CHIRAL SYMMETRY BREAKING
IN HIDDEN LOCAL SYMMETRY

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\textbf{ABSTRACT.} Chiral breaking for baryon and meson interaction is formulated in the
framework of the hidden local symmetric theory of the nonlinear sigma model on the
manifold $U(3)_L \times U(3)_R/ U(3)_V$. The chiral symmetry breaking term transforms
as $(3,3^*)$ under $U(3)_L \times U(3)_R$ at the first order. Several low energy theorems are
derived for the electromagnetic interaction of baryon. The symmetry breaking term
preserves $SU(2) \times U(1)$ symmetry; we have confirmed that the Sakurai formula of
the electromagnetic interaction of vector meson holds and directly shown that the
photon mass vanishes. The fundamental gauge coupling constant $g$ and the mixing
angle $\theta$ of vector meson are fixed by independent phenomena of vector meson masses
and $e\gamma$ decay of vector meson. Using these values of $g$ and $\theta$, we extend our analysis
to the nucleon form factor and indicate a breaking of the OZI rule and a sizable
content of $s$-quark pair in the nucleon.

1. \textbf{INTRODUCTION}

The hidden local symmetry [1] may now be a promising candidate for the effective
low energy theory of the QCD. This theory has a fundamental coupling constant $g$ of vector meson as the dynamical gauge boson and an adjustable parameter $a'$ in the meson interaction. The only crucial assumption is that the kinetic part of the dynamical gauge vector meson owes to the dynamical origin. Low energy theorems in the meson sector such as KSFR relation etc. were shown to be satisfied independently on the parameter $a'$ at the symmetrical limit.

In a previous paper [2], we constructed an effective baryon interaction of the lowest
dimension operators in the hidden local theory based on the $U(3)_L \times U(3)_R/ U(3)_V$
nonlinear sigma model, and successfully reproduced the S wave pion nucleon scattering
lengths, the conserved vector current (CVC) of $\beta$- decays of baryons and the
Sakurai scenario of the electromagnetic interactions (Hereafter, we abbreviate as E.M.I.) of hadrons. The effective interaction contains an adjustable parameter $a'$ with 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 in baryon sector have been shown to be satisfied independently on $a'$ and $a_s$.
In this paper, we introduce the chiral symmetry breaking interaction in a most simple way according to ref. [3] and construct an effective theory of hadrons including octet baryons and mesons interacting with external gauge bosons. Owing to the nonet scheme of the vector meson, we have two more meson interactions with adjustable parameters $c$ and $d$ to the original one of ref. [1]. The effective interaction with chiral breaking enables us to evaluate real values of $a'$ and $a_2$ as well as to fix $g$ and mixing angle $\theta$ of $\omega$ and $\phi$ mesons.

We analyze the the mass splitting of vector mesons, the electron pair decays of vector mesons and the electromagnetic form factor of nucleon. In this analysis, we take into account the leading order of the symmetry breaking term with the neglect of loop corrections. In our treatment of the symmetry breaking, it is to be noted, the $SU(2) \times U(1)$ symmetry is preserved; we check the universal E.M.I., the vanishing of fictitious "photon mass" and the maintenance of the Sakurai formula of vector meson-photon interaction.

This paper is organized as follows. The effective Lagrangian of baryon and meson with chiral symmetry breaking is formulated up to the first order of the current quark mass in section 2. In section 3, we deal with the vector meson mass formula to estimate $g$, $\theta$ and $d/a$. In section 4, the E.M.I. of vector meson is studied; values of $g$ and $\theta$ are obtained independently of the other estimation. In section 5, the E.M.I. of nucleon is constructed, and is shown to satisfy the minimal E.M.I.. Also we establish low energy theorems for both the iso-scalar and iso-vector channels. In section 6, the electromagnetic form factor of nucleon is analyzed on the basis of the low energy theorems, which are used to extract values of $a'$ and $a_2$ in section 7. Finally results and discussions are given in section 7, where we summarize the result on $g$ and $\theta$, and derive a new sum rule for the vector meson pole contribution to the nucleon form factor, and discuss the validity of the OZI rule and the rate of the content of the s-quark pair in the nucleon.

2. LAGRANGIAN

In this section we will build the chiral Lagrangian with the chiral symmetry breaking parts in the hidden local symmetric theory on the manifold $U(3)_L \times U(3)_R / U(3)_V$. The same notations as those in the references [1] and [2] are used without any notice. The other necessary notations are presented in the Appendix. The symmetrical Lagrangians consist of two kinds of building blocks as

\[
\frac{1}{2i}(\not{D}_\mu \xi_L \cdot \xi_L^\dagger \pm \not{D}_\mu \xi_R \cdot \xi_R^\dagger),
\]

where

\[
\xi_L = \exp (i\sigma / f_\pi) \exp (-i\pi f_\pi),
\]

\[
\xi_R = \exp (i\sigma / f_\pi) \exp (i\pi f_\pi).
\]
The $\xi$'s transform as
\begin{equation}
\xi_L(x) = h(x)\xi_L(x)g_L^1, \\
\xi_R(x) = h(x)\xi_R(x)g_R^1,
\end{equation}
where generators are $g_L \in U_L(3)$, $g_R \in U_R(3)$ and $h \in U_V(3)$. The covariant derivatives under $U_V(3)$ are defined as
\begin{equation}
D_\mu \xi_L = \partial_\mu \xi_L - iV_\mu \xi_L + i\xi_L B_{\mu \nu}, \\
D_\mu \xi_R = \partial_\mu \xi_R - iV_\mu \xi_R + i\xi_R B_{\mu \nu}.
\end{equation}

