) \) are determined by the zeroth order, i.e. naive quark model (NQM), valence quark wave function of the proton and

\[
\begin{align*}
    n_p^{(0)}(u_\uparrow) &= 5/3, \quad n_p^{(0)}(u_\downarrow) = 1/3, \\
    n_p^{(0)}(d_\uparrow) &= 1/3, \quad n_p^{(0)}(d_\downarrow) = 2/3.
\end{align*}
\]

In Eq. (11), \( P_{q_\uparrow}(q_\uparrow) \) and \( P_{q_\downarrow}(q_\downarrow) \) are probabilities of finding a quark or an antiquark arise from all quantum fluctuations of a valence quark \( q_\uparrow. \) The probabilities \( P_{q_\uparrow}(q_\uparrow) \) and \( P_{q_\downarrow}(q_\downarrow) \) can be obtained from the effective Lagrangian (1) and have been listed in Table I, where only \( P_{q_\uparrow}(q_\uparrow) \) and \( P_{q_\downarrow}(q_\downarrow) \) are shown. Those arise from \( q_\downarrow \) can be obtained by using \( P_{q_\downarrow}(q_\uparrow) = P_{q_\uparrow}(q_\downarrow) \) and \( P_{q_\downarrow}(q_\downarrow) = P_{q_\uparrow}(q_\uparrow). \) The notations appeared in Table I are defined as

\[
    f \equiv 1/2 + \epsilon_n/6 + \zeta^2/48 + \epsilon_c/16, \\
    f_s \equiv 2\epsilon_n/3 + \zeta^2/48 + \epsilon_c/16,
\]

and

\[
    \tilde{A} \equiv 1/2 - \sqrt{\epsilon_n}/6 - \zeta'/12, \quad \tilde{B} \equiv -\sqrt{\epsilon_n}/3 + \zeta'/12, \\
    \tilde{C} \equiv 2\epsilon_c/3 + \zeta'/12, \quad \tilde{D} \equiv \epsilon_c/4.
\]

Analogous to the SU(3) case, the special combinations \( A, \ B, \ C, \) and \( D \) stem from the definitions (2)-(4), which show the quark and antiquark contents in the neutral bosons \( G_n^{u,s,c} \) from the SU(3) ones. This difference shows that the charm contribution is not only presented in the charm term which is proportional to \( \epsilon_c, \) but also affected by the \( \zeta' \) term. Taking \( \epsilon_c \to 0 \) and \( \zeta' \to 4\zeta' \), one can see from Eq. (13) that the \( f \) and \( f_s \) indeed reduce to the corresponding quantities in the SU(3) case,

\[
    (f)_{SU(3)} = 1/2 + \epsilon_n/6 + \zeta^2/3, \\
    (f_s)_{SU(3)} = 2\epsilon_n/3 + \zeta^2/3,
\]

which is exactly Eq.(6b) in \[28\]. Taking \( \epsilon_n \to 0 \) and \( \zeta' \to 4\zeta' \), one has \( \tilde{D} \to 0 \) and

\[
    \tilde{A} \to A_{SU(3)}/3, \quad \tilde{B} \to B_{SU(3)}/3, \quad \tilde{C} \to C_{SU(3)}/3,
\]

where \( A_{SU(3)}, \ B_{SU(3)}, \) and \( C_{SU(3)} \) are the same as \( A, \ B, \) and \( C \) in Eq. (6a) in \[28\].

If Eq. (12) is replaced by \( n_n^{(0)}(d_\uparrow) = 5/3, \ n_n^{(0)}(d_\downarrow) = 1/3, \ n_n^{(0)}(u_\uparrow) = 1/3, \) and \( n_n^{(0)}(u_\downarrow) = 2/3, \) from (11), we will obtain all flavor and spin contents in the neutron.

3. Flavor and spin contents in the proton

We note that the quark flips its spin in the quark splitting processes \( q_\uparrow \rightarrow q_\downarrow + \text{meson}, \) i.e. processes in (8) and (9), but not in the (10) (no splitting). The quark helicity non-flip contribution in splitting processes is entirely neglected. This is a basic assumption in the model and seems to be consistent with the picture given by the instanton model.

