Model with Gauge Coupling Unification on $S^1/(Z_2 \times Z'_2)$ Orbifold

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We suggest a simple grand unified theory where the fifth dimensional coordinate is compactified on an $S^1/(Z_2 \times Z'_2)$ orbifold. This model contains additional $10 + \overline{10}$, $(15 + \overline{15})$ and two $24$ Higgs multiplets in the non-supersymmetric $SU(5)$ grand unified theory. Although this model is non-supersymmetric theory, the gauge coupling unification is realized due to the mass splittings of Higgs multiplets by $S^1/(Z_2 \times Z'_2)$ orbifolding. The constraints from the $b \to s\gamma$, $\mu \to e\gamma$, and electron and muon anomalous magnetic moments are also discussed.

§1. Introduction

When we consider the non-supersymmetric $SU(5)$ grand unified theory (GUT), one of the most serious problems is that the gauge coupling constants are not unified at the high energy. However, the gauge coupling unification can be realized by a simple extension of the standard model proposed by Murayama and Yanagida$^1$, where one more Higgs doublet and two leptoquark scalar fields are added. On the other hand, the five dimensional $SU(5)$ GUT has been proposed where the fifth dimensional coordinate is compactified on an $S^1/(Z_2 \times Z'_2)$ orbifold$^{2,3,4,5,6,7}$. In these models, only Higgs and gauge fields (vector-like fields) can propagate in the bulk. The non-supersymmetric $SU(5)$ model with $10 + \overline{10}$ Higgs fields on an $S^1/(Z_2 \times Z'_2)$ orbifold proposed by Kawamura$^2$ has the same field contents at the low energy as the model of Ref. $^1$. These two models with additional leptoquarks and a Higgs doublet at the low energy unifies the three gauge couplings, but the unification scale is of order $10^{14}$ GeV, which disagrees with the present proton-decay experiment at Super-Kamiokande$^8$.

In this paper, we suggest a simple grand unified theory where the fifth dimensional coordinate is compactified on an $S^1/(Z_2 \times Z'_2)$ orbifold. This model contains not only $10 + \overline{10}$ (we will also propose another model which includes $15 + \overline{15}$) but also two $24$ Higgs multiplets in the non-supersymmetric $SU(5)$ GUT. The gauge coupling unification is realized due to the mass splittings of Higgs multiplets by...
$S^1/(Z_2 \times Z'_2)$ orbifolding, where the unification scale becomes of order $10^{17}$ GeV. The dominant proton-decay mode is $p \rightarrow e^+\pi^0$ via the exchange of the $X, Y$ gauge bosons which have Kaluza-Klein masses. However, the $X, Y$ gauge bosons are too heavy for the proton decay to be observed at Super-Kamiokande. The constraints from the $b \rightarrow s\gamma, \mu \rightarrow e\gamma$ and electron and muon anomalous magnetic moments will also be discussed.

§2. $SU(5)$ GUT on $S^1/(Z_2 \times Z'_2)$

We here consider the simple extension of non-supersymmetric $SU(5)$ GUT which contains $\mathbf{5} + \overline{\mathbf{5}}, \mathbf{10} + \mathbf{10}' (\mathbf{15} + \overline{\mathbf{15}})$ and two $\mathbf{24}$ Higgs multiplets. Only for satisfaction of the gauge coupling unification and proton stability, this extension is just enough\textsuperscript{a}). We consider the case that the fifth dimensional coordinate ($= y$) is compactified on an $S^1/(Z_2 \times Z'_2)$ orbifold, with compactification radius $R^{\star\star}$. We take the $Z_2$ parity operator as $P = \text{diag}(1, 1, 1, 1, 1)$ and the $Z'_2$ parity operator as $P' = \text{diag}(-1, -1, -1, 1, 1)$ acting on a $\mathbf{5}$ representation in $SU(5)^{(2)\, 3)}$. Under the parity transformation of $(Z_2, Z'_2)$, bosonic fields which can propagate in five dimensions are divided into four-type of eigenstates according to the four-type of eigenvalues, $(\pm, \pm)^{2\, 3)}$.

