SU(4) chiral quark model with configuration mixing

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The chiral quark model with configuration mixing and broken SU(3)×U(1) symmetry is extended to include the contribution from $c\bar{c}$ fluctuations by considering broken SU(4) instead of SU(3). The implications of such a model are studied for quark flavor and spin distribution functions corresponding to E866 and the NMC data. The predicted parameters regarding the charm spin distribution functions, for example, Δc, $\Delta c/\Delta\Sigma$, $\Delta c/c$ as well as the charm quark distribution functions, for example, $\bar{c}$, $2\bar{c}/(\bar{u}+\bar{d})$, $2\bar{c}/(u+d)$ and $(c+\bar{c})/\Sigma(q+\bar{q})$ are in agreement with other similar calculations. Specifically, we find $\Delta c=-0.009$, $\Delta c/\Delta\Sigma=-0.02$, $\bar{c}=0.03$ and $(c+\bar{c})/\Sigma(q+\bar{q})=0.02$ for the χQM parameters $a=0.1$, $\alpha=0.4$, $\beta=0.7$, $\zeta_{E866}=-1-2\beta$, $\zeta_{NMC}=-2-2\beta$ and $\gamma=0.3$; the latter appears due to the extension of SU(3) to SU(4).

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There has been considerable interest in estimating the possible size of the intrinsic charm content of the nucleon [1–5]. Detailed investigations have been carried out regarding the size and implications of the intrinsic charm contribution for the nucleon [6] in a version of the chiral quark model (χQM) [7–13] which is quite successful in giving a satisfactory explanation of "proton spin crisis" [14] including the violation of the Gottfried sum rule [15–17]. Further, the same model is also able to account for the existence of a significant strange quark content $\bar{s}$ [18,19] in the nucleon and is also able to provide a fairly satisfactory explanation for the quark flavor and spin distribution functions [20], baryon magnetic moments [8,9,21], absence of polarizations of the antiquark sea in the nucleon [22], hyperon decay parameters [23–25] etc.

Recently, it has been shown that configuration mixing generated by spin-spin forces [26–28], known to be compatible [29–31] with the χQM, improves the predictions of χQM regarding the quark distribution functions and the spin polarization functions [32]. Further, χQM with configuration mixing (henceforth to be referred to as χQM_{gcm}) when coupled with the quark sea polarization and orbital angular momentum (Cheng-Li mechanism [21]) as well as "confinement effects" [33,34] is able to give an excellent fit [35] to the octet magnetic moments and a perfect fit for the violation of the Coleman Glashow sum rule [36].

The successes of χQM in resolving the "proton spin crisis" and related issues strongly suggest that constituent quarks and the weakly interacting Goldstone bosons (GBs) provide the appropriate degrees of freedom in the nonperturbative regime of QCD. Thus the quantum fluctuations generated by broken chiral symmetry in χQM_{gcm} should be able to provide a viable estimate of the heavier quark flavor, for example, $c\bar{c}$, $b\bar{b}$ and $t\bar{t}$. However, it is known that these flavor fluctuations are much suppressed in the case of $b\bar{b}$ and $t\bar{t}$ as compared to the $c\bar{c}$ because the intrinsic heavy quark contributions scale as $1/M_q^2$, where M_q is the mass of the heavy quark [1,30]. Therefore, regarding the intrinsic charm flavor content of the nucleon one should estimate only the contribution of $c\bar{c}$ fluctuations and for that one should be considering the extension of SU(3) symmetry in χQM to SU(4).

The purpose of the present paper, on the one hand, is to extend χQM_{gcm} with broken SU(3)×U(1) symmetry to broken SU(4)×U(1) symmetry. On the other hand, using the New Muon Collaboration (NMC) [16] and the latest E866 data [17], we intend to study the implications of such a model for quark flavor and spin distribution functions, in particular the charm quark flavor and spin distribution functions.

