Intrinsic Charm in the Nucleon

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Abstract

The quark flavor and spin structure of the nucleon is discussed in SU(4) symmetry breaking chiral quark model. The flavor and spin contents for charm quarks and anti-charm quarks are predicted and compared with the results given by other models. The intrinsic charm quark contribution to the Ellis-Jaffe sum rule is discussed.

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I. Introduction

As suggested by several authors long time ago [1–3], there are so called ‘intrinsic’ heavy quark components in the proton wave function. The ‘extrinsic’ heavy quarks are created on a short time scale in associate 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 intrinsic heavy quarks, however, exist over a long time scale independent of any external probe momentum. They are created from the quantum fluctuations associated with the bound state hadron dynamics. Hence the probability of finding the intrinsic heavy quark in the hadron is completely determined by nonperturbative mechanism. Since the chiral quark model provides a useful tool in studying the quark spin-flavor structure of the nucleon in nonperturbative way, we will use this model to discuss the heavy quark components of the proton. The quark components from the bottom and top quarks are negligible in the proton at the scale $m_c^2$ or lower, hence we only discuss the intrinsic charm (IC) quarks in this paper.

Although the SU(3) chiral quark model with symmetry breaking [3] has been quite successful in explaining the quark flavor and spin contents in the nucleon, the model is unnatural from the point of view of the standard model. According to the symmetric GIM model [6], one should deal with the weak axial current in the framework of SU(4) symmetry. It implies that the charm quark should play some role in determining the spin and flavor structure of the nucleon. An interesting question in high energy spin physics is whether the intrinsic charm exists in the proton. If it does, what is the size of the IC contribution to the flavor and spin observables of the proton. There are many publications on this topic (see for instance [5–18]).

In an ICTP internal report [4], we have extended the SU(3) chiral quark model given in [5] to the SU(4) case and obtained main results of the spin and flavor contents in the SU(4) chiral quark model. In this paper, we will give more detailed results on the contributions to the structure of the proton from the intrinsic charm and anticharm quarks. The results are compared with those given by other approaches. The intrinsic charm contribution to the Ellis-Jaffe sum rule is also discussed.

II. SU(4) chiral quark model with symmetry breaking

In the framework of SU(4), there are sixteen pseudoscalar bosons, a 15-plet and a singlet. The effective Lagrangian describing interaction between quarks and the bosons is

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

where $G^0_{u(d)}$ and $G^0_{s,c}$ are defined as

\[ G^0_{u(d)} = \frac{1}{\sqrt{2}} \pi^0 - \sqrt{\epsilon_c} \eta^0 - \frac{\zeta \eta^0}{\sqrt{3}} + \sqrt{\epsilon_c} \eta_c \]

\[ G^0_s = -\sqrt{\epsilon_c} \eta^0 + \zeta \eta^0 - \sqrt{\epsilon_c} \eta_c \frac{4}{\sqrt{3}} \]

(1)
\[ G_c^0 = -\zeta' \sqrt{3} \eta_0^0 + \sqrt{3} \eta_c^0 \]  

(2c)

with

\[ \pi^0 = \frac{1}{\sqrt{2}} (u \bar{u} - d \bar{d}); \quad \eta = \frac{1}{\sqrt{6}} (u \bar{u} + d \bar{d} - 2s \bar{s}) \]  

(3a)

\[ \eta' = \frac{1}{\sqrt{3}} (u \bar{u} + d \bar{d} + s \bar{s}); \quad \eta_c = (c \bar{c}). \]  

(3b)

The breaking effects are explicitly included in (1) and the SU(4) singlet term has been neglected. Defining \( a \equiv |g_{15}|^2 \), which denotes the transition probability of splitting \( u(d) \rightarrow d(u) + \pi^+(-) \), then \( \epsilon a \) denotes the probability of splitting \( u(d) \rightarrow s + K^-(0) \). Similar definitions are used for \( \epsilon_u a \) and \( \epsilon_d a \). If the breaking effects are dominated by mass differences, we expect \( 0 < \epsilon_c a < \epsilon_u a < \epsilon_d a < a \). We also have \( 0 < \zeta'^2 << 1 \) as shown in [5].

For a valence u-quark with spin-up, the allowed fluctuations are

\[ u_{\uparrow, (\downarrow)} \rightarrow d_{\downarrow, (\uparrow)} + \pi^+, \quad u_{\uparrow} \rightarrow s_{\downarrow} + K^+, \quad u_{\uparrow} \rightarrow u_{\downarrow} + G_0^0, \quad u_{\uparrow} \rightarrow c_{\downarrow} + \bar{D}^0, \quad u_{\uparrow} \rightarrow u_{\uparrow}. \]  

(4)

Similarly, one can write down 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 non-charmed baryons, the fluctuations from a valence charmed quark are not discussed here.