Let us show the field contents in our model. The contents of fermions are the same as that of the ordinal $SU(5)$ GUT. We assume that chiral matter fermions cannot propagate in the bulk and are localized on the four dimensional wall at $y = 0$ $(\pi R)^{2\, 3)}$. The $\mathbf{5} + \overline{\mathbf{5}}$ Higgs fields as well as gauge bosons can exist in the bulk. Their gauge quantum numbers of the standard model, eigenvalues of $Z_2 \times Z'_2$ discrete symmetries, and mass spectra at the tree level are shown in Table I.

| rep. | 4d fields | quantum numbers | $Z_2 \times Z'_2$ parity | mass |
|------|-----------|-----------------|-------------------------|------|
| $24$ | $A^0_{\nu}^{(2n)}$ | $\{8, 1\} + \{1, 1\}$ | $(+, +)$ | $\frac{2\pi}{R}$ |
|      | $A^1_{\nu}^{(2n+1)}$ | $\{2, 3\} + \{3, 2\}$ | $(+, -)$ | $\frac{2n+1}{R}$ |
|      | $A^0_{\nu}^{(2n+2)}$ | $\{8, 1\} + \{1, 1\}$ | $(-, +)$ | $\frac{2n+2}{R}$ |
|      | $A^1_{\nu}^{(2n+1)}$ | $\{2, 3\} + \{3, 2\}$ | $(-, -)$ | $\frac{2n+1}{R}$ |
| $5$  | $\phi^0_{\xi}^{(2n+1)}$ | $\{3, 1\}$ | $(+, -)$ | $\frac{2\pi}{R}$ |
|      | $\phi^0_{\xi}^{(2n)}$ | $\{1, 2\}$ | $(+, +)$ | $\frac{2\pi}{R}$ |
| $\overline{5}$ | $\phi^0_{\xi}^{(2n)}$ | $\{3, 1\}$ | $(+, -)$ | $\frac{2n+1}{R}$ |
|      | $\phi^0_{\xi}^{(2n+1)}$ | $\{1, 2\}$ | $(+, +)$ | $\frac{2n}{R}$ |

Table I. The gauge quantum numbers of the standard model, eigenvalues of $Z_2 \times Z'_2$ discrete symmetries, and mass spectra at the tree level of gauge bosons and $\mathbf{5} + \overline{\mathbf{5}}$ Higgs scalars.

In addition to the above bosonic fields contained in the minimal $SU(5)$ GUT, we

\textsuperscript{a)} The gauge hierarchy problem, which means the weak scale masses of Higgs doublets are not stabilized by the radiative corrections, is not solved in our non-supersymmetric model.

\textsuperscript{**} The five dimensional supersymmetric standard model compactified on an $S^1/(Z_2 \times Z'_2)$ orbifold has been constructed in Refs.\textsuperscript{9).} There had been several works of the supersymmetry reduction by the compactification, for example, in Refs.\textsuperscript{10\, 11).} The extensions of the discrete symmetry and the gauge symmetry are also discussed in Refs.\textsuperscript{12\, 13),} respectively.
introduce additional scalar fields. We propose model I and II here. The model I has additional $10 + 10$ and two $24$ Higgs multiplets, and the model II contains additional $15 + 15$ and two $24$ Higgs multiplets. Their gauge quantum numbers of the standard model, eigenvalues of $Z_2 \times Z'_2$ discrete symmetries, and mass spectra at the tree level are shown in Table II. It suggests that only leptoquark fields $(3, 2) + (\bar{3}, 2)$, which are denoted by $Q$ and $\overline{Q}$, have the Kaluza-Klein zero mode in $10 + 10$ $(15 + 15)$ in the model I (II). Therefore, only $(Q + \overline{Q})$ in $10 + 10$ $(15 + 15)$ can survive in the low energy. As for the $24$ Higgs fields, $(8, 1) + (1, 3) + (1, 1)$ components in $(SU(3)_c, SU(2)_L)$ representation have Kaluza-Klein zero mode and survive in the low energy. The $24$ Higgs fields do not have Yukawa couplings with the matter fermions.

