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AN OASIS IN THE DESERT: WEAKLY BROKEN PARITY IN GRAND UNIFIED THEORIES†

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1. INTRODUCTION

Grand unified theories[1] offer us a possible way of unifying the interactions between elementary particles (except for gravity). They suggest, as a by-product, a spectacular prediction: the decay of matter, with hopefully soon measurable proton lifetime. The basic feature, at least of the simplest of such theories, appears to be the desert in energies above the mass scale of weak bosons. The minimal model, based on the SU(5) gauge group predicts the desert all the way up to 10^{14} GeV. Namely, a necessary chain of symmetry breaking is

$$SU(5) \xrightarrow[M_X]{} SU(2)_L \times U(1)_Y \times SU(3)_c \xrightarrow[M_W]{} U(1)_{em} \times SU(3)$$

where M_X corresponds to the mass of superheavy bosons which mediate baryon-number violating forces and are responsible for nucleon decay. The values of low-energy parameters α_s, and $\sin^2 \theta_W$ determine[2] $M_X \approx 10^{14}$-10^{15} GeV. In turn, one can predict the proton lifetime[3] as $\tau_p \approx 10^{31\pm1}$ years.

Actually, the above picture seems to be qualitatively true in many other grand unified models. Namely, if the value of $\sin^2 \theta_W = 0.23 \pm 0.02$, suggested by the standard electroweak model, and α_s (the QCD coupling constant) are taken in inputs, the Georgi-Quinn-Weinberg (GQW) program[2], which determines the mass scales by the use of renormalization group equations, tends to suggest that the intermediate mass scales have to be quite large ($\gtrsim 10^6$-10^9 GeV), leading again to a practical equivalent of the desert. If that is so, the future accelerators should not discover any new forms of interactions, once W and Z bosons are found!(?).

In this talk I will discuss some recent work of Rizzo and myself[4], which offers a way of avoiding such a situation, by suggesting an oasis in the desert, just above M_W. Our task appeared to be twofold: first, to find an alternative to the standard $SU(2)_L \times U(1)_Y$ model[5] (in order to change the $\sin^2 \theta_W = 0.23$ prediction) with a new energy threshold above M_W; and second, to show that such a scheme is consistent with grand unification. I will now try to offer arguments in favour of such a low intermediate mass scale.

The first part of our program was simplified by the fact that we did not have to search for a new candidate for a low-energy electroweak theory. A number of years ago, Pati, Salam, Mohapatra and myself[6] constructed a left-right symmetric gauge theory, based on the $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ group, in order to explain parity violation in weak interactions. The theory starts by being invariant under parity conjugation and only through non invariance of the vacuum, which results in heavy right-handed gauge bosons, parity gets broken and V + A interactions become suppressed at low energies. However, at higher energies, above M_{W_R}, parity is expected to gradually become a good symmetry. It is therefore important to find constraints, phenomenological or theoretical and preferably both, on M_{W_R}. Now, phenomenological analysis which I will describe below, allows W_R to be surprisingly light: $M_{W_R} \gtrsim 2\, M_{W_L}$. The hint on its value comes, on the other hand, from unification constraints. For example, $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ can be embedded in SO(10). As I mentioned before, assuming $\sin^2 \theta_W \simeq 0.23$ gives $M_{W_R} \gtrsim 10^9$ GeV, which would eliminate the possibility of direct parity restoration.

Fortunately, the above is not true. The analysis of Rizzo and myself[4] shows that for light W_R the theory successfully passes all the low energy tests, but for larger values of $\sin^2 \theta_w$: $\sin^2 \theta_w = 0.27$–0.28. Since the existence of low intermediate mass scale tends to increase $\sin^2 \theta_w$, it enabled us to construct an SO(10) grand unified theory with rather low-energy parity restoration: $M_{W_R} = (2\text{–}3) M_{W_L}$. <u>There may be an oasis in the desert!</u>

I will only list the predictions of the model and then deal with them in subsequent sections:

- $M_{W_R} \simeq (150\text{–}250)$ GeV, $\sin^2 \theta_w = 0.27$–0.28,
- $M_{W_L} \simeq (70\text{–}72)$ GeV, $M_z \simeq (80\text{–}84)$ GeV,
- a rather stable proton (in the model with minimal Higgs assignment): $\tau_p \gtrsim 10^{38}$ years,
- appreciable lepton number violation in neutrino — less double β decay[7] (not discussed here).

