Examination of the strangeness contribution to the nucleon magnetic moment

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We examine the nucleon strangeness magnetic moment μ_s with a lowest order meson cloud model. We observe that (1) strangeness in the nucleon is a natural requirement of the empirical relation $\mu_p/\mu_n=-3/2$, which favors an SU(3) octet meson cloud instead of merely the SU(2) pions. (2) In a consistent perturbative calculation, the quark vertex contribution to μ_s is divergently positive, the meson cloud contribution to μ_s is divergently negative, and the sum is convergent and negative. (3) In the rest frame of the nucleon, μ_s cannot be separated into a quark part and an antiquark part, neither can μ_s be calculated via the spin and orbital angular momentum of the strange quarks and antiquarks. (4) While the overall sign of μ_s is under debate, the spin part of μ_s (which is related to the strange quark tensor charge) is better known to be negative.

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I. INTRODUCTION

The strangeness content of the nucleon is purely a sea quark effect and therefore is a clean and important window to look into the nucleon internal structure and dynamics. Of particular recent interest to the community is the nucleon strangeness magnetic moment $\mu_s \equiv G_M^s(Q^2=0)$ [1]: By measuring the nucleon weak neutral current form factor in parity-violating electron-nucleon scattering [2,3], a determination of the strange magnetic form factor $G_M^s(Q^2)$ becomes possible. G_M^s and/or μ_s has also been extensively studied in many theoretical approaches, such as the lattice QCD calculation [4–7], chiral perturbation and dispersion relation [8–10], GDH sum rule [11], various quark models [12–18], correlating the octet baryon magnetic moments by assuming SU(3) flavor symmetry [19–21], and so on [1].

The interest in μ_s was partially stimulated by the EMC finding that the nucleon contains significant strangeness polarization [22], which was then regarded as startling. However, we will explain in Sec. II with a lowest order meson cloud model that strangeness content in the nucleon is in fact a natural requirement of the renowned empirical relation $\mu_p/\mu_n=-3/2$. In Sec. III various contributions to μ_s are explicitly calculated with lowest order perturbation theory. A detailed comparison of μ_s with the nucleon strangeness polarization Δ_s is performed in Sec. IV, where we also comment on a tendency in some studies [15,19–21] to compute μ_s via the spin and orbital angular momentum of the strange quarks and antiquarks. In the end we give a brief summary and discuss the sign of μ_s which is under debate among the community.

II. THE NUCLEON MAGNETIC MOMENTS AND THE STRANGENESS

Historically, the SU(6) valence quark model gave a good description of the nucleon magnetic moments, particularly the empirical relation $\mu_p/\mu_n=-3/2$. It is clear today that the nucleon contains also sea quarks. Especially, spontaneous chiral symmetry breaking tells that pseudoscalar meson degrees of freedom should be important in the nucleon. The meson cloud would modify the bare quark magnetic moment, therefore the relation $\mu_p/\mu_n=-3/2$ respected by the valence configuration should be rechecked. We will show that it is the SU(3) instead of SU(2) meson cloud that preserves $\mu_p/\mu_n=-3/2$, in this sense the nucleon strangeness content is required by $\mu_p/\mu_n=-3/2$.

First we specify our formalism to compute various contributions to nucleon magnetic moments. We take a renormalizable model Lagrangian

$$\mathcal{L} = \bar{\psi}[i\,\partial\!\!\!/ - S(r) - \gamma^0 V(r)]\psi + \frac{1}{2}(\partial_\mu\phi_i)^2 - \frac{1}{2}m_i^2\phi_i^2 - \frac{1}{2F_\pi}\bar{\psi}[S(r)i\gamma^5\lambda^i\phi_i + i\gamma^5\lambda^i\phi_i S(r)]\psi. \tag{1}$$

