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Trilinear Production by Neutrinos and
SU(3)\times U(1) Gauge Model *

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Abstract
A gauge model of weak interactions is proposed to naturally incorporate copious production of charged heavy leptons leading to trimuon events in high energy neutrino reactions and a small violation of muon number conservation.

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The recent experiments [1, 2] on trimuon production by neutrinos done at Fermilab can be explained by production of heavy charged leptons and subsequent cascade decay into leptonic modes. Though the results have not so far been confirmed at CERN [3], their implications in theory are important, if they are true. With normal leptonic branching ratios of about 10% or so, the strength of production of heavy leptons must be a substantial fraction of that of single-muons [4]. In order to accommodate a weak interaction involving such a heavy lepton, one has to introduce a conceptually new modification into universality of weak interactions.

Gauge models along this line were proposed by one of the authors phenomenologically in a different context [5]. In this Letter, we give a theoretical basis to such models within the unified gauge theory, reconstruct the quark sector in a way consistent with the latest development in the charmed particles, and discuss briefly on the consequences of a simple version of such models.

In order to allow copious production of heavy lepton $H^-$ through $\nu_e$, we introduce two doublets

$$
\left( \begin{array}{c}
\nu_e \cos \alpha + N_\ell \sin \alpha \\
\nu_e \sin \alpha + N_\ell \cos \alpha 
\end{array} \right)_L,
\left( \begin{array}{c}
-H^+ \\
N^-
\end{array} \right)_L,
$$

where $N_\ell$ is a neutral heavy lepton lighter than $H^-$ and the subscript $L$ denotes the left-handed helicity. Two doublets are introduced correspondingly in the electron sector as

$$
\left( \begin{array}{c}
\nu_e \cos \alpha + N_\ell \sin \alpha \\
\nu_e \sin \alpha + N_\ell \cos \alpha 
\end{array} \right)_L,
\left( \begin{array}{c}
-e^- \\
E^-
\end{array} \right)_L.
$$
In the hadron sector four doublets of quarks are introduced, keeping the \( \Delta C = \Delta S \) selection rule of the charmed hadron decays:

\[
\begin{pmatrix}
    u \cos \alpha + t \sin \alpha \\
    d
\end{pmatrix}_L ,
\begin{pmatrix}
    -u \sin \alpha + t \cos \alpha \\
    b
\end{pmatrix}_L ,
\begin{pmatrix}
    c \cos \alpha + \bar{t} \sin \alpha \\
    s
\end{pmatrix}_L ,
\begin{pmatrix}
    -c \sin \alpha + \bar{t} \cos \alpha \\
    \bar{b}
\end{pmatrix}_L ,
\tag{3}
\]

where \((t, \bar{t})\) and \((b, \bar{b})\) are heavy quarks of charge \(2/3\) and \(-1/3\), respectively.

In Eq. (3), we have suppressed the Cabibbo rotation, which will be discussed shortly. The angle \(\alpha\) common to the lepton and hadron sectors is the basic feature of this type of models since the universality of low energy weak interactions has to be maintained. We first show how the common angle can appear naturally in a gauge model.

The weak gauge group is enlarged for this purpose to \(SU(4)_L \times U(1)\), in which all the fermions are assigned to quartets:

\[
\begin{pmatrix}
    \nu_e \\
    \nu_{\mu} \\
    \nu_{\tau} \\
    e^-
\end{pmatrix}_L ,
\begin{pmatrix}
    \mu^- \\
    \tau^- \\
    e^- \\
    \nu^-
\end{pmatrix}_L ,
\begin{pmatrix}
    u \\
    d
\end{pmatrix}_L ,
\begin{pmatrix}
    c \\
    s
\end{pmatrix}_L ,
\begin{pmatrix}
    t \\
    \bar{b}
\end{pmatrix}_L ,
\begin{pmatrix}
    \bar{c} \\
    \bar{s}
\end{pmatrix}_L .
\tag{4}
\]

We introduce four pairs of Higgs quartets \(X^{(j)}_a, j = 1, 2, 3, 4\) and two Higgs multiplets of adjoint representation \(\phi^a_b\) and \(\psi^a_b\) .

