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Low Energy, Left-Right Symmetry Restoration in SO(N) GUTS

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LOW ENERGY, LEFT-RIGHT SYMMETRY
RESTORATION IN SO(N) GUTS

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Abstract

It is shown that a general n-step symmetry breaking pattern of SO(4K+2) down to $SU_C(3) \times SU_L(2) \times U_Y(1)$, which uses regular subgroups only, does not allow low-energy left-right symmetry restoration. In these theories, the smallest mass scale at which such restoration is possible is $\sim 10^9$ GeV as in the SO(10) case.

We also find that the unification mass in SO(4K+2) GUTS must be at least as large as that in SU(5). These results assume standard values of the Weinberg angle and strong coupling constant.
I. Introduction

The unification group SU(5) of Georgi and Glashow (1) is the smallest simple group which contains the low-energy gauge group G_{\text{WS}} = SU_C(3) \times SU_L(2) \times U_Y(1). Although the SU(5) model has been quite successful in some areas, it leaves some questions unanswered. One of these questions concerns the nature of parity violation. In the SU(5) model, left-right symmetry violation is intrinsic, that is, it is imposed at the outset. This is aesthetically unappealing and leads us to consider theories with spontaneously broken left-right symmetry. The simplest grand unified theory which is left-right symmetric is the SO(10) theory of Fritzsch and Minkowski (3) and Georgi (4). It contains the subgroup SO_{LR}(4) \cong SU_L(2) \times SU_R(2) under which the left-handed fermions transform as (2,1) and their charge conjugates transform as (1,2). Thus, as long as SO_{LR}(4) remains unbroken, left-right symmetry exists (for the phenomenology of SU_L(2) \times SU_R(2) \times U(1) theories, see ref. (5)). At what energy scale is SO_{LR}(4) a good symmetry? Using the method of Georgi, Quinn and Weinberg (6) and known values of the Weinberg angle, \Theta_W, and of the strong fine structure constant, \alpha_s, (both evaluated at M_W), it has been shown that SO_{LR}(4) symmetry can be restored only at energies larger than 10^9 GeV (7). The question we ask (and answer) in this paper is the following: can SO(4K+2) (K>2) (8) grand unification groups be found which exhibit low-energy (0(M_W)) left-right symmetry restoration? If we assume standard charge, color and weak Is-spin assignments for the fermions (9), that only regular subgroups (10) are allowed in the symmetry breaking pattern and that standard values of \sin^2 \Theta_W and \alpha_s are used, then we find that the answer is no. The lowest mass scale for left-right symmetry restoration is O(10^9 GeV) as in the SO(10) case. This result is, in a sense, akin to that of Dawson and Georgi (11) for SU(N) groups. They
show that under our assumptions, the unification mass in all such SU(N) models is the same as in the SU(5) case.

This paper is organised as follows: in Sec. II, we collect some general results on n-step symmetry breaking patterns. In Sec. III, we write down the most general symmetry breaking pattern of an SO(4K+2) group to G_{ws} through regular subgroups which could allow low-energy left-right symmetry restoration. Sec. IV uses the known ranges of values for \( \sin^2 \Theta_{w} \) and \( \alpha_{e}(M_{w}) \) to impose constraints on the left-right symmetry restoration mass scale in the symmetry breaking pattern of Sec. III. Sec. V summarizes our results and lists possible ways to evade the conclusions of our analysis.

II. N-Step Symmetry Breaking in General

Let G be the unification group. As previously stated, we assume standard charge, color and weak I-spin assignments for the fermions. As in ref. (12), we consider an N-step symmetry breaking pattern of G down to G_{ws} of the form:

\[
G \rightarrow G_{1}^{C} \times G_{1}^{F} \times U_{1}^{C}(1) \times U_{1}^{F}(1) \rightarrow \ldots \rightarrow G_{j}^{C} \times G_{j}^{F} \times G_{ws}^{C_{j}} \times G_{ws}^{F_{j}} \times U_{j}^{C}(1) \times U_{j}^{F}(1) \rightarrow \ldots \rightarrow G_{ws}
\]

(2.1)

In Eq (2.1), the superscript C (F) indicates that the non-abelian group

\( G_{j}^{C} \) (\( G_{j}^{F} \)) (\( j = 1 \ldots N \)) contains SU_{C}(3) (SU_{L}(2)). We also have

\[
G_{j}^{(r)} \supseteq G_{j}^{(r)} \times U_{j}^{(r)}(1), \quad j = 2, \ldots, N, \quad r = C \text{ or } F,
\]

(2.2a)

with
In Eq (2.2b), $Y$ denotes the hypercharge operator of the Weinberg-Salam theory.