3.1. Quark flavor content

Using (11), (12) and the probabilities \( P_{q_\uparrow}(q_\uparrow) \) and \( P_{q_\downarrow}(q_\downarrow) \) listed in Table I, one obtains all quark and antiquark flavor contents in the proton,

\[
    u = 2 + \bar{u}, \quad d = 1 + \bar{d}, \quad s = 0 + \bar{s}, \quad c = 0 + \bar{c}.
\]
where
\[ \bar{u} = a[1 + \bar{\Lambda}^2 + (1 - \Lambda)^2], \quad \bar{d} = a[2(1 + \bar{\Lambda}^2) + (1 - \Lambda)^2], \]
(18)
\[ \bar{s} = 3a[\epsilon + \bar{\Lambda}^2], \quad \bar{c} = 3a[\epsilon_c + \bar{\Lambda}^2]. \]
(19)
From (18), one obtains
\[ \frac{\bar{u}}{\bar{d}} = 1 - 6\Lambda/[3\Lambda - 1]^2 + 8, \]
(20)
and
\[ \bar{d} - \bar{u} = 2a\Lambda. \]
(21)
Similarly, one can obtain \( 2\bar{c}/(\bar{u} + \bar{d}), 2\bar{c}/(\bar{u} + d), 2\bar{c}/\sum (q + \bar{q}) \) and other flavor observables related to charm quark and charm antiquark. We note that in the SU(4) case, one has \( \Delta_{\text{charm}} \approx \Delta_{\text{antiquark}} \). We note that in the SU(4) case, one has
\[ \bar{q} \equiv \bar{\epsilon} + \bar{\epsilon}_c, \]
\[ \Delta \equiv \sum_{q=u,d,s,c} \Delta q = 1 - 2a(1 + \epsilon + \epsilon_c + f), \]
(30)
or
\[ \Delta \equiv \sum_{q=u,d,s,c} \Delta q = 1/2 - a\xi_1, \]
(31)
where \( \xi_1 \) is defined in (22), and
\[ \Delta \bar{q} = 0, \quad (\bar{q} = \bar{u}, \bar{d}, \bar{s}, \bar{c}). \]
(32)
Before going to the numerical calculation, we would like to make several remarks on some results which are basically independent of parameters.

- Comparing with the SU(3) case, a new \( \epsilon_c \) term, which presents the intrinsic charm contribution, appeared in \( \Delta u, \Delta d, \Delta c, \) and \( \Delta \Sigma \), but not in \( \Delta s \). This is because there is no process which can mix the strange helicity and charm helicity contributions. \( \Delta s \) can only come from the processes like \( u \to s + K^+ \), while \( \Delta c \) comes only from the processes like \( u \to c + D^0 \). Although there are \( s, \bar{s} \) (or \( c, \bar{c} \)) in all neutral bosons \( G_0, G_d, G_s, G_c \), they give no contributions to \( \Delta s \) (or \( \Delta c \)) due to \( s_\uparrow \) and \( s_\downarrow \) (or \( c_\uparrow \) and \( c_\downarrow \)) appeared with \textit{equal probability} in these neutral bosons.

- The charm quark helicity \( \Delta c \), (29), is \textit{nonzero} as far as \( \epsilon_c \) is nonzero. Analogous to the strange quark helicity, \( \Delta c \) is definitely \textit{negative}, but the size of the intrinsic charm helicity depends on the parameter \( \epsilon_c \) and the splitting probability \( a \).

- The physical meaning of (31) is that the total loss of the quark helicity arises from four splitting processes with quark spin-flip, \textit{three} in (8) and \textit{a new} splitting in (9). Comparing with the SU(3) case, where \( \Delta \Sigma/2 = 1/2 - a(1 + \epsilon + f) \), we now have an additional reduction, \(-ac_a\), of the total quark spin due to the splitting related to the charm.

- In the splitting process \( u_{\uparrow(\downarrow)} \to c_{\downarrow(\uparrow)} + D^0 \), the anticharm resides only in the charmed meson, e.g. \( D^0(\bar{c}, u) \). The probabilities of finding \( \bar{c}_\uparrow \) and \( \bar{c}_\downarrow \) are equal in the spinless charmed meson. Therefore \( \Delta \bar{c} = 0 \). Similar discussion in the SU(3) case has led to \( \Delta \bar{q} = 0 \) for \( \bar{q} = \bar{u}, \bar{d}, \bar{s} \). The result (32) shows that the helicities of the sea quark and antiquark are not equal, \( \Delta q_{\text{sea}} \neq \Delta \bar{q} \). This is different from the usual gluon splitting \( g \to q + \bar{q} \) model and \( gg \to q + \bar{q} \) model [4]. In the gluon splitting and gluon fusion models, the sea quark and antiquark with the same flavor are perturbatively or nonperturbatively created as a pair from the gluon or gluons and \( \Delta q_{\text{sea}} = \Delta \bar{q} \). The DIS data seems to support the prediction \( \Delta \bar{q} \simeq 0 \) but with large errors.
• From (19) and (29), using \( \tilde{D}^2 = \epsilon_c/16 \) in (14), one can see that the ratio
\[
\Delta c/c = -16/51
\]
is a constant independent of any splitting parameters. This is a special prediction for the charm flavor in the SU(4) quark meson model.