The details of χQM_{gcm} within the SU(3) framework have already been discussed in Ref. [32]; here we discuss the essentials of its extension to SU(4) χQM_{gcm}. To begin with, the basic process in the χQM is the emission of a GB which further splits into a $q\bar{q}$ pair, for example,

$$q_{\pm}\rightarrow \text{GB}^0+q'_{\mp}\rightarrow (q\bar{q}')+q'_{\mp}, \tag{1}$$

wherein $q\bar{q}'$ pairs and q' constitute the "quark sea" with q' having opposite helicity as that of q. The effective Lagrangian describing interaction between quarks and the mesons in the SU(4) case is

$$\mathcal{L}=g_{15}\bar{q}\phi q, \tag{2}$$

where g_{15} is the coupling constant,

$$q=\begin{pmatrix} u \\ d \\ s \\ c \end{pmatrix}$$

and ϕ represents the SU(4) matrix

$$\phi=\begin{pmatrix} \frac{\pi^o}{\sqrt{2}}+\beta\frac{\eta}{\sqrt{6}}+\zeta\frac{\eta'}{4\sqrt{3}}-\gamma\frac{3\,\eta_c^o}{4} & \pi^+ & \alpha K^+ & \gamma\overline{D}^o \\ \pi^- & -\frac{\pi^o}{\sqrt{2}}+\beta\frac{\eta}{\sqrt{6}}+\zeta\frac{\eta'}{4\sqrt{3}}-\gamma\frac{3\,\eta_c^o}{4} & \alpha K^o & \gamma D^- \\ \alpha K^- & \alpha\overline{K}^o & -\beta\frac{2\,\eta}{\sqrt{6}}+\zeta\frac{\eta'}{4\sqrt{3}}-\gamma\frac{3\,\eta_c^o}{4} & \gamma D_s^- \\ \gamma D^o & \gamma D^+ & \gamma D_s^+ & -\zeta\frac{3\,\eta'}{4\sqrt{3}}+\gamma\frac{3\,\eta_c^o}{4} \end{pmatrix}.$$

SU(4) symmetry breaking is introduced by considering different quark masses $M_c>M_s>M_{u,d}$ as well as by considering the masses of GBs to be nondegenerate ($M_D>M_{K,\eta}>M_\pi$) similar to the SU(3) case [11–13,21], whereas the axial U(1) breaking is introduced by $M_{\eta'}>M_{K,\eta}$ [10,12,13,21]. The parameter $a(=|g_{15}|^2)$ denotes the transition probability of chiral fluctuation of the splittings $u(d)\rightarrow d(u)+\pi^{+(-)}$, whereas α^2a, β^2a, ζ^2a and γ^2a denote the probabilities of transition of $u(d)\rightarrow s+K^{-(o)}$, $u(d,s)\rightarrow u(d,s)+\eta$, $u(d,s)\rightarrow u(d,s)+\eta'$ and $u(d)\rightarrow c+\overline{D}^o(D^-)$, respectively.

The detailed effects of configuration mixing generated by spin-spin forces [26–28] in the context of χQM has already been discussed in χQM_{gcm} [32]; however to make the manuscript readable as well as self-contained we include here some of the essentials of configuration mixing. Following Ref. [32], the wave function for the octet of baryons after configuration mixing is given as

$$|B\rangle=(|56,0^+\rangle_{N=0}\cos\theta+|56,0^+\rangle_{N=2}\sin\theta)\cos\phi+(|70,0^+\rangle_{N=2}\cos\theta'+|70,2^+\rangle_{N=2}\sin\theta')\sin\phi, \tag{3}$$

where θ, θ' and ϕ are the mixing angles with

$$|56,0^+\rangle_{N=0,2}=\frac{1}{\sqrt{2}}(\chi'\phi'+\chi''\phi'')\psi^s(0^+), \tag{4}$$

$$|70,0^+\rangle_{N=2}=\frac{1}{2}[(\phi'\chi''+\phi''\chi')\psi'(0^+)+(\phi'\chi'-\phi''\chi'')\psi''(0^+)], \tag{5}$$

$$|70,2^+\rangle_{N=2}=\frac{1}{\sqrt{2}}[\phi'\chi^s\psi'(2^+)+\phi''\chi^s\psi''(2^+)]. \tag{6}$$

The spin wave functions are as follows:

$$\chi'=\frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow-\downarrow\uparrow\uparrow),\quad \chi''=\frac{1}{\sqrt{6}}(2\uparrow\uparrow\downarrow-\uparrow\downarrow\uparrow-\downarrow\uparrow\uparrow).$$

The isospin wave functions for the proton are

$$\phi'=\frac{1}{\sqrt{2}}(udu-duu),\quad \phi''=\frac{1}{\sqrt{6}}(2uud-udu-duu).$$

The above mixing can effectively be reduced to nontrivial mixing [28,34,37] and the corresponding "mixed" octet of baryons is expressed as

$$|B\rangle\equiv\left|8,\frac{1}{2}^+\right\rangle=\cos\phi|56,0^+\rangle_{N=0}+\sin\phi|70,0^+\rangle_{N=2}. \tag{7}$$

Henceforth, we would not distinguish between configuration mixing given in Eq. (3) and the "mixed" octet given above.