Thus, in Eq (2.1), the unification mass (at which color and flavor are first separated) is $M_1$ and the weak $I$-spin mass scale is $M_w = M_{N+1}$.

Next, we use the renormalization group equations (13) for the various gauge couplings to obtain equations for $\alpha_s(M_w^2), \alpha_T(M_w^2)$ ($\alpha_s = \frac{g_s^2}{4\pi}, \alpha_I = \frac{g_I^2}{4\pi}$), where $g_s$ and $g_I$ are the gauge couplings of the groups SU$_C(3)$ and SU$_L(2)$ respectively) in terms of the intermediate mass scales in Eq (2.1). Following ref. (12), we define

$$A^2 = \frac{Tr(Y^2)}{Tr(I_3^2)},$$

$$\Gamma = \frac{6\alpha_\epsilon^{-1}}{11} \left[ 1 - (1 + A^2) \sin^2 \theta_w \right],$$

$$\Lambda = \frac{6\alpha_\epsilon^{-1}}{11} \left[ \sin^2 \theta_w - \frac{\alpha_\epsilon}{\alpha_s} \right],$$

$$x_i = \ln \frac{M_i}{M_{i+1}} \quad i=1, \ldots, N,$$

where $\alpha_\epsilon$ is the electromagnetic fine structure constant, $I_3$ is the diagonal generator of SU$_L(2)$,

$$\sin^2 \theta_w = \frac{\alpha_\epsilon}{\alpha_I},$$

and all coupling constants are evaluated at $Q^2 = (2M_w)^2$. For standard charge assignments, $A^2$ is given by its value in the SU(5) model, i.e.

$$A^2 = \frac{5}{3}.$$  

Using the results of ref. (12), we may write:
\[
\Gamma = \sum_{j=1}^{N} a_j x_j \tag{2.6a}
\]
\[
\Lambda = \sum_{j=1}^{N} b_j x_j, \tag{2.6b}
\]

where

\[
a_j \equiv c_j^F (A^2 - [N_j^F]^2) - c_j^C [N_j^C]^2 \tag{2.7a}
\]
\[
b_j \equiv c_j^C - c_j^F. \tag{2.7b}
\]

Here, \(c_j^r\), \([N_j^r]^2\) (\(r = C\) or \(F\)) are the eigenvalue of the second Casimir operator acting on the adjoint representation of \(G^r_j\) and the embedding coefficient of the hypercharge \(Y\) into \(G^r_j\), respectively. \([N_j^r]^2\) is a measure of the fraction of generators of \(G^r_j\) which go into the makeup of \(Y\).

If we write

\[
Y = Y^r_j + Y^-, \tag{2.8}
\]

with \(Y^r_j\) (\(Y^-\)) contained (not contained) in \(G^r_j\), then

\[
[N_j^r]^2 \equiv \frac{\text{Tr} \left[ (Y^r_j)^2 \right]}{\text{Tr} \left[ I_3^2 \right]}, \tag{2.9}
\]

The formalism of Appendix B of ref. (12) gives a straightforward way of calculating \([N_j^r]^2\) for any group (for the SU(N) case, these may be found in ref. (11) and ref. (14). We list the values of \(c_j^r\) and \([N_j^r]^2\) below:

\[
C_j^r = \begin{cases} 
N & G_j^r \equiv \text{SU}(N) \\
N-2 & G_j^r \equiv \text{SO}(N) \\
0 & G_j^r \equiv \text{U}(1),
\end{cases} \tag{2.10a}
\]
Using Eqs (2.10a,b), we evaluate $a_j$, $b_j$ of Eqs (2.7a,b) for the intermediate subgroups which will be relevant to later discussions. Let $K_i$ denote the intermediate symmetry group which is unbroken at the $i$th-step of symmetry breaking. Then we have:

$$a_j = -\frac{2}{3} \Delta_j, \quad b_j = \Delta_j \text{ if } K_j \cong SO_C(n_j) \times SO_F(m_j)$$

