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Nucleon Electromagnetic Form Factors in Hidden Local Symmetry Theory

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ABSTRACT. In the previous papers, the hidden local symmetry of the chiral theory based on the nonlinear sigma model on the manifold $U(3)_L \times U(3)_R/U(3)_V$ was extended to the baryon interaction and shown to reproduce well the low energy theorems. Introducing an $SU(3)$ breaking in the theory, the mass formula and the Sakurai formula of the electromagnetic interaction of vector mesons are obtained consistently. In this paper, by introducing the effective tensor interactions of order $O(p^2)$, the magnetic form factor of the nucleon is analyzed as well as the electric form factor, partly done in the previous paper, and it is indicated again a breaking of the OZI rule and a sizable content of s-quark pair in both the electric and magnetic form factors of the nucleon.

1. Introduction

The dynamics of the vector mesons and the pseudoscalar(PS) mesons in the hadron physics has been shown to be described succesfully in terms of the hidden local symmetry[1] based on the manifold $G/H = U(3)_{\rm L} \times U(3)_{\rm R}/U(3)_{\rm V}$ of the chiral theory. In this respect, it would be interesting to notice that the effective interactions of order $O(p^4)$ in the chiral perturbation theory was shown[2] to be completely dominated by a contribution of resonances including vector mesons. The hidden local symmetry theory contains essentially a fundamental coupling constant g of the vector meson as a dynamical gauge boson and one adjustable parameter a. The only crucial assumption is that the kinetic part of the gauge boson is of the dynamical origin in order to make the boson propagate without being eliminated by the equation of motion.

In the previous papers, we extended the gauge principle to the baryon and built an effective interaction of the lowest order $O(p)$ in the framework of the hidden local symmetry theory and succesfully reproduced the low energy theorems; the conserved vector current (CVC) of β-decays of baryons and the Sakurai scinario of the electromagnetic interaction (E.M.I.) of hadrons in the paper [3](hereafter refered as I). The effective interaction contains an adjustable parameter a' corresponding to the parameter a in the meson sector and one more parameter a_S due to a non-vanishing $U(1)$ component of $U(3)$ trace in addition to the fundamental coupling constant g. The low energy theorems have been shown to be satisfied independently of a' and a_S. In the paper [4](hereafter refered as II), an $SU(3)$ symmetry breaking was introduced in accordance with the paper of Bando, Kugo and Yamawaki[5] and was shown that the $SU(2) \times U(1)$ natures of E.M.I., i.e. the minimal and universal E.M.I. of baryons, the vanishing of the "ficticious" photon mass and the Sakurai formula of the vector meson-photon interaction are preserved. On this scheme, the realistic magnitudes of g and the mixing angle θ of ω and ϕ mesons were obtained consistently with the electron pair decay of vector mesons and the vector meson masses. The mixing angle θ shows almost an ideal mixing. The electric form factor of nucleon was also discussed to get a low energy theorem and was shown that its iso-scalar part indicates a validity of the vector meson dominance model(VMD), a breakdown of OZI rule and a sizable content of s-pair in the nucleon.

In this paper, we introduce the covariant tensors(Pauli term) of order $O(p^2)$ in the effective E.M.I. of baryons to discuss the magnetic interaction. For this interaction, we introduce the effective Lagrangian with the order $O(p^2)$ involving a derivative of the external gauge boson which associates an effective coupling constant containing an energy scale Λ. By choosing the energy scale as about 1 GeV, we could indeed get the reasonable magnitude for the anomalous magnetic moment of the nucleon. To account for the experimental values of the magnetic moment, there needs two kinds of covariant tensors. Together with the electric interaction introduced in II, we derive the low energy theorems for the vector meson pole contributions with similar forms in both the electric and magnetic interactions and discuss the consequences of phenomenological analysis of the form factors of the nucleon without loop contribution.

This paper is organized as follows. The relevant effective Lagrangians of meson and baryon including the $SU(3)$ breaking and the interactions which were derived in I and II are recaptulated in section 2. Covarint tensors are introduced to construct the magnetic interaction of baryons in section 3. In section 4, it is shown that the low energy theorems hold both for electric and magnetic interactions and, in section 5, the electric and magnetic form factors of nucleon are analyzed. Finally in section 6, we summarize the result and give some remarks.