• For the strange flavor, from \( \tilde{B} \) in (14) and \( \tilde{s} \) in (19), one has \( s = s' \approx \epsilon_0 a/(10/3)\left[1 + [\zeta']/(20\sqrt{3})\right] \) due to \( \zeta'^2 << 1 \). In the limit \( \zeta'^2 \to 0 \), we have
\[
\Delta s/s = -3/10.
\]
Hence \( \Delta s/s \) is also a constant in this limit.

• From (33) and (32), one obtains the ratio of the charm with positive helicity to that with negative helicity is also a constant,
\[
c\uparrow/c\downarrow = 35/67 \approx 0.522.
\]
It shows that more \( c\downarrow \) is created than \( c\uparrow \) in the splitting processes \( u\downarrow \to c\uparrow + \bar{D}^0 \) and \( d\downarrow \to c\uparrow + D^- \). This is because the total contribution from \( u\uparrow \) and \( d\uparrow \) is larger than that from \( u\downarrow \) and \( d\downarrow \). Similar situation occurs for the strange quarks. From (34) and (32), we have, for \( \zeta' = 0 \),
\[
s\uparrow/s\downarrow = 7/13 \approx 0.538.
\]

• For the \( u \)-flavor and \( d \)-flavor, we do not have similar exact relations like (33) and (34). This is because the quantities \( u\uparrow - u\downarrow \) and \( d\uparrow - d\downarrow \) depend on \( \epsilon_c \), while \( u\uparrow + u\downarrow \) and \( d\uparrow + d\downarrow \) do not. Hence \( \Delta u/u \) and \( \Delta d/d \) depend on all three splitting parameters. The numerical calculation (see next section) shows that
\[
\Delta u/u \approx 0.383, \quad \Delta d/d \approx -0.287.
\]
From (37) and (32), we obtain
\[
d\uparrow/d\downarrow \approx 0.554,
\]
and
\[
u \uparrow/u \downarrow \approx 2.241.
\]
Comparing with the zeroth approximation (NQM), where \( d\uparrow/d\downarrow = 1/2 \) and \( u\uparrow/u \downarrow = 5/1 \), hence the quark-meson splittings lead to a small enhancement for \( d\downarrow/d\uparrow \), but a significant reduction for \( u\uparrow/u\downarrow \).

• The ratios of the flavor or spin contents predicted in this paper are also defined at \( Q^2 = \mu^2 \) scale, where the sea (light or heavy) quark contents are ‘intrinsic’ and determined by nonperturbative mechanism. To compare the predictions with data at higher \( Q^2 \) range, one needs to use perturbative QCD and treat these ratios (at \( Q^2 = \mu^2 \)) as inputs, i.e. boundary conditions, in the QCD evolution equations. If the numerator and denominator of the ratio have the same or almost the same factor of \( Q^2 \) dependence, then this ratio will not sensitive to the change of \( Q^2 \).

### 3.3. Ellis-Jaffe sum rule

In the framework of SU(4) parton model, the first moment of the spin structure function \( g_1^u(x, Q^2) \) in the proton is
\[
\Gamma_1^p = \int_0^1 g_1^u(x, Q^2)dx
\]
\[
= (4\Delta u + \Delta d + \Delta s + 4\Delta c)/18,
\]
which can be rewritten as
\[
\Gamma_1^p = \int_0^1 g_1^u(x, Q^2)dx
\]
\[
= (3a_3 + a_s - a_{15} + 5a_0)/36
\]
where the notations
\[
a_3 = \Delta u - \Delta d, \quad a_s = \Delta u + \Delta d - 2\Delta s
\]
\[
a_{15} = \Delta u + \Delta d + \Delta s - 3\Delta c
\]
\[
a_0 = \Delta u + \Delta d + \Delta s + \Delta c
\]
have been introduced. Using exchange \( \Delta u \leftrightarrow \Delta d \), or \( a_3 \leftrightarrow -a_3 \) in (41), we can obtain \( \Gamma_1^p \) for the neutron.

