Mini-Charge Non-Conservation in $SU(3)_c \times SU(2)_L \times U(1)_Y$ Models

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Models of spontaneously breaking of electric charge symmetry are constructed. The charge symmetry is broken by the mini-charged Higgs bosons which couple to fermions. The characteristic feature of these models is that neutrinos, neutron and atoms have mini-charges, while the photon mass can be made very small. The measurement of these charges should be considered seriously.

There are symmetries which seem never to be broken. If the symmetry is not broken, there needs some superselection rule which guarantees this symmetry. The charge symmetry is one of such symmetries. It is our general belief that the charge symmetry would be an exact symmetry. This is partly due to the severe experimental limit on the photon mass ($m_\gamma < 10^{-33}$ MeV) which is obtained from the stability argument of the Small Magellanic Cloud and also the difficulty of the construction of models which are consistent from both theoretical and experimental point of view. If the charge is quantized, then only possible charge non-conserving processes would be those of $\Delta Q = \pm n$ ($n=1, 2, \ldots$), such as $e \rightarrow \gamma \nu$, $e \rightarrow \nu \bar{\nu}$ and $e^- - e^+$ mixing. Recent experimental study on $e \rightarrow \gamma \nu$, $e \rightarrow \nu \bar{\nu}$ is reported by Ejiri et al. If these processes occur due to the explicit breaking of the charge symmetry, electron becomes unstable due to the famous catastrophic decay by emitting multi-longitudinal photons, independently of the charge non-conserving couplings strength. On the other hand, if this charge non-conservation is due to the spontaneous breaking by the acquisition of the vacuum expectation value of Higgs boson with unit charge, the catastrophic multi-longitudinal photon bremsstrahlung may be avoided as Suzuki pointed out. But due to its very small vacuum expectation value ($\sim m_\gamma / e$), the model predicts an almost massless charged boson whose existence contradicts to the experimental observation.

In below, we explore the possibility of the charge non-conservation of very small amount. This type of model requires “mini-charged” Higgs bosons whose acquisition of vacuum expectation values causes the “mini-charge” non-conservation. There are arguments based on monopole and GUTs such as $SU(5)$ and $SO(10)$, but here we confine to the $SU(3)_c \times SU(2)_L \times U(1)_Y$ theories where some arguments have been presented for the charge quantization. In particular, Babu and Mohapatra showed the theorem that the charge is quantized if anomaly free conditions and Majorana mass term of neutrinos are taken into account. In their argument the charge conservation is assumed as granted. In order to construct the charge non-conservation model, these arguments have to be avoided.

There are two classes of spontaneous charge symmetry breaking models. One is
the case where matters which have non-quantized charges are only Higgs bosons whose acquisition of vacuum expectation values causes the spontaneous breaking. The physical consequences are the longitudinal photon and the mini-charged Higgs boson. The astrophysical argument has given the upper limit of such mini-charge to be less than of order $10^{-14}$.\(^{(9)}\)

The other is the case where charges of the left-handed fermions are slightly different from their right-handed counterparts. Higgs doublets which couple with these fermions have non-quantized charges. By the acquisition of vacuum expectation values of these mini-charged Higgs bosons, the $SU(3)_c \times SU(2)_L \times U(1)_Y$ symmetry is broken into $SU(3)_c$. This class of model was first discussed by Suzuki.\(^{(5)}\) The explicit realization of this idea has recently been made by Babu and Mohapatra.\(^{(12)}\)