2. Vector Interactions

In this section, we recaptulate the effective Lagrangian including the $SU(3)$ breaking in the hidden local symmetry given in II. We write only the vector interactions which are relevant to the following argument. The same notations as those in previous papers I and II are used without any notice. The building block of the effective Lagrangian giving the vector interaction is assumed as

$$\alpha_\mu^V = \frac{1}{2i}(D_\mu\xi_{\rm L}\cdot\xi_{\rm L}{}^\dagger + D_\mu\xi_{\rm R}\cdot\xi_{\rm R}{}^\dagger + D_\mu\xi_{\rm L}\cdot\epsilon_{\rm V}\xi_{\rm R}^\dagger + D_\mu\xi_{\rm R}\cdot\epsilon_{\rm V}^\dagger\xi_{\rm L}^\dagger) \ , \qquad (2.1)$$

where

$$\xi_{\rm L(R)} = \exp(\frac{i\sigma}{f})\exp(\mp\frac{i\pi}{f}) \ , \qquad (2.2)$$

and

$$D_\mu\xi_{\rm L(R)} = \partial_\mu\xi_{\rm L(R)} - igV_\mu\xi_{\rm L(R)} + i\xi_{\rm L(R)}B_{{\rm L(R)}\mu} \ . \qquad (2.3)$$

In Eq.(2.1), we assume a most simple form for the symmetry breaking in accordance with ref.[5], where $\epsilon_{\rm V}$ transforms as $(\mathbf{3},\mathbf{3}^*)$ under $U(3)_{\rm L}\times U(3)_{\rm R}$. For the local $U(3)_{\rm V}$, we fix the gauge as $\sigma = 0$ so that $\xi_{\rm L(R)} = \exp(\mp i\pi/f)$.

In II, we have shown that the interaction of vector meson with photon has indeed the form of the Sakurai formula as follows

$$\mathcal{L}(\gamma{\rm V}) = e\sum_{\rm V}\frac{m_{\rm V}^2}{f_{\rm V}}V_\mu A^\mu \ , \qquad (2.4)$$

where $m_{\rm V}$ denotes the mass of vector meson including $SU(3)$ breaking effect and

$$f_\rho = g \ , \quad f_\omega = \frac{\sqrt{3}\,g}{\sin\theta} \ , \quad f_\phi = \frac{\sqrt{3}\,g}{\cos\theta} \ . \qquad (2.5)$$

Here the angle θ gives a mixing of ω and ϕ as

$$\omega_8 = \phi\cos\theta + \omega\sin\theta \ , \qquad (2.6)$$

$$\omega_1 = -\phi\sin\theta + \omega\cos\theta \ .$$

As was shown in II, it was obtained $g = 5.93$ and $\theta = 37.08°$ from $(\omega,\,\phi) \to e\bar{e}$ decay.

The effective Lagrangian of baryon with order O(p) which yields the vector interaction is given as follows,

$$\mathcal{L}_{\text{baryon}} = \mathcal{L}_{\text{B}}^{(0)} + a'\mathcal{L}_{\text{B}}' + a_{\text{S}}\mathcal{L}_{\text{B}}^{\text{S}} , \tag{2.7}$$

where

$$\mathcal{L}_{\text{B}}^{(0)} = i\langle \overline{B}\gamma^{\mu} D_{\mu} B\rangle = i\langle \overline{B}\gamma^{\mu}\partial_{\mu} B\rangle + g\langle \overline{B}\gamma^{\mu}[V_{\mu}, B]\rangle , \tag{2.8}$$

$$a'\mathcal{L}_{\text{B}}' = a'\langle \overline{B}\gamma^{\mu}[\alpha_{\mu}{}^{V}, B]\rangle , \tag{2.9}$$

$$a_{\text{S}}\mathcal{L}_{\text{B}}^{\text{S}} = a_{\text{S}}\langle \overline{B}\gamma^{\mu} B\rangle\langle \alpha_{\mu}{}^{V'}\rangle . \tag{2.10}$$

In Eq.(2.10), the quantity $\alpha_{\mu}^{V'}$ is defined by Eq.(2.1) with replacing ϵ_{V} by ϵ_{V}'. The baryon field is defined as follows,

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & -\Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix} . \tag{2.11}$$

The parametrization of ϵ's is given as

$$a' f^2 \epsilon_{\text{V}} = C_{\text{B}}\boldsymbol{m} , \qquad a_{\text{S}} f^2 \epsilon_{\text{V}}' = D_{\text{B}}\boldsymbol{m} , \tag{2.12}$$

where $\boldsymbol{m} = diag\{m_u, m_d, m_s\}$ with the current quark masses. In the above, $a_{\text{S}}\mathcal{L}_{\text{B}}^{\text{S}}$ is needed in general because α_{μ}'s have non-vanishing $U(1)$ conponent of $U(3)$ trace. This interaction gives a correct coupling with ω and ϕ as was shown in II.

The lowest configuration of the vector interaction of baryon is given as follows,

$$\mathcal{L}_{\text{B}}^{(0)} + a'\mathcal{L}_{\text{B}}' = g\langle \overline{B}\gamma^{\mu}[V_{\mu}, B]\rangle - a'\langle \overline{B}\gamma^{\mu}[(gV_{\mu} - eQA_{\mu})(1+\epsilon_{\text{V}}), B]\rangle , \tag{2.13}$$

$$a_{\text{S}}\mathcal{L}_{\text{B}}^{\text{S}} = -a_{\text{S}}\langle \overline{B}\gamma^{\mu} B\rangle\langle (gV_{\mu} - eQA_{\mu})(1+\epsilon_{\text{V}}')\rangle . \tag{2.14}$$