For local $U_V(3)$, we fix the gauge as $\sigma = 0$ and then have $\xi_{L(R)}$ as $\xi_{L(R)} = \exp(\mp i\pi / f_A)$. We introduce the symmetry breaking terms in accordance with the paper by Bando, Kugo and Yamawaki [3]. We replace two blocks of (2.1) by new building blocks as
\begin{equation}
\alpha_\mu^V \equiv \frac{1}{2i}(D_\mu \xi_L \cdot \xi_L^\dagger + D_\mu \xi_R \cdot \xi_R^\dagger + D_\mu \xi_L \cdot \epsilon_V \xi_R^\dagger + D_\mu \xi_R \cdot \epsilon_V^\dagger \xi_L^\dagger),
\end{equation}
\begin{equation}
\alpha_\mu^A \equiv \frac{1}{2i}(D_\mu \xi_L \cdot \xi_L^\dagger - D_\mu \xi_R \cdot \xi_R^\dagger + D_\mu \xi_L \cdot \epsilon_A \xi_R^\dagger - D_\mu \xi_R \cdot \epsilon_A^\dagger \xi_L^\dagger),
\end{equation}
where $\epsilon_V(A)$ transforms as $(3,3^*)$ under $U(3)_L \times U(3)_R$ and the explicit expression will be given later. The meson part of the Lagrangian $L_M$ is given in terms of $\alpha_\mu^V(A)$ of Eqs.(2.5) and (2.6) as
\begin{equation}
L_M := l_A + aL_V + cL_A + dL_A^*,
\end{equation}
where
\begin{equation}
l_A = f^2 < (\alpha_\mu^A)^2 >, \\
aL_V = af^2 < (\alpha_\mu^V)^2 >, \\
cL_A = cf^2 < \alpha_\mu^V >^2, \\
dL_A^* = df^2 < \alpha_\mu^V >^2.
\end{equation}
In Eqs.(2.8), the mass term of the pseudoscalar meson and the kinetic term of the external gauge boson are omitted. $\alpha_\mu^{V'(A')}$ are defined by Eqs.(2.5),(2.6) with replacing $\epsilon_V(A)$ by $\epsilon_V(A)$. The assumption of the existence of the kinetic term of dynamical gauge vector mesons is essential in the hidden local symmetric theory. In Eqs.(2.8), we reparametrize the breaking $\epsilon$ terms as
\begin{equation}
2af^2 \epsilon_V = C_0 \mathbf{m},
\end{equation}
\begin{equation}
2df^2 \epsilon_A = D_0 \mathbf{m}.
\end{equation}
where $\mathbf{m}$ is expressed in terms of the current quark masses as follows,
\begin{equation}
\mathbf{m} = \begin{pmatrix} m_u & 0 \\ m_d & m_s \end{pmatrix}.
\end{equation}
The $e_A$ terms are irrelevant in the following analysis and we do not redefine them. Lagrangian $L_B$ of the baryon is given as follows,

$$L_B = L_B^{(0)} + a' l_B^{(1)} + l_B^{(2)} + L_B^{(3)} + a_s L_B^{(4)} + L_B^{(m)} ,$$

where

$$L_B^{(0)} = < B i \gamma^\mu D_\mu B > = < B i \gamma^\nu \partial_\nu B > + g < B \gamma^\nu [V_\nu , B] >,$$

$$a' l_B^{(1)} = a' < \bar{B} \gamma^\nu [\alpha_\nu , B] >,$$

$$l_B^{(2)} = - b_F < B \gamma^\nu \gamma_5 [\alpha_\nu , B] > - b_D < \bar{B} \gamma^\nu \gamma_5 \{ \alpha_\nu , B \} >,$$

$$l_B^{(3)} = - b_s < \bar{B} \gamma^\nu B > < \alpha_\nu >,$$

$$a_s L_B^{(4)} = a_s < \bar{B} \gamma^\nu B > < \alpha_\nu > ,$$

and

$$L_B^{(m)} = - M_0 < \bar{B} B > + \kappa_F < \bar{B} \{ \frac{1}{2} (\xi_L \rho \xi_L + \xi_R \sigma \xi_L) , B \} > + \kappa_D < \bar{B} \{ \frac{1}{2} (\xi_L \rho \xi_L + \xi_R \sigma \xi_L) , B \} > .$$

In Eqs.(2.12), we replace $e$ term as we did in Eq.(2.9),

$$a' \epsilon_V = C_B \ m ,$$

$$a_s \epsilon_V = D_B \ m .$$

$L_B$ has essentially only one parameter $a'$ which corresponds to the parameter $a$ in $L_M$. $a_s L_B^{(4)}$ should in general be added because $\alpha_\mu$ has non-vanishing $U(1)$ component of $U(3)$ trace. This interaction has an important role for the electromagnetic form factor of nucleon as will be shown later.

3. Masses of Vector Meson

The mass part of the Lagrangians Eqs.(2.8) is given as follows up to the first order $m$

$$L_M^{(m)} = - g^2 f^2 < V_\mu V^\mu > - g^2 \xi_0 < V_\mu mV^\mu > - g^2 D_0 < V_\mu m > < V^\mu > .$$

1The authors of ref.[3] keep $m^2$ term, but take only $a l_V$ without $d l_V$. Even when the $m^2$ term is added to our mass term Eq.(3.1), it can be later shown that the same low energy theorems are also satisfied and that under $m_0 = m_\mu = 0$ a mass fitting to all the vector mesons gives constraints on parameters consistent with ours in e.g. Eqs.(3.13) and (3.16). It should be noted, in any case, $d l_V$ needs to exist through it is much smaller than $a l_V$. So we retain only the first order of $m$ term throughout this paper for simplicity.
The masses of the nonmixing particles are obtained by Eq. (3.1) as

\[ m_{\rho^\pm} = a g^2 f^2 + \frac{1}{2} g^2 C_0 (m_u + m_d) \equiv a g^2 f^2 + m_3, \]

\[ m_{K^*0} = a g^2 f^2 + \frac{1}{2} g^2 C_0 (m_d + m_s) \equiv a g^2 f^2 + \frac{1}{4} (m_3 + 3m_8) - \frac{\sqrt{3}}{2} m_{\rho^0}, \]

\[ m_{K^*+} = a g^2 f^2 + \frac{1}{2} g^2 C_0 (m_u + m_s) \equiv a g^2 f^2 + \frac{1}{4} (m_3 + 3m_8) + \frac{\sqrt{3}}{2} m_{\rho^0}. \]  