Their model consists of two doublet Higgs; one Higgs doublet $\phi_1$ with hypercharge slightly deviated from one ($Y_1 - 1 = \epsilon$) couples with fermions and the other $\phi_2$ with unit hypercharge does not. Upon their acquisition of vacuum expectation values, the charge symmetry is broken. In this model, neutrinos have a minicharge of order $\epsilon$ while the photon mass is $\epsilon v_1 v_\phi / \sqrt{2 (v_1^2 + v_\phi^2)}$ with $v_\phi$ being the vacuum expectation value of a doublet Higgs $\phi_i$ so that $v_\phi \sim 100$ GeV. Then, the severe bound on the photon mass implies that the neutrino charge should be very small. In the following, in the framework of $SU(3)_c \times SU(2)_L \times U(1)_Y$ theory, we present a different model. We propose the model with two doublet Higgs and a singlet Higgs $\sigma$ which predicts charges of neutrinos, neutron and atoms to be of order $\delta$, while the photon mass is of order $\delta^3 \langle \sigma \rangle$. That is, there is a natural mechanism to suppress the photon mass in this model. Then, there arises a possibility that neutrinos, neutron and atoms have mini-charges without conflicting to the severe photon mass constraint. We also present another model with right-handed neutrinos which has a similar feature to the model above.

**Model 1: The model consisting of the standard fermion content.**

Fermions consist of the left-handed doublet quark, right-handed singlet $u, d$ quarks, the left-handed doublet lepton and a right-handed singlet electron, whose hypercharges are expressed as $Y_q, Y_u, Y_d, Y_\ell, Y_e$, respectively. We assume the repetition of generations. The anomaly free constraints are expressed as

\[
\begin{align*}
[SU(3)_c]^2 U(1)_Y: & \quad 2 Y_q - Y_u - Y_d = 0, \\
[SU(2)_L]^2 U(1)_Y: & \quad 3 Y_q + Y_\ell = 0, \\
[U(1)_Y]^3: & \quad 6 Y_q^3 + 2 Y_u^3 - 3 Y_d^3 - 3 Y_\ell^3 - Y_e^3 = 0.
\end{align*}
\]

Three types of Yukawa interactions are assumed

\[
\begin{align*}
\bar{q}_L \phi_1 d_R: & \quad Y_1 + Y_d - Y_q = 0, \\
\bar{q}_L \phi_2 u_R: & \quad - Y_1 + Y_u - Y_q = 0, \\
\ell_L \phi_2 e_R: & \quad Y_2 + Y_e - Y_\ell = 0,
\end{align*}
\]

where $\phi_i = i \tau_2 \phi_i^*$, and $Y_1$ and $Y_2$ are hypercharges of $\phi_1$ and $\phi_2$, respectively. By combining Eqs. (1), (2) and (4), we find
\[ Y_q = -\frac{1}{3} Y_t, \quad Y_d = -Y_u - \frac{2}{3} Y_t \]  \hspace{1cm} (5)

and

\[ Y_t = Y_u + \frac{1}{3} Y_t, \quad Y_2 = Y_1 - Y_e. \]  \hspace{1cm} (6)

By adjusting the scale of hypercharges, we can take \( Y_t = 1 \) and then we find

\[ Y_u = 1 - \frac{1}{3} Y_t, \quad Y_2 = -1 - \frac{1}{3} Y_t. \]  \hspace{1cm} (7)

By substituting Eq. (7) into Eq. (3), we have the equation between \( Y_t \) and \( Y_e \) as

\[ Y_e^2 = 2 Y_t(Y_t^2 + 3). \]  \hspace{1cm} (8)

Here, we are dealing with the case where deviations of hypercharges from the quantized ones are small. Thus, we parametrize \( Y_t \) as

\[ Y_t = -1 + \delta \]  \hspace{1cm} (9)

with \(|\delta| < 1\). Now, hypercharges are expressed in terms of the small parameter \( \delta \) as

\[ Y_q = \frac{1}{3} - \frac{\delta}{3}, \quad Y_u = \frac{4}{3} - \frac{\delta}{3}, \quad Y_d = \frac{-2}{3} - \frac{\delta}{3}, \]

\[ Y_e = -2 + \delta + \frac{\delta^3}{12} + O(\delta^4), \quad Y_1 = 1, \quad Y_2 = 1 - \frac{\delta^3}{12} + O(\delta^4). \]  \hspace{1cm} (10)

