Octet and decuplet baryon magnetic moments in the chiral quark model

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Octet and decuplet baryon magnetic moments have been formulated within the chiral quark model (χQM) with configuration mixing incorporating the sea quark polarizations and their orbital angular momentum through a generalization of the Cheng-Li mechanism. When the parameters of the χQM without configuration mixing are fixed by incorporating the latest data pertaining to $\bar{u}$-$\bar{d}$ asymmetry (E866) and the spin polarization functions, in the case of octet magnetic moments the results not only show improvement over the nonrelativistic quark model results but also give a nonzero value for the right hand side of the Coleman-Glashow sum rule, usually zero in most of the models. In the case of decuplet magnetic moments, we obtain a good overlap for Δ^{++}, Ω^-, and the transition magnetic moment ΔN for which data are available. In the case of the octet, the predictions of the χQM with the generalized Cheng-Li mechanism show remarkable improvements in general when the effects of configuration mixing and "mass adjustments" due to confinement are included, specifically in the case of p, Σ^+, Ξ^0, and the $\Sigma\Lambda$ transition magnetic moment and in the violation of the Coleman-Glashow sum rule an almost perfect agreement with data is obtained. When the above analysis is repeated with the earlier NMC data, a similar level of agreement is obtained; however, the results in the case of E866 look to be better. In this case, we incorporate in our analysis the gluon polarization Δg, found phenomenologically through the relation $\Delta\Sigma(Q^2)=\Delta\Sigma-[3\alpha_s(Q^2)/2\pi]\Delta g(Q^2)$; not only do we obtain an improvement in the quark spin distribution functions and magnetic moments, but also the value of Δg comes out in good agreement with certain recent measurements as well as theoretical estimates.

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I. INTRODUCTION

The measurements of the polarized structure functions of the proton in deep inelastic scattering (DIS) experiments [1–3] have shown that the valence quarks of the proton carry only about 30% of its spin. This "unexpected" conclusion from the point of view of the nonrelativistic quark model (NRQM) becomes all the more intriguing when it is realized that the NRQM is able to give a reasonably good description of baryon octet magnetic moments using the assumption that magnetic moments of quarks are proportional to the spin carried by them. Further, this issue regarding spin and magnetic moments becomes all the more difficult to understand when it is realized that the magnetic moments of baryons receive contributions not only from the magnetic moments carried by the valence quarks but also from various complicated effects, such as orbital excitations [4], relativistic and exchange current effects [5,6], pion cloud contributions [7], the effect of the confinement on quark masses [8,9], the effects of configuration mixing [5,9,10], "quark sea" polarizations [11–15], pion loop corrections [16], etc. Recently, it has been emphasized [15,17] that the problem regarding magnetic moments gets further complicated when one realizes that the Coleman-Glashow sum rule (CGSR) for octet magnetic moments [18], valid in a large variety of models, is convincingly violated by the data [19].

Recently, in a very interesting work, Cheng and Li [13] have shown that the DIS conclusions regarding the proton spin and the success of the NRQM in explaining magnetic moments can be reconciled in the chiral quark model χQM [11,20–22] if the $q\bar{q}$ sea, produced by the chiral fluctuations, in addition to being polarized, is also endowed with angular momentum. In particular, in the case of the nucleon they showed that the above mentioned mechanism (to be referred to as the Cheng-Li mechanism) leads to almost cancellations of the magnetic moment contribution of the polarized "quark sea" and its angular momentum, leaving a description of the magnetic moment of the nucleon in terms of the polarization of the valence quarks. The authors, in a very recent Rapid Communication [23], by considering the generalization of the Cheng-Li mechanism to hyperons incorporating coupling breaking and mass breaking terms, found that one is able to get a nonzero value for the violation of CGSR (ΔCG) [24] apart from improving the NRQM predictions for magnetic moments of the octet baryons. This fact, when viewed in the context of the success of the χQM [11–15,22] for the explanation of $\bar{u}$-$\bar{d}$ asymmetry [25–27], the existence of significant strange quark content [1–3], quark flavor and spin distribution functions [2], hyperon decay parameters, etc., strongly indicates that constituent quarks, weakly interacting Goldstone bosons (GBs), and $q\bar{q}$ pairs provide the appropriate degrees of freedom at the leading order in the scale between chiral symmetry breaking (χ_{SB}) and the confinement scale. This is further borne out by the fact that when the generalized Cheng-Li mechanism is combined with the effects of configuration mixing, known to improve the predictions of the NRQM [5,10,28–30] as well as compatible [31–33] with the χQM, and "mass adjustments" arising due to confinement of quarks [8,9], it leads to an almost perfect fit for the ΔCG and an excellent fit for the octet magnetic moments [23]. In view of this, it is desirable to broaden the scope of Ref. [23] by extending the calculations to decuplet magnetic moments and transition magnetic moments and by delving into the detailed implications of some of the crucial ingredients such as the generalized Cheng-Li mechanism (with and without configuration mixing) and ''mass adjustments'' of the octet magnetic moments, not detailed in Ref. [23]. At the same time, for an appropriate appraisal of the implications of the calculated magnetic moments, it is desirable to fine-tune the χQM parameters by analyzing the latest data pertaining to $\bar{u}-\bar{d}$ asymmetry [26], and spin polarization functions [2] as well as the flavor nonsinglet components.

The purpose of the present paper is to detail the formulation of the octet and decuplet magnetic moments in the χQM incorporating the generalized Cheng-Li mechanism (with and without configuration mixing). In order to make our analysis regarding magnetic moments more responsive, we have carried out a brief analysis to fix the χQM parameters using the latest data regarding the quark distribution functions and spin distribution functions. A brief discussion on the flavor singlet component of the total helicity including gluon polarization and its implications for the magnetic moments is also very much in order. Further, we also intend to study the implications of variation of the quark masses as well as the angle pertaining to configuration mixing on magnetic moments.

The plan of the paper is as follows. To make the manuscript readable as well as to facilitate discussion, in Sec. II we present some of the essentials of the χQM and Cheng-Li mechanism with an emphasis on the details of its generalization. In Sec. III, the modifications due to configuration mixing in the generalized Cheng-Li mechanism have been discussed. Section IV includes a discussion of the various inputs used in the analysis; in particular, the χQM parameters have been obtained by fitting the χQM with and without configuration mixing to the latest data. In Sec. V, we present the numerical results and their discussion including a brief reference to the flavor singlet component as well as gluon polarization. Section VI comprises the summary and conclusions. To make the manuscript self-contained, in the Appendix a few typical cases pertaining to octet as well as decuplet baryons have been fully worked out.

II. MAGNETIC MOMENTS IN THE χQM WITH THE GENERALIZED CHENG-LI MECHANISM

The basic process in the χQM is the emission of a GB by a constituent quark which further splits into a $q\bar{q}$ pair, for example,

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

where $q\bar{q}'+q'$ constitute the ''quark sea'' [12–15]. The effective Lagrangian describing interaction between quarks and a nonet of GBs, consisting of the octet and a singlet, can be expressed as

$$\mathcal{L}=g_8\bar{q}\Phi q, \tag{2}$$

$$q=\begin{pmatrix} u\\ d\\ s\end{pmatrix}, \quad \Phi=\begin{pmatrix} \frac{\pi^0}{\sqrt{2}}+\beta\frac{\eta}{\sqrt{6}}+\zeta\frac{\eta'}{\sqrt{3}} & \pi^+ & \alpha K^+\\ \pi^- & -\frac{\pi^0}{\sqrt{2}}+\beta\frac{\eta}{\sqrt{6}}+\zeta\frac{\eta'}{\sqrt{3}} & \alpha K^0\\ \alpha K^- & \alpha\bar{K}^0 & -\beta\frac{2\eta}{\sqrt{6}}+\zeta\frac{\eta'}{\sqrt{3}}\end{pmatrix}, \tag{3}$$

where $\zeta=g_1/g_8$ and g_1 and g_8 are the coupling constants for the singlet and octet GBs, respectively.

SU(3) symmetry breaking is introduced by considering $M_s>M_{u,d}$ as well as by considering the masses of GBs to be nondegenerate ($M_{K,\eta}>M_\pi$) [12–15], whereas the axial U(1) breaking is introduced by $M_{\eta'}>M_{K,\eta}$ [11–15]. The parameter $a(=|g_8|^2)$ denotes the transition probability of chiral fluctuation of the splittings $u(d)\rightarrow d(u)+\pi^{+(-)}$, whereas $\alpha^2 a$, $\beta^2 a$, and $\zeta^2 a$, respectively, denote the probabilities of transitions of $u(d)\rightarrow s+K^{-(0)}$, $u(d,s)\rightarrow u(d,s)+\eta$, and $u(d,s)\rightarrow u(d,s)+\eta'$.