As the baryon interactions with photon and vector meson which are necessary for the analysis of nucleon form factors, we obtain the direct γNN interaction and the VNN interaction as follows,

$$\mathcal{L}_{\text{V}}(\gamma\text{NN})_{\text{direct}} = e\frac{1}{2}\{A_{1\text{V}}(\overline{p}\gamma_{\mu}p - \overline{n}\gamma_{\mu}n) + A_{1}(\overline{p}\gamma_{\mu}p + \overline{n}\gamma_{\mu}n)\}A^{\mu} , \tag{2.15}$$

$$\mathcal{L}_{\text{V}}(\text{V}^0\text{NN}) = g\frac{1}{2}(1 - A_{1\text{V}})(\overline{p}\gamma_{\mu}p - \overline{n}\gamma_{\mu}n)\rho^{0\mu}$$

$$+g\frac{\sqrt{3}}{2}\{(1 - A_{1})\sin\theta - \sqrt{2}\,B_{1}\cos\theta\}(\overline{p}\gamma_{\mu}p + \overline{n}\gamma_{\mu}n)\omega^{\mu}$$

$$+g\frac{\sqrt{3}}{2}\{(1-A_1)\cos\theta+\sqrt{2}\,B_1\sin\theta\}(\overline{p}\gamma_\mu p+\overline{n}\gamma_\mu n)\phi^\mu\ , \tag{2.16}$$

where

$$A_{1\mathrm{V}}=a'+C_{\mathrm{B}}\overline{m}\ , \tag{2.17a}$$

$$A_1=a'+\frac{1}{3}C_{\mathrm{B}}(2m_s+\overline{m})-\frac{2}{3}D_{\mathrm{B}}(m_s-\overline{m})\ , \tag{2.17b}$$

$$B_1=a_{\mathrm{S}}-\frac{1}{3}C_{\mathrm{B}}(m_s-\overline{m})+\frac{1}{3}D_{\mathrm{B}}(m_s+2\overline{m})\ . \tag{2.17c}$$

Here we assume an $SU(2)$ symmetry for the breaking so that $m_u=m_d=\overline{m}$. In II, it was shown that the low energy theorem of minimal E.M.I. is obtained from the direct interaction $\mathcal{L}_{\mathrm{V}}(\gamma\mathrm{NN})_{\mathrm{direct}}$ and the contribution of the vector meson through $\mathcal{L}_{\mathrm{V}}(\mathrm{V^0NN})$.

3. Tensor interactions

For the effective magnetic(Pauli-term) interaction of baryon, we introduce tensor operators with order $\mathrm{O}(p^2)$. To account for the experimental values of magnetic moment, there need two covariant tensor operators. These are as follows,

$$\beta_{\mu\nu}=g\{\partial_\mu V_\nu-\partial_\nu V_\mu-ig[V_\mu,V_\nu]\}\{1+\frac{1}{2}(\xi_{\mathrm{L}}\epsilon^0_{\mathrm{V}}\xi^\dagger_{\mathrm{R}}+\xi_{\mathrm{R}}\epsilon^{0\dagger}_{\mathrm{V}}\xi^\dagger_{\mathrm{L}})\}\ , \tag{3.1}$$

$$\alpha^V_{\mu\nu}=\frac{1}{2i}\{D_\mu(D_\nu\xi_{\mathrm{L}})\cdot\xi^\dagger_{\mathrm{L}}+D_\mu(D_\nu\xi_{\mathrm{R}})\cdot\xi^\dagger_{\mathrm{R}}+D_\mu(D_\nu\xi_{\mathrm{L}})\cdot\epsilon_{\mathrm{V}}\xi^\dagger_{\mathrm{R}}+D_\mu(D_\nu\xi_{\mathrm{R}})\cdot\epsilon^\dagger_{\mathrm{V}}\xi_{\mathrm{L}}{}^\dagger-(\mu\leftrightarrow\nu)\}\ , \tag{3.2}$$

where

$$D_\mu(D_\nu\xi_{\mathrm{L(R)}})=\partial_\mu(D_\nu\xi_{\mathrm{L(R)}})-igV_\mu D_\nu\xi_{\mathrm{L(R)}}+i(D_\nu\xi_{\mathrm{L(R)}})B_{\mathrm{L(R)}\mu}\ . \tag{3.3}$$

These are transformed in the hidden local space as

$$\beta_{\mu\nu}\ \rightarrow\ h\beta_{\mu\nu}h^\dagger\ ,\qquad \alpha^V_{\mu\nu}\ \rightarrow\ h\alpha^V_{\mu\nu}h^\dagger\ . \tag{3.4}$$