Following Refs. [11,13], the total probability of no emission of GB from a q quark ($q=u,\ d,\ s,\ c$) can be calculated from the Lagrangian for the SU(4) case and is given by

$$P_q=1-\sum P_q, \tag{8}$$

where

$$\sum P_u=a\left(\frac{3}{2}+\alpha^2+\frac{\beta^2}{6}+\frac{\zeta^2}{48}+\gamma^2\right), \tag{9}$$

$$\sum P_d=a\left(\frac{3}{2}+\alpha^2+\frac{\beta^2}{6}+\frac{\zeta^2}{48}+\gamma^2\right), \tag{10}$$

$$\sum P_s=a\left(2\alpha^2+\frac{2}{3}\beta^2+\frac{\zeta^2}{48}+\gamma^2\right), \tag{11}$$

$$\sum P_c=a\left(\frac{3}{16}\zeta^2+\frac{57}{16}\gamma^2\right). \tag{12}$$

Before getting into the details of the calculations one needs to formulate experimentally measurable quantities having implications for the charm content of the nucleon as well as dependent on the unpolarized quark distribution functions and the spin polarization functions in χQM_{gcm} with broken SU(4) symmetry. We first calculate the spin polarizations and the related quantities which are affected by the "mixed" nucleon. The spin structure of a nucleon for the SU(4) case is defined in a similar manner as that of the SU(3) case [10,12,13] and is

$$\hat{B}\equiv\langle B|N|B\rangle, \tag{13}$$

where $|B\rangle$ is the nucleon wave function defined in Eq. (7) and N is the number operator given by

$$N=n_{u^+}u^+ + n_{u^-}u^- + n_{d^+}d^+ + n_{d^-}d^- + n_{s^+}s^+ + n_{s^-}s^- + n_{c^+}c^+ + n_{c^-}c^-, \tag{14}$$

where $n_{q^\pm}$ are the number of $q^\pm$ quarks. The spin structure of the "mixed" nucleon, defined through Eq. (7), is given by

$$\left\langle 8,\frac{1}{2}^+|N|8,\frac{1}{2}^+\right\rangle=\cos^2\phi\langle 56,0^+|N|56,0^+\rangle + \sin^2\phi\langle 70,0^+|N|70,0^+\rangle. \tag{15}$$

Using Eqs. (4) and (5), for the proton we get

$$\langle 56,0^+|N|56,0^+\rangle=\frac{5}{3}u^+ + \frac{1}{3}u^- + \frac{1}{3}d^+ + \frac{2}{3}d^-, \tag{16}$$

$$\langle 70,0^+|N|70,0^+\rangle=\frac{4}{3}u^+ + \frac{2}{3}u^- + \frac{2}{3}d^+ + \frac{1}{3}d^-. \tag{17}$$

The spin structure after one interaction can be obtained by substituting in the above equations for every quark, for example,

$$q^\pm \to P_q q^\pm + |\psi(q^\pm)|^2, \tag{18}$$

where P_q is the probability of no emission of GB from a q quark defined in Eq. (8) and the probabilities of transforming a $q^\pm$ quark are $|\psi(q^\pm)|^2$ which are given for the SU(4) broken χQM as

$$|\psi(u^\pm)|^2=a\left(\frac{1}{2}+\frac{\beta^2}{6}+\frac{\zeta^2}{48}+\frac{\gamma^2}{16}\right)u^\mp + a d^\mp + a\alpha^2 s^\mp + a\gamma^2 c^\mp, \tag{19}$$

