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The proton spin and glueball effects

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ABSTRACT

We explain the smallness of the proton matrix element of the flavor-singlet axial vector current considered as the proton spin. The divergence of the flavor-singlet axial vector current which contains the axial anomaly caused by the gluon fields is replaced by the pseudoscalar meson η , η' , and glueball ι fields under the PCAC assumption. We estimate the coupling constant $f^{0\eta}$, $f^{0\eta'}$ and $f^{0\iota}$ using $U(3) \times U(3)$ current algebraic approach. We determine the strength of the coupling constant $g_{NN\eta}$, $g_{NN\eta'}$, and $g_{NN\iota}$ explaining the smallness of the proton spin. Estimated $g_{NN\eta}$ and $g_{NN\eta'}$ are small and $g_{NN\iota}$ is comparable to $g_{NN\pi}$.

I. INTRODUCTION

The EMC (European Muon Collaboration) data [1] on the spin-dependent proton structure function suggest that the proton matrix element of the flavor-singlet axial vector current constructed by quarks is consistent with zero,

$$\begin{aligned} \langle p | A_\mu^0 | p \rangle &\equiv \frac{1}{2} \sqrt{\frac{2}{3}} \langle p | (\bar{u} \gamma_\mu \gamma_5 u + \bar{d} \gamma_\mu \gamma_5 d + \bar{s} \gamma_\mu \gamma_5 s) | p \rangle \\ &= \frac{1}{2} \sqrt{\frac{2}{3}} (\Delta u' + \Delta d' + \Delta s') s_\mu(p) = \sqrt{\frac{2}{3}} (0.06 \pm 0.12) s_\mu(p), \end{aligned} \quad (1)$$

where s_μ is a covariant proton spin. Naively, one would associate the proton matrix element of the above axial current $\frac{1}{2} \Sigma = \frac{1}{2} (\Delta u' + \Delta d' + \Delta s')$ with the spin of the proton constructed by the quark spin, then the above result contradicts with the usual quark model. The recent SMC (Spin Muon Collaboration) and E143 data [2] show similar results.

However, this contradiction could be remedied by the axial anomaly caused by gluon fields as mentioned in many authors [3]-[8]. The perturbative analyses suggest to us that $\Delta q'_i$ ($\Delta u'$, $\Delta d'$ and $\Delta s'$) is constituted by Δq_i and Δg [4, 5]

$$\Delta q'_i = \Delta q_i - \frac{\alpha_s}{2\pi} \Delta g, \quad (2)$$

where Δq_i is the fraction of the chirality of the proton carried by quarks and antiquarks of flavor i and Δg is the chirality carried by gluons, and Δq_i satisfies the naive quark model. In these authors, Cheng and Li [6] discussed the anomaly term using the current divergence equations in which the flavor-singlet pseudoscalar density matrix element was given approximately by the correction to the Goldberger-Treiman relation. Hatsuda [7] and Bagchi and Basu [8] analyzed the anomaly term considering the pole dominance approximation of the (π^0, η, η') mesons in the coupling of the anomaly operator to the nucleon.

We have analyzed the effects of the anomaly term upon the existence of a pseudoscalar glueball for which the $\eta(1440)$ is considered as a good candidate at present, and upon the

mixing among the η , η' , and ι [12, 13] which is named the $\eta(1440)$ at present. We, in this paper, make a similar analysis to the above authors [7, 8] considering the PCAC relation for $\partial^\mu A_\mu^0$ and saturating $\partial^\mu A_\mu^0$ by the (η, η', ι) mesons, and analyze the effects of the glueball ι on the smallness of the proton matrix element of axial-vector current.

II. RELATION AMONG $\Delta q'_i$, f^{0A} AND g_{NNA}

The EMC experiment [1] measured the first moment of the spin structure function of the proton $\Gamma_1 = \int_0^1 dx g_1^p(x, Q^2)$ expressible as [9]

$$\Gamma_1 = \int_0^1 dx g_1^p(x, Q^2) = \frac{1}{2} \sum_i e_i^2 \Delta q'_i(Q^2) (1 + C_i), \quad (3)$$

$$s_\mu \Delta q'_i = \langle p | \bar{q}_i \gamma_\mu \gamma_5 q_i | p \rangle, \quad (4)$$

where e_i is the charge of the quark q_i and C_i the QCD correction for q_i ($C_u = -\frac{2\alpha_S}{3\pi}$, $C_d = C_s = \frac{\alpha_S}{3\pi}$ for flavor number 3), and got the result

$$\Gamma_1 = 0.126 \pm 0.010 \pm 0.015. \quad (5)$$

Combined this with the experimental results of the neutron and hyperon β -decays [10],

$$\frac{g_A}{g_V} = \Delta u' - \Delta d' = F + D = 1.254 \pm 0.006, \quad (6)$$

$$\Delta u' + \Delta d' - 2\Delta s' = 3F - D = 0.688 \pm 0.035, \quad (7)$$

the quark-spin density functions are estimated as

$$\Delta u' = 0.782 \pm 0.078, \quad \Delta d' = -0.472 \pm 0.078, \quad \Delta s' = -0.190 \pm 0.078, \quad (8)$$

and then the total quark-spin contribution for the proton is

$$\Sigma = \Delta u' + \Delta d' + \Delta s' = 0.120 \pm 0.232. \quad (9)$$

Eqs. (4) and (9) mean the result Eq. (1).