The effective tensor inrcractions with order $\mathrm{O}(p^2)$ are assumed as follows,

$$\begin{aligned}\mathcal{L}^{(1)}_{\mathrm{T}}&=-\frac{1}{\Lambda}\{\beta_{\mathrm{F}}\langle\overline{B}\sigma^{\mu\nu}[\beta_{\mu\nu},B]\rangle+\beta_{\mathrm{D}}\langle\overline{B}\sigma^{\mu\nu}\{\beta_{\mu\nu},B\}\rangle+\beta_{\mathrm{S}}\langle\overline{B}\sigma^{\mu\nu}B\rangle\langle\beta'_{\mu\nu}\rangle\}\\&=-\frac{1}{\Lambda}\{\beta_{\mathrm{F}}\langle\overline{B}\sigma^{\mu\nu}[gV_{\mu\nu}(1+\epsilon^0_{\mathrm{V}}),B]\rangle+\beta_{\mathrm{D}}\langle\overline{B}\sigma^{\mu\nu}\{gV_{\mu\nu}(1+\epsilon^0_{\mathrm{V}}),B\}\rangle\\&\qquad+\beta_{\mathrm{S}}\langle\overline{B}\sigma^{\mu\nu}B\rangle\langle gV_{\mu\nu}(1+\epsilon^{0'}_{\mathrm{V}})\rangle\}+\cdots\ ,\end{aligned} \tag{3.5}$$

$$\mathcal{L}^{(2)}_{\mathrm{T}}=-\frac{1}{\Lambda}\{\eta_{\mathrm{F}}\langle\overline{B}\sigma^{\mu\nu}[\alpha^V_{\mu\nu},B]\rangle+\eta_{\mathrm{D}}\langle\overline{B}\sigma^{\mu\nu}\{\alpha^V_{\mu\nu},B\}\rangle+\eta_{\mathrm{S}}\langle\overline{B}\sigma^{\mu\nu}B\rangle\langle\alpha^{V'}_{\mu\nu}\rangle\}$$

$$= -\frac{1}{\Lambda}\{\eta_{\rm F}\langle \overline{B}\sigma^{\mu\nu}[(gV_{\mu\nu} - eQF_{\mu\nu})(1+\epsilon_{\rm V}), B]\rangle + \eta_{\rm D}\langle \overline{B}\sigma^{\mu\nu}\{(gV_{\mu\nu}$$

$$-eQF_{\mu\nu})(1+\epsilon_{\rm V}), B\}\rangle + \eta_{\rm S}\langle \overline{B}\sigma^{\mu\nu}B\rangle\langle (gV_{\mu\nu} - eQF_{\mu\nu})(1+\epsilon_{\rm V}^{'})\rangle\} + \cdots , \qquad (3.6)$$

where Λ denotes an energy scale of the effective interaction and

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu \ , \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \ , \qquad (3.7)$$

and the second lines in Eqs.(3.5) and (3.6) denote the contribution from lowest configurations. We parametrize the symmetry breaking effect ϵ's as follows,

$$\begin{array}{lll} \beta_{\rm F}\epsilon_{\rm V}^0 = H_{\rm F}^0\boldsymbol{m} \ , & \beta_{\rm D}\epsilon_{\rm V}^0 = H_{\rm D}^0\boldsymbol{m} \ , & \beta_{\rm S}\epsilon_{\rm V}^{0'} = H_{\rm S}^0\boldsymbol{m} \ , \\ \eta_{\rm F}\epsilon_{\rm V} = H_{\rm F}\boldsymbol{m} \ , & \eta_{\rm D}\epsilon_{\rm V} = H_{\rm D}\boldsymbol{m} \ , & \eta_{\rm S}\epsilon_{\rm V}^{'} = H_{\rm S}\boldsymbol{m} \ . \end{array} \qquad (3.8)$$

From Eqs.(3.5),(3.6), the direct tensor interaction of nucleon and photon is given as follows,

$$\mathcal{L}_{\rm T}(\gamma{\rm NN})_{\rm direct} = \frac{e}{2}\{A_{2\rm V}(\overline{p}\sigma_{\mu\nu}p - \overline{n}\sigma_{\mu\nu}n) + A_2(\overline{p}\sigma_{\mu\nu}p + \overline{n}\sigma_{\mu\nu}n)\}F^{\mu\nu} \ , \qquad (3.9)$$

where

$$A_{2\rm V} = \frac{1}{\Lambda}\{\eta_{\rm F} + \eta_{\rm D} + (H_{\rm F} + H_{\rm D})\overline{m}\} \ , \qquad (3.10a)$$

$$A_2 = \frac{1}{3\Lambda}\{3\eta_{\rm F} - \eta_{\rm D} + H_{\rm F}(2m_s + \overline{m}) - H_{\rm D}(2m_s - \overline{m}) - 2H_{\rm S}(m_s - \overline{m})\} \ . \qquad (3.10b)$$