(3.2)

The mass matrix of the mixed particle is given as follows,

\[ V_{\nu}^{\mu} = -\frac{1}{2} V_{\nu}^{\mu} m V_{\nu}^{\mu}, \]  

(3.3)

where

\[ V_{\nu}^{\mu} = (\rho, \omega, \omega_1)_\mu. \]  

(3.4)

The mass matrix \( m \) is

\[ m = \begin{pmatrix} a g^2 f^2 + m_3 & m_{\rho^0} & m_{\rho^+} \\ m_{\rho^0} & a g^2 f^2 + m_8 & m_{K^*0} \\ m_{\rho^+} & m_{K^*0} & a g^2 f^2 + m_1 \end{pmatrix}, \]  

(3.5)

where

\[ m_3 \equiv g^2 C_0 m, \quad m_8 \equiv \frac{1}{3} g^2 C_0 (m + 2m_8), \]

\[ m_1 \equiv \frac{1}{3} g^2 (C_0 + 3D_0)(2m + m_8) - \frac{3}{2} d g^2 f^2, \]

\[ m_{K^*0} \equiv \frac{1}{3 \sqrt{2}} g^2 (C_0 + 3D_0)(m - m_8), \]

\[ m_{\rho^0} \equiv \frac{1}{2 \sqrt{3}} g^2 C_0 (m_u - m_d), \]

\[ m_{\rho^+} \equiv \frac{1}{\sqrt{6}} g^2 (C_0 + 3D_0)(m_u - m_d), \]

\[ \tilde{m} \equiv \frac{1}{2} (m_u + m_d). \]  

(3.6)

Under the approximation \((SU(2)\) invariant\)

\[ m_{\rho^0} = m_{\rho^+} = 0, \]  

(3.7)

we obtain the masses of the \( \rho \) and \( K^* \) mesons as

\[ m_\rho^2 \equiv m_{\rho^0}^2 = m_{\rho^+}^2 = a g^2 f^2 + m_3, \]

\[ m_{K^*}^2 \equiv \frac{1}{2} (m_{K^*0}^2 + m_{K^*+}^2) = a g^2 f^2 + \frac{1}{4} (m_3 + 3m_8). \]  

(3.8)
The $\omega$ and $\phi$ mesons are mixing states of $\omega_8$ and $\omega_1$. We define the mixing angle $\theta$ as

$$
\omega_8 = \phi \cos \theta + \omega \sin \theta,
$$

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

The mass matrix of the mesons $\omega_8$ and $\omega_1$ is diagonalized with the mixing angle $\theta$,

$$
\tan 2\theta = 2m_{S1}/(m_1 - m_8),
$$

and eigenmass values of $\omega$ and $\phi$ mesons are given as

$$
m_{\omega}^2 = a^2 f^2 + m_8 + m_{S1}/\tan \theta,
$$

$$
m_{\phi}^2 = a^2 f^2 + m_8 - m_{S1} \tan \theta.
$$

The input experimental data are four mass values of $m_{\omega}^2, m_{K^*}^2, m_{\phi}^2$, and $m_{\rho}^2$. The mass matrix has six parameters; $a^2 f^2, m_3, m_8, m_{S1}, m_1$, and $\theta$, of which one parameter is fixed by the diagonalization condition. Thus we have one free parameter. The number of parameters in the mass matrix is just equals to the number of parameters involved in the Lagrangian $L_{\chi'}$ of Eq.(3.1); $a^2 f^2, g^2 f^2, g^2 \alpha \tilde{m}, g^2 D_0 \tilde{m}, m_{S1}/\tilde{m}$ and $\theta$. It should be noticed that $\theta$ and $D_0/C_0$ are numerically fixed independently on the free parameter and they are

$$
\sin^2 \theta = \frac{3m_{\phi}^2 - 4m_{K^*}^2 + m_{\omega}^2}{3(m_1^2 - m_{\omega}^2)},
$$

$$
\frac{D_0}{C_0} = \frac{2}{3} \left[ \sqrt{(3m_{\phi}^2 - 4m_{K^*}^2 + m_{\omega}^2)(4m_{K^*}^2 - m_{\omega}^2 - 3m_8^2)} / 2\sqrt{2(m_{K^*}^2 - m_{\omega}^2)} - 1 \right].
$$

Using the experimental mass values of the vector mesons, we have

$$
\theta = 39.16^\circ,
$$

$$
D_0/C_0 = 0.042.
$$

Eq.(3.13) shows the value of $\theta$ nearly equals to the ideal mixing angle ($\theta = 35.3^\circ$). Eq.(3.12) is nothing but the Gell-Mann Òkubo mass formula for nonet scheme. We choose the free parameter as $x \equiv m_3/\tilde{m}$, and then $a^2 f^2$ is expressed as

$$
a^2 f^2 = \frac{1}{x - 1}[m_3^2(x + 1) - 2m_{K^*}^2].
$$

As the value of $x$, we use $x = 25.7$ which is given by Q.C.D. analysis [4]. Using $a = 2 [1]$ and $f = 92.5 MeV$, we obtain the gauge coupling constant $g$ of the vector meson as

$$
g = 5.76.
$$

---

\[2\text{As was noticed before, if the } m^2 \text{ term is added to the mass term, this does not hold [3]. Under } m_u = m_d = 0, \text{ we can obtain } \theta = 32.97^\circ, g = 5.87 \text{ and } d/f = -0.110 \text{ from the mass fitting.}\]
The values of the other parameters are fixed as follows,

\[
\frac{m_1}{ag^2f^2} = 0.030, \quad \frac{m_8}{ag^2f^2} = 0.52, \\
\frac{-m_1}{ag^2f^2} = 0.37, \quad \frac{m_8}{ag^2f^2} = -0.37,
\]