The rest of this paper is then organized in the following manner: in Section 2 I review the left-right symmetric model, with special emphasis on the leptonic (neutrino) sector. There I discuss the phenomenological constraints on our model. Section 3 deals with the embedding of the model in SO(10) and unification constraints that result from the GQW program, and also briefly touches upon baryon creation in the early universe in this kind of theory. Finally, Section 4 summarizes the basic features discussed in this talk.

2. LEFT-RIGHT SYMMETRY

The minimal gauge group which incorporates left-right symmetry is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. The theory is assumed to be invariant under parity conjugation. That results in

- $g_L = g_R \equiv g$, where g_L and g_R are $SU(2)_L$ and $SU(2)_R$ coupling constants;
- the fermionic sector consists of left- and right-handed doublets

$$\psi_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L , \quad \psi_R = \begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L , \quad Q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R \tag{2.1}$$

  where we restrict ourselves to one generation case, the general case being a trivial extension;
- from Eq. (2.1), electric charge is

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2} \tag{2.2}$$

- the Higgs sector has to be fully left-right symmetric.

In the following, I will discuss the version of the theory recently suggested by Mohapatra and myself[7] in order to understand the smallness of neutrino mass by tying it to the maximality of parity violation at low energies. The Higgs sector complies with the principles of simplicity and the possibility of dynamical symmetry-breaking, i.e. the scalar fields carry the quantum numbers of fermionic bilinears.

$$\phi\left(\tfrac{1}{2},\tfrac{1}{2},0\right) \sim \bar{\psi}_L\,\psi_R$$

$$\Delta_L(1,0,2) \sim \psi_L^T C\,\psi_L \quad ; \quad \Delta_R(0,1,2) \sim \psi_R^T C\,\psi_R \tag{2.3}$$

where the representation content in the brackets corresponds to $SU(2)_L$, $SU(2)_R$ and B-L, respectively. The field ϕ gives the masses to charged fermions and Δ's complete the symmetry breaking, and as we shall see, they play a major role in the question of neutrino mass.

Now, the symmetric potential allows for the asymmetric absolute minimum[6,7]

$$\langle\Delta_R\rangle \gg \langle\phi\rangle \quad , \quad \langle\Delta_L\rangle = \gamma\,\frac{\langle\phi\rangle^2}{\langle\Delta_R\rangle} \tag{2.4}$$

where γ is a ratio of various Higgs self-couplings. In turn one obtains the following set of gauge mesons (besides the photon)

$$W_L^{\pm}\ ,\ W_R^{\pm}\ ,\ Z_1,\ Z_2 \tag{2.5}$$

with

$$\begin{aligned} M_{W_L}^2 &= g^2\langle\phi\rangle^2 & M_{W_R}^2 &= g^2\langle\Delta_R\rangle^2 \\ M_{Z_1}^2 &\simeq \frac{M_{W_L}^2}{\cos^2\theta_W} & M_{Z_2}^2 &\simeq 2\,\frac{\cos^2\theta_W}{\cos 2\theta_W}\,M_{W_R}^2 \end{aligned} \tag{2.6}$$

where we ignore tiny W_L-W_R mixing and $\tan^2\theta_w \equiv g'^2/g^2+g'^2$, so that $e^2 = g^2\sin^2\theta_w$ as in the standard model. Therefore, besides the usual gauge bosons W_L and Z_1 [W and Z in $SU(2)_L \times U(1)$], we have heavier bosons W_R and Z_2, whose presence could effect low-energy predictions. In short, we have the following picture of symmetry breaking

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow[\langle\Delta_R\rangle \simeq M_{W_R}]{} SU(2)_L \times U(1)_Y \xrightarrow[\langle\phi\rangle \simeq M_{W_L}]{} U(1)_{em}$$

Neutrinos

The charged fermions get their masses in the usual way; however, the situation with neutrinos is worth discussing. What happens is the following[7]: since Δ's have the right quantum numbers to couple to $\psi^T C \psi$ terms, the right-handed and left-handed neutrinos are separately two-component Majorana massive spinors. Actually, the right-handed neutrino $\nu_R \equiv N$ becomes a heavy neutral lepton[8] with

$$m_N \simeq \langle \Delta_R \rangle \gtrsim 100 \text{ GeV} \tag{2.7}$$

The left-handed neutrino ($\nu_L \equiv \nu$), in turn, picks up a small Majorana mass

$$m_\nu \propto \frac{1}{m_N} \tag{2.8}$$

Therefore, the smallness of neutrino mass gets tied up to the maximality of observed parity violation in weak interactions. In the V - A limit of the theory, i.e. infinite M_{W_R}, $m_N \approx |\langle \Delta_R \rangle| \to \infty$; so that m_ν vanishes.