It is derived from the nonlinear σ model in which meson fields are introduced to restore chiral symmetry [23]; $S(r) = cr+m$ represents the linear scalar confinement potential cr and the quark mass matrix m, $V(r)=-\alpha/r$ is the Coulomb-type vector potential, $F_\pi=93$ MeV is the pion decay constant, ϕ_i (i runs from 1 to 8) are the pseudoscalar meson fields, and λ_i are the Gell-Mann matrices. The conserved electromagnetic current given by Eq. (1) is $j^\mu=\Sigma_q j_q^\mu + j_\phi^\mu$, with j_q^μ and j_ϕ^μ the quark and meson currents, respectively:

$$j_q^\mu = Q_q\bar{\psi}_q\gamma^\mu\psi_q,$$

$$j_\phi^\mu = e(\phi_1\partial^\mu\phi_2 - \phi_2\partial^\mu\phi_1 + \phi_4\partial^\mu\phi_5 - \phi_5\partial^\mu\phi_4). \tag{2}$$

The nucleon magnetic moment is obtained by taking the expectation value of the operator $\vec{\mu}=\int d^3x\vec{r}\times\vec{j}$ in a nucleon state. At zeroth order the quark-meson coupling is turned off and the nucleon is described by the usual SU(6) three-quark ground state of the Hamiltonian,

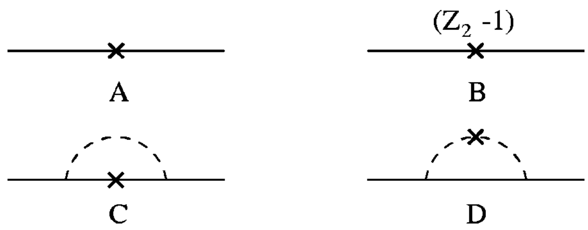

FIG. 1. Dressed quark magnetic moment up to second order in quark-meson coupling; a cross on the quark or meson line denotes the insertion of a magnetic moment operator.

$$H_q = \int d^3x\ \psi^\dagger\left[\vec{\alpha}\cdot\frac{1}{i}\vec{\partial} + \beta S(r) + V(r)\right]\psi. \qquad (3)$$

Figure 1 gives the "dressed" quark magnetic moment up to second order in quark-meson coupling. Figure 1(a) is the bare quark contribution $\mu_u^0 = -2\mu_d^0$. Figure 1(b) is the wave-function renormalization counter term, the renormalization factor Z_2 is the same for u,d quarks assuming SU(2) flavor symmetry. Figures 1(c) and 1(d) are the one-loop quark vertex and meson cloud contributions, respectively. A explicit computation of these diagrams will be postponed until the next section, here it suffices to denote the amplitudes of Figs. 1(c) and 1(d) by A_ϕ and C_ϕ, with spin-isospin factors dropped out. The subscript $\phi = \pi, K, \eta$ refers to the meson type in the loop. It is understood that the intermediate quark is s for $\phi = K$, and is u or d for $\phi = \pi, \eta$. Working out the spin-isospin factors, we find the "dressed" u and d quark magnetic moments

$$\tilde{\mu}_u = Z_2^u\mu_u^0 - \frac{2}{3}A_K + \frac{2}{9}A_\eta + 2C_\pi + 2C_K, \qquad (4a)$$

$$\tilde{\mu}_d = Z_2^d\mu_d^0 + A_\pi - \frac{2}{3}A_K - \frac{1}{9}A_\eta - 2C_\pi. \qquad (4b)$$

Note that the subscripts u, d in $\tilde{\mu}_u$, $\tilde{\mu}_d$ just indicate that this is the contribution evolved from a single u or d "parent" quark. The real u, d or s flavor contribution is identified by the line type on which the magnetic moment operator is inserted. The meson cloud contribution is partitioned according to its quark contents. For example, of the $K^+(=u\bar{s})$ contribution $2/3$ is counted as from the u flavor and $1/3$ from the s flavor. A useful reminder is that although the chargeless $K^0(=d\bar{s})$ does not contribute magnetic moment in total, the d and $\bar{s}$ quarks inside it contribute *separately* if the orbital angular momentum of K^0 is nonzero.

