COULD VECTOR LEPTOQUARKS BE RATHER LIGHT?

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ABSTRACT

A possible Standard Model extension of the Pati-Salam type with a lepton number as the fourth color is reexamined. A new type of mixing in the interaction of the SU(4)V (leptoquark with quarks and leptons) is shown to be required. An additional arbitrariness of the mixing parameters could allow to decrease noticeably the lower bound on the leptoquark mass $M_X$ originated from the $\tau$ and $K$ decays and the $e$ conversion. The only mixing independent bound emerging from the cosmological limit on the $\beta\beta \rightarrow e^+e^-$ decay width is $M_X > 18$ TeV.

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Although the Standard Model predictions are in good agreement with experiment now, see e.g. ref [1], a hope for new physics beyond the Standard Model undoubtedly exists. If the consecutive restoration of higher symmetries with an energy increase is assumed, one can speak about some stairway of the symmetries and the corresponding mass levels. The question is pertinent what the next stair after the Standard Model could be? Considering the concept widely covered in the literature of low-energy supersymmetry one can point out that the symmetry of fermions and bosons would be higher than the symmetry within the fermion sector, namely, the quark-lepton symmetry. There could also be expected the symmetry within the boson sector of gauge weak bosons interacting with the left and right currents, namely, the left-right symmetry. Thus the supersymmetry restoration could be connected, in our opinion, with higher mass scale than the others. We should like to discuss one of the possibilities when the left-right symmetry restores at an appreciably higher mass scale then the quark-lepton one. So, we take the minimal symmetry of the Pati-Salam type with a lepton number as the fourth color based on the gauge group $SU(4)_V \times SU(2)_L \times G_R$. The fermions are combined into the following representations of $SU(4)_V$ subgroup

$$T_{15} = \begin{pmatrix} s \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ 0 & \text{diag} & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{pmatrix}; \quad (i = 1; 2; 3),$$

where the $i$ index labels the fermion generations. Some attractive features of the model should be pointed out:

1. Let us remember that some quark-lepton symmetry is necessary for the renormalizability of the Standard Model, namely, the fermions are bound to be combined into generations for the cancellation of the triangle anomalies.

2. The proton decay is absent in this model.

3. The model gives a natural explanation for the quark fractional hypercharge. Really, the 15-th generator of $SU(4)$ can be written in the form:

$$T_{15} = \frac{s}{8} \begin{pmatrix} 1 \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ 1 \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{pmatrix}; \quad 1 = \frac{s}{8} Y_L.$$

It is traceless and the values of the left hypercharge appear to be placed on the diagonal. Let us call it the vector hypercharge, $Y_L = Y_V$.

4. Let us suppose that $G_R = U (1)_{L}$ and try to find the values of the right hypercharge $Y_R$ for quarks and leptons. Recall that the values of the hypercharge of left and right, and up and down quarks and leptons in the Standard Model are the following:
If we write now $Y_{SM} = Y_V + Y_R$, then the values of the right hypercharge $Y_R$ occur to be equal 1 for the up and down fermions, both quarks and leptons. It is tempting to interpret this fact as the evidence for the right hypercharge to be actually the doubled third component of the right isospin. Hence the $G_R$ group is possibly SU(2)$_R$ and thus the symmetry of the $SU(4)_V SU(2)_L SU(2)_R$ type could be the next step of the above-mentioned stairway.

The most exotic object of the Pati-Salam type symmetry is the charged and colored gauge $X$ boson named leptoquark. Its mass $M_X$ should be the scale of reducing of $SU(4)_V$ to $SU(3)_C$. The bounds on the vector leptoquark mass were obtained from the data on the ! e decay to be $m_X > 125$ TeV [3] and from the upper limit on $K^0_L \rightarrow e^+ e^-$ decay to be $m_X > 350$ TeV [6]. In fact, these estimations were not comprehensive because the phenomenon of a mixing in the lepton-quark currents was not considered there. It can be shown that such a mixing inevitably occurs in the theory. Really, three fermion generations are combined into the $f_{4,2g}$ representations of the semi-simple group $SU(4)_V SU(2)_L$ of the type