(3.16)

\[
d = -0.038.
\]

Eqs.(3.16) show that the order of the symmetry breaking coupling to the symmetric one is up to about 50%. The magnitudes of the neglected \(m_{\rho,8}\) and \(m_{\rho,1}\) are

\[
\frac{m_{\rho,8}}{ag^2f^2} = -0.0081, \quad \frac{m_{\rho,1}}{ag^2f^2} = -0.012.
\]

(3.17)

Eqs.(3.16) and (3.17) show that the magnitude \(m_{\rho,1}\) is close to that of \(m_1\). However, it should be noted that the contribution of \(m_{\rho,1}\) arises from the mass difference of \(u\) and \(d\) quarks and the E.M.I. should come into an effect. Accordingly, as an approximation, we neglect \(m_{\rho,1}\) and \(m_{\rho,8}\) in the diagonalization of the mass matrix.

4. ELECTROMAGNETIC INTERACTION OF THE VECTOR MESON AND \(V \to c\bar{c}\) DECAY

In this section, we estimate the gauge coupling constant \(g\) of the vector meson and the mixing angle \(\theta\) from the analysis of the decay \(V \to c\bar{c}\). At first, we confirm that our Lagrangian preserves the \(SU(1)\) symmetry of E.M.I.. The explicit interaction Lagrangian of the vector meson and the electromagnetic field is given from Eq.(2.8) as

\[
L(\gamma - V) = \varepsilon_g [(af^2 + C_0m_1)\rho_\mu^0 + \frac{1}{\sqrt{3}} (af^2 + C_0\frac{m + 2m_s}{3})\omega_{8\mu}] \\
- \frac{2}{3\sqrt{6}} (\varepsilon_0 + \frac{3}{2} D_0) (m_s - \bar{m}) \omega_{1\mu}] A^\mu
\]

(4.1)

\[
= \frac{c}{g} [(af^2 + m_1)\rho_\mu^0 + \frac{1}{\sqrt{3}} (af^2 f^2 + m_s) \omega_{8\mu} + \frac{1}{\sqrt{3}} m_{1\mu} \omega_{1\mu}] A^\mu
\]

\[
= \frac{c}{g} [m_0^2 \rho_\mu^0 + \frac{1}{\sqrt{3}} m_s^2 \sin \theta \omega_{8\mu} + \frac{1}{\sqrt{3}} m_{1\mu} \cos \theta \omega_{1\mu}] A^\mu
\]

Here we have used Eqs.(3.8) and (3.11). Eq.(4.1) shows that our Lagrangian gives the Sakurai formula

\[
L(\gamma - V) = c \sum_V \frac{mV^2}{f_V} V^\mu A^\mu
\]

(4.2)

with

\[
f_\rho = g, \quad f_\omega = \frac{\sqrt{3}g}{\sin \theta}, \quad f_\phi = \frac{\sqrt{3}g}{\cos \theta}
\]

(4.3)
Eq. (4.3) leads to \( f_\delta / f_\omega = \tan \theta \). This relation is also followed from only \( SU(3) \) argument. Our results show that such relations hold even under the presence of the chiral symmetry breaking. It should be noted that the all \( f_\nu \) are given in terms of the fundamental coupling constant \( g \) and only the mixing angle \( \theta \). Now we show the vanishing of the fictitious "photon mass" which means that our Lagrangians preserve the electromagnetic \( U(1) \) symmetry even under the presence of the breaking effects. The Lagrangian Eq.(2.8) contains the fictitious "photon mass" term such as

\[
L(A_\mu^\nu) = \left[-\frac{\pi}{3} \mu e^2 f^2 + \frac{1}{9} e^2 C_\mu (m_\pi + 5 m_\pi)\right] A_\mu^2 \quad (4.4)
\]

On the other hand, the exchange process of the vector meson by the interaction Eq.(4.2) gives at the low energy limit

\[
\Delta L(A_\mu^\nu) = \frac{1}{2} c^2 \left[ \frac{m_\rho^2}{f^2} + \frac{m_\omega^2}{f^2} + \frac{m_\phi^2}{f^2} \right] A_\mu^2 \quad (4.5)
\]

This \( \Delta L(A_\mu^\nu) \) cancels \( L(A_\mu^\nu) \) exactly and thus the \( U(1) \) symmetry is preserved.

Next, we proceed to estimate the coupling constant \( g \) and the mixing angle \( \theta \) from the decay process \( V \to e^+e^- \). By the well known formula \( f_\nu^2 = 4\pi \alpha^2 m_\nu / (3\Gamma(V \to e^+e^-)) \), we obtain the following values of the \( f_\nu \) as

\[
f_\rho = 5.03 \quad , \quad f_\omega = 17.1 \quad , \quad f_\phi = 12.9 \quad . \quad (4.6)
\]

Eqs.(4.3) and (4.6) give us the following values of \( g \) and \( \theta \),

\[
\rho \, \text{decay} : \quad g = 5.03 \\
\omega, \phi \, \text{decay} : \quad g = 5.93 \quad , \quad \theta = 37.08^\circ \quad . \quad (4.7)
\]

The value of \( \theta \) is consistent with the result obtained in section 3 from the masses of the vector mesons. The values of \( g \) may be consistent under the tree diagram approximation and the neglect of \( m_\rho \) and \( m_\omega \). The equality of the values of \( \theta \) in Eq.(4.7) with the one of Eq.(3.13) was known as an "accidental agreement" [5] but this result shows theoretical consistency of our framework.

