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Light Lepto-Quarks in $SO(10)$

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Abstract. It is shown that a particular chain of symmetry breaking in $SO(10)$ theory which leads to a standard picture of low energy phenomena, allows the scale of $SU(4)_c$ quark-lepton symmetry breaking to be as low as 10^5-10^6 GeV. This, among other predictions, gives rise to rare kaon decays with $B(K_L \to \bar{\mu}e) \cong 10^{-9}-10^{-13}$ and proton lifetime in the range $10^{31}-10^{34}$ years. Also, there exist the second neutral gauge boson and right-handed neutrinos with masses in the range: few hundred-10^5 GeV.

Almost a decade ago, Pati and Salam [1] suggested that at high energies quarks and leptons may be indistinguishable, in that $SU(3)_c$ color symmetry gets enlarged in such a way that leptons behave as an additional quark color. The Q smallest group which realizes this idea is $SU(4)_c$, with fermions in the following multiplets [1]: (u_i, ν) and (d_i, e) $(i=1,2,3$ denotes ordinary quark color). This, besides gluons and the neutral gauge boson associated with $U(1)_{B-L}$ symmetry predicts the existence of lepton-quark bosons X_i which transform quarks into leptons through the interaction [1]

$$L_X = X_i^\mu [\bar{\nu}\gamma_\mu u_i + \bar{e}\gamma_\mu d_i] \tag{1}$$

These particles induce rare kaon decays $K_L \to \bar{\mu}e$ without any mixing suppression and hence the limit on their mass [1,2] $\gtrsim 10^5$ GeV. In the context of $SU(4)_c$ symmetry this corresponds to the mass scale (we call it M_c hereafter) at which $SU(4)_c$ is broken down to $SU(3)_c$. A question then naturally appears as to whether this mass scale can be somehow determined and more interestingly, whether it can be close to its lower limit to generate new physical phenomena. This question is best studied in the context of grand unification which relates low energy parameters to large unifying mass scales [3]. In this paper we show that there exists a particular chain of symmetry breaking in simple models that allows M_c to be in the interval 10^4-10^6 GeV, while preserving the standard picture of low energy electro-weak phenomena.

The most natural and simplest candidate for a grand unified theory which contains the whole $SU(2)_L \times SU(2)_R \times SU(4)_c$ group of Pati and Salam's is $SO(10)$. Since $SU(2)_R$ (and also left-right symmetry) has to be broken above M_c, or else $M_c > 10^{12}$ GeV as the previous analysis has shown [3-4], one is naturally led into breaking $SU(2)_R$ at the scale of grand unification if one is to generate low M_c. The general first stage of symmetry breaking becomes $O(10) \to SU(2)_L \times U(1)_R \times SU(4)_c$, where $U(1)_R$ corresponds to T_{3R}.

Next, we have to break $SU(4)_c$ symmetry; and to keep the analysis more general, we leave $U(1)_{B-L}$ (or the fifteenth generator of $SU(4)_c$ unbroken at this stage. The complete chain of symmetry breaking takes the unique form[5],

$$\begin{aligned}
&O(10) \underset{M_X}{\to} SU(2)_L \times U(1)_R \times SU(4)_c \underset{M_c}{\to} \\
&\cdot SU(2)_L \times U(1)_{B-L} \times SU(3)_c \underset{M_{BL}}{\to} \\
&\cdot SU(2)_L \times U(1) \times SU(3)_c \times SU(2)_L \times U(1)_R \\
&\times U(1)_{B-L} \times SU(3)_c \underset{M_W}{\to} U(1)_{\text{em}} \times SU(3)_c,
\end{aligned} \tag{2}$$

where $M_W \leqq M_{BL} \leqq M_c$.