Following Cheng and Li [13], the magnetic moment of a given baryon that receives contributions from valence quarks, sea quarks, and the orbital angular momentum of the ''quark sea'' is expressed as

$$\mu(B)_{\mathrm{total}}=\mu(B)_{\mathrm{val}}+\mu(B)_{\mathrm{sea}}+\mu(B)_{\mathrm{orbit}}. \tag{4}$$

The valence and the sea contributions, in terms of quark spin polarizations, can be written as

$$\mu(B)_{\mathrm{val}}=\sum_{q=u,d,s}\Delta q_{\mathrm{val}}\mu_q \quad \text{and} \quad \mu(B)_{\mathrm{sea}}=\sum_{q=u,d,s}\Delta q_{\mathrm{sea}}\mu_q, \tag{5}$$

where $\mu_q=e_q/2M_q$ $(q=u,d,s)$ is the quark magnetic moment, and e_q and M_q are the electric charge and the mass, respectively, for the quark q. Similarly, the orbital angular momentum contribution of the sea, $\mu(B)_{\mathrm{orbit}}$, can be ex-

TABLE I. Sea quark spin polarizations for the ''mixed'' octet baryons and decuplet baryons in terms of the χQM parameters a, α, β, and ζ as discussed in the text. The spin polarizations for the other baryons can be found from isospin symmetry. The spin structure of the octet baryon B without configuration mixing can be obtained by taking $\phi=0$.

Baryons	$\Delta u_{\rm sea}$	$\Delta d_{\rm sea}$	$\Delta s_{\rm sea}$
$p(uud)$	$-\cos^2\phi\{(a/3)[7+4\alpha^2+(4/3)\beta^2+(8/3)\zeta^2]\}$	$-\cos^2\phi\{(a/3)[2-\alpha^2-(1/3)\beta^2-(2/3)\zeta^2]\}$	$-a\alpha^2$
	$-\sin^2\phi\{(a/3)[5+2\alpha^2+(2/3)\beta^2+(4/3)\zeta^2]\}$	$-\sin^2\phi\{(a/3)[4+\alpha^2+(1/3)\beta^2+(2/3)\zeta^2]\}$	
$\Sigma^+(uus)$	$-\cos^2\phi\{(a/3)[8+3\alpha^2+(4/3)\beta^2+(8/3)\zeta^2]\}$	$-\cos^2\phi[(a/3)(4-\alpha^2)]$	$-\cos^2\phi\{(a/3)[2\alpha^2-(4/3)\beta^2-(2/3)\zeta^2]\}$
	$-\sin^2\phi\{(a/3)[4+3\alpha^2+(2/3)\beta^2+(4/3)\zeta^2]\}$	$-\sin^2\phi[(a/3)(2+\alpha^2)]$	$-\sin^2\phi\{(a/3)[4\alpha^2+(4/3)\beta^2+(2/3)\zeta^2]\}$
$\Xi^0(uss)$	$-\cos^2\phi\{(a/3)[3\alpha^2-2-(1/3)\beta^2-(2/3)\zeta^2]\}$	$-\cos^2\phi[(a/3)(4\alpha^2-1)]$	$-\cos^2\phi\{(a/3)[7\alpha^2+(16/3)\beta^2+(8/3)\zeta^2]\}$
	$-\sin^2\phi\{(a/3)[2+3\alpha^2+(1/3)\beta^2+(2/3)\zeta^2]\}$	$-\sin^2\phi[(a/3)(1+2\alpha^2)]$	$-\sin^2\phi\{(a/3)[5\alpha^2+(8/3)\beta^2+(4/3)\zeta^2]\}$
$\Lambda(uds)$	$-\cos^2\phi[a\alpha^2]$	$-\cos^2\phi[a\alpha^2]$	$-\cos^2\phi[(a/3)(6\alpha^2+4\beta^2+2\zeta^2)]$
	$-\sin^2\phi[(a/9)(9+6\alpha^2+\beta^2+2\zeta^2)]$	$-\sin^2\phi[(a/9)(9+6\alpha^2+\beta^2+2\zeta^2)]$	$-\sin^2\phi[(4/9)a(3\alpha^2+2\beta^2+\zeta^2)]$
$\Sigma\Lambda$	$-\cos^2\phi[(a/2\sqrt{3})(3+3\alpha^2+\beta^2+2\zeta^2)]$	$\cos^2\phi[(a/2\sqrt{3})(3+3\alpha^2+\beta^2+2\zeta^2)]$	0
	$\sin^2\phi\{(a/2\sqrt{3})[1+\alpha^2+(\beta^2/3)+(2/3)\zeta^2]\}$	$-\sin^2\phi\{(a/2\sqrt{3})[1+\alpha^2+\beta^2/3+(2/3)\zeta^2]\}$	
$\Delta^{++}(uuu)$	$-a(6+3\alpha^2+\beta^2+2\zeta^2)$	$-3a$	$-3a\alpha^2$
$\Delta^+(uud)$	$-a[5+2\alpha^2+(2/3)\beta^2+(4/3)\zeta^2]$	$-a[4+\alpha^2+(1/3)\beta^2+(2/3)\zeta^2]$	$-3a\alpha^2$
$\Sigma^{*+}(uus)$	$-a[4+3\alpha^2+(2/3)\beta^2+(4/3)\zeta^2]$	$-a(\alpha^2+2)$	$-2a[2\alpha^2+(2/3)\beta^2+(1/3)\zeta^2]$
$\Sigma^{*0}(uds)$	$-a[3+2\alpha^2+(1/3)\beta^2+(2/3)\zeta^2]$	$-a[3+2\alpha^2+(1/3)\beta^2+(2/3)\zeta^2]$	$-2a[2\alpha^2+(2/3)\beta^2+(1/3)\zeta^2]$
$\Xi^{*0}(uss)$	$-a[2+3\alpha^2+(1/3)\beta^2+(2/3)\zeta^2]$	$-a(2\alpha^2+1)$	$-a[5\alpha^2+(8/3)\beta^2+(4/3)\zeta^2]$
$\Omega^-(sss)$	$-3a\alpha^2$	$-3a\alpha^2$	$-6a[\alpha^2+(2/3)\beta^2+(1/3)\zeta^2]$
ΔN	$-(2/3\sqrt{6})(3+3\alpha^2+\beta^2+2\zeta^2)$	$(2/3\sqrt{6})(3+3\alpha^2+\beta^2+2\zeta^2)$	0

pressed in terms of the valence quark polarizations and the orbital moments of the sea quarks, the details of which are given in Sec. II B. Following Refs. [11,13,15], the quark spin polarization can be defined as

$$\Delta q = q_+ - q_- + \bar{q}_+ - \bar{q}_-, \tag{6}$$

where $q_\pm$ and $\bar{q}_\pm$ can be calculated from the spin structure of a baryon defined as

$$\hat{B} \equiv \langle B|\mathcal{N}|B\rangle, \tag{7}$$

where $|B\rangle$ is the baryon wave function and $\mathcal{N}$ is the number operator, for example,

$$\mathcal{N} = n_{u_+}u_+ + n_{u_-}u_- + n_{d_+}d_+ + n_{d_-}d_- + n_{s_+}s_+ + n_{s_-}s_-, \tag{8}$$

with the coefficients of the $q_\pm$ giving the number of $q_\pm$ quarks.

To calculate $\mu(B)_{\rm val}$, we need to calculate the valence spin polarizations $\Delta q_{\rm val}$. For ready reference some essential details of the calculations for valence quark polarizations pertaining to typical cases are presented in the Appendix.

A. Contribution of the ''quark sea'' polarizations to the magnetic moments

To evaluate the ''quark sea'' magnetic moment, one has to find $\Delta q_{\rm sea}$ corresponding to each baryon. For detailed evaluation of $\Delta q_{\rm sea}$, we refer the reader to Refs. [12–15]; however, to facilitate its extension to the case with configuration mixing, we summarize some of the essentials adopted for present use. The spin structure for the process given in Eq. (1), after one interaction, can be obtained by substituting for every valence quark, for example,

$$q_\pm \rightarrow \sum P_q q_\pm + |\psi(q_\pm)|^2, \tag{9}$$

where ΣP_q is the probability of emission of a GB from a q quark and the probabilities of transforming a $q_\pm$ quark are $|\psi(q_\pm)|^2$. The relevant details pertaining to the calculations of $\Delta q_{\rm sea}$, again for some typical cases, are presented in the Appendix. The expressions for $\Delta q_{\rm sea}$ in the case of the proton are as follows:

$$\Delta u_{\rm sea} = -\frac{a}{3}\left(7+4\alpha^2+\frac{4}{3}\beta^2+\frac{8}{3}\zeta^2\right),$$

$$\Delta d_{\rm sea} = -\frac{a}{3}\left(2-\alpha^2-\frac{1}{3}\beta^2-\frac{2}{3}\zeta^2\right),$$

$$\Delta s_{\rm sea} = -a\alpha^2. \tag{10}$$

The expressions for the other octet baryons can be found from Table I.

The ''quark sea'' spin polarizations for the decuplet baryons can be calculated in a similar manner to that of octet baryons. For example, the general expressions for the spin structure of the decuplet baryons of the types $B^*(xxy)$, $B^*(xxx)$, and $B^*(xyz)$, using Eq. (9), are, respectively, given as

$$\hat{B}^*(xxy)=2\left(\sum P_x x_+ + |\psi(x_+)|^2\right)$$
$$+\left(\sum P_y y_+ + |\psi(y_+)|^2\right), \quad (11)$$

$$\hat{B}^*(xxx)=3\left(\sum P_x x_+ + |\psi(x_+)|^2\right), \quad (12)$$

$$\hat{B}^*(xyz)=\left(\sum P_x x_+ + |\psi(x_+)|^2\right)$$
$$+\left(\sum P_y y_+ + |\psi(y_+)|^2\right)$$
$$+\left(\sum P_z z_+ + |\psi(z_+)|^2\right), \quad (13)$$

where x, y, and z correspond to any of the u, d, and s quarks. The detailed expressions for the spin polarizations $\Delta q_{\rm sea}$, corresponding to the decuplet baryons, can again be found from Table I.