They are to develop vacuum expectation values as follows:

\[
\mathcal{F}_a = \begin{pmatrix}
    \phi \cos 2\alpha , 0 , \phi \sin 2\alpha , 0 \\
    0 , \phi , 0 , 0 \\
    -\phi \sin 2\alpha , 0 , \phi \cos 2\alpha , 0 \\
    0 \end{pmatrix}, \quad \mathcal{F}_b = \begin{pmatrix}
    \psi \sin 2\alpha , 0 , \psi \cos 2\alpha , 0 \\
    0 , 0 , 0 , \psi \\
    \psi \cos 2\alpha , 0 , -\psi \sin 2\alpha , 0 \\
    0 \end{pmatrix},
\]

\[
\chi^{(1)}_a = (\chi , 0 , 0 , 0), \quad \chi^{(2)}_a = (0, \chi , 0 , 0),
\]

\[
\chi^{(3)}_a = (0, 0, \chi , 0), \quad \chi^{(4)}_a = (0, 0, 0, \chi ),
\tag{5}
\]

where \(|\phi|\) and \(|\psi|\) are to be much larger than \(|\chi|\) and \(|\chi'|\) . Twelve of the sixteen gauge bosons acquire very large mass through \(\phi\) and \(\psi\), breaking \(SU(4)_L \times U(1)\) down to the ordinary \(SU(2)_L \times U(1)\). The quartets produce diagonal mass matrices for leptons and quarks through the interaction

\[
H_{\text{int}} = \sum_{j=1}^{6} \sum_{a=1}^{4} \{ s_j \chi^{(j)}_a \nu_{\bar{L},J} + r_j \chi^{(j)}_a \nu_{L,J} \}
+ \text{H. c.},
\tag{6}
\]

where \(R\) and \(L\) are helicities, and \(\bar{L}\) and \(L\) stand for the Dirac fields of leptons and quarks, respectively. This specific form of Higgs interactions presumes implicitly existence of a global symmetry of \(U(1)_Y \times U(1)_Y \times U(1)_Y \times U(1)_Y\).

The quartet Higgs particles also give rise to masses for the three of the remaining gauge bosons, leaving the photon as the only massless particle. Note that the vacuum expectation values of \(\mathcal{F}_a\) and \(\mathcal{F}_b\) given in Eq. (5) are the most general ones that break down \(SU(4)_L \times U(1)\), preserving the \(SU(2)_L \times U(1)\) of the Weinberg-Salam type. Other forms are reduced to them by redefining rotation angles. The common mixing angle \(\alpha\) is induced here through diagonalization of the \(W\) boson mass matrix, since the axes of diagonalization of the fermion and \(W\) boson mass matrices mismatch each
other by angle $\alpha$. For instance, the light charged W bosons are given in the tensor notation by $W^- = \sqrt{3}/2 \left( \nu_u^c + \nu_d^c \right) Q \cos \alpha + \sqrt{2}/2 \left( Q^2 - \nu_u^c \right) \sin \alpha$ and its Hermitian conjugate.

The Cabibbo angle $\theta_C$ is a little different from the angle $\alpha$, since $\theta_C$ is a mixing angle, not within a single quartet, but between members of two different quartets. The present mechanism works to induce the Cabibbo rotation if the gauge group is further enlarged to $SU(3)_L \times U(1)$. The Cabibbo rotation is thus introduced for both leptons and quarks between the upper components of pairs of $SU(2)_L$ doublets. When $\nu_e$ and $\nu_\mu$ are both massless, however, the Cabibbo rotation between them disappears after redefinition of the physical $\nu_e$ and $\nu_\mu$ states. Therefore, we finally have the $SU(2)_L$ weak doublets as follows:

$$(\nu_e \cos \alpha + \nu_\mu \sin \alpha)_L, \quad (\nu_e \sin \alpha - \nu_\mu \cos \alpha)_L,$$

$$(\nu_\mu \cos \alpha + \nu_e \sin \alpha)_L, \quad (\nu_\mu \sin \alpha + \nu_e \cos \alpha)_L,$$

$$(u' \cos \alpha + t' \sin \alpha)_L, \quad (u' \sin \alpha + t' \cos \alpha)_L,$$

$$(c' \cos \alpha + \bar{s}' \sin \alpha)_L, \quad (c' \sin \alpha + \bar{s}' \cos \alpha)_L,$$

$$(d' \cos \alpha + b' \sin \alpha)_L, \quad (d' \sin \alpha + b' \cos \alpha)_L,$$

where the primes stand for the Cabibbo rotation within the pairs of $(\nu_e, \nu_\mu)$, $(u, c)$, and $(t, \bar{c})$.