### 4. Numerical results and discussion.

Since the probability of charm-related splitting (9) is much smaller than \( u,d,s \)-related splittings (8), we expect that the values of parameters \( a \) and \( \epsilon \) in SU(4) should be very close to those used in the SU(3) version. We choose \( a = 0.143, \epsilon = 0.454 \) [note that \( a = 0.145, \epsilon = 0.460 \) in SU(3)], and leave \( \epsilon_c \) as a variable, then express the quark flavor and helicity contents as functions of \( \epsilon_c \).

To determine the range of \( \epsilon_c \), we plot \( a_3 \) as the function of \( \epsilon_c \) in Fig.1. Using the most precise data from the neutron \( \beta \)-decay, \( a_3 = (G_A/G_V)_{n-p} = 1.2670 \pm 0.0035 \), we obtain \( \epsilon_c \approx 0.06 \pm 0.02 \). To include other possible theoretical uncertainties arise from the model approximations, however, we prefer to introduce a larger uncertainty and take
\[
\epsilon_c \approx 0.06 \pm 0.04.
\]

In addition to the three-parameter set \{\( a, \epsilon, \epsilon_c \)\} [SU\(^{(a)}\)(4)], we also consider the four-parameter set:\{\( a, \epsilon, \zeta', \epsilon_c \)\} [SU\(^{(b)}\)(4)] to show the \( \eta^0 \) effect. The parameter sets used in this paper and in previous SU(3) version are listed in Table II.

Using the parameter sets SU\(^{(a)}\)(4) and SU\(^{(b)}\)(4), the flavor and spin observables in the proton are calculated and listed in Tables III and IV respectively. For comparison, we also list the existing data, the results from previous SU(3) description [7, 8], the naive quark model
(NQM) prediction, and results given by other models or analyses. Including the QCD radiative corrections, the first moments of the spin structure functions \( g_1^u \) and \( g_1^d \) are also shown in Table IV. We also calculated two reduced matrix elements \( F \) and \( D \), and the ratios \( G_A/G_V \) of the hyperon beta decays. The results are listed in Table V. One can see that both SU\(^{(a)}\)(4) and SU\(^{(b)}\)(4) versions satisfactorily describe almost all the existing data. Furthermore, they give many new predictions on charm-related observables, which are in the bold type shown in Tables III and IV (for simplicity, we use \( \epsilon_c \equiv 0.06 \) in SU\(^{(b)}\)(4) without the uncertainty). A few main predictions selected from SU\(^{(a)}\)(4) results are listed in the following:

\[
2\bar{\epsilon}/\sum (q + \bar{q}) \simeq 0.011 \pm 0.008 \quad (46)
\]

measures the size of the intrinsic charm in the proton,
\[
\Delta c \simeq -0.009 \pm 0.006 \quad (47)
\]

is the charm helicity, and
\[
\Delta c/\Delta \Sigma \simeq -(0.021 \pm 0.014) \quad (48)
\]

is the fraction of total quark helicity carried by the charmed quark. Several remarks are in order:

- Comparing the SU\(^{(a)}\)(4) with SU\(^{(b)}\)(4) predictions, one can see that there are 10-20% differences between them only for the light-flavor contents, e.g. \( \bar{d}/\bar{u} \) (0.111 \(-\) 0.141), \( \bar{d}/\bar{u} \) (0.71 \(-\) 0.64), \( 2\bar{s}/(\bar{u} + \bar{d}) \) (0.66 \(-\) 0.75), and \( 2\bar{s}/(u + d) \) (0.118 \(-\) 0.133) [we note that both predictions are consistent with the existing data within errors], and all other predictions are almost no changes. It shows that the \( \eta^0 \) has minor or no effect on the spin and charm-related observables in the model. This is because first the \( \eta^0 \) does not have \( c, \bar{c} \) components and second the \( g_1 \) and \( \eta_4 \) (or \( q_4 \) and \( \bar{q}_4 \), \( q = u, d, s \), appeared with equal probability in \( \eta^0 \)). It should be noted that the approximation \( \zeta^2 \simeq 0 \) does not mean the probability of fluctuation \( q \rightarrow q' + \eta^0 \) \((\zeta^2 a)\) is smaller than that of \( q \rightarrow q' + D^0 \) \((\epsilon_c a)\). Actually, we have \( \epsilon_c < \zeta^2 \). Hence we use the approximation \( \zeta^2 = 0 \) in SU\(^{(a)}\)(4) version only for the practical reason explained here.