5. ELECTROMAGNETIC INTERACTION OF THE OCTET BARYONS

We investigate the electromagnetic interaction of the octet baryon in our framework at first and then show that the minimal photon interaction of the baryon holds even under the presence of the symmetry breaking at the low energy limit. Next we derive the low energy electromagnetic effective coupling constants for the isospin \( I = 0 \) and \( I = 1 \) channels.
The direct interaction of the baryon and photon is obtained by Eq. (2.12) as

\[
L(\gamma BB) = e\alpha \left( \bar{P}\gamma_{\mu}P + \Sigma^{+} \gamma_{\mu} \Sigma^{+} - \Sigma^{-} \gamma_{\mu} \Sigma^{-} - \Xi^{-} \gamma_{\mu} \Xi^{-} \right) A^{\mu} + eC_{B} \frac{1}{3} (m_{s} + 2\bar{m}) \bar{P}\gamma_{\mu}P \\
+ \frac{1}{3} (m_{s} - \bar{m}) N_{\gamma} \gamma_{\mu} N + \frac{1}{3} \left( \Sigma^{+} \gamma_{\mu} \Sigma^{+} - \Sigma^{-} \gamma_{\mu} \Sigma^{-} \right) - \frac{1}{3} (m_{s} - \bar{m}) \Xi^{0} \gamma_{\mu} \Xi^{0} \\
- \frac{1}{3} (m_{s} + 2\bar{m}) \Xi^{-} \gamma_{\mu} \Xi^{-} \right) A_{\mu} - eD_{B} \frac{1}{3} (m_{s} - \bar{m}) < \bar{B} \gamma_{\mu} B > A_{\mu} \\
\] (5.1)

\[
e \alpha \left[ < \bar{B} \gamma_{\mu} B >_{1} + < B \gamma_{\mu} B >_{2} \right] A_{\mu} + eC_{B} \bar{m} < \bar{B} \gamma_{\mu} B >_{1} \\
+ \frac{1}{3} (2m_{s} - \bar{m}) < B \gamma_{\mu} B >_{2} \right] A_{\mu} - eD_{B} \frac{1}{3} (m_{s} - \bar{m}) < \bar{B} \gamma_{\mu} B > A_{\mu},
\]

where

\[
< \bar{B} \gamma_{\mu} B >_{1} = \left[ P\gamma_{\mu}P - \bar{N} \gamma_{\mu} N + 2(\Sigma^{+} \gamma_{\mu} \Sigma^{+} - \Sigma^{-} \gamma_{\mu} \Sigma^{-}) \\
+ \Xi^{0} \gamma_{\mu} \Xi^{0} - \Xi^{-} \gamma_{\mu} \Xi^{-} \right]. \\

< \bar{B} \gamma_{\mu} B >_{2} = \left[ (P\gamma_{\mu}P + \bar{N} \gamma_{\mu} N) - (\Xi^{0} \gamma_{\mu} \Xi^{0} + \Xi^{-} \gamma_{\mu} \Xi^{-}) \right].
\] (5.2)

The interaction of the neutral vector boson and baryon is given as

\[
L(\nu^{0} BB) = G_{\mu}^{\rho} \nu^{\rho} + G_{\mu}^{s} \nu^{s} + G_{\mu}^{1} \nu^{1},
\] (5.3)

where

\[
G_{\mu}^{\rho} \equiv \alpha \left[ (1 - a') - C_{\mu} \bar{m} \right] < \bar{B} \gamma_{\mu} B >_{1},
\]

\[
G_{\mu}^{s} \equiv \alpha \left[ \frac{1}{\sqrt{3}} (1 - a') + \frac{1}{\sqrt{3}} C_{B} (2m_{s} + \bar{m}) \right] < \bar{B} \gamma_{\mu} B >_{2} \\
+ \frac{1}{\sqrt{3}} gD_{B} (m_{s} - \bar{m}) < \bar{B} \gamma_{\mu} B >.
\] (5.4)

\[
G_{\mu}^{1} \equiv \frac{2}{\sqrt{6}} gC_{B} (m_{s} - \bar{m}) < B \gamma_{\mu} B >_{2} - \frac{1}{\sqrt{6}} gD_{B} (m_{s} + 2\bar{m}) < \bar{B} \gamma_{\mu} B > \\
- \frac{2}{\sqrt{6}} a_{s} g < \bar{B} \gamma_{\mu} B >.
\]

The interaction of the vector meson and photon Eq. (4.2) gives the following effective baryon-photon interaction as shown in Fig. 1.

Fig. (1a) Fig. (1b)
\[ \Delta L(\text{tree}) = \frac{e}{g}(G^\rho_\mu + (G^a_\mu \sin \theta + G^i_\mu \cos \theta) \frac{1}{\sqrt{3}} \sin \theta + (G^8_\mu \cos \theta - G^i_\mu \sin \theta) \frac{1}{\sqrt{3}} \cos \theta) A^\mu \]
\[ = \frac{e}{g}(G^\rho_\mu - \frac{1}{\sqrt{3}} G^a_\mu) A^\mu \]
\[ = e[< B \gamma_\mu B >_1 + < B \gamma_\mu B >_2] A^\mu - e[a'|| < B \gamma_\mu B >_1 + < B \gamma_\mu B >_2]
\[ + C_B(m < B \bar{\gamma}_\mu B >_1 + \frac{1}{3}(2m_s + \bar{m}) < B \bar{\gamma}_\mu B >_2)
\[ - \frac{1}{3} D_B(m_s - \bar{m}) < B \bar{\gamma}_\mu B >_1] A^\mu. \]

(5.5)

It should be noted that \( G^i_\mu \) and \( \theta \) are dropped out at the second line in Eq.(5.5).