In general, hypercharges are not quantized \((\delta \neq 0)\) and consequently charges are not quantized. Note that Eq. (10) represents that one Higgs doublet case leads to the charge dequantization. \(^7\)

If we consider the model consisting of only these two Higgs doublets, there arises a serious trouble due to the interaction between electrons and the Goldstone boson which is eaten by the photon. This problem may be avoided by introducing a singlet Higgs \( \sigma \) just like the invisible axion scenario. There are various versions of Higgs potentials due to the choice of coupling of \( \sigma \) to two doublets. For definiteness, we adopt

\[ \phi_1^* \phi_2 \sigma^3 + h.c. \]  \hspace{1cm} (11)

Then, the hypercharge of \( \sigma \), \( Y_\sigma \) is

\[ Y_\sigma = (1 - Y_2)/2 = \delta^3/24 + O(\delta^4). \]  \hspace{1cm} (12)

Now the gauge invariance restricts that the Higgs potential has the same Higgs structure as the one used by Dine, Fischler and Srednicki. \(^{13}\) Also, due to this assignment of hypercharge, \( \sigma \) does not couple to fermions.

Once \( \phi_1, \phi_2 \) and \( \sigma \) get the vacuum expectation values,

\[ \langle \phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix}, \quad (i = 1, 2); \quad \langle \sigma \rangle = \frac{v_\sigma}{\sqrt{2}}, \]  \hspace{1cm} (13)
both $SU(2)_L$ and $U(1)_Y$ symmetries are broken spontaneously. For a finite range of parameters in the potential, one can have $|v_2|>|v_1|, |v_2| \sim 100 \text{ GeV}$. Then, the Goldstone boson which is eaten by photon consists mainly of $\text{Im} \sigma$ and the components from Higgs doublets are only of order $v_1/v_\sigma$ or $v_2/v_\sigma$ which are very small, where we assumed all vacuum expectation values are real for simplicity. From the stability of red giants under the process $\gamma + e^{-} \rightarrow e^{-} + G_\gamma$ with $G_\gamma$ being the Goldstone boson, $v_\sigma$ is required to be greater than about $10^9 \text{ GeV}$ for $G_\gamma$ to be invisible just as the invisible axion scenario.

The mass matrix for $W^3$ and $B_\nu$ is given by

$$M^2 = -\frac{1}{4} \left( \begin{array}{cc} g^2 V^2 & -gg' \left[ V^2 + (Y_2 - 1) |v_2|^2 \right] \\ -gg' \left[ V^2 + (Y_2 - 1) |v_2|^2 \right] & g^2 \left[ V^2 + (Y_2^2 - 1) |v_2|^2 + Y_\sigma^2 |v_\sigma|^2 \right] \end{array} \right),$$

where $V = \sqrt{|v_1|^2 + |v_2|^2}$. By diagonalizing this mass matrix, we obtain the mass of photon as

$$m_\gamma \approx \frac{1}{2} \epsilon_0 Y_2 - 1 \sqrt{\left| v_\sigma \right|^2 + \frac{|v_1|^2 |v_2|^2}{V^2}} \approx \frac{1}{48} \epsilon_0 |v_\sigma| \delta^3,$$

where $\epsilon_0 = gg' \sqrt{g^2 + g'^2}$. The Weinberg angle is slightly modified as

$$\sin \theta_w \approx \frac{g'}{\sqrt{g^2 + g'^2}} \left( 1 - \frac{g^2}{g^2 + g'^2} \frac{|v_2|^2}{V^2} \delta^3 \right).$$