We start with the divergence of the axial-vector current $A_\mu^a = \bar{q}\gamma_\mu\gamma_5\frac{\lambda^a}{2}q$,

$$\partial^\mu A_\mu^a = \sum_{b,c} d^{abc}\epsilon^b v^c + \delta^{a0}\sqrt{\frac{3}{2}}\partial^\mu K_\mu, \quad (10)$$

which contains the axial anomaly

$$\partial^\mu K_\mu = \frac{g^2}{16\pi^2} G_{\mu\nu}^{(\alpha)} \tilde{G}^{(\alpha)\mu\nu} = \frac{\alpha_S}{2\pi} \text{Tr} G_{\mu\nu} \tilde{G}^{\mu\nu}, \quad (11)$$

where $\epsilon^0 = \sqrt{\frac{2}{3}}(m_u + m_d + m_s)$, $\epsilon^3 = m_u - m_d$, $\epsilon^8 = \frac{1}{\sqrt{3}}(m_u + m_d - 2m_s)$, v^a is the pseudoscalar density $i\bar{q}\gamma_5\frac{\lambda^a}{2}q$, and $G_{\mu\nu}^{(\alpha)}$ is the gluon field tensor and $\tilde{G}_{\mu\nu}^{(\alpha)}$ its dual tensor.

In this paper, we neglect the $SU(2)$ symmetry breaking of quark masses then $m_u = m_d$, though several authors [6, 7, 8] considered the large $SU(2)$ breaking effect. Cheng and Li [6] estimated Δg using the Goldberger-Treiman relation correction and the difference $m_u - m_d$, but the sign of Δg was wrong. Hatsuda [7] and Baguchi and Li [8] estimated the isospin breaking effects for Δq and Δg , but they set the net effect for $\Delta q'$ in isospin independent. Because the mass difference $m_u - m_d$ does not cause the large effect to the $\Delta q'$ in our analysis, we neglect it.

We assume the PCAC assumption for $\partial^\mu A_\mu^a$ in which $\partial^\mu A_\mu^a$ are expressed by the pseudoscalar fields ϕ^A as

$$\partial^\mu A_\mu^a = \sum_A m_A^2 f^{aA} \phi^A, \quad A = \pi, K, \eta, \eta', \iota, \quad (12)$$

where f^{aA} represents the decay constant and m_A the mass of the pseudoscalar meson A . In the pseudoscalar multiplet, the glueball has been considered to exist by many authors [11, 12, 13] and, at present, the most likely candidate for this glueball is $\iota(1440)$ (now this is $\eta(1440)$).

From the PCAC assumption (12) with $A_\mu^{1\pm i2}$ sandwiched between the proton state and the neutron state,

$$\begin{aligned} \langle p(p_p) | \partial^\mu A_\mu^{1\pm i2} | n(p_n) \rangle &= i [2M G_1(q^2) + q^2 G_2(q^2)] \bar{u}(p_p) \gamma_5 u(p_n) \\ &= \sqrt{2} f_\pi m_\pi^2 \langle p(p_p) | \phi^{\pi^+} | n(p_n) \rangle, \end{aligned} \quad (13)$$

where G_1 and G_2 are the form factors of the nucleon, $q = p_p - p_n$, M is the nucleon mass, and $u(p_p)$ and $u(p_n)$ are the spinor of the proton and the neutron respectively, one can get the Goldberger-Treiman relation

$$M g_A = f_\pi g_{NN\pi}. \quad (14)$$

Deriving the relation (14), we used the pole approximation in the right hand side of Eq. (13)

$$\sqrt{2} f_\pi m_\pi^2 \langle p(p_p) | \phi^{\pi^+} | n(p_n) \rangle = 2 f_\pi m_\pi^2 \frac{-g_{NN\pi}(q^2)}{q^2 - m_\pi^2} i \bar{u}(p_p) \gamma_5 u(p_n) \quad (15)$$

and the definition

$$G_1(0) = g_A. \quad (16)$$

We consider a similar relation for the singlet part between the proton states,

$$\begin{aligned} \langle p' | \partial^\mu A_\mu^0 | p \rangle &= \sum_A f^{0A} m_A^2 \langle p' | \phi^A | p \rangle \\ &= \sum_A f^{0A} \frac{-m_A^2 g_{NNA}}{q^2 - m_A^2} i \bar{u}(p') \gamma_5 u(p), \quad A = \eta, \eta', \iota. \end{aligned} \quad (17)$$