The spin-up and spin-down quark or antiquark contents in the proton, up to first order of fluctuation, can be written as

\[ n_p(q_{\uparrow, \downarrow}' \text{, or } \bar{q}_{\uparrow, \downarrow}') = \sum_{q = u, d, h} \sum_{n = \uparrow, \downarrow} n_p^{(0)}(q_h) P_{q_n}(q_{\uparrow, \downarrow}', \text{or } \bar{q}_{\uparrow, \downarrow}'), \]  

(5)

where \( P_{q_n}(q_{\uparrow, \downarrow}') \) and \( P_{q_n}(\bar{q}_{\uparrow, \downarrow}') \) are the probabilities of finding a quark \( q_{\uparrow, \downarrow}' \) or an antiquark \( \bar{q}_{\uparrow, \downarrow}' \) arise from all chiral fluctuations of a valence quark \( q_{\uparrow, \downarrow} \). The probabilities \( P_{q_{\uparrow, \downarrow}}(q_{\uparrow, \downarrow}') \) and \( P_{q_{\downarrow, \uparrow}}(q_{\downarrow, \uparrow}') \) can be obtained from the effective Lagrangian (1). In Table I only \( P_{q_{\uparrow}}(q_{\uparrow, \downarrow}') \) and \( P_{q_{\downarrow}}(\bar{q}_{\downarrow, \uparrow}') \) are listed. Those arise from \( q_{\uparrow} \) can be obtained by using the relations,

\[ P_{q_{\downarrow}}(q_{\uparrow, \downarrow}') = P_{q_{\downarrow}}(q_{\downarrow, \uparrow}'), \quad P_{q_{\downarrow}}(\bar{q}_{\downarrow, \uparrow}') = P_{q_{\downarrow}}(\bar{q}_{\downarrow, \uparrow}). \]  

(6)

The notations appeared in Table I are defined as

\[ f \equiv \frac{1}{2} + \frac{\epsilon_u \zeta'^2}{2} + \frac{\epsilon_c \zeta'^2}{16}, \quad f_s \equiv \frac{2 \epsilon_u}{3} + \frac{\zeta'^2}{48} + \frac{\epsilon_c}{16}. \]  

(7a)

and

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

(7b)

The special combinations \( \tilde{A}, \tilde{B}, \tilde{C}, \) and \( \tilde{D} \) stem from the quark and antiquark contents in the neutral bosons \( G_{u,d,s,c}^0 \) appeared in the effective Lagrangian (1) and defined in (2a)-(2c). The numbers \( f a \) and \( f_s a \) stand for the probabilities of the quark splitting \( u_{\uparrow}(d_{\uparrow}) \rightarrow u_{\downarrow}(d_{\downarrow}) + G_0^0 \) and \( s_{\uparrow} \rightarrow s_{\downarrow} + G_s^0 \) respectively.

In the limit \( \epsilon_c \rightarrow 0 \) and change \( \zeta' \) to \( 4\zeta' \), the \( f \) and \( f_s \) reduce to the corresponding quantities in the SU(3) case. We also have

\[ \tilde{A} \rightarrow \frac{1}{3} A_{SU(3)}, \quad \tilde{B} \rightarrow \frac{1}{3} B_{SU(3)}, \quad \tilde{C} \rightarrow \frac{1}{3} C_{SU(3)}, \quad \tilde{D} \rightarrow 0 \]  

(8)
II. Quark flavor and spin contents

We note that the quark helicity flips in the chiral splitting processes $q_{t,\uparrow} \rightarrow q_{t,\downarrow} + \text{GB}$, i.e. the first four processes in (4), but not for the last one. In the valence approximation, the SU(3)$\otimes$SU(2) proton wave function gives

$$n_p^{(0)}(u_\uparrow) = \frac{5}{3}, \quad n_p^{(0)}(u_\downarrow) = \frac{1}{3}, \quad n_p^{(0)}(d_\uparrow) = \frac{1}{3}, \quad n_p^{(0)}(d_\downarrow) = \frac{2}{3}. \quad (9)$$