It is a common feature of relativistic meson cloud models that the bare quark magnetic moment is too small to account for the nucleon magnetic moments, therefore A_ϕ and C_ϕ in Eq. (4) are expected to be quite large. If SU(3) flavor symmetry is unbroken, then $A_K = A_\pi$, $C_K = C_\pi$, and Eq. (3) tells us that $\tilde{\mu}_u = -2\tilde{\mu}_d$. Thus, by including an octet meson cloud (and hence strangeness) into the nucleon, $\mu_p/\mu_n = -3/2$ will be preserved, with slight violation from SU(3) flavor symmetry breaking and the exchange current contribution [24]. On the other hand, if one merely includes the SU(2) pions, strong violation will be found for $\tilde{\mu}_u = -2\tilde{\mu}_d$, and thus also for $\mu_p/\mu_n = -3/2$.

III. COMPUTATION OF μ_s

In this paper we do not aim to make a fine tuning to the bulk nucleon magnetic moments. Instead, we try to gain some insights into μ_s that do not depend on or only loosely depend on our model assumptions. Since no strangeness is assigned to the nucleon at zeroth order, up to second order the only contributions to μ_s are from Figs. 1(c) and 1(d). The effect of wavefunction renormalization on μ_s starts at fourth order, and the exchange current does not contribute to μ_s at second order either. Working out the spin-isospin factors, we have

$$\mu_s = 2A_K - 2C_K. \qquad (5)$$

Note that the quark charge is excluded in μ_s which is defined as the *total* strangeness magnetic moment of the nucleon, but included in $\tilde{\mu}_u$ and $\tilde{\mu}_d$ which refer to the dressed magnetic moment evolved from a *single* "parent" quark.

The ingredients needed for calculating Figs. 1(c) and 1(d) are the quark wave functions and the lowest order quark and meson propagators. The meson propagator given by Eq. (1) is the free one:

$$\Delta_{ij}(x_1,x_2) \equiv \langle 0|T\{\phi_i(x_1),\phi_j(x_2)\}|0\rangle = \frac{i}{(2\pi)^4}\int d^4k \frac{\delta_{ij}e^{-ik\cdot(x_1-x_2)}}{k^2 - m_i^2 + i\epsilon}. \qquad (6)$$

Since the nonperturbative confinement is included in H_q the quark propagator has to be obtained numerically, and in practice we have to work with time-ordered perturbation theory. We write the solution of H_q as

$$\psi(x) = \sum_\alpha u_\alpha(x)a_\alpha + \sum_\beta v_\beta(x)b_\beta^\dagger, \qquad (7)$$

where $u_\alpha(x) = e^{-iE_\alpha t}u_\alpha(\vec{x})\tau_\alpha$, $v_\beta(x) = e^{iE_\beta t}v_\beta(\vec{x})\tau_\beta$; τ is the flavor wave function and the spatial wave function is

$$u_\alpha(\vec{x}) = \begin{pmatrix} g_{njl}(r) \\ -i\vec{\sigma}\cdot\hat{\vec{r}}f_{njl}(r)\end{pmatrix}Y_{jl}^m(\hat{\vec{r}}), \qquad (8)$$

and similarly for $v_\beta(\vec{x})$. In Eq. (8), g and f are real functions, n is the radial quantum number, and $Y_{jl}^m(\hat{\vec{r}})$ is the spinor spherical harmonics.

Corresponding to Eq. (7), the quark propagator is

$$D(x_1,x_2) \equiv \langle 0|T\{\psi(x_1),\overline{\psi}(x_2)\}|0\rangle = \theta(t_1 - t_2)\sum_\alpha u_\alpha(x_1)\overline{u}_\alpha(x_2) - \theta(t_2 - t_1)\sum_\beta v_\beta(x_1)\overline{v}_\beta(x_2). \qquad (9)$$

Applying the propagators to Fig. 1(c), we get the quark vertex amplitude (with the initial and final states denoted as u_i and u_f, respectively):