Charges of quarks and leptons are defined by the strength of couplings with photon and are given by

$$e_Q = g \sin \theta_w T_l + g' \cos \theta_w \frac{Y}{2}.$$

By substituting Eqs. (10) and (14) into Eq. (15), we find

$$e_Q(u_L) \approx \epsilon_0 \left[ \frac{2}{3} - \frac{\delta}{6} + \frac{1}{g^2 + g'^2} \left( -\frac{1}{2} g^2 + \frac{1}{6} g'^2 \right) \frac{|v_2|^2}{V^2} \delta^3 \right],$$

$$e_Q(u_R) \approx \epsilon_0 \left[ \frac{2}{3} - \frac{\delta}{6} + \frac{2}{g^2 + g'^2} \frac{|v_2|^2}{V^2} \delta^3 \right],$$

$$e_Q(d_L) \approx \epsilon_0 \left[ -\frac{1}{3} \frac{\delta}{6} + \frac{1}{g^2 + g'^2} \left( \frac{1}{2} g^2 + \frac{1}{6} g'^2 \right) \frac{|v_2|^2}{V^2} \delta^3 \right],$$

$$e_Q(d_R) \approx \epsilon_0 \left[ -\frac{1}{3} \frac{\delta}{6} + \frac{1}{3} g^2 + g'^2 \frac{|v_2|^2}{V^2} \delta^3 \right],$$

$$e_Q(e_L) \approx \epsilon_0 \left[ -\frac{1}{2} + \frac{1}{2} \frac{g'^2 - g^2}{g^2 + g'^2} \frac{|v_2|^2}{V^2} \delta^3 \right],$$

$$e_Q(e_R) \approx \epsilon_0 \left[ -\frac{1}{2} + \frac{1}{2} \frac{g^2 - g'^2}{g^2 + g'^2} \frac{|v_2|^2}{V^2} \delta^3 \right],$$

$$e_Q(\nu_L) \approx \epsilon_0 \left[ \frac{\delta}{2} - \frac{1}{2} \frac{|v_2|^2}{V^2} \delta^3 \right].$$
where $e$ is introduced to represent the charge of electron in the order $\delta$, i.e.,

$$e = -e_0(1 - \delta/2).$$

The interesting feature of the model is that neutrinos, neutron and atoms are not absolutely charge neutral particles. Up to the order $\delta$, charges of neutrinos $Q(\nu)$, neutron $Q(n)$ and atom $Q_{\text{atom}}(Z, A)$ where $Z$ and $A$ are atomic number and nucleon number, respectively are given by

$$Q(\nu) = \frac{\delta}{2}, \quad Q(n) = -\frac{\delta}{2}, \quad Q_{\text{atom}}(Z, A) = -\frac{\delta}{2}(A - Z).$$

The characteristic feature of this model is that the measure of charge symmetry violation is the deviation of hypercharges of doublet Higgs bosons from one, i.e., $Y_2 - 1$ and not due to vacuum expectation values, $V_1$ and $V_2$, whose values are of order the electroweak scale ($\sim 250$ GeV). Therefore, masses of all physical Higgs bosons are expected to be larger than 100 GeV except for the Goldstone boson which is eaten by the photon. The small value of $Y_2 - 1(\approx -\delta^2/12)$ is due to the anomaly free conditions. There are two scales for charge non-conservation. One is the photon mass which is of order $(Y_2 - 1)|v_\sigma|$. The other is the scale of the electromagnetic current non-conservation, which is of order $(Y_2 - 1)m$, with $m$ being the fermion mass. The order of the current non-conservation is much smaller than the photon mass scale due to our assumption $|v_\sigma| \gg |v_1|, |v_2|$ and this is the reason why the longitudinal photon (the Goldstone boson) couplings to fermions are suppressed. These mechanisms allow us to the possibility of mini charges for neutrinos, neutron and atoms, while the photon mass are kept very small.