Using (5), (9) and the probabilities $P_{q_t,\uparrow}(q_{t,\downarrow}')$ and $P_{q_t,\downarrow}(\bar{q}_{t,\uparrow}')$ listed in Table I, we obtain the quark and antiquark flavor contents

$$u = 2 + \bar{u}, \quad d = 1 + \bar{d}, \quad s = 0 + \bar{s}, \quad c = 0 + \bar{c}, \quad (10a)$$

where

$$\bar{u} = a[1 + \tilde{A}^2 + 2(1 - \tilde{A})^2], \quad \bar{d} = a[2(1 + \tilde{A}^2) + (1 - \tilde{A})^2], \quad (10b)$$

$$\bar{s} = 3a[\epsilon + \tilde{B}^2], \quad \bar{c} = 3a[\epsilon + \tilde{D}^2] \quad (10c)$$

From (10b), one obtains

$$\frac{\bar{u}}{\bar{d}} = 1 - \frac{6\tilde{A}}{(3\tilde{A} - 1)^2 + 8} \quad (11a)$$

$$\bar{d} - \bar{u} = 2a\tilde{A} \quad (11b)$$

Similarly, one can obtain $2\bar{c}/(\bar{u} + \bar{d})$, $2\bar{c}/\sum(q + \bar{q})$ and other flavor observables. It is easy to verify that in the limit $\epsilon_c \rightarrow 0$, all results reduce to those given in the SU(3) case.

For quark spin contents, we have

$$\Delta u = \frac{4}{3}[1 - a(\epsilon + \epsilon_c + 2f)] - a \quad (12a)$$

$$\Delta d = -\frac{1}{3}[1 - a(\epsilon + \epsilon_c + 2f)] - a \quad (12b)$$

$$\Delta s = -a\epsilon \quad (12c)$$

$$\Delta c = -a\epsilon_c \quad (12d)$$

$$\Delta \Sigma \equiv \sum_{q=u,d,s,c} \Delta q = 1 - 2a(1 + \epsilon + \epsilon_c + f) \quad (12e)$$

and

$$\Delta \bar{q} = 0, \quad (q = u, d, s, c) \quad (12f)$$

Comparing to the SU(3) case, a new $\epsilon_c$ term has been included in $\Delta u$, $\Delta d$ and $\Delta \Sigma$, but there is no change for $\Delta s$. In SU(4) chiral quark model, the charm quark helicity $\Delta c$ is nonzero and definitely negative. The size of the intrinsic charm (IC) helicity depends on the parameters $\epsilon_c$ and $a$. We will see below that the range of $\epsilon_c$ is about 0.1–0.3. Since $a \simeq 0.14$, one has

$$\Delta c \simeq -0.03 \quad (13a)$$
The ratio of $\Delta c/\bar{c}$, however, is a constant

$$\frac{\Delta c}{\bar{c}} = -\frac{16}{51} \simeq -0.314$$  \hspace{1cm} (13b)$$

which does not depend on any chiral parameters. This is a special prediction from the chiral quark model.

In the framework of SU(4) parton model, the first moment of the spin structure function $g_1(x, Q^2)$ in the proton is

$$\int_0^1 g_1^p(x, Q^2) dx = \frac{1}{2} [\frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s + \frac{4}{9} \Delta c]$$  \hspace{1cm} (14)$$

which can be rewritten as

$$\int_0^1 g_1^p(x, Q^2) dx = \frac{1}{12} [a_3 + \frac{\sqrt{3}}{3} a_8 - \frac{\sqrt{6}}{3} a_{15} + \frac{5}{3} a_0]$$  \hspace{1cm} (15)$$

where the notations

$$a_3 = \Delta u - \Delta d, \quad a_8 = \frac{1}{\sqrt{3}} [\Delta u + \Delta d - 2 \Delta s], \quad a_{15} = \frac{1}{\sqrt{6}} [\Delta u + \Delta d + \Delta s - 3 \Delta c]$$  \hspace{1cm} (16a)$$

and

$$a_0 = \Delta u + \Delta d + \Delta s + \Delta c$$  \hspace{1cm} (16b)$$

have been introduced.

**IV. Numerical results and discussion.**

To estimate the size of $\Delta c$ and other intrinsic charm contributions, we use the same parameter set given in [5], $a = 0.145$, $\epsilon_\eta \simeq \epsilon = 0.46$, $\zeta^2 = 0.10$. We choose $\epsilon_c$ as a variable, then other quark flavor and helicity contents can be expressed as functions of $\epsilon_c$. We found that

$$\epsilon_c \simeq 0.1 - 0.3$$  \hspace{1cm} (17)$$

Our model results, data and theoretical predictions from other approaches are listed in Table II and Table III respectively, where $\epsilon_c = 0.20 \pm 0.10$ is assumed. One can see that the fit to the existing data is as good as in the SU(3) case.