Though we take the π^0 contribution for ϕ^A , $f^{a\pi^0}$ ($a \neq 3$) is considered to be very small and then we neglect the π^0 contribution in the above equation. From the definition

$$\langle p' | \partial^\mu A_\mu^0 | p \rangle = \frac{1}{2} \sqrt{\frac{2}{3}} 2M \sum_i \Delta q'_i i \bar{u}(p') \gamma_5 u(p), \quad i = u, d, s, \quad (18)$$

we can get the Goldberger-Treiman relation (G-T relation)-like relation for the singlet part,

$$\sqrt{\frac{2}{3}} M \sum_i \Delta q'_i = \sum_A f^{0A} g_{NNA}, \quad A = \eta, \eta', \iota. \quad (19)$$

III. f^{0A} AND g_{NNA}

A. Determination of f^{0A}

We can determine the decay constants f^{0A} using only the decay processes and masses of mesons. One of us (T. T.) calculated these constants under $U(3) \times U(3)$ current algebraic

approach [13]. We start with the following two equations obtained in the framework of QCD,

$$\partial^\mu A_\mu^a = \sum_{b,c} d^{abc} \epsilon^b v^c + \delta^{a0} \sqrt{\frac{3}{2}} \partial^\mu K_\mu, \quad (10)$$

$$[Q_5^a(t), v^b(x, t)] = -i \sum_c d^{abc} u^c(x, t). \quad (20)$$

Sandwiching these equations between the vacuum state $\langle 0|$ and the pseudoscalar meson state $|P^A\rangle$ ($A = \pi, K, \eta, \eta',$ and ι), where

$$Q_5^a(t) \equiv \int d^3x A_0^a(x, t), \quad u^a \equiv \bar{q} \frac{\lambda^a}{2} q,$$

we can get the following relations,

$$m_A^2 f^{aA} = \sum_b m^{ab} (Z^{1/2})^{bA} + \delta^{a0} \lambda_A, \quad (21)$$

$$\sum_A f^{aA} (Z^{1/2})^{bA} = \sigma^{ab}. \quad (22)$$

Here, parameters m^{ab} , λ_A , etc., are defined as

$$\begin{aligned} m^{ab} &\equiv \sum_c d^{abc} \epsilon^c, \quad ik_\mu^A f^{aA} \equiv \langle 0 | A_\mu^a(0) | P^A(\vec{k}) \rangle, \\ (Z^{1/2})^{aA} &\equiv \langle 0 | v^a(0) | P^A(\vec{k}) \rangle, \quad \lambda_A \equiv \langle 0 | \sqrt{\frac{3}{2}} \partial^\mu K_\mu | P^A(\vec{k}) \rangle, \\ \sigma^{ab} &\equiv - \sum_c d^{abc} \langle 0 | u^c | 0 \rangle. \end{aligned}$$

For the $I \neq 0$ states, Eqs.(21) and (22) are rewritten in the usual form,

$$\begin{aligned} m_\pi^2 f_\pi &= Z_\pi^{1/2} 2m_u, \quad m_K^2 f_K = Z_K^{1/2} (m_u + m_s), \\ f_\pi Z_\pi^{1/2} &= \sigma_u, \quad 2f_K Z_K^{1/2} = \sigma_u + \sigma_s, \end{aligned} \quad (23)$$

where $\sigma_u = - \langle 0 | \bar{u}u | 0 \rangle = - \langle 0 | \bar{d}d | 0 \rangle = \sigma_d$, and $\sigma_s = - \langle 0 | \bar{s}s | 0 \rangle$. For $I = 0$ states, η, η' and ι , the mixing among them has to be considered and the state $|P^A\rangle$ is expressed as the mixing state of the bases $|P^{\bar{a}}\rangle$ ($\bar{a} = \bar{0}, \bar{8}, G_0$ (pure glueball); the superscript $\bar{a}$ is used to distinguish it from the superscript a of the operator) as

$$|P^A\rangle = \sum_{\bar{a}} R^{A\bar{a}} |P^{\bar{a}}\rangle, \quad A = \eta, \eta', \iota, \quad \bar{a} = \bar{8}, \bar{0}, G_0. \quad (24)$$

In the previous paper [13], mixing parameters among (η, η', ι) were approximated by two mixing angles, but in this paper, we analyze this mixing problem without any approximation for mixing angles. We use the following expression for $R^{A\bar{a}}$,

$$R^{A\bar{a}} = \begin{pmatrix} \alpha_8 & \alpha_0 & \alpha_G \\ \beta_8 & \beta_0 & \beta_G \\ \gamma_8 & \gamma_0 & \gamma_G \end{pmatrix}, \quad A = \eta, \eta', \iota, \quad (25)$$

$$\alpha_8 = c_1 c_2, \quad \alpha_0 = -c_1 s_2 s_3 - s_1 c_3, \quad \alpha_G = -c_1 s_2 c_3 + s_1 s_3$$

$$\beta_8 = s_1 c_2, \quad \beta_0 = -s_1 s_2 s_3 + c_1 c_3, \quad \beta_G = -s_1 s_2 c_3 - c_1 s_3,$$

$$\gamma_8 = s_2, \quad \gamma_0 = c_2 s_3, \quad \gamma_G = c_2 c_3,$$

$$c_i \equiv \cos \theta_i, \quad s_i \equiv \sin \theta_i, \quad i = 1, 2, 3,$$

where the mixing angle θ_1 corresponds to the usual $\eta - \eta'$ mixing angle.