From the above derivation, we can see the following: If the fermion content of the standard model is assumed, the nonzero charges of neutrinos, neutron and atoms imply that the charge symmetry is broken. The similar observation was first made by Babu and Mohapatra by considering the charge non-conservation model. The experiments to explore charges of these particles would be very interesting. As for neutrino charge, the most stringent limit is obtained by Barbiellini and Cocconi from SN1987A observation to be $|Q(\nu)| < 10^{-17}$. The experimental upper limit of the neutron charge is $Q(n) = (-0.4 \pm 1.1) \times 10^{-21}$ which gives $|Q(\nu)| < 10^{-21}$ and the upper limit on $\delta$ as

$$|\delta| < 10^{-21}.$$ (20)

This in turn leads to the photon mass limit $m_\gamma < 10^{-52} \text{MeV} \cdot (|v_\sigma|/10^{10} \text{GeV})$ which is well below the experimental limit. The better limit on $\delta$ may be given by analyzing the Eötvös experiment.

We shall discuss several aspects of the model; the mass of neutrinos, the contribution from the radiative correction to photon mass.

In this model, neutrinos have to be massless not to contradict to experimental data. There are two ways to provide masses for neutrinos. One is to introduce a triplet Higgs which couples to two doublet leptons so that its hypercharge is $2Y_1$. This is the triplet Majoron model which is denied by the $\rho$ parameter data and the $Z$ width observation. The other is to introduce a charged singlet $H$ with the hypercharge $Y_H$ and another doublet $(\phi_3)$ which has the hypercharge $Y_H - Y_2$. There is a
global symmetry which predicts a Nambu-Goldstone boson like a doublet Majoron model. Then, the stability argument of the red giant under $\gamma + e \rightarrow e + \text{Majoron}$ and the $Z$ width data reject this model. Thus, both possibilities are not realized.

The radiative correction to photon mass is evaluated in the one loop approximation by using the interaction lagrangian

$$L_{\text{int}} = e Q_L \bar{\psi}_L \gamma_{\mu} \psi_L A^\mu + e Q_R \bar{\psi}_R \gamma_{\mu} \psi_R A^\mu,$$

where $\psi_L$ and $\psi_R$ denote chiral components of a fermion $\phi$ and $e Q_L, R$ denote their electric charges. The result is given by

$$\delta m_\gamma (\mu^2) = -\frac{e^2}{4\pi^2} (Q_L^2 + Q_R^2) m^2 \int_0^1 dx \frac{m^2 - x(1-x)}{m^2 - x(1-x)} \left| \frac{m^2}{m^2} \right|^2 + \frac{e^2}{8\pi^2} (Q_L - Q_R)^2 m^2 \int_0^1 dx \log \left| \frac{m^2 - x(1-x)}{m^2 - x(1-x)} \right|,$$  

where $m$ is the mass of $\phi$ and $\mu$ is the renormalization scale. We find that the first term is much less than $m^2$ and is not important. The second one is unimportant either because $|Q_L - Q_R| < \delta^3/24$ or neutrinos are massless in this model. Thus, the radiative correction does not upset the small photon mass prediction in the tree level.

Now, we discuss the role of the mixed gauge-gravitational anomaly free condition,$^{16)}$

$$6 Y_q - 3 Y_u - 3 Y_d + 2 Y_e - Y_\nu = 0,$$  

which we have ignored so far. If this condition is imposed to our model where the exact repetition of quantum numbers of members of each generation is assumed, we have $\delta = 0$. That is, the charge is quantized as was first pointed out by Geng and Marshak.$^6$ Thus, the charge conservation is maintained. At present, we do not know how serious the inclusion of this condition would be. In below, we consider this condition seriously. There two possibilities of charge non-conservation are considered. One is the model by Babu and Mohapatra who considered two doublet Higgs model. These two doublets have different hypercharges and only one doublet couples to fermions. Then, the photon mass bound forces the charges of neutrinos, neutrons and atoms to be very small. The other is the model where the exact repetition of generations is abandoned and an possibility the inter-generation cancellation is taken into account. Since the quark mixing should present, only possibility is for leptons where there is no so severe constraint on mixing. Then, the mixed gauge-gravitational anomaly free condition can be accommodated. It turns out that in this kind of models neutrinos are slightly charged, but neutron is essentially neutral. This is a quite different type of the model which will be discussed in the forthcoming paper.$^{17}$