Several remarks are in order:

1. The chiral quark model predicts an intrinsic charm component of the nucleon $(2\bar{c}/\sum (q + \bar{q}))$ around 3%, which agrees with the result given in [7] and the earlier number given in [8]. But the result given in [8] is much smaller (0.5%) than ours.

2. The prediction of intrinsic charm polarization $\Delta c = -0.029 \pm 0.015$ from the chiral quark model is very close to the result $\Delta c = -0.020 \pm 0.005$ given in the instanton QCD vacuum model [17]. We note that the size of $\Delta c$ given in [18] is about two order of magnitude smaller than ours. Hence further investigation in this matter is needed.

3. We plot the ratio $\Delta c/\Delta \Sigma$ as function of $\epsilon_c$ in Fig.1. In the range $0.1 < \epsilon_c < 0.3$, we have

$$\frac{\Delta c}{\Delta \Sigma} = -0.08 \pm 0.05$$  \hspace{1cm} (18)$$
which agrees well with the prediction given in [15] and is also not inconsistent with the result given in [17].

(4) For the first moment of the spin structure function $g_1^{(p,n)}$, we have included the QCD radiative corrections and the results agree well with the data.

To summarize, we have discussed the intrinsic charm contribution to the quark flavor and spin observables in the chiral quark model with symmetry breaking. The results are compatible with other theoretical predictions.

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REFERENCES

[1] J. F. Donoghue and E. Golowich, Phys. Rev. D15, 3421 (1977).
[2] S. J. Brodsky, P. Hoyer, C. Peterson and N. Sakai, Phys. Lett. B93, 451 (1980).
    S. J. Brodsky, and C. Peterson, Phys. Rev. D23, 2745 (1980).
[3] E. Hoffmann and R. Moore, Z. Phys. C20, 71 (1983).
[4] X. Song, Internal Report, ICTP, June (1998).
[5] X. Song, Phys. Rev. D57, 4114 (1998).
    X. Song, hep-ph/9802203.
[6] S. L. Glashow et al., Phys. Rev. D2, 2185 (1970).
[7] S. J. Brodsky, and I. Schmidt, Phys. Rev. D43, 179 (1991).
[8] T. Hatsuda, and T. Kunihiro, Phys. Rep. 247, 221 (1994).
[9] S. J. Brodsky, W. K. Tang and P. Hoyer, Phys. Rev. D52, 6285 (1995).
[10] B. W. Harris, J. Smith and R. Vogt, Nucl. Phys. B461, 181 (1996).
[11] R. Vogt and S. J. Brodsky, Nucl. Phys. B478, 311 (1996).
[12] G. Ingelman and M. Thunman, Z. Phys. C73, 505 (1997).
[13] I. Halperin and A. Zhitnitsky, Phys. Rev. D56, 7247 (1997).
[14] W. Melnitchouk and A. W. Thomas, Phys. Lett. B414, 134 (1997).
[15] A. Blotz and E. Shuryak, Phys. Lett. B439, 415 (1998).
[16] Y. A. Golubkov, hep-ph/9811351.
[17] F. Araki, M. Musakhanov and H. Toki, hep-ph/9808290.
[18] M. V. Polyakov, A. Schafer, and O. V. Teryaev, hep-ph/9812393.
TABLE I. The probabilities $P_{u,}(q_{t,+}^\prime, q_{t,-}^\prime)$ and $P_{s,}(q_{t,+}^\prime, q_{t,-}^\prime)$