$$|\psi(d^\pm)|^2=a u^\mp + a\left(\frac{1}{2}+\frac{\beta^2}{6}+\frac{\zeta^2}{48}+\frac{\gamma^2}{16}\right)d^\mp + a\alpha^2 s^\mp + a\gamma^2 c^\mp, \tag{20}$$

$$|\psi(s^\pm)|^2=a\alpha^2 u^\mp + a\alpha^2 d^\mp + a\left(\frac{2}{3}\beta^2+\frac{\zeta^2}{48}+\frac{\gamma^2}{16}\right)s^\mp + a\gamma^2 c^\mp, \tag{21}$$

$$|\psi(c^\pm)|^2=a\gamma^2 u^\mp + a\gamma^2 d^\mp + a\gamma^2 s^\mp + a\left(\frac{3}{16}\zeta^2+\frac{9}{16}\gamma^2\right)c^\mp. \tag{22}$$

Substituting Eqs. (16), (17) and (18) in Eq. (15), we can derive the spin polarizations, defined as $\Delta q = q^+ - q^- + \overline{q}^+ - \overline{q}^-$, for example

$$\Delta u=\cos^2\phi\left[\frac{4}{3}-\frac{a}{3}\left(7+4\alpha^2+\frac{4}{3}\beta^2+\frac{1}{6}\zeta^2+\frac{9}{2}\gamma^2\right)\right] + \sin^2\phi\left[\frac{2}{3}-\frac{a}{3}\left(5+2\alpha^2+\frac{2}{3}\beta^2+\frac{1}{12}\zeta^2+\frac{9}{4}\gamma^2\right)\right], \tag{23}$$

$$\Delta d=\cos^2\phi\left[-\frac{1}{3}-\frac{a}{3}\left(2-\alpha^2-\frac{1}{3}\beta^2-\frac{1}{24}\zeta^2-\frac{9}{8}\gamma^2\right)\right] + \sin^2\phi\left[\frac{1}{3}-\frac{a}{3}\left(4+\alpha^2+\frac{1}{3}\beta^2+\frac{1}{24}\zeta^2+\frac{9}{8}\gamma^2\right)\right], \tag{24}$$

$$\Delta s=-a\alpha^2, \tag{25}$$

$$\Delta c=-a\gamma^2. \tag{26}$$

After having formulated the spin polarizations of various quarks in terms of SU(4) $\chi\mathrm{QM}_{gcm}$, we consider several measured quantities which are expressed in terms of the above mentioned spin polarization functions. Some of the quantities usually calculated in the χQM are the weak axial-vector form factors and are expressed as

$$(G_A/G_V)_{n\to p}=\Delta_3=\Delta u-\Delta d, \tag{27}$$

$$(G_A/G_V)_{\Lambda\to p}=\frac{1}{2}(2\Delta u-\Delta d-\Delta s), \tag{28}$$

$$(G_A/G_V)_{\Sigma^-\to n}=\Delta d-\Delta s, \tag{29}$$

$$(G_A/G_V)_{\Xi^-\to\Lambda}=\frac{1}{3}(\Delta u+\Delta d-2\Delta s). \tag{30}$$

Another quantity which is usually evaluated is the total helicity fraction carried by the quark q defined as

$$\Delta q/\Delta\Sigma, \tag{31}$$

where

$$\Delta\Sigma=\Delta_0=\Delta u+\Delta d+\Delta s+\Delta c, \tag{32}$$

which is the total quark spin content. It may be added that the expressions for the Bjorken [38] and Ellis-Jaffe sum rules [39] are not affected in the present case, however, the contributions to these get affected as Δu and Δd include contributions from charm quark fluctuations also. For the sake of completeness we express these in terms of the above mentioned spin polarization functions, for example, the Bjorken sum rule is

$$\int_0^1 [g_1^p(x,Q^2)-g_1^n(x,Q^2)]dx=\frac{G_A/G_V}{6}, \tag{33}$$

where $g_1^{p(n)}(x,Q^2)$ is the spin structure function of the proton (neutron) and G_A/G_V is the β decay constant for the neutron. The Ellis-Jaffe sum rule is given by

$$\Delta_8 = \Delta u + \Delta d - 2\Delta s = 3F - D, \tag{34}$$

where F and D are the axial coupling constants estimated from the weak decays of hyperons and their relation to the spin polarization functions remain the same in the case of SU(3) and SU(4) χQM, for example,

$$F = \frac{1}{2}(\Delta u - \Delta s), \tag{35}$$

$$D = \frac{1}{2}(\Delta u - 2\Delta d + \Delta s). \tag{36}$$

However, again Δu and Δd take on different values compared to SU(3) because there is an additional term corresponding to the charm quark fluctuations and also the coefficient corresponding to the η' term is different. This can be seen by comparing the expressions for Δu and Δd in the present case [Eqs. (23) and (24)] and the corresponding expressions for Δu and Δd in the SU(3) case [32].