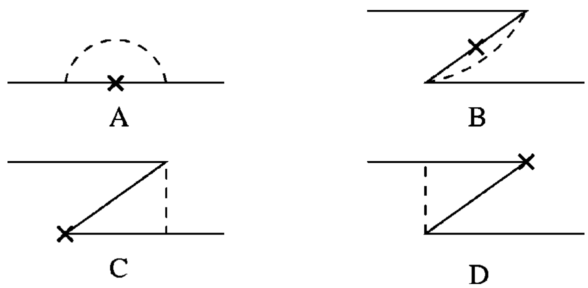

FIG. 2. Time-ordered diagrams of Fig. 1(c); (a) is the quark state contribution; (b) is the anti-quark state contribution; (c) and (d) are the quark-antiquark pair creation and annihilation "Z" diagrams.

$$A_K = \int d^4x_1 d^4x_2 \overline{u_f}(x_2)\Gamma^i(r_2)\Big[\theta(t_2-t)\theta(t-t_1) \times \sum_{\alpha\alpha'} u_\alpha(x_2)\Gamma_{\alpha\alpha'}\overline{u}_{\alpha'}(x_1) + \theta(t_1-t)\theta(t-t_2) \times \sum_{\beta\beta'} v_\beta(x_2)\Gamma_{\beta\beta'}\overline{v}_{\beta'}(x_1) - \theta(t_2-t)\theta(t_1-t) \times \sum_{\alpha\beta'} u_\alpha(x_2)\Gamma_{\alpha\beta'}\overline{v}_{\beta'}(x_1) - \theta(t-t_2)\theta(t-t_1) \times \sum_{\beta\alpha'} v_\beta(x_2)\Gamma_{\beta\alpha'}\overline{u}_{\alpha'}(x_1)\Big] \times \Gamma^j(r_1)u_i(x_1)\frac{i}{(2\pi)^4}\int d^4k\frac{\delta_{ij}e^{-ik\cdot(x_1-x_2)}}{k^2-m_i^2+i\epsilon}, \qquad (10)$$

where $\Gamma^i(r)\equiv S(r)\gamma^5\lambda^i/F_\pi$, $\Gamma_{\alpha\alpha'}\equiv\int d^3x\, u_\alpha^\dagger(\vec{x}\times\vec{\alpha})^3 u_{\alpha'}$, and similarly for $\Gamma_{\beta\beta'}$, etc. The four time-ordered terms in Eq. (11) correspond to the time-ordered diagrams of Fig. 2.

Similarly, the Kaon cloud amplitude of Fig. 1(d) is found to be

$$C_K = \int d^4x_1 d^4x_2 \overline{u_f}(x_2)\Gamma^i(r_2)D(x_2,x_1)\Gamma^j(r_1)u_i(x_1)\frac{1}{(2\pi)^8} \times \int d^4k_1 d^4k_2 d^3x \frac{e^{-ik_2\cdot(x_2-x)}}{k_2^2-m_i^2+i\epsilon}(\vec{x}\times i(\vec{k}_1+\vec{k}_2))^3 \times(\delta_{i4}\delta_{j5}-\delta_{i5}\delta_{j4})\frac{e^{-ik_1\cdot(x-x_1)}}{k_1^2-m_i^2+i\epsilon}. \qquad (11)$$

We omit the details for calculating Eqs. (10) and (11). The integrals can be reduced analytically to radial integrations at the vertex points and of loop momentum $|\vec{k}|$. The remaining integrations are carried out numerically.

As we did for Δ_s in Ref. [25], we allow here strong variations of the model parameters (see Table I) entering in the Lagrangian of Eq. (1), so as to check the model-dependence of our results. The last column of Table I gives the bare magnetic moment of the nucleon. As in many other meson cloud models, the bare value is much smaller than the experimental value. The rest is to be provided by sea quarks. The one-loop quark vertex and Kaon cloud contributions to μ_s are given in Figs. 3 and 4 in units of μ_N, and their sum in Fig. 5, as functions of the energy up to which the intermediate quark and antiquark states are consistently summed.