- The probability \( a \) of the fluctuation \( u \rightarrow d + \pi^+ \) has been estimated in chiral field theory (see e.g. [22, 27])

\[
a_{u \rightarrow d + \pi^+} = \int_0^1 dx \Theta(\Lambda^2 - \tau(z)) P_{u \rightarrow d + \pi^+}(z), \quad (49)
\]

where

\[
P_{u \rightarrow d + \pi^+}(z) = \frac{g_2^2 (m_u + m_d)^2}{32 \pi^2 f_{\pi}^2 z} \cdot \int_{-\Lambda^2}^{-\tau(z)} dt \frac{t - (m_u + m_d)^2}{(t - m_\pi^2)^2}, \quad (50)
\]

and \( -\tau(z) = m_\pi^2 z - m_\pi^2 z/(1 - z) \). In Eq.(50), \( g_A \simeq 0.75 \) is the dimensionless axial-vector coupling, \( f_{\pi} \simeq 0.093 \) GeV the pion decay constant, \( m_u \) (\( m_d \)) the constituent mass of the \( u \) (\( d \)) quark, \( \Lambda \) the ultraviolet cutoff, and \( m_\pi \) is the pion mass. For \( \Lambda \simeq 2.4 \) GeV, one obtains \( a \simeq 0.142 \). For the strange quark fluctuation, \( u \rightarrow s + K^+ \), similar calculation with some approximation leads to the probability \( a \simeq 0.062 \), which gives \( \epsilon \simeq 0.44 \). We assume the same formula can be used for the charm fluctuation, \( u \rightarrow c + D^0 \), and obtain \( \epsilon_c \simeq 0.004 \), which gives \( \epsilon_c \simeq 0.03 \), which is consistent with \( \epsilon_c \simeq 0.06 \pm 0.04 \) given in Eq.(45). Physically, the probability of splitting to the heavier mesons should be less than or splitting to the lighter ones. Hence the above estimation is quite reasonable.

- The theoretical uncertainties shown in (46)-(48) and in Tables III, IV and V arise only from the uncertainty of \( \epsilon_c \) in (45). If the observable does not depend on \( \epsilon_c \), such as \( d - \bar{u}, d/\bar{u}, 2\bar{s}/(\bar{u} + \bar{d}) \), etc. (these quantities depend only on \( \tilde{A}, \tilde{B} \), and \( \tilde{C} \), and not on \( \tilde{D} \), i.e. independent of \( \epsilon_c \), there is no uncertainty for them. This has been shown in Table III. Two special quantities \( \Delta \epsilon/\epsilon \) and \( \Delta s/s \) are also independent of \( \epsilon_c \) as shown in Table IV. We put a star (*) mark on some ‘data’ in Tables III and IV to denote they are model predictions or from theoretical analyses.

- The SU(4) quark-meson model predicts an intrinsic charm component of the nucleon, \( \bar{\epsilon}/\sum (q + \bar{q}) \simeq 1\% \), which agrees with the predictions given in [3, 7, 12] and is also close to the those given in [4, 5] and [13, 17]. We note that the IC component is almost one order of magnitude smaller than the intrinsic strange component \( 2\bar{s}/\sum (q + \bar{q}) \).

- Using the approach given in a previous work (see Eq. (3.6) in [22]), we can show that

\[
2 \int_0^1 dx \bar{x} \epsilon(x)/\sum \int_0^1 dx [x \bar{q}(x) + \bar{q}(x)] < 2\bar{\epsilon}/\sum (q + \bar{q}), \quad (51)
\]

where, as defined in this paper, \( \bar{\epsilon} \equiv \int_0^1 dx \bar{x} \epsilon(x) \) and \( \sum (q + \bar{q}) \equiv \int_0^1 dx [x \bar{q}(x) + \bar{q}(x)] \). The l.h.s. of Eq. (51) is the fraction of the total quark momentum carried by the charm and anticharm quarks. The prediction (46) implies that this fraction is less than 1\%. Assuming the quark and antiquark share about one half of the nucleon momentum, then the charm and anticharm carry about 0.5\% of the nucleon momentum or less.

- From Table III, we have

\[
\begin{align*}
    u + \bar{u} & : d + \bar{d} : s + \bar{s} : c + \bar{c} \\
    \simeq 0.53 & : 0.37 : 0.09 : 0.01.
\end{align*}
\]

(52)
If we assume the quarks carry about 55% of the nucleon momentum, Eq. (52) implies that the fractions of the nucleon momentum carried by $u$, $d$, $s$, and $c$-flavors are approximately 29.2%, 20.3%, 4.9%, and 0.6% respectively. They may compare with 31.4%, 17.8%, 4.3%, and 1.2% given by the DIS data at $Q^2 = 20$ GeV$^2$, where the gluons carry about 45% of the nucleon momentum.