The unpolarized valence quark distribution functions are not affected by configuration mixing, however these get affected due to the addition of $c\bar{c}$ fluctuations and hence are dependent on the $\mathrm{SU}(4)\times\mathrm{U}(1)$ symmetry breaking parameters. A calculation of these quantities also assumes importance in the present case as we attempt to effect a unified fit to spin and quark distribution functions. The quark distribution functions which have implications for the symmetry breaking parameters of SU(4) are the antiquark flavor contents of the "quark sea" which can be expressed as [6,10,13]

$$\bar{u} = \frac{1}{48}[(2\beta + \zeta + 2)^2 + 80]a, \tag{37}$$

$$\bar{d} = \frac{1}{48}[(2\beta + \zeta - 2)^2 + 128]a, \tag{38}$$

$$\bar{s} = \frac{1}{48}[(\zeta - 4\beta)^2 + 144\alpha^2]a, \tag{39}$$

$$\bar{c} = \frac{51}{16}\gamma^2 a. \tag{40}$$

The deviation from the Gottfried sum rule [15–17] can be expressed in terms of the symmetry breaking parameters β and ζ as

$$\left[I_G - \frac{1}{3}\right] = \frac{2}{3}\left[\frac{a}{6}(2\beta + \zeta - 6)\right], \tag{41}$$

where $I_G = \int_0^1 dx([F_2^p(x) - F_2^n(x)]/x)$ is the Gottfried integral. Similarly, $\bar{d}/\bar{u}$ [17,40] measured through the ratio of muon pair production cross sections σ_{pn} and σ_{pp}, is expressed in the present case as follows:

$$\bar{d}/\bar{u} = \frac{(2\beta + \zeta - 2)^2 + 128}{(2\beta + \zeta + 2)^2 + 80}. \tag{42}$$

Further, some of the quark flavor fractions usually discussed in the literature [2,4,5,19] are also expressed as follows:

$$f_q = \frac{q + \bar{q}}{\left[\sum_q (q + \bar{q})\right]}, \tag{43}$$

$$\frac{2\bar{s}}{\bar{u} + \bar{d}} = \frac{(\zeta - 4\beta)^2 + 144\alpha^2}{(2\beta + \zeta)^2 + 108}, \tag{44}$$

$$\frac{2\bar{c}}{\bar{u} + \bar{d}} = \frac{153\gamma^2}{(2\beta + \zeta)^2 + 108}, \tag{45}$$

$$\frac{2\bar{s}}{u + d} = \frac{a[(\zeta - 4\beta)^2 + 144\alpha^2]}{72 + a[(2\beta + \zeta)^2 + 108]}, \tag{46}$$

$$\frac{2\bar{c}}{u + d} = \frac{153\gamma^2 a}{72 + a[(2\beta + \zeta)^2 + 108]}. \tag{47}$$

The q and $\bar{q}$ distributions in the case of the proton are normalized as

$$u - \bar{u} = 2, \quad d - \bar{d} = 1, \quad s - \bar{s} = 0, \quad c - \bar{c} = 0. \tag{48}$$