Figure 3 tells that for all choices of parameter sets, the quark vertex contribution to μ_s turns out to be positive, as long as enough excited quark states are taken into account. On the other hand, Fig. 4 tells us that the meson cloud contribution to μ_s is always negative. Both Figs. 3 and 4 indicate a divergent result. This is because in the chiral Lagrangian of

TABLE I. Model parameters and the bare value of nucleon magnetic moments.

Parameter set	$m_{u,d}$ (MeV)	m_s (MeV)	α	c (GeV^2)	$\mu_p=-1.5\mu_n$ (μN)
1	10	150	0.26	0.11	1.60
2	10	150	0.26	0.16	1.33
3	300	500	0.26	0.11	1.16
4	10	150	0.50	0.18	1.25

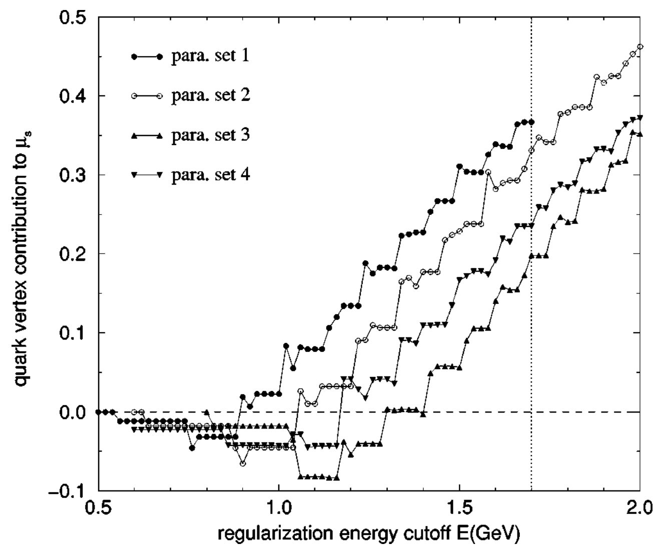

FIG. 3. Quark vertex contribution to μ_s as a function of the regularization energy cutoff.

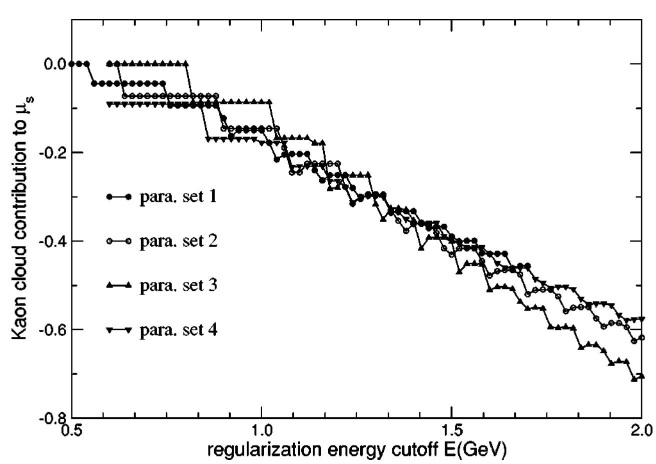

FIG. 4. Kaon cloud contribution to μ_s as a function of the regularization energy cutoff.

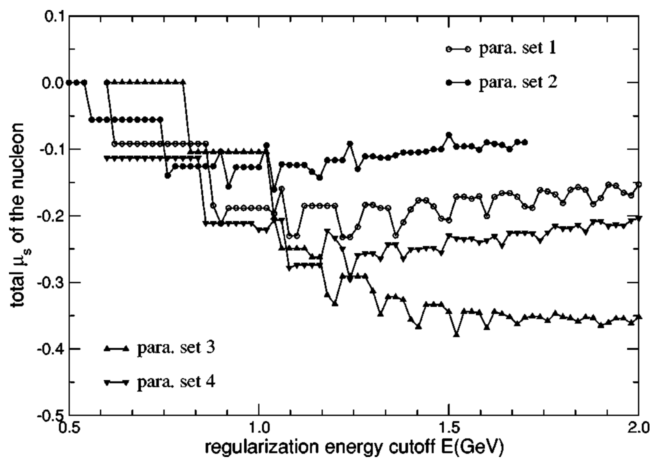

FIG. 5. The sum of Figs. 3 and 4, which is the total μ_s of the nucleon.