(2.11a)

$$a_j = -\frac{2}{3} \Delta_j + \frac{2}{3}, \quad b_j = \Delta_j + 2 \text{ if } K_j \cong SU_C(n_j) \times SO_F(m_j) \times U^C_j(1)$$

(2.11b)

$$a_j = -\frac{2}{3} \Delta_j + \frac{10}{3}, \quad b_j = \Delta_j - 2 \text{ if } K_j \cong SO_C(n_j) \times SU_F(m_j) \times U^F_j(1)$$

(2.11c)

$$a_j = -\frac{2}{3} \Delta_j + 4, \quad b_j = \Delta_j \text{ if } K_j \cong SU_C(n_j) \times SU_F(m_j) \times U^C_j(1) \times U^F_j(1),$$

(2.11d)

where

$$\Delta_j \equiv n_j - m_j.$$  

(2.12)

III. $N$-step Symmetry Breaking for $SO(4k+2)$

We now let $G = SO(4k+2)$ and consider an $N$-step symmetry breaking pattern of $G$ down to $G_{WS}$, subject to the constraint that only regular subgroups of $G$ be allowed to appear. From Dynkin(15), we see that the subgroups $G_j(r)$ can only be of the form $SO(2\ell)$, $SU(\ell)$ ($\ell \leq 2k+1$). This constraint also implies that once an $SO(2\ell)$ group has broken down to an $SU(m)$ subgroup, this $SU(m)$ can only break down into subgroups of the form $SU(n_1) \times SU(n_2) \times U(1)$ ($n_1 + n_2 \leq m$).

We consider the following symmetry breaking pattern:
\[ M = \text{SO}_c(n_{a-1}) \times \text{SO}_f(m_1) + \ldots + \text{SO}_c(n_{a-1}) \times \text{SO}_f(m_{a-1}) + M_a \text{SU}_c(n_a) \times \text{SO}_f(m_a) \times U^c(1) \]

\[ + \ldots + \text{SU}_c(n_{a-1}) \times \text{SO}_f(m_{a-1}) + \Pi \text{SU}_c(n_a) \times \text{SU}_f(m_a) \times U^c(1) \]

For this pattern, Eqs (2.6a, b) become:

\[ \Gamma = -\frac{2}{3} \sum_{i=1}^{N-1} \Delta_i x_i + \frac{2}{3} \sum_{i=\alpha}^{\beta-1} x_i + 4 \sum_{i=\beta}^{N-1} x_i + \frac{10}{3} x_N \]  \hspace{1cm} (3.2a)

\[ \Lambda = \sum_{i=1}^{N-1} \Delta_i x_i + 2 \sum_{i=\alpha}^{\beta-1} x_i + x_N, \]  \hspace{1cm} (3.2b)

where \( \Delta_i \) is defined as in Eq (2.12)(16). The relevant quantity in our analysis will be \( \Omega \), defined by:

\[ \Omega = \frac{1}{4} \left[ \Gamma + \frac{2}{3} \Lambda \right] = \frac{6 \alpha e - 1}{11} \frac{1}{4} \left[ 1 - 2 \sin^2 \theta_w - \frac{2}{3} \frac{\alpha e}{\alpha s} \right], \]  \hspace{1cm} (3.3)

where all couplings are evaluated at \( Q^2 = (2M_w)^2 \). Dawson and Georgi(11) have shown that if \( M_G \) denotes the unification mass in the \( G = \text{SU}(N) \) case, then

\[ \Omega = \frac{\ln M_G}{M_w} \]  \hspace{1cm} (3.4)

From Eqs (3.2a, b) we find(17)

\[ \Omega = \sum_{i=\beta}^{N} x_i + \frac{1}{2} \sum_{i=\alpha}^{\beta-1} x_i. \]  \hspace{1cm} (3.5)