We will investigate briefly several qualitative consequences of the present model. Quantitative comparison in detail is still premature in the light of the presently available data.

1. Copious production of heavy charged leptons (identified with $W^\pm$) through $\nu_e$ can be accommodated with the new angle parameter $\alpha$, $W^\pm$ decays into $\nu_e \mu^\pm$ with the universality of the $\beta$ decay. The $W^\pm \nu_e \nu_\mu$ decay rate is suppressed by $\tan^2 \alpha$ as compared with the value predicted by a naive universality. In the same way, $\nu_\mu$ decays into $\mu^- \nu_e \nu_\mu$ with the universality modified by $\cos^2 \alpha \cos \alpha$.

2. The $U$ particle of Perl et al. can be tentatively identified with $K$. Its decay obey the universality modified by $\tan^2 \alpha$.

3. The $c$ rotation followed by the Cabibbo rotation necessarily causes a small violation of muon number conservation through $\mu \rightarrow (\nu_e$ or $\nu_\mu) \rightarrow e$ with the angle factor of $\cos \alpha \sin \theta_C \sin 2\alpha$ in matrix element. [7] As compared with the estimate made in [7], however, the $\Gamma(\mu \rightarrow e\nu X)/\Gamma(\mu \rightarrow e\nu e)$ ratio is expected to be more than an order of magnitude smaller. The final electron in the $\mu \rightarrow e\nu$ decay is polarized left-handedly.

4. Suppression of $\Delta S = 2$ transitions imposes a restriction on the masses of $t$ and $\bar{t}$ as

$$|(m_c^2 - m_t^2) \cos 2\alpha + (m_c^2 - m_t^2) \sin^2 \alpha| \leq 2 \text{ GeV}^2.$$  (8)

Provided that $m_c$ and $m_t$ are larger than 1 GeV and that $\sin^2 \alpha$ is comparable with $\cos^2 \alpha$, this means that $t$ and $\bar{t}$ are nearly degenerate in mass. This is an important prediction soon to be tested in $e^+e^-$ annihilation. We could, however, interchange the roles of $c$ and $\bar{t}$ in Eq.(7). In this case, the charged quark would obey the modified universality of $\tan \alpha$, and one would obtain a mass relation $m_c/m_t \approx \tan \alpha$.

5. Even if $|\beta|$ and $|\gamma|$ are infinitely larger than $|\xi|$ and $|\xi'|$, the scale of neutral current interactions is changed relative to the $\beta$ decay
interaction because of the of rotation. [5] If $|\psi|$ is comparable to $|\chi|$ and $|\chi'|$, the situation is more involved. Our model in the present version stands at the same place as the standard model as long as parity violation in atomic physics is concerned. [6] If the data and theoretical calculations are confirmed further, the present model need to be modified to incorporate the right-handed current of the electron. Though not aesthetic, it is possible to do so.

6. The scaling parton model does not explain the high y anomaly in antineutrino reactions in our model. We expect in the present model that dynamical corrections to scaling and possibly a small amount of left-handed b quark production are responsible for the high y anomaly as well as the anomalous $d(\bar{p})/d(\bar{p})$ ratio. Note that there is no evidence whatsoever for existence of the b quark in the dimuon production data.

Alternative symmetry breaking schemes in which Higgs couplings to fermions are more general suggest that it is possible to obtain approximate universality for light fermions, $\nu_\tau$, $\nu_\mu$, and $u$, but not for c. Details on this generalisation will be discussed elsewhere.

The present model has only one new parameter $\alpha$ at the level of SU(2)$_L \times$ U(1) in addition to those of the standard model. Yet it predicts copious production of charged heavy leptons through $\nu_\mu$, neutral heavy leptons, a small violation of muon number conservation, the heavy quark mass spectrum of charge 2/3, and so forth.

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