Eq. (1), the electromagnetic current of the strange quark (j_s^μ) and of the Kaon cloud (j_K^μ) are not separately conserved. To obtain a meaningful finite result, we must renormalize the composite, nonconserved magnetic moment operator. Analogous to the lattice renormalization, we cut the intermediate quark and antiquark states at a certain energy, which should roughly correspond to the inverse of the lattice spacing ($a^{-1} \sim 1.7$ GeV) in the lattice QCD calculation of nucleon properties [27]. The cutoff point is indicated in Fig. 3.

The complete strangeness electromagnetic current is certainly conserved (in the absence of the flavor-changing weak interaction), therefore by adding the quark vertex and the Kaon cloud contributions together, one should get a convergent total strangeness contribution to the nucleon magnetic moment. A rough convergence is indeed seen in Fig. 5.

IV. COMPARING μ_s with Δ_s

In our lowest order perturbation theory, the nucleon strangeness polarization Δ_s receives a contribution only from the quark vertex diagram, Fig. 1(c), but not from the spinless Kaon cloud itself. It is quite interesting to notice that Fig. 1(c) contributes to μ_s and Δ_s [25] with opposite signs. To see how this difference occurs, in Fig. 6 we give the separate contributions to μ_s from the time-ordered diagrams of Fig. 2 for the second set of model parameters. Accordingly, in Fig. 7 we indicate the corresponding contributions to Δ_s [25].

The results of Figs. 6 and 7 explain why μ_s and Δ_s from Fig. 1(c) have opposite signs: The intermediate quark states give a contribution of the same sign (both negative) to μ_s and Δ_s, which is as expected. The antiquark states contribute a positive amount to Δ_s, but a negative amount to μ_s. This is also reasonable since the antiquark has an opposite charge to the quark. However, one would not expect the usual relation between magnetic moment and spin for the contributions from the "Z" diagrams in which a quark-antiquark ($q\overline{q}$) pair is created or annihilated. Figures 6 and 7 show that the "Z" diagrams give a negative contribution to the polarization while they generate a positive contribution to the magnetic moment. They are also the dominating contributions (note

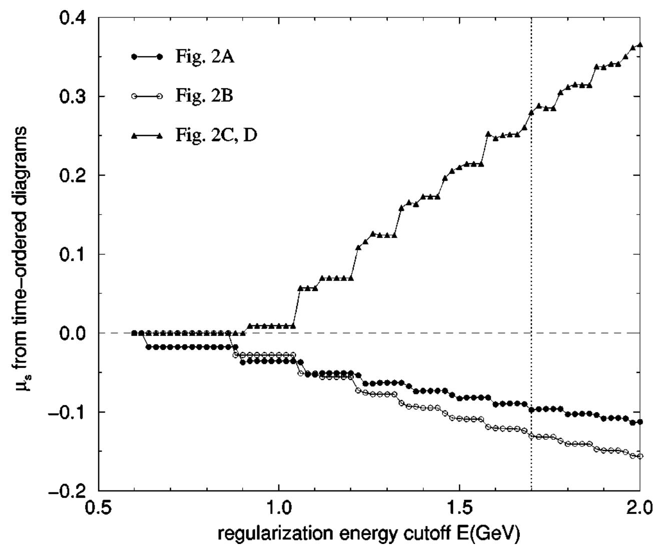

FIG. 6. Contributions to μ_s from the time-ordered diagrams of Fig. 2 as functions of the energy cutoff; the quark and antiquark states both generate a negative contribution, while the two "Z" diagrams yield a positive contribution.

that there are two "Z" diagrams); so eventually we get in total a negative strangeness polarization but a positive strangeness magnetic moment from Fig. 1(c).