If we set

\[ x_i = 0 \quad i = 1, \ldots, \beta - 1, \]  \hspace{1cm} (3.6)
then only groups of the form

\[ \text{SU}_C(n_J) \times \text{SU}_F(m_J) \times \Pi \left[ \text{U}_A^C(1) \times \text{U}_A^F(1) \right] \]  

(3.7)
can appear in Eq (3.1). The unification mass \( M_u \) is given by

\[
\ln \frac{M_u}{M_w} = \sum_{i=\beta}^{N} x_i = \Omega, 
\]  

(3.8)

which is the SU(N) result stated above. That this should be the case can be seen by realizing that all subgroups of the form in Eq (3.7) are contained within the SU(2K+1) subgroup of SO(4K+2). Thus, the fact that they are also embedded in SO(4K+2) becomes irrelevant.

IV. Constraints on Mass Scales

We now proceed to find constraints on some of the intermediate mass scales appearing in Eq (3.1). We are especially interested in constraints on \( M_B \), the scale at which the flavor group changes from an orthogonal group to a unitary one. This change signals the breakdown of left-right symmetry amongst the fermions since \( \text{SO}_F(m) \) treats both particles and their charge conjugates in an identical fashion. Thus, it is at \( M_B \) that the flavor interactions become left-handed.

We shall use values of \( \sin^2 \theta_w(M_u) \) and \( \alpha^{-1}_e(M_u) \) in the ranges \(^{(18)}\)

\[
\sin^2 \theta_w(M_u) = 0.19 - 0.24 \quad (4.1a) \\
\alpha^{-1}_e(M_u) = 7.5 - 9.3 \quad (4.1b)
\]

We shall also take \( \alpha^{-1}_e(M_u) \) to be \(^{(18)}\)
\[ a_e^{-1}(M_w) = 128.5. \]  

(4.2)

The quantity that we are interested in is

\[ \frac{M_\beta}{M_w} = \sum_{i=1}^{N} x_i \equiv \phi \]  

(4.3)

Since all the \( x_i \) (\( i=1, \ldots, N \)) are non-negative, we may use Eq (3.5) to find the crude bound:

\[ \phi \leq \Omega, \]  

(4.4)

with equality if and only if all \( x_i \) (\( i=\alpha, \ldots, \beta-1 \)) vanish. In this case only groups of the form \( \text{SO}_C(n_1) \times \text{SO}_F(m_1) \) appear in Eq (3.1). Since we have the bound

\[ \Omega \geq 28 \]  

for \( \sin^2 \theta_w \) and \( a_e^{-1} \) as in Eqs (4.1a, b), this implies that when \( x_i \) (\( i=\alpha, \ldots, \beta-1 \)) vanish, left-right symmetry can only be restored for \( M_\beta \geq 10^{14} \text{ GeV} \). This would also imply that the unification mass, \( M_1 \), of Eq (3.1) could be larger than \( 10^{14-15} \text{ GeV} \). This result agrees with those found in ref. (19) where the two-step case

\[ \text{SO}(N) \rightarrow ^{1}_1 \text{SO}_C(n_1) \times \text{SO}_F(m_1) \rightarrow ^2 \text{G}_{\chi_8} \]  

is treated.

We can find a better bound on \( \phi \) as follows: from Eq (3.5), we have

\[ \phi + \sum_{i=\alpha}^{\beta-1} x_i = \Omega. \]  

(4.7)

Let us compute \( \ln \frac{M_1}{M_\beta} \):
Using Eq (4.3), we find
\[ \ln \frac{M_a}{M_B} = \ln M_a + \ln M_B = 2 \Omega - \phi + x_\beta \geq 2 \Omega - \phi, \]  
(4.9)

since \( x_\beta \geq 0 \). If we now make the reasonable assumption that the unification mass, \( M_1 \), must be less than the Planck mass \( M_P \sim 10^{19} \) GeV \( \sim 10^{17} M_w \), we arrive at the constraint:

\[ \ln \frac{M_P}{M_w} > 39 \geq \sum_{i=1}^{N} x_i \geq \sum_{i=1}^{N} x_1 = \ln \frac{M_a}{M_w} \geq 2 \Omega - \phi, \]  
(4.10a)

or
\[ \phi \geq 2 \Omega - 39 \geq 17, \]  
(4.10b)

or
\[ M_\beta > 10^9 \text{ GeV}, \]  
(4.10c)

where Eq (4.5) was used in Eq (4.10b). Thus we see that the pattern of Eq (3.1) does not allow low-energy left-right symmetry restoration. Since the pattern of Eq (3.1) is the most general one (subject to our earlier constraints) which could give rise to low-energy left-right symmetry restoration, we must conclude that this phenomenon is not compatible with our assumptions.