In the case when $|\langle \Delta_L \rangle|$ is not directly contributing to neutrino mass, one gets

$$m_\nu = \frac{m_f^2}{m_N} \quad , \tag{2.9}$$

when f = electron or up quark. Therefore, we shall assume in further discussion $|\langle \Delta_L \rangle| = 0$, since it appears a phenomenological necessity [in other words, I put $\gamma = 0$ in Eq. (2.4)]. Actually $\gamma \lesssim 10^{-10}$, to ensure small m_{ν_e}. I should add, though, that once γ is small, the ν_μ and ν_τ masses are predicted by Eq. (2.9).

The above result is not accidental. From Eq. (2.2), in the energy region $M_{W_L} < E < M_{W_R}$

$$\Delta Q = 0, \quad \Delta I_{3L} \simeq 0 \tag{2.10}$$

and so[9]

$$\Delta(B-L) \simeq -2\,\Delta I_{3R} \tag{2.11}$$

The breaking of B-L is proportional to the amount of parity violation[7,9], hence one gets massive Majorana ν_R.

Phenomenology

i) Charged current processes

We just demonstrated: $m_{\nu_R} \approx M_{W_R}$. The exchange of W_R does not contribute then to μ and β decay, and so we have no sensible limit on M_{W_R} from these processes. In other words, the world at low energies is V - A not because $M_{W_R} >> M_{W_L}$, but because the right-handed neutrino is very heavy[7].

ii) Neutral current processes

Fortunately, as is seen from Eq. (2.6), the masses of W_R and Z_2 are tied up, so that the constraints on M_{Z_2} from neutral-current data can be used to put the limit on M_{W_R}.

There are only two relevant types of processes:

A. Neutrino interactions,

B. Parity violation in e-q scattering.

We now give the relevant effective low q^2 neutral current Hamiltonians, ignoring as before W_L-W_R mixing and setting $\langle\Delta_L\rangle = 0$. For a general case the reader should consult an original work[4].

A. Neutrino scattering

$$H^{\nu} = \frac{G_F}{\sqrt{2}} \bar{\nu} \gamma_\mu (1+\gamma_5) \nu \, \bar{f} \gamma^\mu (g_V + g_A \gamma_5) f$$

where f denotes charged fermions (for leptons, we consider only $\nu_\mu e$ scattering)

$$g_V = (1 + \eta_R)\left[T_3 - 2Q \sin^2\theta_W\right]$$
$$g_A = T_3 \tag{2.12}$$

and η_R is defined through

$$\frac{M_{W_L}^2}{M_{W_R}^2} = \frac{\eta_R}{1+\eta_R} \tag{2.13}$$

It is easily seen from Eq. (2.12) that the effect of η_R is to increase $\sin^2\theta_W$ relative to the standard model prediction.

B. Parity-violating electron-quark scattering

In the above limit

$$H_{pv} = H_{pv}\,(\text{standard model}) \tag{2.14}$$

Now, the SLAC experiment by itself (i.e. without constraints from ν-hadron scattering) does not restrict $\sin^2\theta_w$ very precisely. It turns out that the data are consistently described with η_R as large as 0.3 (M_{W_R} = 150 GeV), if $\sin^2\theta_w$ = = 0.27-0.28 (of course, as well as $\eta_R = 0$, $\sin^2\theta_w = 0.23 \pm 0.02$, as in the standard model). The large predictions for $\sin^2\theta_w$ will turn out to be crucial in achieving the consistent unification conditions.

In any case, it is worth keeping in mind that independently of grand unification, the correct electroweak gauge theory may substantially differ from the standard $SU(2)_L \times U(1)_Y$ model, with the differences that would make dramatic changes at at higher energies.

For the sake of completeness, I have included Table 1 which gives the values of gauge boson masses as functions of $\sin^2\theta_w$ and η_R.