| $q'$ | $P_{u,}(q_{t,+}^\prime)$ | $P_{d,}(q_{t,+}^\prime)$ | $P_{s,}(q_{t,+}^\prime)$ |
|------|----------------|----------------|----------------|
| $u_{t}$ | $1 - (\frac{1 + \epsilon + \epsilon}{2} + f)a + \frac{a}{2}(1 - \bar{A})^2$ | $\frac{a}{2}A^2$ | $\frac{a}{2}B^2$ |
| $v_{t}$ | $(\frac{1 + \epsilon + \epsilon}{2} + f)a + \frac{a}{2}(1 - \bar{A})^2$ | $a + \frac{a}{2}\bar{A}^2$ | $ea + \frac{a}{2}\bar{B}^2$ |
| $d_{t}$ | $\frac{a}{2}\bar{A}^2$ | $1 - (\frac{1 + \epsilon + \epsilon}{2} + f)a + \frac{a}{2}(1 - \bar{A})^2$ | $\frac{a}{2}\bar{B}^2$ |
| $d_{t}$ | $\frac{a}{2}\bar{A}^2$ | $(\frac{1 + \epsilon + \epsilon}{2} + f)a + \frac{a}{2}(1 - \bar{A})^2$ | $ea + \frac{a}{2}\bar{B}^2$ |
| $s_{t}$ | $\frac{a}{2}\bar{B}^2$ | $\frac{a}{2}\bar{B}^2$ | $1 - (\epsilon + f_{s} + \frac{a}{2})a + \frac{a}{2}\bar{C}^2$ |
| $s_{t}$ | $ea + \frac{a}{2}\bar{B}^2$ | $ea + \frac{a}{2}\bar{B}^2$ | $(\epsilon + f_{s} + \frac{a}{2})a + \frac{a}{2}\bar{C}^2$ |
| $c_{t}$ | $\frac{a}{2}\bar{B}^2$ | $\frac{a}{2}\bar{B}^2$ | $\frac{a}{2}\bar{D}^2$ |
| $c_{t}$ | $\epsilon_{a}a + \frac{a}{2}\bar{D}^2$ | $\epsilon_{a}a + \frac{a}{2}\bar{D}^2$ | $\epsilon_{a}a + \frac{a}{2}\bar{D}^2$ |

TABLE II. Quark flavor observables

| Quantity | Data | SU(3) | SU(4) |
|----------|------|-------|-------|
| $d - \bar{u}$ | 0.147 ± 0.039 | 0.147 | 0.120 |
|          | 0.110 ± 0.018 |       |       |
| $\bar{u}/d$ | $\frac{d(x)}{d(x)}|_{0.1 < x < 0.2} = 0.67 ± 0.06$ | 0.65 | 0.69 |
|          | $\frac{d(x)}{d(x)}|_{x = 0.18} = 0.51 ± 0.06$ |       |       |
| $2s/(\bar{u} + d)$ | $\frac{<2xS(x)>}{<x(\bar{u}(x) + d(x))>}$ | 0.477 ± 0.051 | 0.69 | 0.69 |
| $2c/(\bar{u} + d)$ | $\frac{<2xS(x)>}{<x(\bar{u}(x) + d(x))>}$ | 0 | 0.28 ± 0.14 |
| $2s/(u + d)$ | $\frac{<2xS(x)>}{<x(u(x) + d(x))>}$ | 0.099 ± 0.009 | 0.128 | 0.120 |
| $2c/(u + d)$ | $\frac{<2xS(x)>}{<x(u(x) + d(x))>}$ | 0 | 0.05 ± 0.02 |
| $f_{s} \equiv 2s/\sum(q + \bar{q})$ | 0.10 ± 0.06 | 0.10 | 0.09 |
|          | 0.15 ± 0.03 |       |       |
| $f_{c} \equiv 2c/\sum(q + \bar{q})$ | $\frac{<2xS(x)>}{\sum<x(q(x) + \bar{q}(x))>}$ | 0.076 ± 0.022 | 0.03 | 0.03 ± 0.01 |
|          | 0.02 |       |       |
|          | 0.005 |       |       |
| $\bar{q}/\sum q$ | $\frac{<x\bar{q}(x)>}{\sum<x\bar{q}(x)>} = 0.245 ± 0.005$ | 0.235 | 0.246 |
| $f_{s}/f_{s}$ | 0.23 ± 0.05 | 0.21 | 0.22 |
TABLE III. Quark spin observables

| Quantity | Data         | SU(3) | SU(4)  |
|----------|--------------|-------|--------|
| Δu       | 0.85 ± 0.04  | 0.86  | 0.83   |
| Δd       | −0.41±0.04   | −0.40 | −0.39  |
| Δs       | −0.07±0.04   | −0.07 | −0.07  |
| Δc       | −0.020 ± 0.004 [17] | 0    | −0.029 ± 0.015 |
| Δu, Δd   | −0.02 ± 0.11 | 0     | 0      |
| Δs, Δc   | 0            | 0     | 0      |
| Δc/ΔΣ    | −0.08 ± 0.01 [13] | 0     | −0.08 ± 0.05 |
| Δc/ c    | −0.033 [17]  | −     | −0.314 |
| Γ\text{p} | 0.136 ± 0.016 | 0.133 | 0.133 |
| Γ\text{n} | −0.036 ± 0.007 | −0.037 | −0.034 |
| Δ3       | 1.257 ± 0.0028 | 1.26  | 1.259 |
| Δs       | 0.579 ± 0.025  | 0.60  | 0.578  |
FIG. 1. Intrinsic charm quark polarization in the proton as function of $\epsilon_c$. 