If there are no $24$ Higgs fields, the field content in the low energy is just the same as the model of Ref.\(^1\), since the light $Q$ and $\overline{Q}$ have Kaluza-Klein zero mode while other components in $10 + 10$ $(15 + 15)$ representation Higgs fields are super-heavy with Kaluza-Klein masses. This is the model in Ref.\(^2\). However, this field content suggests that the gauge couplings are unified at $(5.0 - 7.8) \times 10^{14}$ GeV\(^1\), which disagrees with the current proton-decay experiments\(^8\). Thus, we introduce two more additional $24$ Higgs fields, which make the unification scale higher.

We assume that $10 + 10, 15 + 15$ and two $24$ multiplets have a gauge invariant common mass $m_{\text{scalar}}$, for simplicity. The magnitude of $m_{\text{scalar}}$ must be larger than 1 TeV in order not to conflict with the experimental data of oblique corrections, $S$ and $T$ parameters\(^14\).

\section*{§3. Gauge Coupling Unification}

Now let us discuss the gauge coupling unification in our model following to the approach by Hall and Nomura\(^4\)\(^15\). We consider one loop renormalization group equation for the three gauge couplings. Three gauge couplings are unified at a unification scale $M_*$ with the unified gauge coupling $g_*$. After compactification, we need to consider threshold correction of Kaluza-Klein modes\(^4\). The running of

\begin{table}[h]
\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
Rep & Quantum numbers & $Z_2 \times Z'_2$ parity & mass \\
\hline
$10$ & $(3, 2)$ & $(+, +)$ & $\frac{2n+1}{N}$ \\
& $(\bar{3}, 1) + (1, 1)$ & $(+, -)$ & $\frac{2n+1}{N}$ \\
\hline
$10$ & $(3, 2)$ & $(+, +)$ & $\frac{2n+1}{N}$ \\
& $(3, 1) + (1, 1)$ & $(+, -)$ & $\frac{2n+1}{N}$ \\
\hline
$15$ & $(3, 2)$ & $(+, +)$ & $\frac{2n+1}{N}$ \\
& $(6, 1) + (1, 3)$ & $(+, -)$ & $\frac{2n+1}{N}$ \\
\hline
$15$ & $(3, 2)$ & $(+, +)$ & $\frac{2n+1}{N}$ \\
& $(\bar{6}, 1) + (1, 3)$ & $(+, -)$ & $\frac{2n+1}{N}$ \\
\hline
$24$ & $(8, 1) + (1, 3) + (1, 1)$ & $(+, +)$ & $\frac{2n+1}{N}$ \\
& $(3, 2) + (\bar{3}, 2)$ & $(+, -)$ & $\frac{2n+1}{N}$ \\
\hline
\end{tabular}
\end{center}
\caption{The gauge quantum numbers of the standard model, eigenvalues of $Z_2 \times Z'_2$ discrete symmetries, and mass spectra at the tree level of additional scalars.}
\end{table}
gauge coupling constants up to the one-loop level is given by

\[
\alpha_i^{-1}(m_Z) = \alpha_i^{-1}(M_*) + \frac{1}{2\pi} \left\{ \alpha_i \ln \frac{m_{\text{scalar}}}{m_Z} + \beta_i \ln \frac{M_*}{m_Z} + \gamma_i \sum_{n=1}^{N_i} \ln \frac{M_*}{2nM_c} \right. \\
+ \left. \delta_i \sum_{n=1}^{N_i} \ln \frac{M_*}{(2n-1)M_c} \right\},
\]

(3.1)

where \(M_c = R^{-1}\), and \(N_i\) represents the number of the Kaluza-Klein mode which can propagate in the bulk, satisfying \(M_* = 2N_iM_c\). The beta functions of \(\alpha_i, \beta_i,\) and \(\gamma_i\), which are common both in model I and II, are \((\alpha_1, \alpha_2, \alpha_3) = (-1/15, -7/3, -8/3),\)

\((\beta_1, \beta_2, \beta_3) = (64/15, -2/3, -13/3),\) and \((\gamma_1, \gamma_2, \gamma_3) = (4/15, -4, -22/3),\) where \(\alpha_i + \beta_i\) corresponds to the beta function in the standard model. \(\gamma_i\) is induced from Kaluza-Klein modes with \((+, +)\) and \((-,-),\) which have \(2n/R\) masses. The difference of beta functions between model I and II only appears in the values of \(\delta_i,\) since Kaluza-Klein modes with \((+, -)\) and \((-,+\)) parity contribute to \(\delta_i.\) Model I and II show \((\delta_1, \delta_2, \delta_3) = (-184/15, -8, -14/3),\) and \((\delta_1, \delta_2, \delta_3) = (-164/15, -20/3, -10/3),\) respectively.