B. Contribution of the "quark sea" orbital angular momentum to the magnetic moments

Following Cheng and Li [13], the contribution of the angular momentum of the "quark sea" to the magnetic moment of a given quark is given as

$$\mu(q_+ \to q'_-)=\frac{e_{q'}}{2M_q}\langle l_q\rangle+\frac{e_q-e_{q'}}{2M_{\rm GB}}\langle l_{\rm GB}\rangle, \quad (14)$$

where

$$\langle l_q\rangle=\frac{M_{\rm GB}}{M_q+M_{\rm GB}} \text{ and } \langle l_{\rm GB}\rangle=\frac{M_q}{M_q+M_{\rm GB}}, \quad (15)$$

and $\langle l_q, l_{\rm GB}\rangle$ and $(M_q, M_{\rm GB})$ are the orbital angular momenta and masses of the quark and GB, respectively. The orbital moment of each process is then multiplied by the probability for such a process to take place to yield the magnetic moment due to all the transitions starting with a given valence quark, for example,

$$[\mu(u_\pm(d_\pm)\to)]$$
$$=\pm a\left[\mu(u_+(d_+)\to d_-(u_-))+\alpha^2\mu(u_+(d_+)\to s_-)\right.$$
$$\left.+\left(\frac{1}{2}+\frac{1}{6}\beta^2+\frac{1}{3}\zeta^2\right)\mu(u_+(d_+)\to u_-(d_-))\right], \quad (16)$$

$$[\mu(s_\pm\to)]$$
$$=\pm a\left[\alpha^2\mu(s_+\to u_-)+\alpha^2\mu(s_+\to d_-)+\left(\frac{2}{3}\beta^2+\frac{1}{3}\zeta^2\right)\right.$$
$$\left.\times\mu(s_+\to s_-)\right]. \quad (17)$$

The above equations, derived by Cheng and Li, along with $\Delta q_{\rm sea}$, constitute the essentials of Cheng-Li mechanism. Equations (16) and (17) can easily be generalized by including the coupling breaking and mass breaking terms. For example, in terms of the parameters a, α, β, and ζ, the orbital moments of u, d, and s quarks, respectively, are

$$\mu(u_+\to)=a\left[\frac{-M_\pi^2+3M_u^2}{2M_\pi(M_u+M_\pi)}-\frac{\alpha^2(M_K^2-3M_u^2)}{2M_K(M_u+M_K)}\right.$$
$$\left.+\frac{(3+\beta^2+2\zeta^2)M_\eta^2}{6M_\eta(M_u+M_\eta)}\right]\mu_N, \quad (18)$$

$$\mu(d_+\to)=a\frac{M_u}{M_d}\left[\frac{2M_\pi^2-3M_d^2}{2M_\pi(M_d+M_\pi)}-\frac{\alpha^2M_K^2}{2M_K(M_d+M_K)}\right.$$
$$\left.-\frac{(3+\beta^2+2\zeta^2)M_\eta^2}{12M_\eta(M_d+M_\eta)}\right]\mu_N, \quad (19)$$

$$\mu(s_+\to)=a\frac{M_u}{M_s}\left[\frac{\alpha^2(M_K^2-3M_s^2)}{2M_K(M_s+M_K)}\right.$$
$$\left.-\frac{(2\beta^2+\zeta^2)M_\eta^2}{6M_\eta(M_s+M_\eta)}\right]\mu_N, \quad (20)$$

where μ_N is the nuclear magneton. Equations (18), (19), and (20) along with $\Delta q_{\rm sea}$ will be referred to as the generalized Cheng-Li mechanism. The orbital contribution to the magnetic moment of the octet baryon of type $B(xxy)$ in terms of the above equations as well as the valence spin polarizations is given by

$$\mu(B)_{\rm orbit}=\Delta x_{\rm val}[\mu(x_+\to)]+\Delta y_{\rm val}[\mu(y_+\to)]. \quad (21)$$

Similarly, the orbital contributions in the cases of the decuplet baryons $B^*(xxy)$, $B^*(xxx)$, and $B^*(xyz)$ are respectively given by

$$\mu(B^*)_{\rm orbit}=\Delta x_{\rm val}[\mu(x_+\to)]+\Delta y_{\rm val}[\mu(y_+\to)], \quad (22)$$

$$\mu(B^*)_{\rm orbit}=\Delta x_{\rm val}[\mu(x_+\to)], \quad (23)$$

$$\mu(B^*)_{\rm orbit}=\Delta x_{\rm val}[\mu(x_+\to)]+\Delta y_{\rm val}[\mu(y_+\to)]$$
$$+\Delta z_{\rm val}[\mu(z_+\to)]. \quad (24)$$

III. GENERALIZED CHENG-LI MECHANISM WITH CONFIGURATION MIXING

Spin-spin forces, known to be compatible [31–33] with the χQM, generate configuration mixing [10,28,29] for the octet baryons which effectively leads to modification of the valence quark and "quark sea" spin distribution functions [34]. From Eqs. (5) and (21), it is evident that the effects of configuration mixing on magnetic moments can be included if one is able to estimate the same on the valence and sea contributions to magnetic moments. The most general configuration mixing generated by the spin-spin forces in the case of octet baryons [10,29,35] can be expressed as

$$|B\rangle=(|56,0^+\rangle_{N=0}\cos\theta+|56,0^+\rangle_{N=2}\sin\theta)\cos\phi+(|70,0^+\rangle_{N=2}\cos\theta'+|70,2^+\rangle_{N=2}\sin\theta')\sin\phi, \tag{25}$$

where ϕ represents the $|56\rangle$-$|70\rangle$ mixing, whereas θ and θ', respectively, correspond to the mixing among $|56,0^+\rangle_{N=0}$-$|56,0^+\rangle_{N=2}$ states and $|70,0^+\rangle_{N=2}$-$|70,2^+\rangle_{N=2}$ states. For the present purpose, it is adequate [5,9,29,34] to consider the mixing only between $|56,0^+\rangle_{N=0}$ and the $|70,0^+\rangle_{N=2}$ states, for example,

$$|B\rangle\equiv\left|8,\frac{1}{2}^+\right\rangle=\cos\phi|56,0^+\rangle_{N=0}+\sin\phi|70,0^+\rangle_{N=2}, \tag{26}$$

where

$$|56,0^+\rangle_{N=0}=\frac{1}{\sqrt{2}}(\chi'\phi'+\chi''\phi'')\psi^s(0^+), \tag{27}$$

$$|70,0^+\rangle_{N=2}=\frac{1}{2}[(\phi'\chi''+\phi''\chi')\psi'(0^+)+(\phi'\chi'-\phi''\chi'')\psi''(0^+)], \tag{28}$$

with

$$\chi'=\frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow-\downarrow\uparrow\uparrow),\quad \chi''=\frac{1}{\sqrt{6}}(2\uparrow\uparrow\downarrow-\uparrow\downarrow\uparrow-\downarrow\uparrow\uparrow), \tag{29}$$

representing the spin wave functions. In general, the isospin wave functions for octet baryons of the type $B(xxy)$ are given by

$$\phi'_B=\frac{1}{\sqrt{2}}(xyx-yxx),\quad \phi''_B=\frac{1}{\sqrt{6}}(2xxy-xyx-yxx), \tag{30}$$

whereas for $\Lambda(xyz)$ and $\Sigma^0(xyz)$ they are given by

$$\phi'_\Lambda=\frac{1}{2\sqrt{3}}(xzy+zyx-zxy-yzx-2xyz-2yxz),$$

$$\phi''_\Lambda=\frac{1}{2}(zxy+xzy-zyx-yzx), \tag{31}$$

$$\phi'_{\Sigma^0}=\frac{1}{2}(zxy+zyx-xzy-yzx),$$

$$\phi''_{\Sigma^0}=\frac{1}{2\sqrt{3}}(zyx+zxy+xzy+yzx-2xyz-2yxz). \tag{32}$$

For the definition of the spatial wave functions (ψ^s,ψ',ψ'') as well as the definitions of the overlap integrals, we refer the reader to Ref. [36]. The mixing expressed through Eq. (26) would be referred to as the "mixed" octet; henceforth we will not distinguish between configuration mixing and the "mixed" octet.

Using the above wave functions, one can easily find the spin polarizations for the proton, for example,

$$\Delta u_{\rm val}=\cos^2\phi\left[\frac{4}{3}\right]+\sin^2\phi\left[\frac{2}{3}\right],$$

$$\Delta d_{\rm val}=\cos^2\phi\left[-\frac{1}{3}\right]+\sin^2\phi\left[\frac{1}{3}\right],\quad \Delta s_{\rm val}=0. \tag{33}$$

These expressions would replace $\Delta q_{\rm val}$ in Eqs. (5) and (21) for calculating the effects of configuration mixing on the valence and the orbital parts in the case of the proton. Similarly, one can easily find the spin polarization functions for other "mixed" octet members.