The above observation invalidates a tendency in some studies [15,19–21] to separate μ_s into a quark part $\mu_s^{(+)}$ and an antiquark part $\mu_s^{(-)}$, which are then related to the spin and orbital angular momentum of the strange quarks and antiquarks, respectively:

$$\mu_s = \mu_s^{(+)} + \mu_s^{(-)} = \frac{1}{2m_s}(\Delta_s^{(+)} + L_s^{(+)}) - \frac{1}{2m_s}(\Delta_s^{(-)} + L_s^{(-)}), \tag{12}$$

where $\frac{1}{2}\Delta_s^{(\pm)}$ and $L_s^{(\pm)}$ are the strange quark/antiquark spin and orbital contributions to the nucleon spin.

The failure of Eq. (12) can be seen more explicitly by expanding the relevant operators in a plane wave basis. For the quark field of flavor q, the magnetic moment and the spin and orbital angular momentum operators are

$$\vec{\mu}_q \equiv \int d^3x\ \psi_q^\dagger \vec{x} \times \vec{\alpha}\psi_q; \tag{13}$$

$$\vec{S}_q = \frac{1}{2}\int d^3x\ \overline{\psi_q}\vec{\gamma}\gamma^5\psi_q, \quad \vec{L}_q = \int d^3x\ \psi_q^\dagger \vec{x} \times \frac{1}{i}\vec{\partial}\,\psi_q. \tag{14}$$

By expanding $\psi(x)$ in Eqs. (13) and (14) at a given time (say $t=0$) in terms of the Dirac spinors:

$$\psi(x) = \frac{1}{(\sqrt{2\pi})^3}\int d^3k(a_{\vec{k}\lambda}u_{\vec{k}\lambda}e^{i\vec{k}\cdot\vec{x}} + b_{\vec{k}\lambda}^\dagger v_{\vec{k}\lambda}e^{-i\vec{k}\cdot\vec{x}}), \tag{15}$$

the $a^\dagger a$ and $b^\dagger b$ terms can be readily identified as the quark and antiquark contributions, respectively. However, one also gets $a^\dagger b^\dagger$ and ab terms which create or annihilate a $q\overline{q}$ pair.

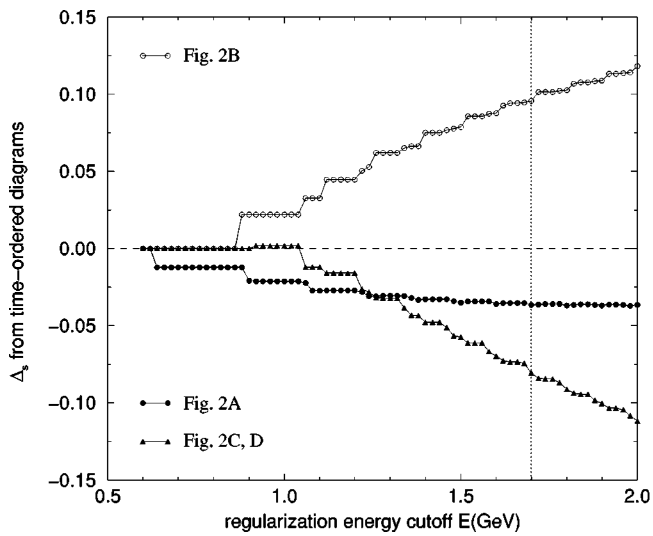

FIG. 7. Contributions to Δ_s from the time-ordered diagrams as functions of the energy cutoff; the quark, antiquark states, and the "*Z*" diagrams give a negative, positive, and negative contribution, respectively.

Such pair terms cannot be attribute separately to the quark or antiquark, and they generally do not vanish except in the infinite momentum frame. So we write

$$\vec{\mu}_q = \vec{\mu}_q^{(+)} + \vec{\mu}_q^{(-)} + q\bar{q}\ \text{terms}, \tag{16a}$$

$$\vec{S}_q = \int d^3k\, \vec{S}_{q\vec{k}}^{(+)} + \int d^3k\, \vec{S}_{q\vec{k}}^{(-)} + q\bar{q}\ \text{terms}, \tag{16b}$$

$$\vec{L}_q = \int d^3k\, \vec{L}_{q\vec{k}}^{(+)} + \int d^3k\, \vec{L}_{q\vec{k}}^{(-)} + q\bar{q}\ \text{terms}. \tag{16c}$$