$$u^c_i d^c_i; \quad (i = 1; 2; 3); \quad (4)$$

where $c$ is the color index to be further omitted. The mixing in the quark interaction with the $W$ bosons being depicted by the Cabibbo-Kobayashi-Maskawa matrix is sure to exist in Nature. Therefore, at least one of the states $u$ or $d$ in [4] is not the mass eigenstate. It can be easily seen that in the general case, none of the components in [4] is the mass eigenstate because of arising of the mixing at the loop level. For example, if we start from the $d$ state to be diagonal with respect to mass it becomes non-diagonal when the one-loop transitions of the type $d \uparrow u + W \downarrow d^0$ are taken into account. It leads to the non-diagonal transitions $d \uparrow d + X \downarrow d^0$ through the quark-leptoquark loop. Consequently, it is necessary for the renormalizability of the model to include all kinds of mixing at the tree level. Due to the identity of the three representations [4] they always could be regrouped so that one of the components was diagonalized with respect to mass. The diagonalization of the charged lepton mass matrix seems to be the most natural, and the representations [4] can be rewritten in the form

$$Y_{SM} = \begin{pmatrix}
8 & 0 & 1 & 0 & 1 & 9 \\
1 & 1 & 0 & 1 & 0 & 1 \\
\otimes & \frac{1}{3} A & C & \otimes & \frac{1}{3} A & \otimes \\
\otimes & \frac{4}{3} A & C & \otimes & \frac{2}{3} A & \otimes
\end{pmatrix}$$

(3)
where the indices ' = e; ; ' correspond to the states which are not the mass eigenstates and are included into the same representations as the charged leptons ' = K ' i ; u ' i = U ' i u ' p ; d ' i = D ' i d ' i .

Here u ' p ; and d ' i are the mass eigenstates

\[ u ' = ( 1 ; 2 ; 3 ) ; u ' p = ( u_1 ; u_2 ; u_3 ) = ( u ; c ; t ) ; d ' i = ( d_1 ; d_2 ; d_3 ) = ( d ; s ; b ) ; \]

and K ' i ; U ' p , and D ' i are the unitary mixing matrices.

The well-known Lagrangian of the interaction of the charged weak currents with the W bosons in our notations has the form

\[ L_W = \frac{g}{2} \left( \bar{u} ' ( i \sigma ^ \mu ) + ( u ' O ' d ' ) W ^ \mu + h c \right) \]

where g is the SU (2) L group constant, and O ' = ( 1 0 5 ). The standard Cabibbo (Kobayashi-Maskawa) matrix is thus seen to be V = U + D . This is as far as we know about U and D matrices. The K matrix description of the mixing in the lepton sector has been the object of intensive experimental investigations in recent years.

Subsequent to the spontaneous SU (4) V symmetry breaking up to SU (3) c on the M \(_X\) scale six massive vector bosons are separated from the 15-plet of the gauge elds to generate three charged and colored leptoquarks. Their interaction with the fermions (7) has the form

\[ L_X = \frac{g_8 (M_X)}{2} \left( D \gamma ( c ' ) + ( K^ + U ) \gamma ( u ' p ) \right) \sigma ^ \mu \sigma ^ \nu + h c \]

where the color index c is written once again. The constant \( g_8 (M_X) \) can be expressed in terms of the strong coupling constant \( g \) at the leptoquark mass scale M \(_X\); \( g_8^2 (M_X) = 4 \) at \( M_X \).

If the momentum transferred is \( q \) M \(_X\), then the Lagrangian (8) in second order leads to the effective four-fermion vector-vector interaction of quarks and leptons. By using the Fierz transformation, lepton-current-to-quark-current terms of the scalar, pseudoscalar, vector and axial-vector types may be separated in the effective Lagrangian. Let us note that the construction of the effective lepton-quark interaction Lagrangian requires taking account of the QCD corrections estimated by known techniques. In our case the leading log approximation in \( M_X = \) 1
with 1 GeV to be the typical hadronic scale is quite applicable. Then the QCD correction amounts to the appearance of the magnifying factor $Q(\bar{s})$ at the scalar and pseudoscalar terms $s$

$$Q(\bar{s}) = \frac{s(\bar{s})}{s(M_X)}^{4-b} \quad (10)$$

Here $s(\bar{s})$ is the effective strong coupling constant at the hadron mass scale, $b = 11 \frac{2}{3} n_f$; $n_f$ is the averaged number of the quark flavors at the scales $d^2 \leq M_X^2$. If the condition $M_X^2 \geq M_X^2$ is valid, then we have $n_f' = 6$, and $b' = 7$.

It is interesting to investigate the contribution of the leptoquark interaction $\bar{e}$ to the low-energy processes in order to establish the bounds on the model parameters from existing experimental limits. As the analysis shows, the tightest restrictions on the leptoquark mass $M_X$ and the mixing matrix elements $D$ can be obtained from experimental data on rare $K$ and $D$ decays and $e^+e^- \to \mu^+\mu^-$ conversion in nuclei. They are represented in Table 1. The amplitudes of these processes can be found in our paper. Compared to ref. [1] we obtain here the improved bounds based on the recent experimental data from TRIUMF, PSI, and BNL.