3. SO(10) AND WEAKLY BROKEN PARITY

As I emphasized before, we need unification constraints or otherwise M_{W_R} remains an arbitrary parameter with $M_{W_R} \geq 150$ GeV. A minimal left-right symmetric grand unified theory is based on the SO(10) group[10]. SO(10) has rank five and it contains the $SU(2)_L \times SU(2)_R \times SU(4)_c$ group of Pati and Salam[1].

Since it also contains SU(5), we can imagine two basically different chains of symmetry breaking:

i) $$SO(10) \xrightarrow[M_U]{} SU(5) \xrightarrow[M_X]{} SU(2)_L \times U(1)_Y \times SU(3)_c \xrightarrow[M_W]{} U(1)_{em} \times SU(3)_c$$

ii) $$SO(10) \xrightarrow[M_X]{} SU(2)_L \times SU(2)_R \times SU(4)_c \xrightarrow[M_c]{} SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU($$

$$\xrightarrow[M_R]{} SU(2)_L \times U(1)_Y \times SU(3)_c \xrightarrow[M_W]{} U(1)_{em} \times SU(3)_c$$

We now discuss the physics of both possibilities.

i) In this case the situation is analogous to the SU(5) model. Namely, $M_U \geq M_x$ and $M_x \simeq 10^{14}$ GeV (see below). We have a desert, with the proton lifetime $\tau_p \simeq (\tau_p)_{SU(5)} \simeq 10^{31\pm1}$ years. The only difference is in the neutrino sector, where left-handed and right-handed neutrinos are massive Majorana spinors. Particularly interesting is the minimal SO(10) model, where $m_N = 10^9$ GeV appears in higher orders in perturbation theory[11] and $m_{\nu_\tau} \simeq 10$ eV. It is amusing to notice that 10 eV heavy neutrinos could play a major cosmological role by closing up the universe and possibly explaining the dark matter in galactic halos[12].

ii) This chain of symmetry breaking is more interesting, since it allows, at least in principle, the existence of intermediate mass scales. The way to arrive at their values is to follow the change of physical coupling constants with energy [GQW program[2]]. We shall set for simplicity $M_c = M_x$, since, in any case, M_c has to be astronomically large[13]: $M_c \geq 10^{12}$ GeV.

The idea of the GQW program is very simple: the change of coupling constants with energy is given by the renormalization group equation for the SU(N) coupling constant

$$\frac{dg_N}{dt} = b_N\, g_N^3 \tag{3.1}$$

with

$$b_N = -\frac{1}{16\pi^2}\left[\frac{11}{3}N - \frac{4}{3}\sum_F T_F(R) - \frac{1}{6}\sum_S T_s(R)\right] \tag{3.2}$$

where the first term denotes the gauge meson contributions and the second and third terms stand for fermionic and Higgs contributions, respectively. The definition of T(R) is

$$\mathrm{Tr}\, I_a I_b \equiv T(R)\, \delta_{ab} \tag{3.3}$$

where I_a are the group generators for representation R. It is important to notice that $T_s(R)$ is obtained for real Higgs fields; for complex representation the contribution to $T_s(R)$ should be doubled.

Using the decoupling theorem[14] of Appelquist and Carrazone, one can separately treat strong coupling constant g_s, $SU(2)_L$ coupling g_L and $U(1)_Y$ coupling $g_Y = \sqrt{5/3}\, g'$, where

$$\frac{1}{e^2} = \frac{1}{g_L^2} + \frac{1}{g'^2} \tag{3.4}$$

We skip the details of derivations, which can be found in Ref. 4, and give the final expressions for physical parameters α_s and $\sin^2\theta_w$ at $E = M_W$

$$1 - \frac{8}{3}\frac{\alpha(M_W)}{\alpha_s(M_W)} = \frac{11\,\alpha(M_W)}{3\pi}\left[\left(3 + \frac{T_L + \frac{5}{3}T_Y}{44}\right)\ln\frac{M_X}{M_W} - \left(1 - \frac{T_R + \frac{2}{3}T_{BL} - \frac{5}{3}T_Y}{44}\right)\ln\frac{M_X}{M_R}\right]$$

$$\sin^2\theta_W(M_W) = \frac{3}{8} - \frac{11\,\alpha}{3\pi}\left[\frac{5}{8}\left(1 - \frac{T_L - T_Y}{44}\right)\ln\frac{M_X}{M_W} - \frac{3}{8}\left(1 - \frac{T_R + \frac{2}{3}T_{BL} - \frac{5}{3}T_Y}{44}\right)\ln\frac{M_X}{M_R}\right] \tag{3.5}$$

where $\alpha(M_W) = 1/128$ is the electromagnetic coupling[15] at $E = M_W$ and T's stand for Higgs boson contributions to β functions (in obvious notation) of g_L, g_R, g_{BL} and g_Y couplings.