Besides the pair terms which are characteristic of quantum field theory, $\vec{\mu}_q$, $\vec{S}_q$, and $\vec{L}_q$ also contain relativistic kinetic corrections coming from the small component of Dirac spinors. These kinetic terms are implicitly included in the quark/antiquark parts. In previous studies [26], we have noticed an interesting phenomenon that in the above plane wave basis expansion the relativistic kinetic correction and the pairs terms in $\vec{S}_q$ and $\vec{L}_q$ cancel each other exactly, leaving the sum of $\vec{S}_q$ and $\vec{L}_q$ free of relativistic and quantum corrections.

Writing down explicit expressions of the terms in Eq. (16) and comparing them carefully, one can find that

$$\vec{\mu}_q = \int d^3k \frac{1}{k_0}(\vec{S}_{q\vec{k}} - \vec{S}_{\bar{q}\vec{k}}) + \int d^3k \frac{1}{2k_0}(\vec{L}_{q\vec{k}} - \vec{L}_{\bar{q}\vec{k}}) + \text{pair terms}. \tag{17}$$

Therefore, except for the $q\bar{q}$ pair creation/annihilation terms, the magnetic moment operator in relativistic quantum field theory can indeed be expressed in a quite elegant form which is exactly analogous to our notion of magnetic moment in nonrelativistic quantum mechanics. Namely, magnetic moment equals charge times spin and orbital angular momentum together with the corresponding gyromagnetic factor. However, we are unable to relate the $q\bar{q}$ pair terms of the magnetic moment operator to the pair terms of the spin and orbital angular moment operators in the usual $\vec{\mu}=(1/m)\vec{S}+(1/2m)\vec{L}$ manner. This obstacle is in fact not unexpected: Our general notion is that magnetic moment is proportional to the charge, but when a $q\bar{q}$ pair is created or annihilated we do not know whether it should be counted as the charge of the quark or the antiquark.

V. BRIEF SUMMARY AND DISCUSSION

We have seen in this paper that by properly including strangeness into the nucleon, the renowned empirical relation $\mu_p/\mu_n = -3/2$ which historically was explained by the naive SU(6) quark model assuming $\vec{\mu}=(1/2m)\vec{\sigma}$, is preserved. The nonrelativistic relation between magnetic moment and spin, however, does not survive quantum processes of particle-antiparticle pair creation/annihilation.

By employing a standard lowest order perturbation theory, our model calculation gives a convergent, unambiguous result of $\mu_s \sim -(0.1-0.35)\mu N$ (see Fig. 5), which is the sum of a positive contribution from the quark vertex and a negative contribution from the Kaon cloud. The present experimental result is [2]

$$\mu_s = [0.01 \pm 0.29(\text{stat}) \pm 0.31(\text{sys}) \pm 0.07(\text{theor.})]\mu_N. \tag{18}$$

Most of the theoretical analyses and calculations in the literature yield a negative or close-to-zero μ_s. There is one exception: a significantly positive value is obtained in Ref. [12]. In our opinion, this is because the positive contribution from $q\bar{q}$ pair terms is automatically included in Ref. [12] by a relativistic calculation, while the negative contribution from the Kaon cloud is not properly treated.

Although the experimental result favors a slightly positive μ_s, we argue that there are good reasons to believe that at least the spin part of μ_s is negative. Most recently, we have revealed that the quark magnetic moment can be unambiguously decomposed into a spin and an orbital part, and the spin part is in fact related to the quark tensor charge δq [28]. Since δq can be computed directly as a forward matrix element on the lattice (in contrast, μ_q has to be extrapolated from electromagnetic form factors at finite momentum transfer), the lattice QCD result of a negative strangeness tensor charge $\delta s = -0.046(34)$ [29] can be regarded as relatively reliable in comparison to the lattice QCD prediction of μ_s. Our model gives a similar result [28] as the lattice calculation in Ref. [29].

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