Of course, the theory is not specified before the inclusion of Higgs scalars. The minimal multiplet that is responsible for the first stage of symmetry breaking is a **45** dimensional representation ϕ, where the component which acquires vacuum expectation value

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(vev) $\langle\phi\rangle \simeq M_X$, has (1, 3, 1) content under $SU(2)_L \times SU(2)_R \times SU(4)_c$

The next stage, i.e. the breaking of $SU(4)_c$ is again achieved by ϕ_{45}

$$\langle\phi(1,0,15)\rangle = M_c, \tag{3}$$

where the numbers in the bracket give the $SU(2)_L \times U(1)_R \times SU(4)_c$ representation content.

In order to give a large mass to the right-handed neutrino which leads to its decoupling at low energies, we are forced [6] to choose a **126** Higgs Δ which completes symmetry breaking in the following manner:

$$\langle\Delta(1,-1,\overline{10})\rangle = M_{BL}, \tag{4}$$

where again we show the $SU(2)_L \times U(1)_R \times SU(4)_c$ representation content.

Finally, we have to break $SU(2)_L \times U(1)$ symmetry and give masses to charged fermions. To avoid the well-known wrong relations $m_e/m_\mu = m_d/m_s$, we need a combination of **10** dimensional multiplet H_{10} and **126** dimensional multiplet H_{126}: with the following $SU(2)_L \times U(1)_R \times SU(4)_c$ multiplets developing vev's.

$$\langle H_{126}(2,\tfrac{1}{2},15)\rangle \simeq \langle(H_{10}(2,\tfrac{1}{2},1)\rangle \simeq M_W, \tag{5}$$

Before we display our results regarding the determination of these mass scales, we have to know Higgs boson masses in order to be able to include their contribution to renormalization group equations. A careful application of the survival principle, recently discussed at length [7], gives,

a light $SU(2)_L \times U(1)$ doublet, with $m \sim M_W$

This field is a linear combination of relevant fields from H_{126} (2, 1/2, 15) and H_{10} (2, 1/2, 1),

a colour singlet from $\Delta(1,-1,\overline{10})$ with $m \sim M_{BL}$, and

a colour singlet from $\phi(1,0,15)$ with $m \sim M_c$.

Notice that the $SU(4)_c$ symmetry keeps the rest of the particles in H_{126} (2, 1/2, 15) (actually, a particular linear combination), $\Delta(1,-1,10)$ and $\phi(1,0,15)$ to have the mass at most M_c. All other fields become super-heavy and decouple from the renormalization group equations.

It is now straightforward to determine M_c. Using the standard Georgi–Quinn–Weinberg method [8], we obtain the following implicit expressions for M_c and M_X as functions of $\sin^2\theta_W(M_W)$, $\alpha_s(M_W)$ and M_{BL}:

$$\frac{\alpha(M_W)}{(\alpha_c M_W)} = \frac{3}{8} - \frac{\alpha(M_W)}{48\pi} \cdot \left[(198-15)\ln\frac{M_X}{M_W} + (0+24)\ln\frac{M_c}{M_W} + (0-6)\ln\frac{M_{BL}}{M_W}\right]$$

$$\sin^2\theta_W(M_W) = \frac{3}{8} - \frac{\alpha(M_W)}{48\pi} \cdot \left[(22+45)\ln\frac{M_X}{M_W} + (88-40)\ln\frac{M_c}{M_W} + (0-6)\ln\frac{M_{BL}}{M_W}\right]$$

Table 1. Values of M_c and M_W for given $\sin^2\theta_W(M_W)$; in the range $100\,\text{MeV} \leqq \Lambda_{\overline{MS}} \leqq 300\,\text{MeV}$ or $0.103 \lesssim \alpha_c(M_W) \lesssim 0.123$