The first term in both Eqs. (3.5) corresponds to the SU(5) case, i.e. the case of no intermediate mass scales. The effect of $M_R < M_X$ is then clear: it increases $\sin^2\theta_W$ and decreases α_s compared to the SU(5) predictions.

The procedure, commonly employed, is to take $\alpha_s(M_W)$ (obtained from experiment via tracing energy dependence from below M_W) and $\sin^2\theta_W(M_W)$ as inputs and then determine M_x and M_R. In the SU(5) case $M_R = M_x$, so that one has a consistency check, since it is enough to give $\alpha_s(M_W)$ and determine both M_x and $\sin^2\theta_W$. The reader should recall that the electroweak part of the Higgs sector consists of D ϕ multiplets and T triplets Δ_L (Δ_R), with D = T = 1 in the minimal case. We then end up with two distinct possibilities:

(a) If $M_R \gtrsim 1$ TeV (approximately), then $\sin^2\theta_w = \sin^2\theta_w$ (standard model) $\simeq$ $\simeq 0.23 \pm 0.02$. In that case one can derive a stringent limit[13] on M_R; with possible solutions:

$$\sin^2\theta_W = 0.21 \qquad M_X \simeq M_R \simeq 10^{14}-10^{15}\ \mathrm{GeV}$$

$$\sin^2\theta_W = 0.23 \qquad M_X \simeq (10^{15}-10^{16}\ \mathrm{GeV}) \quad M_R \simeq (10^{9}-10^{10}\ \mathrm{GeV})$$

$$\sin^2\theta_W = 0.25 \qquad M_X \simeq (10^{17}-10^{18}\ \mathrm{GeV}), \quad M_R = (10^{6}-10^{7}\ \mathrm{GeV})$$

The first solution corresponds to the SU(5) case. All the values, including $\sin^2\theta_W = 0.25$, give the situation which is practically equivalent to a desert, since we would never directly observe parity restoration. That was the basis for the claim[13] that there can be no low intermediate mass scales in simple grand unified theories.

(b) Light W_R: $M_R \lesssim 250$ GeV -- the case of interest to us[4]).

The lesson of the previous section is, however, that the $\sin^2\theta_W$ condition is only true if one assumes the $SU(2)_L \times U(1)_Y$ model to be correct at low energies, i.e. if one assumes W_R to be heavy ($M_R \gtrsim 1$ TeV). On the other hand, for low M_{W_R} we have seen that $\sin^2\theta_W$ can be as large as 0.28. We should keep that in mind.

Let us now go back to our prediction for α_s and $\sin^2\theta_W$ in Eq. (3.5). To our leading log approximation, we should set $M_R = M_W$, in which case for D ϕ multiplets and T Δ_L (Δ_R) fields (I am assuming, wich is unclear, that these fields do not get superheavy), $T_L = T_R = 2D + 4T$, $T_{BL} = 18T$ and so we arrive at the following expressions

$$1 - \frac{8}{3}\frac{\alpha(M_W)}{\alpha_s(M_W)} = \frac{22\alpha(M_W)}{3\pi}\left(1 + \frac{5T+D}{22}\right)\ln\frac{M_X}{M_W}$$

$$\sin^2\theta_W(M_W) = \frac{3}{8} - \frac{1}{8}\,\frac{22+7T-D}{22+5T+D}\left(1 - \frac{8}{3}\frac{\alpha(M_W)}{\alpha_s(M_W)}\right) \tag{3.6}$$

The strategy is the following: we will use $\alpha_s(M_W)$ as an input and determine M_X and $\sin^2\theta_W(M_W)$, to check the consistency of our results. We give the values of $\alpha_s(M_W)$ that should correspond to $\Lambda_{\overline{MS}} = 0.1\text{-}0.4$ GeV: $\alpha_s(M_W) = 0.1\text{-}0.13$. It is important to notice that the Higgs effects in Eq. (3.6) (especially due to triplets) are substantial.