By taking the suitable linear combination of gauge couplings\(^4)\) in Eq.(3.1), the following relation holds in both model I and II,

\[
5\alpha_1^{-1}(m_Z) - 3\alpha_2^{-1}(m_Z) - 2\alpha_3^{-1}(m_Z) = \frac{1}{2\pi} \left\{ 12 \ln \frac{m_{\text{scalar}}}{m_Z} + 32 \ln \frac{M_*}{m_Z} + 28 \sum_{n=1}^{N_i} \ln \frac{2n-1}{2n} \right\}. \tag{3.2}
\]

On the other hand, we can calculate the same linear combination of gauge couplings in the four dimensional two Higgs doublet model with two leptoquarks and two \((8, 1) + (1, 3) + (1, 1)\) scalars,

\[
5\alpha_1^{-1}(m_Z) - 3\alpha_2^{-1}(m_Z) - 2\alpha_3^{-1}(m_Z) = \frac{1}{2\pi} \left\{ 12 \ln \frac{m_{\text{scalar}}}{m_Z} + 32 \ln \frac{M_U}{m_Z} \right\}, \tag{3.3}
\]

where \(M_U\) is the four dimensional unification scale in such a model. Thus, the model I and II relate to the four dimensional model by

\[
\ln \frac{M_c}{m_Z} = \ln \frac{M_U}{m_Z} + \frac{7}{8} \sum_{n=1}^{N_i} \ln \frac{2n}{2n-1} - \ln(2N_i). \tag{3.4}
\]

We can see the correspondence between \(M_c\) and \(N_i\), since \(M_U\) is determined by the condition of gauge coupling unification.

Under the conditions that \(m_{\text{scalar}} = O(1)\) TeV, \(M_U \gtrsim 5 \times 10^{15}\) GeV, and \(\alpha_U^{-1} > 0\), the values of \(M_U\) and \(m_{\text{scalar}}\) are determined by the gauge coupling unification conditions as

\[
2.5 \times 10^{17}\text{GeV} \lesssim M_U \lesssim 5.2 \times 10^{17}\text{GeV}, \tag{3.5}
\]

\[
1.2 \text{ TeV} \lesssim m_{\text{scalar}} \lesssim 6.9 \text{ TeV}, \tag{3.6}
\]
within the experimental uncertainty of $\alpha_{s}$\textsuperscript{16}. When gravity propagates in the bulk, the four dimensional Planck scale ($M_{pl}$) is related to the five dimensional Planck scale ($M_{pl}^{(5)}$) as $M_{pl}^{(5)} \simeq (2M_{pl}^{2}M_{c}/\pi)^{1/3}$. We take $M_{c} < M_{pl}^{(5)}$, which suggests the number of Kaluza-Klein mode as $N_{i} \leq 3$. Then we can obtain the value of $M_{c}$ according to the number of $N_{i}$ as follows.

\[
\begin{align*}
N_{i} = 1: & \quad 2.3 \times 10^{17} \text{GeV} \lesssim M_{c} \lesssim 4.8 \times 10^{17} \text{GeV}, \\
N_{i} = 2: & \quad 1.5 \times 10^{17} \text{GeV} \lesssim M_{c} \lesssim 3.1 \times 10^{17} \text{GeV}, \\
N_{i} = 3: & \quad 1.2 \times 10^{17} \text{GeV} \lesssim M_{c} \lesssim 2.4 \times 10^{17} \text{GeV}.
\end{align*}
\] (3.7)

The proton-decay experiment at Super-Kamiokande shows the lower bound of $X, Y$ gauge boson mass as $M_{X} \gtrsim 5 \times 10^{15}$ GeV\textsuperscript{8}). Since the $X, Y$ bosons have the Kaluza-Klein masses as $M_{X} \sim M_{c}$ in this model, the above ranges in Eq.(3.7) satisfy the proton-decay constraint\textsuperscript{8}). Although the dominant proton-decay mode is $p \rightarrow e^{+}\pi^{0}$ via the exchange of the $X, Y$ gauge in this model, the $X, Y$ gauge bosons are too heavy for the proton decay to be observed at Super-Kamiokande.