The above mentioned spin polarization functions and the quark distribution functions are to be fitted for the E866 as well as NMC data. In principle, one can obtain this fit by considering all possible variations of SU(4) and U(1) symmetry breaking parameters as well as the mixing angle ϕ. However, keeping in mind the general expectation that the $c\bar{c}$ contribution cannot be large compared to the $s\bar{s}$ contribution as well as to compare our results with the corresponding results of $\chi\mathrm{QM}_{gcm}$ with $\mathrm{SU}(3)\times\mathrm{U}(1)$ symmetry breaking, in our analysis we have considered the parameters a, α and β to be the same as in the SU(3) case. The parameter γ, controlling $c\bar{c}$ contribution, has been varied from 0.1 to 0.3 as considered by other authors [6]. The parameter ζ, as discussed in Refs. [10,13], represents the U(1) symmetry breaking parameter and is responsible for reproducing the violation of the Gottfried sum rule. Similar to the case of SU(3), here also we have derived the relation of ζ in terms of β from the violation of the Gottfried sum rule given in Eq. (41). Its value undergoes a major change in the case of SU(4) as compared to that of SU(3), for example, for E866 we have $\zeta = -1 - 2\beta$ as compared to $\zeta = -0.3 - \beta/2$ and for NMC we have $\zeta = -2 - 2\beta$ as compared to $\zeta = -0.7 - \beta/2$. The mixing parameter ϕ is taken to be 20° as found from neutron charge radius [28,41] and considered in our earlier work [32,35]. The results without configuration mixing can easily be obtained by substituting $\phi = 0$ in the expressions for spin polarization functions.

In Tables I and II we have presented the results of our calculations pertaining to spin distribution and quark distribution functions, respectively. In the tables we have also included the results of $\chi\mathrm{QM}_{gcm}$ with SU(3) symmetry breaking, primarily to compare these with the corresponding

TABLE I. The calculated values of spin polarization functions Δu, Δd, Δs, Δc, quantities dependent on these: $\Delta\Sigma$, G_A/G_V, Δ_8 and the hyperon decay parameters both for NMC and E866 data.

		SU(3)		SU(4)			
		χQM$_{gcm}$		χQM		χQM$_{gcm}$	
Quantity	Data	NMC	E866	NMC	E866	NMC	E866
Δu	0.85 ± 0.04 [20]	0.91	0.92	0.98	1.01	0.92	0.94
Δd	-0.41 ± 0.04 [20]	-0.33	-0.34	-0.37	-0.38	-0.31	-0.32
Δs	-0.07 ± 0.04 [20]	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
Δc	-0.3^{a} [3]						
	-0.02 ± 0.004^{a} [3]	0	0	-0.009	-0.009	-0.009	-0.009
	-5×10^{-4a} [3]						
$\Delta_0/2=\Delta\Sigma/2$	0.19 ± 0.06 [20]	0.28	0.28	0.29	0.30	0.29	0.30
$\Delta_3=G_A/G_V$	1.267 ± 0.0035 [42]	1.24	1.26	1.35	1.39	1.23	1.26
Δ_8	0.58 ± 0.025 [42]	0.62	0.62	0.65	0.67	0.65	0.66
Δ_{15}		0.56	0.56	0.62	0.64	0.62	0.63
$\Delta u/\Delta\Sigma$		1.62	1.64	1.69	1.68	1.59	1.57
$\Delta d/\Delta\Sigma$		-0.59	-0.61	-0.64	-0.63	-0.53	-0.53
$\Delta s/\Delta\Sigma$		-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
$\Delta c/\Delta\Sigma$	-0.08 ± 0.01^{a} [3]	0	0	-0.02	-0.02	-0.02	-0.02
	-0.033^{a} [3]						
$\Delta u/u$		0.41	0.42	0.45	0.46	0.42	0.43
$\Delta d/d$		-0.25	-0.26	-0.28	-0.29	-0.24	-0.25
$\Delta s/s$		-0.14	-0.20	-0.16	-0.19	-0.16	-0.19
$\Delta c/c$		0	0	-0.30	-0.30	-0.30	-0.30
F	0.462	0.47	0.475	0.51	0.51	0.48	0.485
D	0.794	0.78	0.785	0.88	0.87	0.78	0.775
F/D	0.575	0.60	0.605	0.582	0.586	0.615	0.61
$(G_A/G_V)_{n\to p}$	1.26 ± 0.0035 [42]	1.24	1.26	1.35	1.39	1.23	1.26
$(G_A/G_V)_{\Lambda\to p}$	0.72 ± 0.02 [42]	0.72	0.73	0.78	0.81	0.72	0.74
$(G_A/G_V)_{\Sigma^-\to n}$	-0.34 ± 0.02 [42]	-0.31	-0.32	-0.35	-0.36	-0.29	-0.30
$(G_A/G_V)_{\Xi^-\to\Lambda}$	0.25 ± 0.05 [42]	0.22	0.21	0.22	0.22	0.22	0.22

[a]These values correspond to the calculated values.