The "quark sea" polarization also gets modified with the inclusion of configuration mixing and can easily be calculated; the details of the calculations in the cases of p, Λ, and $\Sigma\Lambda$ are given in the Appendix. For the case of the proton, these are expressed as

$$\Delta u_{\rm sea}=-\cos^2\phi\left[\frac{a}{3}\left(7+4\alpha^2+\frac{4}{3}\beta^2+\frac{8}{3}\zeta^2\right)\right]-\sin^2\phi\left[\frac{a}{3}\left(5+2\alpha^2+\frac{2}{3}\beta^2+\frac{4}{3}\zeta^2\right)\right], \tag{34}$$

$$\Delta d_{\rm sea}=-\cos^2\phi\left[\frac{a}{3}\left(2-\alpha^2-\frac{1}{3}\beta^2-\frac{2}{3}\zeta^2\right)\right]-\sin^2\phi\left[\frac{a}{3}\left(4+\alpha^2+\frac{1}{3}\beta^2+\frac{2}{3}\zeta^2\right)\right], \tag{35}$$

$$\Delta s_{\rm sea}=-a\alpha^2. \tag{36}$$

The "quark sea" spin polarizations for the other octet baryons and transition magnetic moments can similarly be calculated and are presented in Table I.

Configuration mixing due to spin-spin forces does not affect decuplet baryons [10,29]; thus the decuplet baryon wave function is given by

$$|B^*\rangle\equiv|56,0^+\rangle_{N=0}=\chi^s\phi^s\psi^s(0^+) \tag{37}$$

with

$$\chi^s=(\uparrow\uparrow\uparrow). \tag{38}$$

The isospin wave functions for decuplet baryons of types $B^*(xxx)$, $B^*(xxy)$, and $B^*(xyz)$, respectively, are

$$\phi^s_{B^*}=xxx,\quad \phi^s_{B^*}=\frac{1}{\sqrt{3}}(xxy+xyx+yxx),$$

$$\phi^s_{B*} = \frac{1}{\sqrt{6}}(xyz+xzy+yxz+yzx+zxy+zyx), \quad (39)$$

where x, y, and z correspond to any of the u, d, and s quarks.

IV. INPUTS

To facilitate the understanding of different inputs based on Eq. (4), in the Appendix we present the complete expressions for two of the octet baryon magnetic moments p and Λ as well as the $\Sigma\Lambda$ transition magnetic moment; for the case of decuplet baryons we considered the example of Δ^+. The other octet and decuplet magnetic moments can be formulated similarly. As is evident from the Appendix, to calculate the magnetic moments we need inputs related to the χQM parameters, mixing angle ϕ, and quark masses. The parameters a, α, β, and ζ of the χQM are usually fixed by considering the spin polarization functions Δu, Δd, Δs [2], and related Q^2 independent parameters $\Delta_3 = \Delta u - \Delta d$ and $\Delta_8 = \Delta u + \Delta d - 2\Delta s$ [37] as well as the quark distribution functions including the violation of the Gottfried sum rule [26,27] measured through the $\bar{u}$-$\bar{d}$ asymmetry. In the present analysis we have taken the pion fluctuation parameter a to be 0.1, in accordance with most other calculations [13–15]. It has been shown [15] that to fix the violation of the Gottfried sum rule [25], we have to consider the relation

$$\bar{u} - \bar{d} = \frac{a}{3}(2\zeta + \beta - 3). \quad (40)$$

In this relation, one immediately finds that in case the value of a is taken to be 0.1 then to reproduce $\bar{u}$-$\bar{d}$ asymmetry one gets the relation $\zeta = -0.3 - \beta/2$ for the E866 data [26] and $\zeta = -0.7 - \beta/2$ for the case of the NMC data [27]. Before carrying out the analysis of the χQM with configuration mixing one has to fix the mixing angle ϕ, which in the present case is taken to be $\phi = 20°$, by fitting the neutron charge radius [29,35,38]. After carrying out our analysis regarding the spin polarization functions and using the latest E866 [26] data and the New Muon Collaboration (NMC) [27] data regarding the $\bar{u}$-$\bar{d}$ asymmetry, in Table II, we present the calculated values of certain phenomenological quantities having implications for the χQM parameters (α and β) with and without configuration mixing. From the table we see that the chiral quark model with configuration mixing (χQM$_{gcm}$) is able to give a fairly good fit to the various spin distribution functions as well as quark distribution functions, in particular, the agreement in the case of $\Delta_3, \Delta_8, f_s, f_3/f_8$ is quite striking. In the table we have not included the flavor singlet component of the total helicity ($\Delta\Sigma = \Delta u + \Delta d + \Delta s$) which is discussed later separately. The χQM parameters thus found are summarized in Table III and constitute the input for magnetic moment calculations.

The orbital angular moment contributions are characterized by the parameters of the χQM as well as the masses of the GBs. For evaluating the contribution of pions, we have used the on-mass-shell value in accordance with several other similar calculations [39]. Similarly, for the other GBs we have considered their on-mass-shell values; however, their contributions are much smaller compared to the pionic contributions.

TABLE II. χQM parameters (with and without configuration mixing) obtained after fitting spin and quark distribution functions. χQM$_{gcm}$ corresponds to the case where the "mixed" nucleon [Eq. (26)] has been used with the mixing angle ϕ=20°.

Parameter	Data	χQM $\alpha=0.6, \beta=0.9$ NMC	χQM $\alpha=0.6, \beta=0.9$ E866	χQM$_{gcm}$ $\alpha=0.4, \beta=0.7$ NMC	χQM$_{gcm}$ $\alpha=0.4, \beta=0.7$ E866
Δu	0.85 ± 0.05 [2]	0.88	0.92	0.91	0.95
Δd	-0.41 ± 0.05 [2]	-0.35	-0.36	-0.33	-0.31
Δs	-0.07 ± 0.05 [2]	-0.05	-0.05	-0.02	-0.02
Δ_3	1.267 ± 0.0035 [19]	1.23	1.28	1.24	1.26
Δ_8	0.58 ± 0.025 [2]	0.63	0.66	0.61	0.67
$\bar{u} - \bar{d}$	-0.147 ± 0.024 [27]	0.147	0.12	0.147	0.12
	-0.118 ± 0.015 [26]				
$\bar{d}/\bar{u}$	1.96 ± 0.246 [46]	1.89	1.59	1.89	1.59
	1.41 ± 0.146 [26]				
f_s	0.10 ± 0.06 [47]	0.15	0.13	0.07	0.05
f_3/f_8	0.21 ± 0.05 [11]	0.25	0.25	0.21	0.21

In accordance with the basic assumptions of the χQM, the constituent quarks are supposed to have only Dirac magnetic moments governed by the respective quark masses. In the absence of any definite guidelines for the constituent quark masses, for the u and d quarks we have used their most widely accepted values in hadron spectroscopy [10,32,36,40,41], for example, $M_u = M_d = 330$ MeV. Apart from taking the above quark masses, one has to consider the strange quark mass implied by the various sum rules derived from the spin-spin interactions for different baryons [5,10,29], for example, $\Lambda - N = M_s - M_u$, $(\Sigma^* - \Sigma)/(\Delta - N) = M_u/M_s$, and $(\Xi^* - \Xi)/(\Delta - N) = M_u/M_s$, respectively, fix M_s for the Λ, Σ, and Ξ baryons. These quark masses and corresponding magnetic moments have to be further adjusted by the quark confinement effects [8,9]. In conformity with the additivity assumption, the simplest way to incorporate this adjustment [8,9] is to first express M_q in the magnetic moment operator in terms of M_B, the mass of the baryon obtained additively from the quark masses, which is then replaced by $M_B + \Delta M$, ΔM being the mass difference between the experimental value and M_B. This leads to the following adjustments in the quark magnetic moments: $\mu_d = -[1 - (\Delta M/M_B)]\mu_N$, $\mu_s = -M_u/M_s[1 - (\Delta M/M_B)]\mu_N$, and $\mu_u = -2\mu_d$. The baryon magnetic moments calculated after incorporating this effect would be referred to as "mass adjusted."

TABLE III. Input values of various parameters used in the analysis.

Parameter	ϕ	a	α	β	ζ_{E866}	ζ_{NMC}
Value	20°	0.1	0.4	0.7	$-0.3 - \beta/2$	$-0.7 - \beta/2$

TABLE IV. Octet baryon magnetic moments in units of μ_N for the latest E866 data.