One can see from Table 1 that the restrictions on the model parameters contain the elements of the unknown unitary mixing matrices $D$ and $U$, which are connected by the condition $U^+D = V$ only. Thus the possibility is not excluded, in principle, that the bounds obtained do not restrict $M_X$ at all, e.g., if the elements $D_{d\bar{d}}$ and $D_{d\bar{s}}$ were rather small. It would correspond to the connection of the lepton largely with the d quark in the $D$ matrix, and the electron and the muon with the s and b quarks. In general, it is not contradictory to anything even if it appears to be unusual.

In this case a leptoquark could give a more noticeable contribution to the $\mu$-$\tau$-changing decays of the lepton and $D^0$, $\bar{D}^0$, and $B$ mesons. However, a relatively poor accuracy of these data doesn't yet allow to restrict the parameters essentially.

We could find only one occasion when the mixing-independent lower bound on the leptoquark mass arises, namely, from the decay $^{0}B \to \mu^+\mu^-$. In the paper the cosmological estimation of the width of this decay was found

$$\text{Br}(^{0}B \to \mu^+\mu^-) < 2 \times 10^{-3}.$$ 

Within the Standard Model value is proportional to $m_d^2$. The process is also possible through the leptoquark mediation, without the suppression by the smallness of neutrino mass. On summation over all neutrino species the decay probability is mixing-independent. As a result the bound on the leptoquark mass is

$$M_X > 18 \text{ TeV}. \quad (11)$$

In conclusion, we have analysed in detail the experimental data on rare $K$ decays and $e^+e^- \to \mu^+\mu^-$ and we have found the restrictions on the vector leptoquark mass to contain the elements of an unknown mixing matrix $D$. The only mixing independent bound [11] arises from cosmological estimations.
Table 1. The bounds on the leptoquark mass and mixing matrix elements from the experimental limits on the branching ratios of various processes.

| No. | Experimental limit $\Xi$ | Ref. | Bound |
|-----|--------------------------|------|-------|
| 1   | $\frac{(! e)}{(!)} = (1.23 \pm 0.01) \times 10^{-4}$ | 1     | $\frac{M_X}{\Re \left( D_{\ell \ell} U_{\ell u} = V_{\ell d} j \right)} > 210 \text{ TeV}$ |
| 2   | $\text{Br}(K^+ \rightarrow \mu^+ e^-) > 7 \times 10^{-9}$ | 2     | $\frac{M_X}{\Re \left( D_{e\ell} D_{\ell \ell} j \right)} > 50 \text{ TeV}$ |
| 3   | $\text{Br}(K^+ \rightarrow \mu^+ e^-) < 2 \times 10^{-10}$ | 3     | $\frac{M_X}{\Re \left( D_{e\ell} D_{\ell \ell} j \right)} > 120 \text{ TeV}$ |
| 4   | $\text{Br}(K^0_L \rightarrow \mu^- e^+) > (7.3 \pm 3.4) \times 10^{-9}$ | 4     | $\frac{M_X}{\Re \left( D_{\ell \ell} D_{\ell \ell} j \right)} > 500 \to 600 \text{ TeV}$ |
| 5   | $\text{Br}(K^0_L \rightarrow \mu^- e^+) < 5 \times 10^{-11}$ | 5     | $\frac{M_X}{\Re \left( D_{e\ell} D_{\ell \ell} j \right)} > 1200 \text{ TeV}$ |
| 6   | $\text{Br}(K^0 \rightarrow \mu^- e^+) > 5 \times 10^{-11}$ | 6     | $\frac{M_X}{\Re \left( D_{e\ell} D_{\ell \ell} j \right)} > 1400 \text{ TeV}$ |
| 7   | $\left( \frac{\text{Ti}! e \text{ Ti}}{\text{Ti}! \text{ capture}} \right) < 4 \times 10^{-12}$ | 7     | $\frac{M_X}{\Re \left( D_{e\ell} D_{\ell \ell} j \right)} > 670 \text{ TeV}$ |

In our opinion, possible experimental manifestations of the considered minimal leptoquark-lepton symmetry model would be an object of further methodical studies. For example, the search for possible leptoquark evidence in the pp collider high-energy experiments via the reactions $d \bar{d} ! e^+ ; e^+$ could be of interest. On the other hand, further searches of flavor-changing decays of lepton and $\nu^0$; and $B$ mesons are desirable.

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