Since $|P^{\bar{0}}\rangle$ and $|P^{\bar{8}}\rangle$ consist of only quarks whereas $|G_0\rangle$ consists of only gluons, the matrix elements of $\partial^\mu K_\mu$ and v^a between the states $\langle 0|$ and $|P^{\bar{a}}\rangle$ may be assumed to satisfy

$$\begin{aligned} \langle 0|\sqrt{\frac{3}{2}}\partial^\mu K_\mu|P^{\bar{b}}\rangle &\equiv \lambda_{\bar{b}} = 0, & \langle 0|v^a|P^{\bar{b}}\rangle &\equiv (Z^{1/2})^{a\bar{b}} \neq 0, \text{ for } \bar{b} = \bar{8}, \bar{0}, \\ \langle 0|\sqrt{\frac{3}{2}}\partial^\mu K_\mu|G_0\rangle &\equiv \lambda_{G_0} \neq 0, & \langle 0|v^a|G_0\rangle &\equiv (Z^{1/2})^{aG_0} = 0. \end{aligned} \quad (26)$$

We define the matrix elements of A_μ^a , v^a , etc., in the bases $|P^{\bar{a}}\rangle$ as

$$\langle 0|A_\mu^a|P^{\bar{b}}\rangle = i \sum_{\bar{c}} (k_\mu)^{\bar{b}\bar{c}} f^{a\bar{c}}, \quad (27)$$

where

$$f^{a\bar{b}} \equiv \sum_A (R^{-1})^{\bar{b}A} f^{aA}, \quad (k_\mu)^{\bar{a}\bar{b}} \equiv \sum_A (R^{-1})^{\bar{a}A} k_\mu^A R^{A\bar{b}}.$$

Then, Eqs. (21) and (22) are rewritten as

$$\sum_{\bar{d}} (M^2)^{\bar{b}\bar{d}} f^{a\bar{d}} = \sum_c m^{ac} (Z^{1/2})^{c\bar{b}} + \delta^{a0} \lambda_{\bar{b}}, \quad (28)$$

$$\sum_{\bar{b}} f^{a\bar{b}} (Z^{1/2})^{c\bar{b}} = \sigma^{ac}, \quad (29)$$

where

$$(M^2)^{\bar{a}\bar{b}} \equiv \sum_A (R^{-1})^{\bar{a}A} m_A^2 R^{Ab}.$$

$|P^{\bar{a}}\rangle$ is assumed to be a good basis for $Z^{1/2}$, i.e.,

$$(Z^{1/2})^{a\bar{b}} = Z_a^{1/2} \delta_{ab}, \quad b = 0, 8 \quad (30)$$

and also $Z_a^{1/2}$'s are assumed to be almost $SU(3)$ invariant,

$$Z_0 = Z_8 = Z_\pi (\equiv Z_3), \quad Z_K/Z_\pi \equiv z_K^2 \simeq 1. \quad (31)$$

Then, from the relations (28) and (29), the $(M^2)^{\bar{b}\bar{a}}$ are expressed as

$$\begin{aligned} (M^2)^{\bar{8}\bar{8}} &= \frac{1}{3} \left(4 \frac{m_K^2}{z_K^2} - m_\pi^2 \right) + \frac{2}{3} \delta \left(\frac{m_K^2}{z_K^2} - m_\pi^2 \right) + \frac{2}{3} \tilde{\lambda} \delta^2, \\ (M^2)^{\bar{0}\bar{8}} &= (M^2)^{\bar{8}\bar{0}} = -\frac{2\sqrt{2}}{3} \left(\frac{m_K^2}{z_K^2} - m_\pi^2 \right) - \frac{\sqrt{2}}{3} \delta \left(\frac{m_K^2}{z_K^2} - m_\pi^2 \right) - \frac{\sqrt{2}}{3} \tilde{\lambda} (3 + \delta) \delta, \\ (M^2)^{\bar{0}\bar{0}} &= \frac{1}{3} \left(2 \frac{m_K^2}{z_K^2} + m_\pi^2 \right) + \frac{1}{3} \delta \left(\frac{m_K^2}{z_K^2} - m_\pi^2 \right) + \frac{1}{3} \tilde{\lambda} (3 + \delta)^2, \\ (M^2)^{\bar{8}G_0} &= (M^2)^{G_0\bar{8}} = -\sqrt{\frac{2}{3}} k \delta, \\ (M^2)^{\bar{0}G_0} &= (M^2)^{G_0\bar{0}} = \frac{1}{\sqrt{3}} k (3 + \delta), \\ (M^2)^{G_0G_0} &= m_{G_0}^2, \end{aligned} \quad (32)$$

where we used the following parametrizations,

$$\begin{aligned} z_K &\equiv \frac{Z_K^{1/2}}{Z_\pi^{1/2}}, \quad \frac{\sigma_s}{\sigma_u} = \frac{2f_K}{f_\pi} z_K - 1 \equiv \frac{1}{1 + \delta}, \\ k &\equiv \frac{Z_\pi^{1/2}}{\sqrt{3}\sigma_u} (\lambda_{G_0} - f^{0G_0} m_{G_0}^2), \quad \tilde{\lambda} \equiv -\frac{Z_\pi^{1/2}}{\sqrt{3}\sigma_u} f^{0G_0} k. \end{aligned}$$