Octet	Data		χQM				χQM with mass adjustments				χQM with mass adjustments and configuration mixing			
baryons	[19]	NRQM	Valence	Sea	Orbital	Total	Valence	Sea	Orbital	Total	Valence	Sea	Orbital	Total
p	2.79 ± 0.00	2.72	3.00	-0.70	0.54	2.84	3.17	-0.59	0.45	3.03	2.94	-0.55	0.41	2.80
n	-1.91 ± 0.00	-1.81	-2.00	0.34	-0.41	-2.07	-2.11	0.24	-0.37	-2.24	-1.86	0.20	-0.33	-1.99
Σ^-	-1.16 ± 0.025	-1.01	-1.12	0.13	-0.29	-1.28	-1.08	0.08	-0.26	-1.26	-1.05	0.07	-0.22	-1.20
Σ^+	2.45 ± 0.01	2.61	2.88	-0.69	0.45	2.64	2.80	-0.55	0.37	2.62	2.59	-0.50	0.34	2.43
Ξ^0	-1.25 ± 0.014	-1.41	-1.53	0.37	-0.23	-1.39	-1.53	0.22	-0.16	-1.47	-1.32	0.21	-0.13	-1.24
Ξ^-	-0.65 ± 0.002	-0.50	-0.53	0.09	-0.06	-0.50	-0.59	0.06	-0.01	-0.54	-0.61	0.06	-0.01	-0.56
Λ	-0.61 ± 0.004	-0.59	-0.65	0.10	-0.08	-0.63	-0.69	0.05	-0.04	-0.68	-0.59	0.04	-0.04	-0.59
$\Sigma\Lambda$	1.61 ± 0.08	1.51	1.41	-0.02	0.30	1.69	1.45	-0.03	0.30	1.72	1.37	-0.04	0.26	1.63
Δ CG	0.49 ± 0.05	0				0.10				0.46				0.48

V. RESULTS AND DISCUSSION

Using Eq. (4) and the inputs discussed above as well as the expressions given in Table I, in Table IV we present the results of octet magnetic moments without taking any of these as inputs. For a general discussion of the contents of Table IV we refer the readers to Ref. [23]; however, in the present case we would like to discuss in detail the role of the generalized Cheng-Li mechanism, configuration mixing, and ‘‘mass adjustments’’ in getting the fit for octet magnetic moments. To this end, one can immediately find that the χQM with the generalized Cheng-Li mechanism, but without configuration mixing and ‘‘mass adjustments,’’ consistently improves the predictions of the NRQM as well as being able to generate a nonzero value of Δ CG. On closer examination of the results, several interesting points pertaining to the generalized Cheng-Li mechanism emerge. The total contribution to the magnetic moment is coming from several sources with similar and opposite signs, for example, the orbital contributes with the same sign as the valence part, whereas the sea contributes with the opposite sign. The sea and orbital contributions are fairly significant as compared to the valence contributions and they cancel in the right direction, for example, the valence contributions of p, Σ^+, and Ξ^o are higher in magnitude than the experimental value, but since the sea contribution is higher in magnitude than the orbital contribution, it reduces the valence contribution, leading to a better agreement with data. Similarly, in the cases of n, Σ^-, and $\Sigma\Lambda$ the valence contribution is lower in magnitude than the experimental value, but in these cases the sea contribution is lower than the orbital part, so it adds on to the valence contribution, again improving the agreement with data. Thus, in a very interesting manner, the orbital and sea contributions together add on to the valence contributions, leading to better agreement with data as compared to the NRQM. This not only endorses the earlier conclusion of Cheng and Li [13] but also suggests that the Cheng-Li mechanism could perhaps provide the dominant dynamics of the constituents in the nonperturbative regime of QCD on which further corrections could be evaluated. To this end, in Table IV, we present the results where the effects of configuration mixing and ‘‘mass adjustments’’ have been included. As is evident from the table, we have been able to get an excellent fit for almost all the baryons; it is almost perfect for p, Σ^+, Ξ^o, $\Sigma\Lambda$, and Δ CG, whereas in the other cases the value is within 5% of the data.

In order to study closely the role of configuration mixing in octet magnetic moments, in Table IV we present the results with and without mixing, but with the inclusion of ‘‘mass adjustments.’’ As is evident from the table, one finds that the individual magnetic moments show improvements after the inclusion of configuration mixing; in particular, in the cases of p, n, Σ^+, Ξ^0, Λ, and $\Sigma\Lambda$ one observes a significant improvement. It may be noted that configuration mixing reduces valence, sea, and orbital contributions to the magnetic moments and the results which are generally on the higher side get corrected in the right direction by the inclusion of configuration mixing. This is particularly manifest in the case of Ξ particles; for example, the magnitude of the Ξ^0 magnetic moment without configuration mixing is lowered so as to achieve an almost perfect fit, whereas in the case of Ξ^-, a difficult case for most models, configuration mixing increases the magnitude for better agreement with the data. In contrast to the general improvement in the case of individual magnetic moments, Δ CG is hardly affected by configuration mixing. In view of the fact that the χQM with configuration mixing involves baryon wave functions which are perturbed by the spin-spin forces, in principle one should employ the fully perturbed wave functions of the octet baryons as derived by Isgur *et al.* [10] given in Eq. (25). However, we found that for the present case the use of a ‘‘mixed’’ octet [Eq. (26)] is adequate to reproduce the results of the fully perturbed wave function to the desired level of accuracy. One may wonder whether Δ CG can also be reproduced by a variation of the mixing angle ϕ. Our calculations in this regard show that variation of ϕ does not lead to any improvement in the magnetic moments or in Δ CG. The present value of angle ϕ, fixed from the neutron charge radius [29,35,38], seems to provide the best fit.

It would also perhaps be interesting to find the implications of configuration mixing for the χQM without ‘‘mass

TABLE V. Octet baryon magnetic moments in units of μ_N for the NMC data.

Octet baryons	Data [19]	NRQM	χ QM Valence	Sea	Orbital	Total	χ QM with configuration mixing Valence	Sea	Orbital	Total	χ QM with mass adjustments and configuration mixing Valence	Sea	Orbital	Total
p	2.79 ± 0.00	2.72	3.00	-0.79	0.53	2.74	2.76	-0.62	0.48	2.62	2.94	-0.65	0.41	2.70
n	-1.91 ± 0.00	-1.81	-2.00	0.30	-0.29	-1.99	-1.76	0.25	-0.39	-1.90	-1.86	0.27	-0.34	-1.93
Σ^-	-1.16 ± 0.025	-1.01	-1.12	0.16	-0.30	-1.26	-1.09	0.10	-0.25	-1.24	-1.05	0.14	-0.26	-1.17
Σ^+	2.45 ± 0.01	2.61	2.88	-0.77	0.43	2.54	2.67	-0.65	0.40	2.42	2.59	-0.59	0.36	2.36
Ξ^0	-1.25 ± 0.014	-1.41	-1.53	0.45	-0.21	-1.29	-1.32	0.26	-0.16	-1.22	-1.32	0.26	-0.14	-1.20
Ξ^-	-0.65 ± 0.002	-0.50	-0.53	0.08	-0.01	-0.46	-0.56	0.09	-0.01	-0.48	-0.61	0.09	-0.02	-0.54
Λ	-0.61 ± 0.004	-0.59	-0.65	0.12	-0.07	-0.60	-0.56	0.07	-0.05	-0.54	-0.59	0.07	-0.05	-0.57
$\Sigma\Lambda$	1.61 ± 0.08	1.51	1.41	-0.01	0.31	1.71	1.41	-0.01	0.26	1.66	1.37	-0.02	0.26	1.61
Δ CG	0.49 ± 0.05	0				0.10				0.12				0.44

adjustments.'' Broadly speaking, the individual magnetic moments can again be fitted; however, Δ CG leaves much to be desired. This can easily be checked from Table V, where we present these calculations with the NMC data; the E866 based fit follows the same pattern. The value of ΔCG registers a remarkable improvement when effects due to ''mass adjustments'' along with configuration mixing are included. This is not surprising as the large value of ΔCG could come only from the valence quark corrections, duly provided by the ''mass adjustments.'' It would be desirable to know what level of fit can be achieved without configuration mixing, but with the inclusion of ''mass adjustments.'' A closer examination of the table immediately brings out that in this case the individual magnetic moments leave much to be desired, whereas one is able to reproduce ΔCG, in accordance with our earlier conclusions. It may also be noted that the ''mass adjustments'' generally lower the various contributions except for the nucleon. In short, we may emphasize that the final fit obtained here cannot be achieved if any of the ingredients, for example, the generalized Cheng-Li mechanism, configuration mixing, and ''mass adjustments,'' is absent.

For the sake of completeness, as mentioned earlier also, we present in Table V the octet magnetic moments when the χ QM parameters are fitted by incorporating the NMC data. This table also includes our results, where magnetic moments have been calculated with configuration mixing but without''mass adjustments,'' not included in Table IV. From the table, one can immediately see that the basic pattern of results remains the same; however, in general the results are lower as compared to the case of the E866 data. This is not difficult to understand when one realizes that the contributions of sea polarization in the cases of E866 and NMC data are quite different. This can be understood easily when one realizes that the sea quark polarization is proportional to the parameter ζ. Because $|\zeta_{E866}|<|\zeta_{NMC}|$, one can easily understand the corresponding lowering of the magnetic moments in the case of the NMC data; however, the two calculations are in good agreement with each other.

In Table VI, we present the results for the decuplet baryons for the the latest E866 and the NMC data. The calculations of decuplet magnetic moments have been carried out with the same χ QM parameters and quark masses as that of the octet magnetic moments. From the table, it is evident that we have been able to obtain a very good agreement pertain-

TABLE VI. Decuplet magnetic moments in units of μ_N for NMC and E866 data.