- The prediction of intrinsic charm polarization, $\Delta c \simeq -0.009 \pm 0.006$ is close to the result $\Delta c = -0.020 \pm 0.005$ given in the instanton model \[3\]. This might be related to the strong suppression of non-spinflip contribution in both models. Our $\Delta c$ in \[1\], \[2\] (±0.3). However, the size of $\Delta c$ given in \[1\] (±5 · 10$^{-4}$) is even smaller. Hence further investigation in this quantity is needed.

- The ratio $\Delta c/\Delta \Sigma$ as the function of $\epsilon_c$ is plotted in Fig. 2. Taking $\epsilon_c \simeq 0.06$, one has $\Delta c/\Delta \Sigma \simeq -0.021$. This is consistent with the prediction given in \[1\], but smaller than that given in \[3\]. Combining with the fractions of the light quark helicities, we have

$$\Delta u/\Delta \Sigma \simeq 2.171, \quad \Delta d/\Delta \Sigma \simeq -0.988, \quad \Delta s/\Delta \Sigma \simeq -0.162, \quad \Delta c/\Delta \Sigma \simeq -0.021,$$

(53)

one can see that the $u$-quark helicity is positive (parallel to the nucleon spin) and about two times larger than the total quark helicity $\Delta \Sigma$. The $d$, $s$, and $c$-helicities, however, are all negative (antiparallel to the nucleon spin), and their sizes decrease as

$$|\Delta d| : |\Delta s| : |\Delta c| \simeq 1 : 10^{-1} : 10^{-2}.$$  

(54)

Compare to the intrinsic strange helicity $\Delta s$, the intrinsic charm helicity is one order of magnitude smaller.

Since the hyperon $\beta$-decay data are measured at low $Q^2$ and and our model predictions are defined at the scale $(0.2 \text{ GeV})^2 < \mu^2 < (1.0 \text{ GeV})^2$, hence we may compare them with less ambiguity. However, many data listed in Tables III and IV are coming from the DIS measurements at higher $Q^2$ range. To make a meaningful comparison of model predictions with these data, we have to discuss the $Q^2$ dependence of these observables. For spin observable, as we mentioned in section III of \[27\] that the model predictions, e.g. $\Delta u$, $\Delta d$, $\Delta s$, etc. are compared with the (factorization) scheme-independent DIS observables $a_q(Q^2) \equiv \Delta q - [a_s(Q^2)/2\pi] \Delta G(Q^2)$ at the same $Q^2$ scale [i.e. $(0.2 \text{ GeV})^2 < \mu^2 < (1.0 \text{ GeV})^2$, where $\Delta G(Q^2)$ is the helicity of the gluon, and the axial charge $a_q(Q^2)$ is defined in the Adler-Bardeen scheme. Although $a_q(Q^2)$ is independent of $Q^2$ at the leading order and changes very slowly with $Q^2$ at NLO, we still need to assume the perturbative QCD can be used down to the scale $\mu^2$. The perturbative QCD evolution approach has been successfully used down to $Q^2 \simeq 0.23$ GeV$^2$ \[24\], it is not clear, however, if the approach still hold below this $Q^2$.

Finally, in the quark meson fluctuation model, it is possible to include the contributions come from quark splittings to the vector mesons such as $K^*$, $\rho$, etc. [1–nonet in SU(3) and 1–15-plet in SU(4)]. However, it will change the formalism completely and is far beyond the goal of this paper. For simplicity and consistency, we only discuss the contributions of $0^+$ pseudoscalar mesons at this moment and defer the discussion of possible vector meson fluctuations to a later time.

In summary, we have calculated the intrinsic charm contribution in the SU(4) quark meson model with symmetry breaking. Despite the approximations and possible theoretical uncertainties, the overall agreement between the predictions and the existing data seems to be quite satisfactory considering the model is simple and has only a few parameters. The model also leads to many new predictions on observables explicitly related to the charm or anticharm. These observables are zero, e.g. $\sum_q (q \cdot \bar{q})$, $\Delta c$, etc. or indefinite, e.g. $\Delta c/c$ and $c_t/c_s$, in the SU(3) description. We hope that these predictions can be tested by the analyses of the DIS data on polarized and unpolarized charm productions in the near future.

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Figures
FIG. 1: $a_3$ as the function of $\epsilon_c$.