Deriving the Eq. (32), we used the relation

$$f^{8G_0} = 0 \quad (33)$$

obtained from the constraint

$$(M^2)^{\bar{a}\bar{b}} = (M^2)^{\bar{b}\bar{a}}.$$

We diagonalize the mass matrix $(M^2)^{\bar{b}a}$ following the procedure in Appendix and using the π , K , η , η' meson masses and $\frac{f_K}{f_\pi} = 1.13$. In expressions (A2) and (A3), the parameter δ is determined from the relation $\frac{2f_K}{f_\pi}z_K - 1 = \frac{1}{1+\delta}$ with the fixing of parameter z_K to a value near to 1.0, and m_S is determined from the relation $m_S^2 = \frac{2+\delta}{z_K^2}m_K^2 - (1+\delta)m_\pi^2$. Unknown parameter is only z_K , and all other parameters are the function of z_K . To determine the unknown parameter z_K , we use the experimental data, η , $\eta' \rightarrow 2\gamma$ decay widths [14],

$$\begin{aligned}\Gamma(\pi^0 \rightarrow 2\gamma) &= 7.74 \pm 0.55 \text{eV}, \\ \Gamma(\eta \rightarrow 2\gamma) &= 0.466 \pm 0.043 \text{keV}, \\ \Gamma(\eta' \rightarrow 2\gamma) &= 4.26 \pm 0.43 \text{keV}.\end{aligned}\tag{34}$$

We analyzed the $P^A \rightarrow 2\gamma$ decays on $U(3) \times U(3)$ formulation in our previous papers [12], and derived the relation

$$\frac{f^{0\iota} f^{8\eta} - f^{8\iota} f^{0\eta}}{f_\pi^2} \frac{F^\eta}{F^\pi} + \frac{f^{0\iota} f^{8\eta'} - f^{8\iota} f^{0\eta'}}{f_\pi^2} \frac{F^{\eta'}}{F^\pi} = \frac{1}{\sqrt{3}} \frac{f^{0\iota}}{f_\pi} - 2\sqrt{\frac{2}{3}} \frac{f^{8\iota}}{f_\pi},\tag{35}$$

where F^A is defined by

$$\lim_{k \rightarrow 0} \langle \gamma(\vec{p}, e) | j_\mu^{EM}(0) | P^A(\vec{k}) \rangle = \lim_{k \rightarrow 0} \epsilon_{\mu\nu\rho\sigma} e^\nu p^\rho k^\sigma F^A.\tag{36}$$

The best-fit value of z_K and those of other parameters for the ι mass $m_\iota = 1.44 \text{GeV}$, and $m_\iota = 2.0 \text{GeV}$ the latter of which is predicted by the recent lattice gauge theory calculations [15], are as follows:

$$\begin{aligned}\text{for } m_\iota &= 1.44 \text{GeV} \\ z_K &= 0.954, \quad \delta = -0.189, \quad \tilde{\lambda} = 0.358, \quad k = -0.288, \\ \theta_1 &= -12.7^\circ, \quad \theta_2 = 0.5^\circ, \quad \theta_3 = -26.0^\circ, \\ R &= \begin{pmatrix} 0.976 & 0.201 & 0.089 \\ -0.220 & 0.876 & 0.430 \\ 0.009 & -0.439 & 0.899 \end{pmatrix}, \\ f^{8\eta} &= 1.10, \quad f^{8\eta'} = -0.35, \quad f^{8\iota} = 0.06, \\ f^{0\eta} &= 0.30, \quad f^{0\eta'} = 1.89, \quad f^{0\iota} = 1.47.\end{aligned}\tag{37}$$

for $m_t = 2.0\text{GeV}$

$$\begin{aligned}
z_K &= 0.952, \quad \delta = -0.185, \quad \tilde{\lambda} = 0.446, \quad k = -0.683, \\
\theta_1 &= -13.3^\circ, \quad \theta_2 = -0.9^\circ, \quad \theta_3 = -22.7^\circ, \\
R &= \begin{pmatrix} 0.973 & 0.207 & 0.102 \\ -0.230 & 0.899 & 0.372 \\ -0.015 & -0.386 & 0.922 \end{pmatrix}, \\
f^{8\eta} &= 1.09, \quad f^{8\eta'} = -0.36, \quad f^{8\iota} = 0.02, \\
f^{0\eta} &= 0.23, \quad f^{0\eta'} = 1.41, \quad f^{0\iota} = 0.63.
\end{aligned} \tag{38}$$