In Model 1, neutrinos are massless and the mixed gauge-gravitational anomaly free condition is ignored, although we discussed some ways to accommodate it. In below, we have considered a model which allows mass of neutrinos and that condition is taken into account by keeping the exact repetition of generations.
**Model 2:** The model consisting of the standard fermion content and $\nu_R$.

The anomaly free conditions in Eqs. (1) and (2) remain valid, but the one in Eq. (3) is slightly modified as

$$[U(1)_Y]^3: \quad 6Y_q^2 + 2Y_l^3 - 3Y_d^2 - 3Y_u^2 - Y_e^2 - Y_\nu^2 = 0$$

by addition of the right-handed neutrino with the hypercharge $Y_\nu$. Now, the mixed gauge-gravitational anomaly free condition,

$$6Y_q - 3Y_d - 3Y_u + 2Y_l - Y_e - Y_\nu = 0$$

is added. As for Higgs content, we add one Higgs doublet $\phi$ and a singlet Higgs $H$ whose hypercharges are $Y_\phi$ and $Y_H$, respectively. Yukawa couplings are those in Eq. (4) and

$$\begin{align*}
T_L \partial_3 \nu_\phi &: \quad -Y_3 + Y_\nu - Y_l = 0, \\
(\nu_R)^c H &: \quad Y_H + 2Y_\nu = 0.
\end{align*}$$

We solve these equations by parametrizing $Y_l = -1 + \delta$ with $|\delta| \ll 1$. The result is

$$\begin{align*}
Y_q &= \frac{1}{3} - \frac{\delta}{3}, \\
Y_u &= \frac{4}{3} - \frac{\delta}{3}, \\
Y_d &= -\frac{2}{3} - \frac{\delta}{3}, \\
Y_t &= -1 + \delta, \\
Y_e &= -2 + \delta, \\
Y_\nu &= \delta, \\
Y_l &= Y_2 = Y_3 = 1, \\
Y_H &= -2 \delta.
\end{align*}$$

Since hypercharges of three $\phi_i$'s are equal, the minimal model of this type consists of one doublet Higgs $\phi$ and one singlet Higgs $H$. We consider this minimal case hereafter. Once these Higgs bosons receive the vacuum expectation values, both $SU(2)_L$ and $U(1)_Y$ symmetries are broken spontaneously. Since hypercharge of $\phi$ is quantized, the charge symmetry is broken only through $\langle H \rangle = v_H / \sqrt{2} \neq 0$. Thus the photon mass is given by

$$m_\gamma \approx e_0 |v_H| \delta.$$  

The Weinberg angle is defined by

$$\sin \theta_W \approx \frac{g'}{\sqrt{g'^2 + g^2}} \left(1 + \frac{4}{g'^2 + g^2} \frac{v_H^2}{v^2} \delta^2\right).$$

Electric charges are

$$\begin{align*}
eQ(u_L) &\approx e_0 \left[\frac{2}{3} - \frac{\delta}{6} + \frac{2}{3} \frac{g'^2(3g^2 - g'^2)}{(g'^2 + g^2)^2} \frac{|v_H|^2}{|v|^2} \delta^2\right], \\
eQ(u_R) &\approx e_0 \left[\frac{2}{3} - \frac{\delta}{6} + \frac{8}{3} \frac{g'^4}{(g'^2 + g^2)^2} \frac{|v_H|^2}{|v|^2} \delta^2\right], \\
eQ(d_L) &\approx e_0 \left[-\frac{1}{3} - \frac{\delta}{6} + \frac{2}{3} \frac{g'^2(3g^2 + g'^2)}{(g'^2 + g^2)^2} \frac{|v_H|^2}{|v|^2} \delta^2\right],
\end{align*}$$