The effective tensor interaction of neutral vector mesons and nucleon is also given as follows,

$$\begin{aligned} \mathcal{L}_{\rm T}({\rm V^0NN}) = & -\frac{g}{2}A_{2\rm V}^{'}(\overline{p}\sigma_{\mu\nu}p - \overline{n}\sigma_{\mu\nu}n)\rho^{0\mu\nu} \\ & -\frac{\sqrt{3}\,g}{2}\{A_2^{'}\sin\theta + \sqrt{2}\,B_2\cos\theta\}(\overline{p}\sigma_{\mu\nu}p + \overline{n}\sigma_{\mu\nu}n)\omega^{\mu\nu} \\ & -\frac{\sqrt{3}\,g}{2}\{A_2^{'}\cos\theta - \sqrt{2}\,B_2\sin\theta\}(\overline{p}\sigma_{\mu\nu}p + \overline{n}\sigma_{\mu\nu}n)\phi^{\mu\nu} \ , \end{aligned} \qquad (3.11)$$

where $A_{2\rm V}^{'}$, $A_2^{'}$ are $A_{2\rm V}$, A_2 of Eqs.(3.10a,b) with η_a and H_a replaced by $\eta_a^{'} = \beta_a + \eta_a$ and $H_a^{'} = H_a^0 + H_a$ respectively, and

$$B_2 = \frac{1}{3\Lambda}\{2\eta_{\rm D}^{'} + 3\eta_{\rm S}^{'} - H_{\rm F}^{'}(m_s - \overline{m}) + H_{\rm D}^{'}(m_s + \overline{m}) + H_{\rm S}^{'}(m_s + 2\overline{m})\} \ . \qquad (3.12)$$

It is to be noted that the quantities $A_{2\rm V}$ and others in tensor interaction are defined as to have an inverse mass dimension by Λ^{-1} in contrast to those in vector interaction.

4. Low energy theorems

In this section, we show that the effective interaction yields all the low energy theorems of baryon E.M.I. satisfying the $SU(2)$ symmetry. In the low energy limit, the neutral vector meson which changes to an external photon in a tree diagram will be replaced in the Lagrangian as

$$gV_\mu \longrightarrow eQA_\mu\ , \quad gV_{\mu\nu} \longrightarrow eQF_{\mu\nu}\ . \tag{4.1}$$

Then the vector interactions Eqs.(2.13), (2.14) become

$$\mathcal{L}_B^{(0)} + a'\mathcal{L}_B' + a_{\rm S}\mathcal{L}_B^{\rm S} = e\langle\overline{B}\gamma^\mu[Q,B]\rangle A_\mu\ , \tag{4.2}$$

which is just the minimal E.M.I. of baryons as was shown in II. The tensor interaction Eq.(3.6) has no contribution and Eq.(3.5) becomes

$$\mathcal{L}_{\rm T}^{(1)} = -\frac{e}{\Lambda}\{\beta_{\rm F}\langle\overline{B}\sigma^{\mu\nu}[Q(1+\epsilon_{\rm V}^0),B]\rangle + \beta_{\rm D}\langle\overline{B}\sigma^{\mu\nu}\{Q(1+\epsilon_{\rm V}^0),B\}\rangle$$
$$+\beta_{\rm S}\langle\overline{B}\sigma^{\mu\nu}B\rangle\langle Q(1+\epsilon_{\rm V}^{0'})\rangle\}F_{\mu\nu}\ , \tag{4.3}$$

which is the static anomalous magnetic moment (a.m.m.) term of baryons with the order $O(p^2)$. By choosing $\Lambda \simeq O(1{\rm GeV})$, the coefficient $e\Lambda^{-1}\beta_{\rm F(D,S)}$ would provide the correct magnitude of order to a.m.m. of baryons. If we denote the static iso-vector and iso-scalar anomalous magnetic moments of nucleon up to e as $\mu_{\rm V}$, $\mu_{\rm S}$ respectively, we find

$$\mu_{\rm V} = -\frac{1}{2\Lambda}\{\beta_{\rm F} + \beta_{\rm D} + (H_{\rm F}^0 + H_{\rm D}^0)\overline{m}\}\ , \tag{4.4}$$

$$\mu_{\rm S} = -\frac{1}{2\Lambda}\{\beta_{\rm F} - \frac{1}{3}\beta_{\rm D} + \frac{1}{3}H_{\rm F}^0(2m_s+\overline{m}) - \frac{1}{3}H_{\rm D}^0(2m_s-\overline{m}) - 2H_{\rm S}^0(m_s-\overline{m})\}\ , \tag{4.5}$$

which are the expression of the a.m.m. of nucleon in terms of $SU(3)$ symmetry including the breaking effect. Thus it means that $A_{2\rm V}' = -2\mu_{\rm V} + A_{2\rm V}$ and $A_2' = -2\mu_{\rm S} + A_2$ from Eqs.(3.10a), (3.10b).