Finally, we have the following effective E.M.I. of the baryon and photon as

\[ L(\gamma BB) + \Delta L(\text{tree}) = e[< B \gamma_\mu B >_1 + < B \gamma_\mu B >_2] A^\mu
\[ = e[\bar{P} \gamma_\mu P + \Sigma^+ \gamma_\mu \Sigma^+ - \Sigma^- \gamma_\mu \Sigma^- - \Xi^- \gamma_\mu \Xi^-] A^\mu. \]

(5.6)

This is the minimal E.M.I. of the baryon. The derivation of Eq.(5.6) does not depend on the parameters \( a' \) and \( a_s \) and the breaking effects in Eqs.(5.1) and (5.5) cancel each other to get Eq.(5.6).

Now we proceed to extract the effective E.M.I. of the nucleon for each isospin channels \( I = 0 \) and \( I = 1 \). These interactions may be used to make analysis of the electromagnetic form factor of the nucleon in the next section. Eq.(2.12) gives the direct E.M.I. of the nucleon as

\[ L(\gamma NN) = e[\frac{1}{2}(a' + C_B \bar{m}) (P \gamma_\mu P - \bar{N} \gamma_\mu N) + \frac{1}{2}(a' + \frac{1}{3} C_B (2m_s + \bar{m})
\[ - \frac{2}{3} D_B(m_s - \bar{m})] (\bar{P} \gamma_\mu P + \bar{N} \gamma_\mu N)] A^\mu. \]

(5.7)

The interaction of the neutral vector meson and the nucleon is obtained in the same way as

\[ L(V^0 NN) = g_{\rho NN} \rho_0^\mu (P \gamma_\mu P - \bar{N} \gamma_\mu N) + (g_{8NN} \omega_8^\mu + g_{1NN} \omega_1^\mu)(P \gamma_\mu P + \bar{N} \gamma_\mu N), \]

(5.8)

where

\[ g_{\rho NN} = \frac{1}{2}[(1 - a') - C_B \bar{m}] g, \]
\[ g_{8NN} = \frac{1}{2}[\sqrt{3}(1 - a') - \frac{1}{\sqrt{3}} C_B (2m_s + \bar{m}) + \frac{2}{\sqrt{3}} D_B(m_s - \bar{m})] g, \]
\[ g_{1NN} = \frac{1}{2}[\sqrt{6} a_s + \frac{2}{\sqrt{6}} C_B (m_s - \bar{m}) - \frac{2}{\sqrt{6}} D_B(m_s + 2\bar{m})] g. \]

(5.9)
Rewriting Eq.(5.8) in terms of mixing eigenstates of $\omega$ and $\phi$ fields, we have

$$L(V^0NN) = g_{SN} P^0 (P_i q_i - N q_i N) + (g_{\omega NN} \omega^\mu + g_{\phi NN} \phi^\mu) (P \gamma_\mu P + N \gamma_\mu N),$$

where

$$g_{\omega NN} = g_{SN} \sin \theta + g_{1NN} \cos \theta,$$  
$$g_{\phi NN} = g_{SN} \cos \theta - g_{1NN} \sin \theta.$$  

The effective E.M.I. of the nucleon at the zero momentum transfer consists of two kinds of process shown in Fig.1, one is the direct interaction (Fig.1a) and the other (Fig.1b) is the process mediated by the vector mesons. We have the following low energy effective coupling constants in the unit of $c$ as follows,

$$\frac{g_{\omega NN}}{f_\omega} + \frac{1}{2} (\omega' + C_B m) = \frac{1}{2}$$

for the isospin $I = 1$ channel, and

$$\frac{g_{\omega NN}}{f_\omega} + \frac{g_{\phi NN}}{f_\phi} + \frac{1}{2} \omega' + \frac{1}{2} C_B (2m_s + m) - \frac{2}{3} D_B (m_s - m) = \frac{1}{2}$$

for the isospin $I = 0$ channel.

6. ELECTROMAGNETIC FORM FACTOR OF THE NUCLEON

On the electromagnetic form factors, it has been known, it is not adequate to use only the simple Breit-Wigner shape for the peak of the $\rho$ meson and simple tree diagram but it is necessary to take into account the pion-nucleon phase shifts for the $I = 1$ channel [6],[7]. On the other hand, the form factor for the $I = 0$ channel may be understood by the contribution of $\omega$ and $\phi$ mesons [5]. Here we use only the information of the form factor for the $I = 0$ channel and write it as [7],

$$F_i^V(t) = \frac{a_i(\omega)}{t + m_{\omega}^2} + \frac{a_i(\phi)}{t + m_{\phi}^2} + \frac{a_i(s)}{t + m_s^2} + C_i F_1^{as},$$

where $a_i(V)$ is the pole residue and $C_i$ is a constant. The $a_i(s)$ term corresponds to a pole of $S$ particle with higher mass 1.68 GeV. In our theory this term and the asymptotic term $F_1^{as}$ may be considered as being frozen into the direct interaction Eq.(5.7). Furuichi and Watanabe [7] gave the best fit values as

$$a_1(\omega) = 0.7627 GeV^2, \quad a_1(\phi) = -0.7665 GeV^2,$$

with the positions

$$m_\omega = 0.784 GeV, \quad m_\phi = 1.02 GeV.$$  

The normalization conditions of the form factors are

$$F_i^V(0) = F_i^V(0) = 1/2.$$
which corresponds to our low energy effective coupling constants by Eqs.(5.12) and (5.13). In our framework, we have the following expressions for $a_1(\omega)$ and $a_1(\phi)$ by Eqs.(4.3) and (5.9) as