B. Determination of g_{NNA}

The coupling constants g_{BBA} are defined as

$$g_{BBA} = \langle B | \phi^A | B \rangle = -\sqrt{2}D\text{Tr}(\{B, B\}\phi^A) + \sqrt{2}F\text{Tr}([B, B]\phi^A). \tag{39}$$

For ϕ^A states with $I = 0$, g_{BBA} are expanded as

$$g_{BBA} = \sum_{\bar{a}} R^{A\bar{a}} \langle B | \phi^{\bar{a}} | B \rangle = \sum_{\bar{a}} R^{A\bar{a}} g_{BB\bar{a}}, \quad \bar{a} = \bar{8}, \bar{0}, G_0 \tag{40}$$

then $g_{NN\eta}$, $g_{NN\eta'}$, and $g_{NN\iota}$ are linear combinations of $g_{NN\bar{8}}$, $g_{NN\bar{0}}$, and g_{NNG_0} . In the $SU(3)$ symmetry consideration, the coupling $g_{NN\bar{0}}$ is independent to $g_{NN\bar{8}}$. However, in our present analysis, gluon contribution is considered to affect $g_{NN\bar{a}}$ through the glueball G_0 , then $g_{NN\bar{0}}$ is contributed from the pure quark content and considered to relate to the octet part $g_{NN\bar{8}}$ in the $SU(3)$ symmetry. Of course g_{NNG_0} is independent to $g_{NN\bar{8}}$ and $g_{NN\bar{0}}$.

$$\begin{aligned}
g_{NN\pi} &= -(D + F), & g_{NN\bar{8}} &= (\sqrt{3} - \frac{4}{\sqrt{3}}\alpha)g_{NN\pi}, \\
g_{NN\bar{0}} &= 2\sqrt{\frac{2}{3}}\alpha g_{NN\pi}, & g_{NNG_0} &= 2\sqrt{\frac{2}{3}}\alpha' g_{NN\pi},
\end{aligned} \tag{41}$$

where

$$\frac{D}{D+F} \equiv \alpha, \quad \frac{D'}{D+F} \equiv \alpha'.$$

D' and α' correspond to D and α of the glueball G_0 . The ratio α is determined from the experimental data cited in Ref. [16] by using the definitions,

$$\begin{aligned} g_{N\Lambda K} &= -\frac{1}{\sqrt{3}}(3-\alpha)g_{NN\pi}, & g_{N\Sigma K} &= -(2\alpha-1)g_{NN\pi}, \\ g_{\Lambda\Sigma\pi} &= \frac{2}{\sqrt{3}}\alpha g_{NN\pi}, & g_{\Sigma\Sigma\pi} &= 2(1-\alpha)g_{NN\pi}, \end{aligned} \quad (42)$$

as

$$\alpha = 0.63, \quad F/D = 0.59. \quad (43)$$

The F/D ratio in the matrix elements of axial-vector currents between nucleons is not the same one of pseudoscalar mesons between baryons, though the $SU(3)$ symmetry is assumed for both matrix elements and the divergence of the axial-vector current is assumed to be proportional to the pseudoscalar meson field in PCAC. It is remarkable that the F/D ratio in the above strong meson-baryon interaction analysis, $F/D = 0.59$, is very similar to that in hyperon β -decay, $F/D = 0.63$ [10].

Because the total quark-spin contribution for proton $\sum_i \Delta q'_i$ is very small, Eq. (9), then we make it zero and estimate the value of α' using Eqs. (19), (37), (38) and (43),

$$\begin{aligned} \alpha' &= -0.49\alpha, & \text{for } m_i = 1.44\text{GeV}, \\ \alpha' &= -0.92\alpha, & \text{for } m_i = 2.0\text{GeV}. \end{aligned} \quad (44)$$

Thus, if the pure glueball G_0 contribution in the flavor-singlet coupling to the proton is about $-0.5 \sim -1.0$ times of the pure quark flavor-singlet meson contribution, the smallness of the total quark-spin contribution for proton $\sum_i \Delta q'_i$ is explained. The total quark-spin contribution for proton $\sum_i \Delta q'_i$ is expressed by $\sum_A f^{0A} g_{NNA}$ in Eq. (19), and f^{0A} and g_{NNA} are linear combinations of $f^{0\bar{a}}$ and $g_{NN\bar{a}}$ ($\bar{a} = \bar{8}, \bar{0}, G_0$), then

$$\begin{aligned} \sum_i \Delta q'_i &= \sum_i \left(\Delta q_i - \frac{\alpha_S}{2\pi} \Delta g \right) \\ &= \frac{1}{M} \sqrt{\frac{3}{2}} \{ f^{0\bar{8}} g_{NN\bar{8}} + f^{0\bar{0}} g_{NN\bar{0}} + f^{0G_0} g_{NNG_0} \}. \end{aligned} \quad (45)$$

First two terms in right hand side of this equation correspond to the term $\sum_i \Delta q_i$ and the last term in right hand side does $3(\alpha_S/2\pi)\Delta g$, because $|P^{\bar{0}}\rangle$ and $|P^{\bar{8}}\rangle$ consist of only quarks whereas $|G_0\rangle$ consists of only gluons. These values of $\sum_i \Delta q_i$ and $3(\alpha_S/2\pi)\Delta g$ are about 1.7 and -1.7 respectively, for both $m_i = 1.44\text{GeV}$, 2.0GeV .