We write the coupling constants $g_{\rm VNN}^{(1)}$ of vector interaction VNN as

$$\mathcal{L}({\rm V^0NN}) = g_{\rho\rm NN}^{(1)}\ \rho^{0\mu}\ (\overline{p}\gamma_\mu p - \overline{n}\gamma_\mu n) + (g_{\omega\rm NN}^{(1)}\ \omega^\mu + g_{\phi\rm NN}^{(1)}\ \phi^\mu)(\overline{p}\gamma_\mu p + \overline{n}\gamma_\mu n)\ , \tag{4.6}$$

where

$$g_{\rho\rm NN}^{(1)} = \frac{g}{2}(1 - A_{1\rm V})\ , \tag{4.7a}$$

$$g_{\omega\rm NN}^{(1)} = \frac{\sqrt{3}\,g}{2}\{(1-A_1)\sin\theta - \sqrt{2}B_1\cos\theta\}\ , \tag{4.7b}$$

$$g_{\phi\rm NN}^{(1)} = \frac{\sqrt{3}\,g}{2}\{(1-A_1)\cos\theta + \sqrt{2}B_1\sin\theta\}\ . \tag{4.7c}$$

Then by using Eqs.(2.17$a \sim c$), we have the low energy theorems on the coupling constants as follows,

$$\frac{g^{(1)}_{\rho\mathrm{NN}}}{f_\rho} + \frac{1}{2}A_{1\mathrm{V}} = \frac{1}{2} \ , \tag{4.8}$$

$$\frac{g^{(1)}_{\omega\mathrm{NN}}}{f_\omega} + \frac{g^{(1)}_{\phi\mathrm{NN}}}{f_\phi} + \frac{1}{2}A_1 = \frac{1}{2} \ , \tag{4.9}$$

for the iso-vector and iso-scaler channels respectively as was shown in II.

For the tensor interaction, if we define the coupling constsnts $g^{(2)}_{\mathrm{VNN}}$ of VNN interaction in Eq.(3.11), then we have

$$\mathcal{L}_\mathrm{T}(\mathrm{V^0NN}) = g^{(2)}_{\rho\mathrm{NN}}\ \rho^{0\mu\nu}\ (\overline{p}\sigma_{\mu\nu}p - \overline{n}\sigma_{\mu\nu}n) + (g^{(2)}_{\omega\mathrm{NN}}\ \omega^{\mu\nu} + g^{(2)}_{\phi\mathrm{NN}}\ \phi^{\mu\nu})(\overline{p}\sigma_{\mu\nu}p + \overline{n}\sigma_{\mu\nu}n) \ , \tag{4.10}$$

where

$$g^{(2)}_{\rho\mathrm{NN}} = \frac{g}{2}(2\mu_\mathrm{V} - A_{2\mathrm{V}}) \ , \tag{4.11a}$$

$$g^{(2)}_{\omega\mathrm{NN}} = \frac{\sqrt{3}\,g}{2}\{(2\mu_\mathrm{S} - A_2)\sin\theta - \sqrt{2}B_2\cos\theta\} \ , \tag{4.11b}$$

$$g^{(2)}_{\phi\mathrm{NN}} = \frac{\sqrt{3}\,g}{2}\{(2\mu_\mathrm{S} - A_2)\cos\theta + \sqrt{2}B_2\sin\theta\} \ . \tag{4.11c}$$

Since the direct interaction is given by Eq.(3.9) in terms of $A_{2\mathrm{V}}$ and A_2, we have the low energy theorems of coupling constants in the iso-vector and iso-scalar channels respectively as follows,

$$\frac{g^{(2)}_{\rho\mathrm{NN}}}{f_\rho} + \frac{1}{2}A_{2\mathrm{V}} = \mu_\mathrm{V} \ , \tag{4.12}$$

$$\frac{g^{(2)}_{\omega\mathrm{NN}}}{f_\omega} + \frac{g^{(2)}_{\phi\mathrm{NN}}}{f_\phi} + \frac{1}{2}A_2 = \mu_\mathrm{S} \ . \tag{4.13}$$

In view of Eqs.(4.8),(4.9), it should be noted that the low energy theorems have the similar expressions in each of the vector and tensor interactions. These will give also the low energy theorems on the electromagnetic form factors of nucleon as will be shown in the next section.

5. Electromagnetic Form Factor of the Nucleon

It has been known that in the iso-vector channel of nucleon form factor the ρ peak deviates largely from the Breit-Wigner shape, and that the simple tree diagram of ρ meson may not be adequate[6]. On the other hand, the bump and dip structures in $\mathrm{Im}F^\mathrm{S}_1$ have been shown to be explained by ω and ϕ exchange, respectively[7]. In a recent analysis[8], the ρ contribution was calculated by using the CGLN (the Chew-Goldberger-Low-Nambu) helicity amplitude and the other contributions are treated by resonance exchange. Hence we use only the information of the form factor of the iso-scalar channel of both the vector and tensor interactions and write them as

$$F_i^{\rm S}(t) = \frac{a_i(\omega)}{t+m_\omega^2} + \frac{a_i(\phi)}{t+m_\phi^2} + \frac{a_i({\rm S})}{t+m_{\rm S}^2} + C_i^{\rm S} F_i^{\rm as}, \tag{5.1}$$

where $a_i({\rm V})$ are the pole residues of the vector meson and $a_i({\rm S})$ term corresponds to a pole of S particle with higher mass 1.68 GeV (i=1, 2 denote the electric and magnetic form factors respectively). $F_i^{\rm as}$ are taken so as to reproduce the asymptotic behavior of the perturbative QCD. It should be noted that in our theory the higher mass $a_i({\rm S})$ term and the asymptotic $C_i^{\rm S}$ term may be considered as being frozen into the direct interactions Eqs.(2.15), (3.9). The normalization conditions of the form factors are