SU(4) symmetry breaking calculations. Similarly, in the case of SU(4) we have also included the results without configuration mixing which allows the comparison of the two results for the SU(4) case. The calculations have been performed for E866 as well as for NMC data and the corresponding results for each case have been included in the tables.

From Table I, one can immediately find out that calculations in SU(4) χQM$_{gcm}$ are able to maintain the agreement achieved in the case of SU(3) χQM$_{gcm}$ for the spin polarizations Δu, Δd, Δs and the related quantities such as $\Delta\Sigma/2$, Δ_8, hyperon decay parameters F and D as well as the weak axial-vector form factors. Expectedly, the two results appear to be similar with the slight changes occurring in the case of SU(4) in comparison to the SU(3) results primarily due to changes induced in Δu and Δd involving the symmetry breaking parameters, ζ and γ, which take different values as compared to SU(3) χQM. One also finds that the quantities involving strange quarks are not affected because in the present formalism there is no process which can mix the strange and charm contributions. The main predictions of SU(4) χQM pertains to quantities such as, Δc, $\Delta c/\Delta\Sigma$ and $\Delta c/c$, which have vanishing amplitudes at the tree level in SU(3) χQM. The charm contribution, corresponding to spin polarization functions, however is smaller by one order of magnitude as compared to the corresponding parameter involving the strange quark which is in accord with another recent analysis [6]. Similarly, we find that $\Delta_{15}(=\Delta u+\Delta d+\Delta s-3\Delta c)$ is also in agreement with the analysis of Ref. [6].

The role of configuration mixing in the present context can easily be examined from Table I. We find that the configuration mixing effects a uniform improvement in the case of spin polarization functions compared to those without configuration mixing. For example, Δu, Δ_8, hyperon decay parameters F and D, weak axial-vector form factors $(G_A/G_V)_{n\to p}$, $(G_A/G_V)_{\Lambda\to p}$ show remarkable improvement whereas the results of Δs, Δc, $\Delta\Sigma$, $(G_A/G_V)_{\Sigma^-\to n}$ and $(G_A/G_V)_{\Xi^-\to\Lambda}$ are in a good deal of agreement with the data.

From Table II, we find that in the SU(4) χQM the important measurable quark distribution functions, for example, $\bar{d}-\bar{u}$, $\bar{d}/\bar{u}$, I_G, $2\bar{s}/(\bar{u}+\bar{d})$, $2\bar{s}/(u+d)$, f_s, f_3/f_8 etc. are in

TABLE II. The calculated values of quark flavor distribution functions and other dependent quantities as calculated in the SU(3) and SU(4) χQM with symmetry breaking with the same values of symmetry breaking parameters as used in spin distribution functions and hyperon β decay parameters.

		SU(3) χQM		SU(4) χQM	
Quantity	Data	NMC	E866	NMC	E866
$\bar{u}$		0.183	0.189	0.167	0.169
$\bar{d}$		0.33	0.31	0.30	0.285
$\bar{s}$		0.14	0.10	0.128	0.104
$\bar{c}$		0	0	0.03	0.03
$\bar{d}-\bar{u}$	0.147 ± 0.039 [16] 0.118 ± 0.018 [17]	0.147	0.117	0.133	0.117
$\bar{d}/\bar{u}$	1.96 ± 0.246 [40] 1.41 ± 0.146 [17]	1.89	1.59	1.80	1.69
I_G	0.235 ± 0.005 [16] 0.259 ± 0.005 [17]	0.235	0.255	0.244	0.256
$\frac{2\bar{s}}{(\bar{u}+\bar{d})}$	0.477 ± 0.051 [19]	0.55	0.41	0.55	0.46
$\frac{2\bar{c}}{(\bar{u}+\bar{d})}$		0	0	0.123	0.126
$\frac{2\bar{s}}{(u+d)}$	0.099 ± 0.009 [19]	0.08	0.06	0.07	0.06
$\frac{2\bar{c}}{(u+d)}$		0	0	0.02	0.02
$f_u=\frac{(u+\bar{u})}{\Sigma(q+\bar{q})}$		0.65	0.66	0.64	0.65
$f_d=\frac{(d+\bar{d})}{\Sigma(q+\bar{q})}$		0.45	0.45	0.44	0.44
$f_s=\frac{(s+\bar{s})}{\Sigma(q+\bar{q})}$	0.076 ± 0.02 [19]	0.08	0.06	0.07	0.06
$f_c=\frac{(c+\bar{c})}{\Sigma(q+\bar{q})}$	0.03[a] [5] 0.02[a] [2] 0.01[a] [4]	0	0	0.02	0.02
$f_3=f_u-f_d$		0.20	0.21	0.20	0.21
$f_8=f_u+f_d-2f_s$		0.94	0.99	0.94	0.97
f_3/f_8	0.21 ± 0.05 [10]	0.21	0.21	0.21	0.22
$\frac{\Sigma\bar{q}}{\Sigma q}$	0.245 ± 0.005 [19]	0.178	0.166	0.172	0.164