FIG. 2: Intrinsic charm quark polarization in the proton as the function of $\epsilon_c$.

Tables

| $q^{'\dagger}$ | $P_{q^{'\dagger}}(q^{'\dagger},\bar{q}^{'\dagger})$ | $P_{d^{'\dagger}}(q^{'\dagger},\bar{q}^{'\dagger})$ | $P_{c^{'\dagger}}(q^{'\dagger},\bar{q}^{'\dagger})$ |
|-----------------|---------------------------------|---------------------------------|---------------------------------|
| $u^{'\dagger}$  | $1-(1+\epsilon_c+2f)a/2 + (1-\tilde{q})a/2$ | $A^2a/2$ | $B^2a/2$ |
| $d^{'\dagger}$  | $(1+\epsilon_c+2f)a/2 + (1-\tilde{q})a/2$ | $a + \tilde{A}^2a/2$ | $\epsilon a + \tilde{B}^2a/2$ |
| $s^{'\dagger}$  | $A^2a/2$ | $1-(1+\epsilon_c+2f)a/2 + (1-\tilde{q})a/2$ | $\epsilon a + \tilde{B}^2a/2$ |
| $c^{'\dagger}$  | $\tilde{A}^2a/2$ | $(1+\epsilon_c+2f)a/2 + (1-\tilde{q})a/2$ | $1-(\epsilon + f s + \epsilon_c/2)a + \tilde{C}^2a/2$ |
| $\bar{u}^{'\dagger}$ | $\epsilon a + \tilde{A}^2a/2$ | $\tilde{D}^2a/2$ | $\epsilon a + \tilde{D}^2a/2$ |
| $\bar{d}^{'\dagger}$ | $\epsilon a + \tilde{D}^2a/2$ | $\epsilon a + \tilde{D}^2a/2$ | $\epsilon a + \tilde{D}^2a/2$ |

| Model | $\alpha$ | $\epsilon$ | $\chi^2_{SU(3)}$ | $\epsilon_c$ |
|-------|----------|----------|----------------|----------|
| SU($a$)(4) | 0.143 | 0.454 | 0.06 ± 0.04 |
| SU($b$)(4) | 0.143 | 0.454 | 0.1 | 0.06 |
| SU(3) | 0.145 | 0.460 | 0.1 | – |
### TABLE III: Quark Flavor Observables.

| Quantity | Data | SU\(^{(a)}\) (4) | SU\(^{(b)}\) (4) | SU\(^{(3)}\) | NQM |
|----------|------|------------------|------------------|-------------|-----|
| \(d - \bar{u}\) | 0.110 ± 0.018 \[3\] | 0.111 | 0.141 | 0.143 | 0 |
| \(\bar{u}/d\) | \(\bar{u}(x)/d(x)\)| \(0.1<x<0.2 = 0.67 ± 0.06\) | \(0.51 ± 0.06\) \[3\] | 0.71 | 0.64 | 0.64 |
| \(2\bar{s}/(\bar{u} + d)\) | \(<2x\bar{s}(x) >/x(\bar{u}(x) + d(x))>/ \approx 0.477 ± 0.051\) | 0.66 | 0.75 | 0.76 |
| \(2\bar{c}/(\bar{u} + d)\) | – | 0 \(0.083 ± 0.055\) | 0.085 | 0 |
| \(2\bar{s}/(u + d)\) | \(<2x\bar{s}(x) >/x(u(x) + d(x))>/ \approx 0.099 ± 0.009\) | 0.118 | 0.133 | 0.136 | 0 |
| \(2\bar{c}/(u + d)\) | – | 0 \(0.015 ± 0.010\) | 0.015 | 0 |
| \((u + \bar{u})/\sum(q + \bar{q})\) | – | 0.530 ± 0.004 | 0.519 | 0.523 | 2/3 |
| \((d + \bar{d})/\sum(q + \bar{q})\) | – | 0.368 ± 0.003 | 0.370 | 0.374 | 1/3 |
| \((s + \bar{s})/\sum(q + \bar{q})\) | \(<2x\bar{s}(x) >/\sum <x(q(x) + \bar{q}(x))>/ \approx 0.076 ± 0.022\) | 0.090 ± 0.001 | 0.100 | 0.103 | 0 |
| \((c + \bar{c})/\sum(q + \bar{q})\) | \(<2x\bar{s}(x) >/\sum <x(q(x) + \bar{q}(x))>/ \approx 0.10 ± 0.06\) | 0.011 ± 0.008 | 0.110 | 0 |
| \(\sum \bar{q}/\sum q\) | \(<xq(x) >/\sum <xq(x)>/ \approx 0.245 ± 0.005\) | 0.230 ± 0.004 | 0.233 | 0.231 | 0 |