In this case, coupling constants $g_{NN\eta}$, $g_{NN\eta'}$ and $g_{NN\iota}$ are estimated as

$$\begin{aligned} \text{for } m_i &= 1.44\text{GeV} \quad \frac{g_{NN\eta}^2}{4\pi} = 2.7, \quad \frac{g_{NN\eta'}^2}{4\pi} = 5.7, \quad \frac{g_{NN\iota}^2}{4\pi} = 11.7, \\ \text{for } m_i &= 2.0\text{GeV} \quad \frac{g_{NN\eta}^2}{4\pi} = 2.1, \quad \frac{g_{NN\eta'}^2}{4\pi} = 3.7, \quad \frac{g_{NN\iota}^2}{4\pi} = 23.7. \end{aligned} \quad (46)$$

Our estimated $g_{NN\eta}$ and $g_{NN\eta'}$ are comparable with the values estimated from the nucleon-nucleon potential analysis [16],

$$\frac{g_{NN\eta}^2}{4\pi} = 3.68, \quad \frac{g_{NN\eta'}^2}{4\pi} = 4.23. \quad (47)$$

In our analysis, the value of $g_{NN\iota}$ is estimated for the first time, and it is rather larger than those of $g_{NN\eta}$ and $g_{NN\eta'}$ and comparable with $g_{NN\pi}$.

IV. DISCUSSIONS

We have explained the smallness of the proton matrix element of the flavor-singlet axial vector current $\sum_i \Delta q'_i$ which has been considered as the spin of the proton constructed by the quark spin, using the effect of the axial anomaly. The divergence of the flavor-singlet axial vector current which contain the anomaly terms caused by the gluon fields has been replaced by the pseudoscalar meson fields, η , η' , and glueball ι under the PCAC assumption. The anomaly term has been considered to correspond to the glueball effects. We could get the G-T relation-like relation $\sqrt{2/3}M \sum_i \Delta q'_i = \sum_A f^{0A} g_{NNA}$ ($A = \eta, \eta', \iota$). We have estimated the coupling constants $f^{0\eta}$, $f^{0\eta'}$ and $f^{0\iota}$ using $U(3) \times U(3)$ current algebraic approach in the purely mesonic processes. We expanded g_{NNA} by $g_{NN\bar{a}}$ ($\bar{a} = \bar{8}, \bar{0}, G_0$) and g_{NNG_0} was assumed to be independent of $g_{NN\bar{8}}$ and $g_{NN\bar{0}}$. The α' for g_{NNG_0} is estimated to be $\alpha' = -0.49\alpha$ for $m_i = 1.44\text{GeV}$ and $\alpha' = -0.92\alpha$ for $m_i = 2.0\text{GeV}$.

$g_{NN\eta}$ and $g_{NN\eta'}$ are estimated for $m_\iota = 1.44\text{GeV}$ as $g_{NN\eta}^2/(4\pi) = 2.7$, $g_{NN\eta'}^2/(4\pi) = 5.7$, for $m_\iota = 2.0\text{GeV}$ as $g_{NN\eta}^2/(4\pi) = 2.1$, $g_{NN\eta'}^2/(4\pi) = 3.7$. The $g_{NN\iota}$ is rather larger than $g_{NN\eta}$ and $g_{NN\eta'}$ and comparable with $g_{NN\pi}$.

In this paper, we have neglected the isospin breaking. Experimentally, the neutron spin is not so different from the proton spin but somewhat larger than that [17]. Then, in order to study the difference between the proton and neutron spin, we have to analyse the isospin breaking. In our analysis, the quark contribution to the spin of proton $\sum_i \Delta q_i$ is rather large than the magnitude expected from the naive quark model. This is considered to be caused by the PCAC assumption extrapolated to the η' and ι states with large masses. We will consider these problems in the next paper.