$$a_1(\omega) = g_{\omega NN} \frac{m_{\omega}^2}{f_{\omega}} = \frac{1}{2} \left[ (\sqrt{3} - a') - \frac{2m_s + m}{\sqrt{3}} C_B + \frac{2(m_s - m)}{\sqrt{3}} D_B \right] \sin \theta$$

$$- \left\{ \frac{1}{\sqrt{6}} a_s - \frac{2(m_s - m)}{\sqrt{6}} C_B + \frac{2(m_s + 2m)}{\sqrt{6}} D_B \right\} \cos \theta \right] \frac{g}{\sqrt{3} g} m_{\omega}^2$$

$$a_1(\phi) = g_{\phi NN} \frac{m_{\phi}^2}{f_{\phi}} = \frac{1}{2} \left[ (\sqrt{3} - a') - \frac{2m_s + m}{\sqrt{3}} C_B + \frac{2(m_s - m)}{\sqrt{3}} D_B \right] \cos \theta$$

$$+ \left\{ \frac{1}{\sqrt{6}} a_s - \frac{2(m_s - m)}{\sqrt{6}} C_B + \frac{2(m_s + 2m)}{\sqrt{6}} D_B \right\} \sin \theta \right] \frac{g}{\sqrt{3} g} m_{\phi}^2$$

(6.5)

By Eq. (6.5) with the values of $a_1(V)$ of Eq.(6.2), we obtain independently on $g$ and $\theta$,

$$a' + \frac{1}{3} C_B (2m_s + m) - \frac{2}{3} D_B (m_s - m) = -0.0146.$$

(6.6)

By using Eq.(6.6) and $\theta = 37.08^\circ$ from the analysis of the $V \rightarrow e\bar{e}$ decay, we have the following result from Eq.(6.5) independently on $g$,

$$a_s - \frac{1}{3} C_B (m_s - m) + \frac{1}{3} D_B (m_s + 2m) = -3.116.$$

(6.7)

The pole residue $a_1(V) = m_{\nu}^2 g_{\nu NN}/f_{\nu}$ with the values of Eqs.(4.6), (6.2) and (6.3) gives us $g_{\omega NN}$ and $g_{\phi NN}$ as

$$g_{\omega NN} = 21.21, \quad g_{\phi NN} = -9.492.$$

(6.8)

If we go back to Eqs.(5.9) and (5.11) and insert the results Eqs.(6.6), (6.7) and (6.8) into Eq.(5.11), we have $g = 5.931$ which reproduces again the value of Eq.(4.7) obtained from the decay $(\omega, \phi) \rightarrow \pi$.$c$. But this is not the independent evaluation of the value of $g$, because we have used the expression Eq.(4.3) in Eq.(6.5) and the values of $\theta$ and $f_{\nu}$ in the evaluation of Eqs.(6.7) and (6.8), respectively. Main results of this section are Eqs.(6.6) and (6.7) and they will be used in the evaluation of the $s$-quark pair content of the nucleon in the following section.

7. RESULTS AND DISCUSSION

We have constructed the effective Lagrangian for both the meson and the baryon in the symmetry breaking hidden local theory. In our treatment, the symmetry breaking comes from the mass of the current quarks. We have shown that the low energy theorem of the E.M.I. holds. Our symmetry breaking term transforms as $(3, 3^*)$ under $U(3)_L \times U_R(3)$ and preserves $SU(2) \times U(1)$ symmetry. We have directly shown that the Sakurai formula of $\gamma - V$ interaction holds and that our effective theory
preserves the vanishing photon mass. We evaluated the fundamental coupling constant \( g \) and the mixing angle \( \theta \) by the analysis of the independent phenomena; the masses of vector mesons, the decay of \( V \rightarrow e\bar{e} \) and used them in the analysis of the electromagnetic form factor. These evaluations of \( g \) and \( \theta \) show that our effective theory gives consistently the values of \( g \) and \( \theta \). The symmetry breaking parameter given by Eq.(3.5) are all consistently small except \( m_b \) comparing with the symmetry limit parameter \( a g^2 f^2 \) as shown in Eqs.(3.16) and (3.17). Here we list up the results of the evaluation of \( g \) and \( \theta \).

Table

The value of the \( g \) estimated by \( \rho \rightarrow e\bar{e} \) decay is about 20\% smaller than the others; this may be due to the other electromagnetic interaction and the mass splitting among the \( \rho \) mesons and the higher order effects which are all neglected in our calculation. This may be said " \( \rho \) meson problem" together with the one of \( \rho \) pole contribution to the nucleon form factor as mentioned in the previous section. We leave this problem to a future study. It may be said that our theory shows that \( \theta = 37^\circ \sim 39^\circ \) and \( g = 5.8 \sim 6.0 \) and this value of \( \theta \) means ideal mixing is rather good and stable under the symmetry breaking effects.

Eqs.(6.6) and (6.7) suggest the following values of the parameters \( a' \) and \( a_s \) as

\[
a' \approx 0.0, \quad a_s \approx -3.1,
\]

(7.1)

if the breaking effects are small and negligible. It should be noted that this result means the VDM and a \( \rho \) universality scenario \((a' = 0)\) as was shown in ref.[2]. This also means to give an interesting sum rule for the vector meson pole contribution to the nucleon form factor as

\[
1 - 2\left( \frac{a_1(\omega)}{m_\omega^2} + \frac{a_1(\phi)}{m_\phi^2} \right) = a' = 0
\]

(7.2)

under the neglect of symmetry breaking effect. Eq.(7.1) means a breaking of the OZI rule. In our interaction, the condition of the OZI rule is as follows. In Eqs.(5.8) and (5.9), the interaction of \( \omega \) and \( \phi \) may be written as

\[
L(\omega, \phi, N) = g\left[ (1 - a') \frac{3}{2} \omega_{8,\mu} - a_s \frac{3}{2} \omega_{1,\mu} \right] [\bar{P}\gamma^\mu P + \bar{N}\gamma^\mu N]
\]