Minimal model

In this case D = T = 1 and therefore

$$1 - \frac{8}{3}\frac{\alpha(M_W)}{\alpha_s(M_W)} = \frac{28\alpha(M_W)}{3\pi}\ln\frac{M_X}{M_W}$$

$$\sin^2\theta_W(M_W) = \frac{1}{4} + \frac{1}{3}\frac{\alpha(M_W)}{\alpha_s(M_W)} \tag{3.7}$$

Table 2 then summarizes the predictions for M_X and $\sin^2\theta_W$. The scheme is clearly consistent, since we predict $\sin^2\theta_W = 0.27\text{-}0.28$, as required by experimental constraints for light W_R.

From $M_X \simeq 10^{16}\text{-}10^{18}$ GeV, we predict for the proton lifetime

$$\tau_p \simeq 10^{38} - 10^{46} \text{ years} \tag{3.8}$$

Expanded Higgs sector

In order to see how strong our prediction for M_X is, we have given in Table 3 the values of M_X and $\sin^2\theta_W$ for the expanded Higgs sector. Whereas the results for $\sin^2\theta_W$ are good again, M_X clearly could be as low as 10^{14} GeV, leading to the usual prediction of SU(5): $\tau_p \simeq 10^{31}$ years. However, if the extra Higgs multiplets are superheavy, one is back to minimal model results.

Combining our results from the previous section with this section, we list the set of predictions of the model (see Tables 1-3 and Ref. 4).

(i) The masses of light gauge bosons

$$M_{W_L} = (70 - 72)\ \mathrm{GeV}\ ; \quad M_{Z_1} = (80 - 84)\ \mathrm{GeV}$$

to be contrasted with the values in the standard model: $M_W = 78$ GeV, $M_Z = 89$ GeV (for $\sin^2\theta_w = 0.23$). This is one of our most clear predictions, which will be crucial in choosing between the two alternatives (see Ref. 4).

ii) The values of heavier gauge bosons vary in the range[4)]

$$M_{W_R} = (150 - 250)\ \mathrm{GeV}\ ; \quad M_{Z_2} = (240 - 400)\ \mathrm{GeV}$$

They are likely to be produced at ISABELLE energies with substantial rates.

iii) In the minimal Higgs model $\tau_p \gtrsim 10^{38}$ years; but if the Higgs sector is expanded it is possible to obtain τ_p as low as 10^{30} years.

Baryon production in the early universe

One of the most exciting predictions of grand unified theories is the possible explanation of the origin of matter-antimatter asymmetry. Recently, Masiero and myself[16)] have shown that the existence of low intermediate mass scales does not spoil the success of arriving at a correct value of n_B/n_γ. The problem seemed to be that the baryon asymmetry, produced through the $\Delta B \neq 0$ decays of superheavy bosons in the early universe, is proportional to the amount of left-right asymmetry[17)] i.e.

$$\frac{n_B}{n_\gamma} \simeq \left(10^{-13} - 10^{-7}\right) \frac{V_L - V_R}{m_H} \tag{3.9}$$

where the prediction in the brackets is obtained in the conventional theories where the breaking of parity is superstrong and V_L, V_R and m_H are the scales that correspond to M_{W_L}, M_{W_R} and superheavy bosons, respectively.

Since $m_H \gtrsim 10^{15}$ GeV in our model and $V_L - V_R \lesssim 10^3$ GeV, we would get

$$\frac{n_B}{n_\gamma} \leq \left(10^{-25} - 10^{-19}\right) \tag{3.10}$$

which is far below the observed number of baryons

$$\left(\frac{n_B}{n_\gamma} \right)_{obs} = 10^{-9 \pm 1} \tag{3.11}$$

As it appears, weak breaking of left-right symmetry is incompatible with observed global properties of the universe, such as the baryon density. However, baryon excess supposedly originated in this picture at temperatures of the order of superheavy boson masses. But then, one should really have

$$\frac{n_B}{n_\gamma} = \left(10^{-13} - 10^{-7}\right) \frac{V_L(T) - V_R(T)}{m_H} \tag{3.12}$$

where $V_L(T)$, $V_R(T)$ are the scales associated with symmetry breaking at high T. Our main point is, as has been argued repeatedly by Mohapatra and myself[18], that the symmetry may remain broken at high temperature. For example, one can have for $T > T_c$ (= 300 GeV), $V_L(T) = 0$, but $V_R(T) \approx T$, in which the left-right asymmetry increases with temperature. In such a case, $V_R(T) \leq m_H$, which eliminates the apparent suppression in Eq. (3.12).