APPENDIX: DIAGONALIZATION OF THE MASS MATRIX (32)

In this appendix, we present the procedure of diagonalization of the mass matrix (32). Transforming the mass matrix (32) on the basis $(\bar{8}, \bar{0}, G_0)$ to the one on the ideal basis $(N = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d), S = \bar{s}s, G_0)$, we can get the very simple form of the mass matrix;

$$M_I^2 = \begin{pmatrix} m_N^2 + 2\lambda_{NN} & \sqrt{2}\lambda_{NS} & \sqrt{2}\lambda_{NG} \\ \sqrt{2}\lambda_{NS} & m_S^2 + \lambda_{SS} & \lambda_{SG} \\ \sqrt{2}\lambda_{NG} & \lambda_{SG} & m_{G_0}^2 \end{pmatrix}, \quad (\text{A1})$$

$$\begin{aligned} m_N^2 &= m_\pi^2, & m_S^2 &= \frac{2+\delta}{z_K^2} m_K^2 - (1+\delta)m_\pi^2, & \lambda_{NN} &= \tilde{\lambda}, \\ \lambda_{NS} &= \tilde{\lambda}(1+\delta), & \lambda_{SS} &= \tilde{\lambda}(1+\delta)^2, & \lambda_{NG} &= k, & \lambda_{SG} &= k(1+\delta), \end{aligned}$$

and one can see into a key to the diagonalization. In fact, diagonalizing the mass matrix M_I^2 (A1) and equating the eigenvalues to the physical mass values m_η^2 , $m_{\eta'}^2$, and m_ι^2 , we can get the expressions for the parameters $\tilde{\lambda}$, k , and $m_{G_0}^2$ containing only unknown parameter z_K (z_K relates to the parameter δ),

$$\tilde{\lambda} = -\frac{1}{2(m_S^2 - m_N^2)^2} \left\{ \frac{2}{(1+\delta)^2} (m_S^2 - m_\eta^2)(m_S^2 - m_{\eta'}^2)(m_S^2 - m_\iota^2) \right.$$

$$\begin{aligned}
& + (m_N^2 - m_{\eta'}^2)(m_N^2 - m_{\eta'}^2)(m_N^2 - m_{\iota}^2) \Big\}, \\
\bar{m}_G^2 &= - \left[m_{\eta}^2 + m_{\eta'}^2 + m_{\iota}^2 - m_N^2 - m_S^2 - \{2 + (1 + \delta)^2\} \tilde{\lambda} \right. \\
& \quad \left. - \frac{m_{\eta}^2 m_{\eta'}^2 m_{\iota}^2}{m_N^2 m_S^2} \right] / \left\{ \left(\frac{2}{m_N^2} + \frac{(1 + \delta)^2}{m_S^2} \right) \tilde{\lambda} \right\}, \\
k^2 &= \tilde{\lambda} \left[m_{\eta}^2 + m_{\eta'}^2 + m_{\iota}^2 - m_N^2 - m_S^2 - \{2 + (1 + \delta)^2\} \tilde{\lambda} - \bar{m}_G^2 \right], \\
m_{G_0}^2 &= \bar{m}_G^2 + \frac{k^2}{\tilde{\lambda}}. \tag{A2}
\end{aligned}$$

The transformation matrix in the ideal basis (N, S, G_0) , R_I , is related to the parameters in the transformation matrix R in the basis $(\bar{8}, \bar{0}, G_0)$, as

$$R_I = \begin{pmatrix} X_{\eta} & Y_{\eta} & Z_{\eta} \\ X_{\eta'} & Y_{\eta'} & Z_{\eta'} \\ X_{\iota} & Y_{\iota} & Z_{\iota} \end{pmatrix} = \begin{pmatrix} \alpha_8/\sqrt{3} + \sqrt{\frac{2}{3}}\alpha_0 & -\sqrt{\frac{2}{3}}\alpha_8 + \alpha_0/\sqrt{3} & \alpha_G \\ \beta_8/\sqrt{3} + \sqrt{\frac{2}{3}}\beta_0 & -\sqrt{\frac{2}{3}}\beta_8 + \beta_0/\sqrt{3} & \beta_G \\ \gamma_8/\sqrt{3} + \sqrt{\frac{2}{3}}\gamma_0 & -\sqrt{\frac{2}{3}}\gamma_8 + \gamma_0/\sqrt{3} & \gamma_G \end{pmatrix} \tag{A3}$$

and X_A , Y_A and Z_A ($A = \eta, \eta', \iota$) are determined from the relations containing the parameter k , δ and $\tilde{\lambda}$;

$$\begin{aligned}
X_A &= \sqrt{2}k(m_S^2 - m_A^2)N_A, \\
Y_A &= k(1 + \delta)(m_N^2 - m_A^2)N_A, \\
Z_A &= \{2(1 + \delta)^2\tilde{\lambda}^2 - (m_N^2 + 2\tilde{\lambda} - m_A^2)(m_S^2 + (1 + \delta)^2\tilde{\lambda} - m_A^2)\}N_A, \tag{A4}
\end{aligned}$$

where

$$\begin{aligned}
N_A &= \left[2k^2(m_S^2 - m_A^2)^2 + k^2(1 + \delta)^2(m_N^2 - m_A^2)^2 \right. \\
& \quad \left. + \{2(1 + \delta)^2\tilde{\lambda}^2 - (m_N^2 + 2\tilde{\lambda} - m_A^2)(m_S^2 + (1 + \delta)^2\tilde{\lambda} - m_A^2)\}^2 \right]^{-\frac{1}{2}}.
\end{aligned}$$

Mixing angles θ_i ($i = 1, 2, 3$) are determined using the above relations and Eq. (25).

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