[a]These values correspond to the calculated values.

good agreement with the data. It may be noted that although in the present case some of the symmetry breaking parameters take different values compared to the SU(3) case still we find that our results are in good agreement with the data. It may also be noted that the quark distribution functions $\bar{u}$, $\bar{d}$ and $\bar{s}$ assume different values in the present case as compared to the SU(3) case because of the changed parameters; however the quantities dependent on these again remain in good agreement with data. The values of the quantities involving c quark, for example, $\bar{c}$, $2\bar{c}/(\bar{u}+\bar{d})$, $2\bar{c}/(u+d)$ and f_c, are in agreement with the predictions given by other authors [2–4]. Interestingly, in the case of $2\bar{s}/(\bar{u}+\bar{d})$ and $2\bar{s}/(u+d)$, our predictions are in better agreement with data compared to another recent analysis [6], therefore a refinement in the measurement of these would have important implications for the details of the χQM.

A closer scrutiny of the tables reveals several additional points. There is a difference in the predictions of the fit corresponding to E866 and NMC data as is evident in the case of Δu, Δ_3, $(G_A/G_V)_{n\to p}$, $(G_A/G_V)_{\Lambda\to p}$, $\bar{s}$, $2\bar{s}/(\bar{u}+\bar{d})$, $2\bar{s}/(u+d)$, f_s, f_3, f_8 and $\Sigma\bar{q}/\Sigma q$. This is primarily due to the fact that the parameter ζ, responsible for fitting the violation of Gottfried sum rule, assumes different values in the two cases. It may be of interest to mention that in SU(4) $\chi\mathrm{QM}_{gcm}$, $\Delta c/c$ is independent of any splitting parameter unlike other similar fractions for different quark flavors $\Delta q/q$.

To summarize, we have extended the $\chi\mathrm{QM}_{gcm}$ with broken SU(3)$\times$U(1) symmetry to broken SU(4)$\times$U(1) symmetry with and without configuration mixing. The implications of such a model have been studied for quark flavor and spin distribution functions corresponding to NMC and the latest E866 data. The charm dependent quantities such as charm spin distribution functions Δc, $\Delta c/\Delta\Sigma$, $\Delta c/c$ and the charm quark distribution functions $\bar{c}$, $2\bar{c}/(\bar{u}+\bar{d})$, $2\bar{c}/(u+d)$ and $(c+\bar{c})/\Sigma(q+\bar{q})$, have been calculated and the results are in agreement with other similar calculations. Specifically, we find $\Delta c=-0.009$, $\Delta c/\Delta\Sigma=-0.02$, $\bar{c}=0.03$ and $(c+\bar{c})/\Sigma(q+\bar{q})=0.02$. Interestingly, the SU(4) results remain in agreement with that corresponding to the SU(3) calculations despite different values of some of the symmetry breaking parameters. It may also be noted that the results with configuration mixing generally show better overlap with data than those without configuration mixing.

In conclusion, we would like to mention that χQM with broken SU(4) symmetry, apart from maintaining the successes of χQM with broken SU(3) symmetry, predicts the intrinsic charm spin and flavor distribution content of the nucleon which is found to be almost an order of magnitude smaller than the strange quark contributions but not entirely insignificant. A measurement of these charm related quantities would not only test the χQM but would also provide an insight into the nonperturbative regime of QCD.

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