\section*{§4. Phenomenological Constraints}

Let us show the phenomenological constraint in this model. In general, $Q$ and $\overline{Q}$ can couple to the quarks and leptons as

\[L = \lambda_{ij} d_{iR} l_{j} L Q + \lambda_{ij}^{d} d_{iR} l_{j} \overline{L} Q^{\dagger} + h.c.\] (4.1)

where $\lambda_{ij}$ and $\lambda_{ij}^{d}$ are unknown coupling constants dependent on the generation index $i$. The interactions in Eq.(4.1) contribute to $b \rightarrow s\gamma$, $\mu \rightarrow e\gamma$ processes and electron and muon anomalous magnetic moments. As for the neutron and electron electric dipole moments, the contribution from above interactions are negligible, since the corresponding one-loop diagrams are always proportional to $|\lambda_{ij}|^{2}$, $|\lambda_{ij}^{d}|^{2}$, or $\lambda_{ij}^{d} \lambda_{ij}^{\dagger}$+h.c., which are real. We must notice here that these interactions do not cause proton decay\textsuperscript{**}.

We consider only $|\lambda_{ij}|^{2}$ term here, since one-loop diagrams which are proportional to $|\lambda_{ij}^{d}|^{2}$ and $\lambda_{ij}^{d} \lambda_{ij}^{\dagger}$+h.c are the same order as $|\lambda_{ij}|^{2}$. At first we estimate the constraint from the $b \rightarrow s\gamma$ and $\mu \rightarrow e\gamma$ processes. The effective Lagrangian for $b \rightarrow s\gamma$ and $\mu \rightarrow e\gamma$ are given by

\[\mathcal{L}(b \rightarrow s\gamma) = \frac{-e}{16\pi^{2}} \lambda_{si}^{*} \lambda_{b_{i}^{*}} m_{b} \left(-Q_{Q} F \left(\frac{m_{b}^{2}}{m_{Q}^{2}}\right) + Q_{d} G \left(\frac{m_{b}^{2}}{m_{Q}^{2}}\right)\right) \overline{s}_{R} \sigma_{\mu\nu} b_{L} F^{\mu\nu},\] (4.2)

\[\mathcal{L}(\mu \rightarrow e\gamma) = \frac{-3e}{16\pi^{2}} \lambda_{\mu_{i}^{R}} \lambda_{\mu_{i}^{L}} \left(Q_{Q} F \left(\frac{m_{\mu}^{2}}{m_{Q}^{2}}\right) + Q_{d} G \left(\frac{m_{\mu}^{2}}{m_{Q}^{2}}\right)\right) \overline{\tau}_{L} \sigma_{\mu\nu} \tau_{R} F^{\mu\nu},\] (4.3)

\textsuperscript{**} We approximately take $\alpha_{U} \sim 35$ in the calculation of the life-time, $\tau_{b} \sim M_{X}^{2}/m_{b}^{2}/\alpha_{U}^{2}$.

\textsuperscript{**} The zero modes of 24 Higgs fields do not cause the proton-decay, too. It is because 24 Higgs fields cannot interact with the fermions.
where $m_\ell_i$ and $m_{d_i}$ denote the masses of the $i$-th generation charged lepton and down-type quark, respectively. $Q_Q$ is the electric charge of the leptoquark, and

\begin{align}
F(x) &= \frac{1}{6(1-x)^4}(1-6x+3x^2+2x^3-6x^2\ln x), \quad (4.4) \\
G(x) &= \frac{1}{6(1-x)^4}(2+3x-6x^2+x^3+6x\ln x). \quad (4.5)
\end{align}