(7.3)

where \( \omega_8 \) and \( \omega_1 \) states are

\[
|\omega_8 \rangle = \frac{1}{\sqrt{6}} (|uu\rangle + |dd\rangle - 2|ss\rangle),
\]

(7.4)

\[
|\omega_1 \rangle = \frac{1}{\sqrt{3}} (|uu\rangle + |dd\rangle + |ss\rangle).
\]

Thus the vanishing of the \( ss \) component in the interaction requires a constraint in terms of our parameters as

\[
\frac{a_s}{1 - a'} = -1.
\]

(7.5)
Hence our result Eq.(7.1) means a breaking of the OZI rule. We express the coupling constants of $q\bar{q}$ pair to nucleon as

\[
g_{\frac{u\bar{u} + d\bar{d}}{\sqrt{2}}}(NN)_{t=0} = \frac{1}{\sqrt{3}}(g_{8NN} + \sqrt{2}g_{1NN}),\]

\[
g_{[ss(NN)]_{t=0}} = \frac{1}{\sqrt{3}}(-\sqrt{2}g_{8NN} + g_{1NN}).\]

Using Eqs.(5.9),(6.6) and (6.7), we obtain

\[
\frac{g_{[ss(NN)]_{t=0}}}{g_{\frac{u\bar{u} + d\bar{d}}{\sqrt{2}}}(NN)_{t=0}} = \sqrt{2} \frac{2.101}{7.246} \approx 0.41.\]

which is consistent with the result by H.Gen and G.Höbler [5]. This result would also be interesting in view of the recent measurement of the spin structure of proton [8], which indicates a sizable $s\bar{s}$ component in the nucleon.

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   see, however, ibid. 92, 339 (1994).
Appendix

Notations:
The $U(3)$ matrices for baryon octet, pseudoscalar and vector meson nonet are as follows,

$$B = \begin{pmatrix}
\frac{\sqrt{6}}{2} + \frac{A}{\sqrt{6}} & \Sigma^+ & P \\
\Sigma^- & -\frac{\sqrt{6}}{2} + \frac{A}{\sqrt{6}} & N \\
\Xi^- & -\Xi^0 & -\frac{\sqrt{2}}{\sqrt{3}} \Lambda
\end{pmatrix},$$
\hspace{1cm} (A1)

$$\Pi = \frac{1}{\sqrt{2}} \begin{pmatrix}
\pi^+ & \pi^- & K^+ \\
K^- & \frac{\sqrt{6}}{2} - \frac{\pi^0}{\sqrt{6}} & K^0 \\
\frac{\sqrt{2}}{\sqrt{3}} \eta & -\frac{\sqrt{2}}{\sqrt{3}} \eta & \frac{\sqrt{2}}{\sqrt{3}} \eta
\end{pmatrix} = \frac{1}{2} \sum_{a=1}^{8} \lambda_a \phi^a, \hspace{1cm} (A2)
$$

$$V = \frac{1}{\sqrt{2}} \begin{pmatrix}
\frac{\rho^+}{\sqrt{2}} + \frac{\pi^0}{\sqrt{6}} & \rho^+ & K^{*+} \\
\rho^- & -\frac{\rho^0}{\sqrt{2}} + \frac{\pi^0}{\sqrt{6}} & K^{*0} \\
K^{*-} & -\frac{\sqrt{2}}{\sqrt{3}} \omega_8 & \frac{\sqrt{2}}{\sqrt{3}} \omega_8 + \frac{\omega_3}{\sqrt{3}}
\end{pmatrix} \hspace{1cm} (A3)
$$

$$= \frac{1}{2} \sum_{a=1}^{8} \lambda_a V^a + \frac{1}{2} \lambda_0 \omega_1.$$

External gauge bosons are defined as follows.

$$B_{L\mu} = e Q (A_{\mu} - \tan \theta_W Z_{\mu}) + 2 g_Z T^L_Z Z_{\mu} + 2 g_W W_{\mu}, \hspace{1cm} (A4)$$

$$B_{R\mu} = e Q (A_{\mu} - \tan \theta_W Z_{\mu}),$$

where

$$g_Z \equiv \frac{e}{2 \cos \theta_W \sin \theta_W}, \quad \frac{g^2_Z}{m_Z^2} = \sqrt{2} G_F,$$

$$g_W \equiv \frac{e}{2 \sqrt{2} \sin \theta_W}, \quad \frac{g^2_W}{m_W^2} = \frac{G_F}{\sqrt{2}}, \hspace{1cm} (A5)$$

$$W_{\mu} = \begin{pmatrix}
0 & \cos \theta_C W_{\mu} & \sin \theta_C W_{\mu} \\
\cos \theta_C W_{\mu}^- & 0 & 0 \\
\sin \theta_C W_{\mu}^- & 0 & 0
\end{pmatrix} \hspace{1cm} (A6)$$

and

$$Q = \frac{1}{3} \begin{pmatrix}
2 & 0 & 0 \\
0 & -1 & 0 \\
0 & 0 & -1
\end{pmatrix},$$

$$T^L_Z = \frac{1}{2} \begin{pmatrix}
1 & 0 & 0 \\
0 & -1 & 0 \\
0 & 0 & -1
\end{pmatrix} \hspace{1cm} (A7)$$
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<tr>
<th>input</th>
<th>estimated values</th>
<th>comment</th>
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<td>$\frac{m_k}{m_1} = 25.7$ is assumed</td>
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<tr>
<td></td>
<td>$g = 5.76$</td>
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<td>$V \rightarrow \pi \pi$</td>
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<td></td>
<td>$g = 5.03$</td>
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**Table 1**