$$F_1^{\rm S}(0) = F_1^{\rm V}(0) = \frac{1}{2}\,, \tag{5.2}$$

and

$$F_2^{\rm S}(0) = \mu_{\rm S}\,, \qquad F_2^{\rm V}(0) = \mu_{\rm V}\,, \tag{5.3}$$

which correspond to our low energy theorems on the coupling constants in Eqs.(4.8),(4.9) and (4.12), (4.13). Furuichi and Watanabe[8] gave the best fit values as

$$\begin{aligned} a_1(\omega) &= 0.7627\ {\rm GeV}^2\,, & a_1(\phi) &= -0.7667\ {\rm GeV}^2\,, \\ a_2(\omega) &= -0.1197\ {\rm GeV}^2 \cdot \mu_{\rm N}\,, & a_2(\phi) &= 0.1537\ {\rm GeV}^2 \cdot \mu_{\rm N}\,, \end{aligned} \tag{5.4}$$

where $\mu_{\rm N} = (2m_{\rm N})^{-1}$ with nucleon mass $m_{\rm N}$, and the pole positions are

$$m_\omega = 0.783\ {\rm GeV}\,, \qquad m_\phi = 1.02\ {\rm GeV}\,. \tag{5.5}$$

In our theory, we have the following expressions for the residues from Eqs.(2.5), (4.7$a \sim c$), (4.11$a \sim c$) by using $a_i({\rm V}) = g^{(i)}_{\rm VNN} m_{\rm V}^2/f_{\rm V}$ as

$$a_i(\omega) = \frac{1}{2}\{(2e_i - A_i)\sin\theta - \sqrt{2}\,B_i\cos\theta\}\sin\theta\cdot m_\omega^2\,, \tag{5.6}$$

$$a_i(\phi) = \frac{1}{2}\{(2e_i - A_i)\cos\theta + \sqrt{2}\,B_i\sin\theta\}\cos\theta\cdot m_\phi^2\,, \tag{5.7}$$

where e_i are defined as follows,

$$e_1 = \tfrac{1}{2}\,, \qquad e_2 = \mu_{\rm S}\,. \tag{5.8}$$

The μ_S is an iso-scalar a.m.m. of nucleon given by Eq.(4.5). By Eqs.(4.9), (4.13), we have the following relations as

$$\frac{a_i(\omega)}{m_\omega^2} + \frac{a_i(\phi)}{m_\phi^2} + \frac{1}{2}A_i = e_i \ , \tag{5.9}$$

which are the low energy theorems for the electric and magnetic form factors, respectively. The A_i terms mean here the contributions of direct interactions given by Eqs.(2.15), (3.9). It should be noted that these are not the normalization conditions but the identity relations in our theory. Using the fitted values Eq.(5.4), we obtain the magnitude of direct interactions as

$$A_1 = -0.0146 \ , \qquad A_2 = -0.0253 \ \mu_{\rm N} \ , \tag{5.10}$$

where we have used $\mu_S = -0.0601 \ \mu_{\rm N}$. From Eqs.(5.6),(5.7), we find

$$B_i = \sqrt{2}\left\{\frac{a_i(\phi)}{m_\phi^2}\tan\theta - \frac{a_i(\omega)}{m_\omega^2\tan\theta}\right\} . \tag{5.11}$$

By using $\theta = 37.08^\circ$ obtained from the analysis of the V $\to$ $e\bar{e}$ decay in II, we find

$$B_1 = -3.12 \ , \qquad B_2 = 0.523 \ \mu_{\rm N} \ . \tag{5.12}$$

Further we obtain the effective coupling constants $g^{(i)}_{\rm VNN}$ as $g^{(1)}_{\omega\rm NN} = 21.21$, $g^{(1)}_{\phi\rm NN} = -9.492$, $g^{(2)}_{\omega\rm NN} = -3.328 \ \mu_{\rm N}$ and $g^{(2)}_{\phi\rm NN} = 1.903 \ \mu_{\rm N}$. Main results in this section are Eqs.(5.10) and (5.12) which will be used in the discussion of next section.

6. Results and Discussion

Following the previous papars I and II, we have constructed the effective E.M.I. of baryons in the hidden local theory including the symmetry breaking. In our treatment, we have assumed a symmetry breaking in a most simple way following to ref.[5] including the current quark masses, which transforms as $(\mathbf{3.3^*})$ under $U(3)_{\rm L} \times U(3)_{\rm R}$ and preserves $SU(2) \times U(1)$ symmetry. We have introduced the effective tensor(magnetic) interactions with the order $O(p^2)$ in addition to the vector(electric) interaction with the order $O(p)$. Without the loop contribution, we have shown the low energy theorems of E.M.I. of baryons hold and analyzed the structure of the electric and magnetic form factors.