Decuplet baryons	Data [19]	NRQM	Song *et al.* [14]	Linde *et al.* [15]	Valence	Sea NMC	Sea E866	Orbital NMC	Orbital E866	Total NMC	Total E866
Δ^{++}	$3.7<\mu_{\Delta^{++}}<7.5$	5.43	5.55	5.21	6.36	-1.59	-1.31	0.94	0.92	5.71	5.97
Δ^+	—	2.72	2.73	2.45	3.18	-0.94	-0.79	0.38	0.37	2.62	2.76
Δ^0	—	0	-0.09	-0.30	0	-0.28	-0.28	-0.18	-0.18	-0.46	-0.46
Δ^-	—	-2.72	-2.91	-3.06	-3.18	0.37	0.23	-0.74	-0.73	-3.55	-3.68
Σ^{*+}	-	3.02	3.09	2.85	3.24	-0.88	-0.73	0.58	0.56	2.94	3.07
Σ^{*0}	—	0.30	0.27	0.09	0.33	-0.28	-0.26	0.01	0.01	0.06	0.08
Σ^{*-}	—	-2.41	-2.55	-2.66	-2.58	0.32	0.20	-0.54	-0.54	-2.80	-2.92
Ξ^{*0}	—	0.60	0.63	0.49	0.52	-0.27	-0.24	0.21	0.21	0.46	0.49
Ξ^{*-}	—	-2.11	-2.19	-2.27	-2.30	0.31	0.21	-0.35	-0.34	-2.33	-2.43
Ω^-	-2.02 ± 0.005	-1.81	-1.83	-1.87	-2.07	0.30	0.21	-0.14	-0.15	-1.91	-2.01
ΔN	3.23 ± 0.10 [a]	2.44	—	—	2.60	-0.53	-0.41	0.46	0.44	2.53	2.63

[a]Pertains to the PDG 1994 data.

TABLE VII. Comparison of the results of the χQM with the generalized Cheng-Li mechanism, configuration mixing, and "mass adjustments" in units of μ_N for different sets of quark masses.

Octet baryons	Data [19]	NRQM	$M_u, M_d = 310$ MeV		$M_u, M_d = 340$ MeV		$M_u, M_d = 330$ MeV	
			NMC	E866	NMC	E866	NMC	E866
p	2.79 ± 0.00	2.72	2.48	2.60	2.69	2.84	2.70	2.80
n	-1.91 ± 0.00	-1.81	-1.79	-1.88	-1.96	-2.06	-1.93	-1.99
Σ^-	-1.16 ± 0.025	-1.01	-1.16	-1.20	-1.28	-1.32	-1.17	-1.20
Σ^+	2.45 ± 0.01	2.61	2.20	2.31	2.42	2.54	2.36	2.43
Ξ^0	-1.25 ± 0.014	-1.41	-1.10	-1.16	-1.26	-1.32	-1.20	-1.24
Ξ^-	-0.65 ± 0.002	-0.50	-0.48	-0.50	-0.56	-0.59	-0.54	-0.56
Λ	-0.61 ± 0.004	-0.60	-0.54	-0.57	-0.63	-0.64	-0.57	-0.59
$\Sigma\Lambda$	1.61 ± 0.08	1.51	1.53	1.50	1.77	1.75	1.61	1.63
ΔCG	0.49 ± 0.05	0	0.29	0.31	0.25	0.31	0.44	0.48

ing to the case of Δ^{++} and Ω^- whereas in the case of the transition magnetic moment ΔN we obtain a fairly good agreement. In order to compare the present results with other recent similar calculations [14,15], in the table we have included these results also. A closer examination of the decuplet magnetic moments reveals several interesting points which would have bearing on the generalized Cheng-Li mechanism. For example, in the case of Δ^- and Σ^-, because the orbital part dominates over the "quark sea" polarization, the magnetic moments are higher as compared to the results of NRQM and Refs. [14,15]. On the other hand, in the case of Δ^+ and Σ^+, the "quark sea" polarization dominates over the orbital part as a consequence of which the magnetic moment contribution is more or less the same as that of the results of NRQM as well as those of Refs. [14,15]. In general, one can find that whenever there is an excess of d quarks the orbital part dominates, whereas when we have an excess of u quarks, the "quark sea" polarization dominates. A measurement of these magnetic moments, therefore, would have important implications for the χQM as well as for the Cheng-Li mechanism with its generalization.

While carrying out the fit, as mentioned earlier, the quark masses employed for the calculations correspond to the generally accepted values used for hadron spectroscopic calculations. It may be of interest to study the variation of these masses with the magnetic moments. To this end, in Table VII, we investigate the effect of varying valence quark masses. As is evident from the table we find that the results worsen in both cases, for example, when they are reduced or increased compared to the ones considered earlier. The violation of the CGSR is also fitted best for the generally accepted mass values employed in our calculations. These results remain true for the E866 as well as the NMC data. This appears surprising as the hadron spectroscopic predictions are known to be somewhat insensitive to the valence quark masses.

While discussing the inputs, we have already seen that χQM$_{gcm}$ is able to give an excellent fit to the Q^2 independent flavor nonsinglet components, for example, Δ_3 and Δ_8. The flavor singlet component $\Delta\Sigma$ is also known to have a weak Q^2 dependence [32,42], therefore in principle we should be able to get a good fit to this quantity also. However, in the absence of a gluon contribution, as expected the agreement does not turn out to be as impressive as in the case of flavor nonsinglet components. The quark spin distribution functions can be corrected by inclusion of the gluon anomaly [32,42] through

$$\Delta q(Q^2) = \Delta q - \frac{\alpha_s(Q^2)}{2\pi}\Delta g(Q^2); \tag{41}$$

therefore, the flavor singlet component of the total helicity in the χQM can be expressed as

$$\Delta\Sigma(Q^2) = \Delta\Sigma - \frac{3\alpha_s(Q^2)}{2\pi}\Delta g(Q^2), \tag{42}$$

where $\Delta\Sigma(Q^2)$ and $\Delta q(Q^2)$ are the experimentally measured quantities whereas $\Delta\Sigma$ and Δq correspond to the calculated quantities in the χQM. Using $\Delta\Sigma(Q^2) = 0.30 \pm 0.06$ [3], $\Delta\Sigma = 0.62$, and $\alpha_s(Q^2 = 5\ \text{GeV}^2) = 0.287 \pm 0.020$ [19], the gluon polarization $\Delta g(Q^2)$ comes out to be 2.33. Interestingly, this value is in fair agreement with certain recent measurements [43] as well as theoretical estimates [44,45]. The effects of the gluon polarization can easily be incorporated into the calculations of spin polarization functions and magnetic moments; without getting into the details, the calculated values of the relevant phenomenological quantities affected by the gluon polarizations are presented in Table VIII. From the table, we find that the present value of Δg improves the results of various quantities; in particular, for Δu, Δd, Δs, $\Delta\Sigma$, μ_n, μ_{Σ^-}, μ_Λ, and $\mu_{\Sigma\Lambda}$ the results leave hardly anything to be desired, whereas μ_{Ξ^-}, a difficult case in most models, also registers a good deal of improvement. The decuplet magnetic moments do not show much change when correction due to Δg are included, for example, in the case of Ω^-, -2.01 changes to -2.04, whereas in the case of Δ^{++}, 5.97 changes to 5.94. In the absence of experimental data for the other decuplet baryons, we have not included the Δg corrected results in the table.

It may be of interest to emphasize here that the excellent fit achieved for the spin distribution functions, quark distribution functions, and hyperon parameters along with the magnetic moments as well as the gluon polarization strongly

TABLE VIII. The phenomenological quantities affected by the inclusion of gluon polarization. The magnetic moments are in units of μ_N.

Quantity	Expt value	NRQM	Without gluon polarization χ QM	Without gluon polarization χ QM$_{gcm}$	With gluon polarization χ QM	With gluon polarization χ QM$_{gcm}$
Δu	0.85 ± 0.05 [2]	1.33	1.02	0.95	0.91	0.84
Δd	−0.41 ± 0.05 [2]	-0.33	-0.38	-0.31	-0.49	-0.42
Δs	−0.07 ± 0.05 [2]	0	-0.02	-0.02	-0.13	-0.13
$\Delta\Sigma$	0.30 ± 0.06 [3]	1	0.62	0.62	0.29	0.29
μ_p	2.79 ± 0.00 [19]	2.72	3.03	2.80	3.00	2.77
μ_n	−1.91 ± 0.00 [19]	-1.81	-2.24	-1.99	-2.21	-1.96
μ_{Σ^-}	−1.16 ± 0.025 [19]	-1.01	-1.26	-1.20	-1.23	-1.17
μ_{Σ^+}	2.45 ± 0.01 [19]	2.61	2.62	2.43	2.59	2.40
μ_{Ξ^0}	−1.25 ± 0.014 [19]	-1.41	-1.47	-1.24	-1.50	-1.27
μ_{Ξ^-}	−0.65 ± 0.002 [19]	-0.50	-0.54	-0.56	-0.57	-0.59
μ_{Λ}	−0.61 ± 0.004 [19]	-0.59	-0.68	-0.59	-0.71	-0.62
$\mu_{\Sigma\Lambda}$	1.61 ± 0.08 [19]	1.51	1.72	1.63	1.69	1.60

suggests a deeper significance of the values of the parameters employed, in particular, the quark masses and the mixing angle.