We may extract one more piece of information from this analysis; using Eqs (4.4, 4.9), we find that
\[ \ln \frac{M_a}{M_w} > \Omega \]  
(4.11)

This implies that the unification mass for the pattern of Eq (3.1) can in general be no smaller than \( 10^{14-15} \) GeV.
V. Conclusions

Given our assumptions on the assignment of fermion quantum numbers, the form of the symmetry breaking pattern of \( \text{SO}(4K+2) \) down to \( \text{G}_{ws} \) and the values of \( \sin^2 \theta_w \) and \( a_s^{-1} \), the mass scale at which left-right symmetry restoration occurs must be \( \gtrsim 10^9 \) GeV. In this respect, the general \( \text{SO}(4K+2) \) case and the \( \text{SO}(10) \) case are identical. If we want left-right symmetry to be restored at energies of the order of \( M_w \), we must relax some of the assumptions made here. The possibilities are as follows:

1. We may allow non-standard assignment of fermion quantum numbers. In ref. (12,20), an \( \text{SO}(14) \) based GUT, with non-standard charge assignments is examined. In this theory, renormalization group arguments allow the appearance of \( \text{SO}_{LR}(4) \) at mass scales
   \( M_\beta \) such that \( 3M_w \lesssim M_\beta \lesssim 10^2 M_w \).

2. We can argue that \( \sin^2 \theta_w(M_w) \), \( a_s^{-1}(M_w) \) do not have to lie in the ranges given in Eqs(4.1a,b). Rizzo and Senjanović(21) have argued that \( \sin^2 \theta_w \) may be as large as 0.27-0.31, when right handed current effects are taken into account. This would then allow \( M_\beta \) to be \( O(M_w) \).

3. Non-regular subgroups of \( \text{SO}(4K+2) \) could be allowed in the symmetry breaking pattern(22). This possibility will be treated in a later work.

\footnote{\textbf{Higgs boson effects in the renormalization group equations (see ref (23)).}}

\textbf{Include Higgs boson effects in the renormalization group equations (see ref (23)).}
We also found that unification mass scale in the SO(4K+2) theories has to be at least as large as that in SU(5). If proton decay is not seen in the near future, it may be because Nature prefers an SO(4K+2) unification group.

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References and Footnotes


2. If all particles are left-handed, this is equivalent to charge conjugation symmetry.


8. SO(4K+2) (K≥2) is used since only these have fermion representations compatible with the requirements of anomaly freedom, complexity with respect to SUc(3) x SU_L(2) x U_Y(1), having only 1, 3, \bar{3}'s of color, irreducibility and the ability to contain more than one fermion generation.
9. This means that only $\frac{1}{3}, \frac{2}{3}, \frac{3}{3}$ of $SU_C(3)$, $1, 2$ of $SU_L(2)$ and quarks with charges $Q = -\frac{1}{3}, +\frac{2}{3}$, leptons with charges $Q = -1, 0$ are allowed.

10. Regular subgroups have as generators subsets of the generators of the unification group. Non-regular subgroups have non-trivial linear combinations of these generators as their generators.


16. This result is true for any group $G$ that breaks down as in Eq (3.1).

17. This is also the result for $\Omega$ in a symmetry breaking pattern where $SO_F(m_j) \rightarrow SU_F(m_{j+1}) \times U^F_{j+1}(1)$ before $SO_C(n_k) \rightarrow SU_C(n_{k+1}) \times U^C_{k+1}(1)$. 


22. Our results are also true if the $n$-regular SO(2$\ell$+1) subgroups of SO(4$K$+2) are used.