We have carried out a detailed analysis to show how one then obtains a reasonable prediction for n_B/n_γ; we refer the reader to Ref. 16 for the details.

In short, the amount of baryon asymmetry provides no limit on M_{W_R}, since it only tests $V_R(T)$ at high T, which can be large.

I have tried to argue in this section that a simple and realistic grand unified theory based on the SO(10) group gives a consistent picture according to which the proton is effectively stable (at least in the minimal Higgs model), but instead one expects new energy thresholds not far from M_W. The predictions of the theory are many and it should be not before long that such an alternative is either rejected or accepted.

4. COMMENTS AND CONCLUSIONS

Left-right symmetric theories provide an appealing alternative to the standard $SU(2)_L \times U(1)_Y$ electroweak model by offering a mechanism to understand parity violation in weak interactions. The question I have tackled in this talk is whether we can hope to observe parity restoration in the near future. Phenomenological analysis and the use of the conditions for the unification with strong interactions provide an affirmative answer. I shall only summarize the predictions, without describing them again:

- $M_W = (70\text{-}72)$ GeV, $M_{Z_1} = (80\text{-}84)$ GeV;
  $M_R = (150\text{-}250)$ GeV, $M_{Z_2} = (240\text{-}400)$ GeV;
- $\tau_p \gtrsim 10^{38}$ years;
- $\Delta L \neq 0$ with $(\beta\beta)^0$ process prediction: $\eta_{th} \gtrsim 10^{-5}$ and $\eta_{exp} \lesssim 10^{-4}\text{-}10^{-5}$ (see Refs. 4, 7);
- $\beta(\mu \to e\gamma) \neq 0$ (how big?), $\frac{\beta(\mu \to ee\bar{e})}{B(\mu \to e\gamma)} = (1\text{-}10)\%$ (see Ref. 7).

Obviously, this oasis in the suggested desert in the grand unified theories may, after all, be only a mirage. Fortunately, we shall be able to tell, since most of the above predictions will be tested in the near future. Could it be that above this oasis there are others, whose presence affects low-energy phenomenology so as to be consistent with the idea of grand unification? Could it be that there is no desert, even within conventional grand unified theories.

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Table 1

Gauge boson masses for various values of $\sin^2\theta_w$ and $\eta_R \left(\frac{M_R^2}{M_L^2} \equiv \frac{1+\eta_R}{\eta_R}\right)$.

$\sin^2\theta_w$	η_R	M_{W_L} (GeV)	M_{Z_1} (GeV)	M_{W_R} (GeV)	M_{Z_2} (GeV)
0.23	0	78	89	∞	∞
0.23	0.1	78	87	260	420
0.25	0.2	75	84	185	295
0.28	0.2	70	81	170	290
0.28	0.3	70	80	150	240

Table 2

The values of the unification scale M_X and $\sin^2\theta_W$ for the minimal model with weakly broken parity. The values of $\alpha_s(M_W)$ for corresponding $\Lambda_{\overline{MS}}$ were suggested to us by A. Buras and W. Marciano.

$\Lambda_{\overline{MS}}$ (GeV):	0.1	0.2	0.3	0.4
$\alpha_s(M_W)$:	0.101	0.113	0.121	0.127
$\sin^2\theta_w(M_w)$:	0.276	0.273	0.272	0.270
M_x (GeV):	5×10^{16}	1×10^{17}	2×10^{17}	3×10^{17}

Table 3

Again, M_X and $\sin^2\theta_W$ are plotted for different $\alpha_s(M_W)$. In this case the Higgs sector is extended. D denotes the number of ϕ fields and T stands for the number of triplets Δ_L (Δ_R). There is an implicit assumption that all of these fields remain non superheavy, which may not hold true (otherwise they do not contribute to β fermions). For D = T = 1 it is, however, a reasonable assumption.

D	T	$\Lambda_{\overline{MS}}$ (GeV)	M_X (GeV)	$\sin^2\theta_W(M_W)$
2	1	0.1	2×10^{16}	0.283
		0.4	9×10^{16}	0.278
1	2	0.1	3×10^{14}	0.270
		0.4	1×10^{15}	0.264
1	3	0.1	6×10^{12}	ruled out
		0.4	2×10^{13}	
2	2	0.1	1×10^{14}	0.276
		0.4	5×10^{14}	0.270
3	1	0.1	5×10^{15}	0.289
		0.4	3×10^{16}	0.284