VI. SUMMARY AND CONCLUSION

To summarize, the input parameters pertaining to the χQM with and without configuration mixing have been fixed by carrying out a brief analysis incorporating the latest data pertaining to $\bar{u}$-$\bar{d}$ asymmetry and spin polarization functions. These parameters of the χQM when used with the generally accepted values of the quark masses M_q, incorporating the "quark sea" contribution as well as its orbital angular momentum through the generalized Cheng-Li mechanism, not only improve the baryon magnetic moments as compared to the NRQM but also give a nonzero value for ΔCG. The predictions of the χQM with the generalized Cheng-Li mechanism improve further when the effects of configuration mixing and "mass adjustments" due to confinement effects are included; for example, in the case of the E866 data we get an excellent fit for the octet magnetic moments and an almost perfect fit for ΔCG. Interestingly, we find that the generalized Cheng-Li mechanism coupled with the effects of configuration mixing plays a crucial role in fitting the individual magnetic moments, whereas "mass adjustments" along with the generalized Cheng-Li mechanism play an important role in fitting ΔCG. When the above analysis is repeated with the earlier NMC data, a similar level of agreement is obtained, but the results in the case of E866 look better. Interestingly, we find that the masses $M_u = M_d = 330$ MeV, after corrections due to configuration mixing and "mass adjustments," provide the best fit for the magnetic moments.

In the case of decuplet baryon magnetic moments, we find a good agreement of Δ^{++} and Ω^- with the experimental data. On comparison of our results with the corresponding results of Song *et al.* and of Linde *et al.*, we find that the measurement of Δ^+, Δ^-, Σ^+, or Σ^- would have implications for the Cheng-Li mechanism.

Within the χQM with configuration mixing, when $\Delta q(Q^2)$ is corrected by the inclusion of the gluon contribution through the axial anomaly [32,42], not only do we obtain improvement in the quark spin distribution functions and magnetic moments but also the gluon polarization found in this manner is very much in agreement with certain recent measurements [43] as well as theoretical estimates [44,45].

In conclusion, we would like to state that the success of the χQM with the Cheng-Li mechanism and configuration mixing in achieving an excellent agreement regarding spin distribution functions, quark distribution functions, and magnetic moments strongly suggests that, at leading order, constituent quarks and the weakly interacting Goldstone bosons constitute the appropriate degrees of freedom in the nonperturbative regime of QCD with the weakly interacting gluons (in the manner of Manohar and Georgi) providing the first order corrections.

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APPENDIX

The magnetic moment of a given baryon in the χQM with sea and orbital contributions, following Eq. (4), is given by

$$\mu(B)_{\rm total} = \mu(B)_{\rm val} + \mu(B)_{\rm sea} + \mu(B)_{\rm orbit}. \qquad (A1)$$

To calculate the valence contribution to the magnetic moment, $\mu(B)_{\rm val}$, we first express it in terms of the valence quark polarizations ($\Delta q_{\rm val}$) and the quark magnetic moments (μ_q), for example,

$$\mu(B)_{\rm val} = \Delta u_{\rm val}\mu_u + \Delta d_{\rm val}\mu_d + \Delta s_{\rm val}\mu_s. \qquad (A2)$$

The quark polarizations can be calculated from the spin structure of a given baryon. Using Eqs. (7) and (26) of the text, the spin structure of a baryon in the "mixed" octet is given by

$$\hat{B} \equiv \langle B|\mathcal{N}|B\rangle = \cos^2\phi \langle 56,0^+|\mathcal{N}|56,0^+\rangle_B + \sin^2\phi \langle 70,0^+|\mathcal{N}|70,0^+\rangle_B . \tag{A3}$$

For the case of the proton, using Eqs. (27) and (28) of the text, we have

$$\langle 56,0^+|\mathcal{N}|56,0^+\rangle_p = \frac{5}{3}u_+ + \frac{1}{3}u_- + \frac{1}{3}d_+ + \frac{2}{3}d_- , \tag{A4}$$

$$\langle 70,0^+|\mathcal{N}|70,0^+\rangle_p = \frac{4}{3}u_+ + \frac{2}{3}u_- + \frac{2}{3}d_+ + \frac{1}{3}d_- . \tag{A5}$$

The valence contribution to the magnetic moment for the proton, $\mu(p)_{\rm val}$, can be found by using Eqs. (A2), (A3), (A4) and (A5), for example,

$$\mu(p)_{\rm val} = \left[\cos^2\phi\left(\frac{4}{3}\right) + \sin^2\phi\left(\frac{2}{3}\right)\right]\mu_u + \left[\cos^2\phi\left(-\frac{1}{3}\right) + \sin^2\phi\left(\frac{1}{3}\right)\right]\mu_d + [0]\mu_s . \tag{A6}$$

For the Λ hyperon, we have

$$\langle 56,0^+|\mathcal{N}|56,0^+\rangle_\Lambda = \frac{1}{2}u_+ + \frac{1}{2}u_- + \frac{1}{2}d_+ + \frac{1}{2}d_- + 1s_+ + 0s_- , \tag{A7}$$

$$\langle 70,0^+|\mathcal{N}|70,0^+\rangle_\Lambda = \frac{2}{3}u_+ + \frac{1}{3}u_- + \frac{2}{3}d_+ + \frac{1}{3}d_- + \frac{2}{3}s_+ + \frac{1}{3}s_- , \tag{A8}$$

and

$$\mu(\Lambda)_{\rm val} = \left[\sin^2\phi\left(\frac{1}{3}\right)\right]\mu_u + \left[\sin^2\phi\left(\frac{1}{3}\right)\right]\mu_d + \left[\cos^2\phi(1) + \sin^2\phi\left(\frac{1}{3}\right)\right]\mu_s . \tag{A9}$$

Similarly, we can calculate the valence contribution to the magnetic moments for other octet baryons; however, the calculation of the transition magnetic moment $\mu(\Sigma\Lambda)$ is somewhat different and for this we have

$$\langle 56,0^+|\mathcal{N}|56,0^+\rangle_{\Sigma\Lambda} = \frac{1}{2\sqrt{3}}u_+ - \frac{1}{\sqrt{3}}u_- - \frac{1}{2\sqrt{3}}d_+ + \frac{1}{\sqrt{3}}d_- , \tag{A10}$$

$$\langle 70,0^+|\mathcal{N}|70,0^+\rangle_{\Sigma\Lambda} = \frac{1}{4\sqrt{3}}u_+ + \frac{3}{4\sqrt{3}}u_- - \frac{1}{4\sqrt{3}}d_+ - \frac{3}{4\sqrt{3}}d_- , \tag{A11}$$

giving

$$\mu(\Sigma\Lambda)_{\rm val} = -\frac{1}{2\sqrt{3}}\left[\left(\cos^2\phi\left(-\frac{1}{\sqrt{3}}\right) + \sin^2\phi\left(-\frac{1}{2\sqrt{3}}\right)\right) - 2\left(\cos^2\phi\left(\frac{1}{\sqrt{3}}\right) + \sin^2\phi\left(\frac{1}{2\sqrt{3}}\right)\right)\right](\mu_u - \mu_d). \tag{A12}$$

The "quark sea" contribution to the magnetic moment of a given baryon, $\mu(B)_{\rm sea}$, can be expressed in terms of the sea quark polarizations ($\Delta q_{\rm sea}$) and μ_q as

$$\mu(B)_{\rm sea} = \Delta u_{\rm sea}\mu_u + \Delta d_{\rm sea}\mu_d + \Delta s_{\rm sea}\mu_s . \tag{A13}$$

To calculate $\Delta q_{\rm sea}$ for different quarks in a given baryon, we consider the spin structure of the baryon alongwith the "quark sea." Using Eq. (9) of the text and Eqs. (A3), (A4) and (A5), the spin structure of the proton and the associated "quark sea" is given by

$$\begin{aligned}\hat{p} = \cos^2\phi\Bigg[&\frac{5}{3}\left(\sum P_u u_+ + |\psi(u_+)|^2\right) + \frac{1}{3}\left(\sum P_u u_- + |\psi(u_-)|^2\right) + \frac{1}{3}\left(\sum P_d d_+ + |\psi(d_+)|^2\right) \\ &+ \frac{2}{3}\left(\sum P_d d_- + |\psi(d_-)|^2\right)\Bigg] + \sin^2\phi\Bigg[\frac{4}{3}\left(\sum P_u u_+ + \left|\psi(u_+)\right|^2\right) + \frac{2}{3}\left(\sum P_u u_- + |\psi(u_-)|^2\right) \\ &+ \frac{2}{3}\left(\sum P_d d_+ + |\psi(d_+)|^2\right) + \frac{1}{3}\left(\sum P_d d_- + |\psi(d_-)|^2\right)\Bigg],\end{aligned} \tag{A14}$$

where

$$\sum P_u=a\left(\frac{9+\beta^2+2\zeta^2}{6}+\alpha^2\right) \quad \text{and} \quad |\psi(u_\pm)|^2=\frac{a}{6}(3+\beta^2+2\zeta^2)u_\mp+ad_\mp+a\alpha^2 s_\mp,$$

$$\sum P_d=a\left(\frac{9+\beta^2+2\zeta^2}{6}+\alpha^2\right) \quad \text{and} \quad |\psi(d_\pm)|^2=au_\mp+\frac{a}{6}(3+\beta^2+2\zeta^2)d_\mp+a\alpha^2 s_\mp,$$

$$\sum P_s=a\left(\frac{2\beta^2+\zeta^2}{3}+2\alpha^2\right) \quad \text{and} \quad |\psi(s_\pm)|^2=a\alpha^2 u_\mp+a\alpha^2 d_\mp+\frac{a}{3}(2\beta^2+\zeta^2)s_\mp .$$