$\Lambda_{\overline{MS}}$(MeV)	$\sin^2\theta_W(M_W)$	M_c(GeV)	M_X(GeV)
	0.250	2×10^5	1×10^{15}
	0.248	5×10^5	1×10^{15}
100	0.246	1×10^6	1×10^{15}
	0.240	3×10^7	7×10^{14}
	0.230	4×10^9	4×10^{14}
	0.250	5×10^4	4×10^{15}
	0.248	1×10^5	3×10^{15}
200	0.246	4×10^5	3×10^{15}
	0.240	7×10^6	2×10^{15}
	0.230	1×10^9	1×10^{15}
	0.250	2×10^4	7×10^{15}
	0.248	6×10^4	6×10^{15}
300	0.246	2×10^5	5×10^{15}
	0.240	3×10^6	4×10^{15}
	0.230	4×10^8	2×10^{15}

where the first numbers in the brackets denote gauge boson contributions and the second ones stand for Higgs boson contributions (fermionic dependence disappears at one-loop level, as is well known). It is clear from (6) that Higgs contribution is crucially important.

The Table 1 summarizes our results. We have varied $\sin^2\theta_W(M_W)$ from 0.23 to 0.25 for fixed values of $\Lambda_{MS} = 100-300$ MeV (Λ_{MS} is the scale of QCD in modified minimal subtraction scheme [9]), its value determines our input $\alpha_s(M_W)$). The reason we do not go below 0.23 is because M_c then becomes too large. We can see from Table 1 that $\sin^2\theta_W$ varies from 0.240 to 0.250 (depending on $\Lambda_{\overline{MS}}$) for $5\times10^4\,\text{GeV} \leqq M_c \leqq 10^6-10^7\,\text{GeV}$. Recently, Marciano and one of us (GS) [10] have emphasized that such values of $\sin^2\theta_W$ are perfectly acceptable if one keeps in mind that the parameter $\rho = M_W^2/(M_Z^2\cos^2\theta_W)$ is allowed to be a few per cent larger than one. The results we are quoting are obtained for $M_{BL} \simeq 10^3$ GeV; the sensitivity on M_{BL} is very tiny and in the right direction, lower M_{BL} decreases M_c slightly for fixed $\sin^2\theta_W$.

The reader may wonder about the disagreement of our results with those quoted in the literature [3, 5, 11]. The reason is that the previous works did not properly apply the survival principle to Higgs boson masses. On the other hand, as is seen from (8), the Higgs dependence is quite dramatic and must be carefully taken into account.

In short, we have demonstrated that a chain of symmetry breaking

$$O(10) \xrightarrow[10^{15}\text{GeV}]{} SU(2)_L \times U(1)_R \times SU(4)_c \xrightarrow[10^5\text{GeV}]{} SU(2)_L \times U(1)_R \times U(1)_{B-L} \times SU(3)_c \xrightarrow[10^3\text{GeV}]{} SU(2)_L \times U(1) \times SU(3) \xrightarrow[80\,\text{GeV}]{} U(1)_{em} \times SU(3)_c$$

leads to the standard model of electro-weak and strong interactions at low energies with $\sin^2\theta_W \simeq 0.24-0.25$. Further predictions of this model are the following:

i) Proton decay $p \to e^+ + \pi^0$ with somewhat more stable proton than in $SU(5)$[12]: $\tau_p \simeq 10^{31} - 10^{34}$ years.

ii) Rare kaon decays: $K_L \to \bar{\mu} e$ with[2] $B(K_L \to \bar{\mu} e) \simeq 10^{-9} - 10^{-13}$

iii) Possible light second neutral gauge boson [5] associated with $U(1)_{B-L}$, with its mass in the approximate range: few hundred GeV $\leqq M_{BL} \leqq 10^5$ GeV.

iv) Heavy right-handed neutrino[13]: m_{ν_R} in the above range and light left-handed Majorana neutrinos with masses in the range [13] 10^{-1} eV $-$ 100 MeV.

v) *No* observable $n - \bar{n}$ oscillations, despite the low value of M_c; they require both $SU(4)_c$ and $SU(2)_R$ to be broken at low energies, which does not occur.

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