Using Eq.(4.2) and (4.3), we can calculate the branching ratios of $b \to s\gamma$ and $\mu \to e\gamma$. For $b \to s\gamma$ we have taken into account the QCD corrections at the next-leading order \cite{17}. The current experimental values are $2 \times 10^{-4} \leq Br(b \to s\gamma)^{\text{exp}} \leq 4.5 \times 10^{-4}$ in Ref.~\cite{18} and $Br(\mu \to e\gamma)^{\text{exp}} \leq 1.2 \times 10^{-11}$ in Ref.~\cite{16}. In this model, $Br(b \to s\gamma)$ and $Br(\mu \to e\gamma)$ are given by

\begin{align}
Br(b \to s\gamma) &\sim 5.0 \times 10^{-9}|\lambda_{s\tau}^\dagger \lambda_{b\tau}|^2, \quad (4.6) \\
Br(\mu \to e\gamma) &\sim 2.1 \times 10^{-15}|\lambda_{eb}^\dagger \lambda_{\mu b}|^2, \quad (4.7)
\end{align}

respectively, where we take $m_Q \sim 1.2$ TeV for the numerical estimation. Even if coupling $\lambda_{s\tau}$, $\lambda_{eb}$ are of order one, the contribution to $Br(b \to s\gamma)$ and $Br(\mu \to e\gamma)$ are small compared to the experimental values.

Next, we estimate the constraints on the couplings from the electron and muon anomalous magnetic moment experiments. The charged lepton anomalous magnetic moments are given by

\begin{align}
\delta a_l &= -\frac{3}{16\pi^2} \left(\frac{m_l}{m_Q}\right)^2 |\lambda_{li}|^2 \left( Q_Q F \left( \frac{m_{d_i}^2}{m_Q^2} \right) + Q_d G \left( \frac{m_{d_i}^2}{m_Q^2} \right) \right). \quad (4.8)
\end{align}

From Eq.(4.8) the anomalous magnetic moments are given by

\begin{align}
\delta a_e &\sim -1.3 \times 10^{-19}|\lambda_{eb}|^2, \quad (4.9) \\
\delta a_\mu &\sim -5.6 \times 10^{-15}|\lambda_{\mu b}|^2, \quad (4.10)
\end{align}

for $m_Q \sim 1.2$ TeV. Notice that the contribution to the anomalous magnetic moments are always negative in this model. Comparing with the current experimental values are $\delta a_e^{\text{exp}} \simeq (31 \pm 23) \times 10^{-12}$ in Refs.~\cite{16}\cite{19} and $\delta a_\mu^{\text{exp}} = (42.6 \pm 16.5) \times 10^{-10}$ in Ref.~\cite{20}, the magnitudes of the anomalous moments are small even if the coupling $\lambda_{ib}$ is of order one. Since there are still sizable theoretical and experimental errors, this model is not excluded by the current experimental data$^*$. 

\section{Summary and Discussion}

We have suggested a simple grand unified theory where the fifth dimensional coordinate is compactified on an $S^1/(Z_2 \times Z_2')$ orbifold. This model contains not

$^*$ The current experiment of muon $g-2$ shows the positive deviation from the standard model \cite{20}. \n
only $10 + \bar{10} (15 + \bar{15})$ but also two 24 Higgs multiplets in the non-supersymmetric $SU(5)$ GUT. The gauge coupling unification is realized due to the mass splittings by $S^1/(\mathbb{Z}_2 \times \mathbb{Z}_2')$ orbifolding, where the unification scale is of order $10^{17}$ GeV. The dominant proton-decay mode is $p \rightarrow e^+\pi^0$ via the exchange of the $X, Y$ gauge bosons which have Kaluza-Klein masses. However, the $X, Y$ gauge bosons are too heavy for the proton decay to be observed at Super-Kamiokande. The constraints for the $b \rightarrow s\gamma$, $\mu \rightarrow e\gamma$ and electron and muon anomalous magnetic moments have been also discussed. The order one couplings between leptoquarks and quarks/leptons are consistent with the current experimental bounds.

Acknowledgment

We would like to thank Y. Kawamura and Y. Nomura for useful discussions. Research of KU is supported in part by the Japan Society for Promotion of Science under the Predoctoral Research Program. This work is supported in part by the Grant-in-Aid for Science Research, Ministry of Education, Science and Culture, Japan (No.12004276, No.12740146, No.13001292).

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