Using Eqs. (A13) and (A14), the "quark sea" contribution to the magnetic moment for the case of the proton is given by

$$\mu(p)_{\rm sea}=\left\{-\cos^2\phi\left[\frac{a}{3}\left(7+4\alpha^2+\frac{4}{3}\beta^2+\frac{8}{3}\zeta^2\right)\right]-\sin^2\phi\left[\frac{a}{3}\left(5+2\alpha^2+\frac{2}{3}\beta^2+\frac{4}{3}\zeta^2\right)\right]\right\}\mu_u+\left\{-\cos^2\phi\left[\frac{a}{3}\left(2-\alpha^2-\frac{1}{3}\beta^2-\frac{2}{3}\zeta^2\right)\right]-\sin^2\phi\left[\frac{a}{3}\left(4+\alpha^2+\frac{1}{3}\beta^2+\frac{2}{3}\zeta^2\right)\right]\right\}\times\mu_d+[-a\alpha^2]\mu_s . \tag{A15}$$

Similarly, the spin structure for Λ can obtained by substituting Eq. (9) in Eqs. (A7) and (A8) and is given by

$$\hat{\Lambda}=\cos^2\phi\left[\frac{1}{2}\left(\sum P_u u_+ +|\psi(u_+)|^2+\sum P_u u_- +|\psi(u_-)|^2+\sum P_d d_+ +|\psi(d_+)|^2+\sum P_d d_- +|\psi(d_-)|^2\right)+\sum P_s s_+ +|\psi(s_+)|^2\right]+\sin^2\phi\left[\frac{2}{3}\left(\sum P_u u_+ +|\psi(u_+)|^2+\sum P_d d_+ +|\psi(d_+)|^2+\sum P_s s_+ +|\psi(s_+)|^2\right)+\frac{1}{3}\left(\sum P_u u_- +|\psi(u_-)|^2+\sum P_d d_- +|\psi(d_-)|^2+\sum P_s s_- +|\psi(s_-)|^2\right)\right]. \tag{A16}$$

The "quark sea" contribution to the magnetic moment for the case of Λ is given by

$$\mu(\Lambda)_{\rm sea}=\left[-\cos^2\phi(a\alpha^2)-\sin^2\phi\left(\frac{a}{9}(9+6\alpha^2+\beta^2+2\zeta^2)\right)\right]\mu_u+\left[-\cos^2\phi(a\alpha^2)-\sin^2\phi\left(\frac{a}{9}(9+6\alpha^2+\beta^2+2\zeta^2)\right)\right]\mu_d+\left[-\cos^2\phi\left(\frac{a}{3}(6\alpha^2+4\beta^2+2\zeta^2)\right)-\sin^2\phi\left(\frac{4}{9}a(3\alpha^2+2\beta^2+\zeta^2)\right)\right]\mu_s . \tag{A17}$$

Similarly, one can calculate the contribution of the "quark sea" spin polarizations to the magnetic moments of the other baryons and these have been listed in Table I. For the transition magnetic moment $\mu(\Sigma\Lambda)$, the spin structure can be obtained from Eqs. (9), (A10), and (A11) and is given by

$$\hat{\Sigma\Lambda}=\cos^2\phi\left[\frac{1}{2\sqrt{3}}\left(\sum P_u u_+ +|\psi(u_+)|^2\right)-\frac{1}{\sqrt{3}}\left(\sum P_u u_- +|\psi(u_-)|^2\right)-\frac{1}{2\sqrt{3}}\left(\sum P_d d_+ +|\psi(d_+)|^2\right)+\frac{1}{\sqrt{3}}\left(\sum P_d d_- +|\psi(d_-)|^2\right)\right]+\sin^2\phi\left[\frac{1}{4\sqrt{3}}\left(\sum P_u u_+ +|\psi(u_+)|^2\right)+\frac{3}{4\sqrt{3}}\left(\sum P_u u_- +|\psi(u_-)|^2\right)-\frac{1}{4\sqrt{3}}\left(\sum P_d d_+ +|\psi(d_+)|^2\right)-\frac{3}{4\sqrt{3}}\left(\sum P_d d_- +|\psi(d_-)|^2\right)\right], \tag{A18}$$

giving the "quark sea" contribution to the transition magnetic moment as

$$\mu(\Sigma\Lambda)_{\rm sea}=-\frac{1}{2\sqrt{3}}\Bigg(-\cos^2\phi\bigg(\frac{a}{2\sqrt{3}}(3+3\alpha^2+\beta^2+2\zeta^2)\bigg)+\sin^2\phi\bigg[\frac{a}{2\sqrt{3}}\bigg(1+\alpha^2+\frac{1}{3}\beta^2+\frac{2}{3}\zeta^2\bigg)\bigg]-2\bigg\{\cos^2\phi\bigg(\frac{a}{2\sqrt{3}}(3+3\alpha^2+\beta^2+2\zeta^2)\bigg)-\sin^2\phi\bigg[\frac{a}{2\sqrt{3}}\bigg(1+\alpha^2+\frac{1}{3}\beta^2+\frac{2}{3}\zeta^2\bigg)\bigg]\bigg\}\Bigg)\times(\mu_u-\mu_d). \tag{A19}$$

For calculating the orbital contribution to the total magnetic moment, one has to use the generalized Cheng-Li mechanism expressed in Eq. (21), and for the case of the proton and Λ it is given as

$$\mu(p)_{\rm orbit}=\cos^2\phi\bigg[\frac{4}{3}[\mu(u_+\to)]-\frac{1}{3}[\mu(d_+\to)]\bigg]+\sin^2\phi\bigg[\frac{2}{3}[\mu(u_+\to)]+\frac{1}{3}[\mu(d_+\to)]\bigg], \tag{A20}$$

$$\mu(\Lambda)_{\rm orbit}=\cos^2\phi[\mu(s_+\to)]+\sin^2\phi\bigg[\frac{1}{3}[\mu(u_+\to)]+\frac{1}{3}[\mu(d_+\to)]+\frac{1}{3}[\mu(s_+\to)]\bigg]. \tag{A21}$$

For the case of $\Sigma\Lambda$, the orbital contribution to the magnetic moment is

$$\mu(\Sigma\Lambda)_{\rm orbit}=\bigg[\cos^2\phi\bigg(\frac{1}{2}\bigg)+\sin^2\phi\bigg(\frac{1}{4}\bigg)\bigg]\{[\mu(u_+\to)]-[\mu(d_+\to)]\}. \tag{A22}$$

Using Eq. (A1) one can calculate the total magnetic moments of p, Λ, and $\Sigma\Lambda$. The magnetic moments of other octet baryons can be calculated similarly.

As an example of the decuplet baryon, we detail below the calculation of the magnetic moment of Δ^+. In the absence of any mixing, the spin structure for Δ^+, using Eqs. (37) of the text, is given by

$$\langle 56,0^+|\mathcal{N}|56,0^+\rangle_{\Delta^+}=2u_++d_+. \tag{A23}$$

The valence contribution to the total magnetic moment is expressed as

$$\mu(\Delta^+)_{\rm val}=\Delta u_{\rm val}\mu_u+\Delta d_{\rm val}\mu_d+\Delta s_{\rm val}\mu_s=2\mu_u+1\mu_d+0\mu_s. \tag{A24}$$

The contribution of the "quark sea" to the total magnetic moment in terms of the "quark sea" polarizations and μ_q is expressed as

$$\mu(\Delta^+)_{\rm sea}=\Delta u_{\rm sea}\mu_u+\Delta d_{\rm sea}\mu_d+\Delta s_{\rm sea}\mu_s. \tag{A25}$$

By substituting Eq. (9) in Eq. (A23), we obtain the spin structure of Δ^+ and the associated "quark sea," which is expressed as

$$\hat{\Delta}^+=2\bigg(\sum P_u u_++|\psi(u_+)|^2\bigg)+\bigg(\sum P_d d_++|\psi(d_+)|^2\bigg), \tag{A26}$$

and the "quark sea" contribution to the magnetic moment is consequently given by

$$\mu(\Delta^+)_{\rm sea}=\bigg[-a\bigg(5+2\alpha^2+\frac{2}{3}\beta^2+\frac{4}{3}\zeta^2\bigg)\bigg]\mu_u+\bigg[-a\bigg(4+\alpha^2+\frac{1}{3}\beta^2+\frac{2}{3}\zeta^2\bigg)\bigg]\mu_d+[-3a\alpha^2]\mu_s. \tag{A27}$$

The contribution of the "quark sea" to the magnetic moment of other decuplet baryons can similarly be calculated in terms of the "quark sea" polarizations, the expressions for which are given in Table I.

The orbital contribution to the total magnetic moment, as given by Eq. (22), is expressed as

$$\mu(\Delta^+)_{\rm orbit}=2[\mu(u_+\to)]+[\mu(d_+\to)]. \tag{A28}$$

Substituting Eqs. (A24), (A27), and (A28) in Eq. (A1), we get the total magnetic moment of Δ^+. We can also calculate the transition magnetic moment $\mu(\Delta N)$ in a similar manner to the calculation of $\mu(\Sigma\Lambda)$.

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