Our results are summarized as follows. Firstly Eq.(5.10) shows the magnitudes of the parameters A_1 and A_2 as

$$A_1 \simeq 0.0 \ , \qquad A_2 \simeq 0.0 \ , \tag{6.1}$$

which means the VMD works very well in both the electric and magnetic form factors of nucleon as was discussed in I. This also means the iso-scalar form factor to satisfy interesting sum rules as

$$c_i - \left\{\frac{a_i(\omega)}{m_\omega^2} + \frac{a_i(\phi)}{m_\phi^2}\right\} = \frac{1}{2}A_i \simeq 0.0 , \qquad (6.2)$$

for the electric and magnetic form factors.

Second, the validity condition of OZI rule is given in our theory. The Lagrangian of vector meson with vector and tensor interactions in the iso-scalar channel is given as

$$\mathcal{L}_{\rm T}({\rm V^0NN}) \propto \{(2c_i - A_i)\omega_8 - \sqrt{2}\, B_i\omega_1\}(\overline{p}p + \overline{n}n) , \quad (i = 1, 2) , \qquad (6.3)$$

where we have suppressed the tensor suffices and the coefficients for the sake of simplicity. The ω states are defined as

$$\begin{aligned} |\omega_8\rangle &= \frac{1}{\sqrt{6}}\{|{\rm u\overline{u}}\rangle + |{\rm d\overline{d}}\rangle - 2\,|{\rm s\overline{s}}\rangle\} , \\ |\omega_1\rangle &= \frac{1}{\sqrt{3}}\{|{\rm u\overline{u}}\rangle + |{\rm d\overline{d}}\rangle + |{\rm s\overline{s}}\rangle\} . \end{aligned} \qquad (6.4)$$

Thus the vanishing of the $\rm s\overline{s}$ component in the interaction requires a constraint in terms of our parameters as

$$p_i \equiv \frac{B_i}{2e_i - A_i} = -1 . \qquad (6.5)$$

By using the results of Eqs.(5.10), (5.12), we find the values of the left-hand side as

$$p_1 = -3.07 , \qquad p_2 = -5.51 , \qquad (6.6)$$

hence the OZI rule may be largely broken in both the electric and magnetic parts.

Third, with respect to the breaking of the OZI rule, the coupling constant of $\rm q\overline{q}$ pair to the nucleon may be obtained from Eq.(6.3) as

$$g^{(i)}\Big[\frac{\rm u\overline{u} + d\overline{d}}{\sqrt{2}}({\rm N\overline{N}})_{I=0}\Big] = \frac{1}{\sqrt{3}}(2e_i - A_i - 2B_i) , \qquad (6.7)$$

$$g^{(i)}[{\rm s\overline{s}}({\rm N\overline{N}})_{I=0}] = -\sqrt{\frac{2}{3}}(2e_i - A_i + B_i) . \qquad (6.8)$$

Thus the ratio of the coupling constants of $\rm s\overline{s}$ to $(\rm u\overline{u} + d\overline{d})/\sqrt{2}$ with nucleon is given as

$$r_i \equiv \frac{g^{(i)}[{\rm s\overline{s}}({\rm N\overline{N}})_{I=0}]}{g^{(i)}[\frac{\rm u\overline{u}+d\overline{d}}{\sqrt{2}}({\rm N\overline{N}})_{I=0}]} = -\sqrt{2}\frac{2e_i - A_i + B_i}{2e_i - A_i - 2B_i} , \qquad (6.9)$$

which yields

$$r_1 = 0.41\,, \qquad r_2 = 0.53\,. \tag{6.10}$$

It should be noted that the ratios are nearly of the same order of magnitudes in the electric as well as magnetic form factors and may indicate a sizable $s\bar{s}$ component in the nucleon. This result is consistent with the one of electric form factor obtained by H.Genz and G.Höhler[7]. Our result on the magnetic form factor would be interesting in view of the recent measurement of the spin structure of proton[10], which indicates a sizable $s\bar{s}$ component in the nucleon. In this paper, we cited the result of the solution given by Furuichi and Watanabe[8] since the other solutions given in ref.[9] show a large content($r_i > 1.0$) of s-quark pair in the nucleon.

Finally, we should give a few remarks. The hidden local theory assigns the dynamical gauge boson as the vector mesons and our low energy theorems consist of the tree diagram of these mesons. This approach has been shown to yield a succesfull description of low energy phenomena of both the mesons and baryons. But as we have mentioned in II, the ρ meson seems to behave heterogeneously from the others, ω and ϕ mesons. The magnitude of the fundamental coupling constant g obtained from f_ρ differs about 20% smaller than those from f_ω and f_ϕ. Also the ρ meson pole in the electromagnetic form factors, as was shown in refs.[6]~[8], may not be adequate to be described by the Breit-Wigner formula. This "ρ meson puzzle" should be lendered to the future study. The loop contribution of the vector mesons and the effect of the heavy baryon CHPT for the nucleon are also neglected in the present work, but we believe that the result of the present work may indicate a basic feature of the E.M.I. and the form factors of nucleon in the hidden local theory.

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