### TABLE IV: Quark Spin Observables

| Quantity | Data | SU\(^{(a)}\) (4) | SU\(^{(b)}\) (4) | SU\(^{(3)}\) | NQM |
|----------|------|------------------|------------------|-------------|-----|
| \(\Delta u\) | 0.85 ± 0.04 \[4\] | 0.871 ± 0.009 | 0.859 | 0.863 | 4/3 |
| \(\Delta d\) | –0.41±0.04 \[4\] | –0.397 ± 0.002 | –0.393 | –0.397 | –1/3 |
| \(\Delta s\) | –0.07±0.04 \[4\] | –0.065 ± 0.000 | –0.065 | –0.067 | 0 |
| \(\Delta c\) | –0.020±0.004 \[1\] | –0.009 \(0.009\) | –0.009 | 0 | 0 |
| \(\Delta \Sigma/2\) | 0.19 ± 0.06 \[1\] | 0.200 ± 0.006 | 0.196 | 0.200 | 1/2 |
| \(\Delta u, \Delta d\) | –0.02 ± 0.11 \[4\] | 0 | 0 | 0 |
| \(\Delta s, \Delta c\) | – | 0 | 0 | 0 |
| \(\Delta u/\Sigma\) | – | 2.171 ± 0.043 | 2.192 | 2.162 | 4/3 |
| \(\Delta d/\Sigma\) | – | –0.988 ± 0.024 | –1.004 | –0.994 | –1/3 |
| \(\Delta s/\Sigma\) | – | –0.162 ± 0.005 | –0.166 | –0.167 | 0 |
| \(\Delta c/\Sigma\) | –0.08 ± 0.01 \[3\] | –0.021 \(0.021\) | –0.022 | 0 | 0 |
| \(\Delta u/u\) | – | 0.383 ± 0.003 | 0.381 | 0.383 | 2/3 |
| \(\Delta d/d\) | – | –0.287 ± 0.001 | –0.283 | –0.284 | –1/3 |
| \(\Delta s/s\) | – | –3/10 | –0.269 | –0.269 | – |
| \(\Delta c/c\) | – | –16/51 | –16/51 | – | – |
| \(u_t/u_{t1}\) | – | 2.241 ± 0.012 | 2.231 | 2.241 | 5 |
| \(d_t/d_{t1}\) | – | 0.554 ± 0.001 | 0.559 | 0.558 | 1/2 |
| \(s_t/s_{t1}\) | – | 7/13 | 0.576 | 0.576 | – |
| \(c_t/c_{t1}\) | – | 35/67 | 35/67 | – | – |
Table V: F, D and $G_A/G_V$ ratios of the hyperon beta decays. [a]: This is the best fit to four measured $(G_A/G_V)$ ($\chi^2 \simeq 1.96$) under the constraint $F+D=1.267$.

| Quantity | Data               | SU(4) | SU(4) | SU(3) | NQM |
|----------|--------------------|-------|-------|-------|-----|
| $\Gamma_1^0$ | 0.136 ± 0.016    | 0.143 ± 0.002 | 0.141 | 0.142 | 5/18 |
| $\Gamma_1^-$ | −0.041 ± 0.007   | −0.042 ± 0.001 | −0.043 | −0.042 | 0    |
| $a_3$    | 1.2670 ± 0.0035   | 1.268 ± 0.010 | 1.252 | 1.260 | 5/3  |
| $a_8$    | 0.579 ± 0.025     | 0.605 ± 0.006 | 0.595 | 0.600 | 1    |

$(G_A/G_V)_{n\rightarrow p}$ | 1.2670 ± 0.0035(a) | 1.268 ± 0.010 | 1.252 | 1.260 | 5/3  |
$(G_A/G_V)_{\Lambda\rightarrow p}$ | 0.718 ± 0.015(b) | 0.735 ± 0.007 | 0.725 | 0.730 | 1    |
$(G_A/G_V)_{\Sigma^+\rightarrow n}$ | −0.340 ± 0.017(c) | −0.332 ± 0.002 | −0.328 | −0.330 | −1/3 |
$(G_A/G_V)_{\Sigma^-\rightarrow \Lambda}$ | 0.25 ± 0.05(d) | 0.202 ± 0.002 | 0.198 | 0.200 | 1/3  |