where \( v \) is the vacuum expectation value of the doublet Higgs \( \phi \) and is of order 250 GeV. Since the modification of Weinberg angle is of order \((v_H \delta/v)^2\), the charge difference between chiral components is of this order. In this model, neutrinos have both Dirac and Majorana mass terms so that neutrinos are Majorana fermions. Babu and Mohapatra\(^7\) have argued that if neutrinos are Majorana fermions, the anomaly free conditions are enough to lead the charge quantization. This theorem is based on the charge conservation which does not apply to our model.

The special feature of this model is that the relevant parameter of the charge symmetry violation is \( v_H \delta \), which should be very small. If \( v_H \) is very small, \( \delta \) may not be very small so that neutrinos, neutron and atoms could have mini-charges as Model 1. In this scheme, physical Higgs particles are real part of the down component of \( \phi \) which is heavy as ordinary Higgs boson and ReH which is light and has a tiny charge \( -\delta \). Since the mixing between them is suppressed by about \( v_H/v < 10^{-17} \) if \( \delta \sim 10^{-21} \) in comparison with the standard Higgs couplings, ReH behaves as a mini-charged boson which interacts very weakly with photon and fermions. Neutrinos are now massive Majorana fermions. Due to its electric charge, they have intrinsic magnetic moments and also anomalous ones which are induced by loop diagrams. We estimated the anomalous magnetic moment of the electron neutrino in one loop order by assuming Majorana mass is much smaller than Dirac mass. The result is

\[
\Delta \mu_{\nu e} \approx \frac{\alpha}{2\pi} \frac{m_\mu}{m_\nu} Q(\nu)^3 \mu_\mu,
\]

where \( \mu_\mu \) is the Bohr magneton and \( m_\nu \gg m_\tau \) is assumed. This charged neutrino scenario may give a mechanism for large \( \Delta \mu_{\nu e} \) if the electron neutrino mass is very small.

If the mixed gauge-gravitational anomaly free condition is not included, \( Y_{\ell} \) and \( Y_\nu \) become arbitrary parameters. Then, three doublets and one singlet are needed. The characteristic parameter of the charge symmetry breaking is \( Y_{\nu} v_H \) and \((Y_{\ell} - Y_\nu + 1)v\). If \( v \) is small, the model becomes a doublet Majoron type which is rejected. Therefore, \( Y_{\ell} - Y_\nu + 1 \) must be very small and this model has essentially the same features as Model 2. The detail of this kind of model is discussed by Tanaka.\(^{18}\)

This model predicts the size of neutrino charge is almost the same as the neutron
charge as in Model 1. If the assumption of the exact repetition of generations is relaxed, these two charges are not related.\textsuperscript{17} Therefore, the neutrino charge measurement could also be meaningful.

In summary, we showed that if the non-standard Higgs content is taken, there arises a possibility of the charge dequantization and the charge non-conservation. The standard model (only one Higgs doublet) has a peculiar status that the charge is quantized and conserved. As concrete examples, we present two models of charge non-conservation. If the standard fermion content is assumed, we showed that the charges of neutrinos, neutron and atoms imply the charge symmetry violation. If $\nu_R$ is introduced, Majorana neutrinos are allowed within the charge dequantization and non-conservation model. In these models, charges of neutrinos, neutron and atoms are related as seen in Eqs. (19) and (30). If the complete repetition of hypercharges of members of generations (especially leptons) is abandoned, new kinds of models arise where the charge of neutrino is independent of that of neutron.\textsuperscript{17} In conclusion, there is a possibility that neutrinos, neutron and atoms have mini-charges and their observation would be related to the deep underlying physics, i.e., the charge non-conservation. The measurement of these charges should be considered seriously.

References