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A VECTORLIKE THEORY WITH A PARITY VIOLATING NEUTRAL CURRENT
AND NATURAL SYMMETRY

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A B S T R A C T

A simple extension of the Weinberg-Salam model based on the gauge group $SU(3) \times U(1)$ is discussed.

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The gauge group $SU(2) \times U(1)$ ¹⁾ has been remarkably successful in describing weak and electromagnetic interactions among the traditional leptons (e, μ and their neutrinos) as well as among the established four quark flavours (u, d, s and c).

However, the $e-\mu$ events discovered at SLAC ²⁾ as well as various anomalies recently observed in high energy ν experiments suggest a much richer structure both in the leptonic and in the hadronic sector of the gauge group.

In this note we present a very simple generalization of the Weinberg-Salam model in which both leptons and hadrons transform as $SU(3)$ multiplets. A similar scheme was recently proposed by Fritzsch and Minkowski ³⁾: taking $SU(3)$ as the gauge group for weak and electromagnetic interactions, they classify left and right-handed quarks in triplets and left and right-handed leptons in octets. In the scheme we propose here, the gauge group is taken to be $SU(3) \times U(1)$. From a theoretical point of view, this allows us to place (left and right-handed) leptons and quarks in $SU(3)$ triplets and to preserve a natural symmetry ⁴⁾ which we believe to be a fundamental prerequisite if quantities such as the n - p mass difference or the Cabibbo angle are to be calculable. From a phenomenological point of view, our model does lead to parity violating effects in the neutral current despite the "vectorlike" character of the theory.

Neglecting for the moment all mixing angles (such as the Cabibbo angle) and denoting by the subscripts L and R left and right-handed particles, respectively, we take as our fundamental quark triplets

$$q_L = \begin{pmatrix} u_L \\ d_L \\ b_L \end{pmatrix} \quad q'_L = \begin{pmatrix} c_L \\ s_L \\ h_L \end{pmatrix} \quad q_R = \begin{pmatrix} u_R \\ b_R \\ d_R \end{pmatrix} \quad q'_R = \begin{pmatrix} c_R \\ h_R \\ s_R \end{pmatrix} \quad (1)$$

where b and h are new quarks with charges $-1/3$. Similarly, the lepton triplets are

$$l_L = \begin{pmatrix} \nu_{eL} \\ e_L^- \\ E_L^- \end{pmatrix} \quad l'_L = \begin{pmatrix} \nu_{\mu L} \\ \mu_L^- \\ M_L^- \end{pmatrix} \quad l_R = \begin{pmatrix} \nu_{eR} \\ E_R^- \\ e_R^- \end{pmatrix} \quad l'_R = \begin{pmatrix} \nu_{\mu R} \\ M_R^- \\ \mu_R^- \end{pmatrix} \quad (2)$$

where E^- and M^- are new leptons, one of which is presumably to be identified with the particle observed at SLAC. Note that ν_e and ν_μ are now four-component Dirac spinors so we will have to be careful to preserve the neutrino masslessness. Left and right triplets differ only in the exchange of second and third components : this symmetry will have important consequences.

The nine gauge bosons of the $SU(3) \times U(1)$ group are labelled $\vec{W}_\mu$ and B_μ where $\vec{W}_\mu$ is, of course, an octet vector. Their coupling to the triplets is given by

$$\mathcal{L}_1 = g \left\{ \bar{q} \gamma^\mu \frac{\vec{\lambda} \cdot \vec{W}_\mu}{2} q + \bar{l} \gamma^\mu \frac{\vec{\lambda} \cdot \vec{W}_\mu}{2} l \right\} + g' \bar{l} \gamma^\mu l B_\mu + (q, l \rightarrow q', l') \quad (3)$$

To go further we must specify the mechanism for generation of masses. We do this in two steps : the first involves introducing a triplet of scalar fields $\Phi = (\Phi^+, \Phi_1^0, \Phi_2^0)$, choosing $\langle \Phi_2^0 \rangle_0 = V$ and $(1/V^2) \ll G_F$. This generates large masses for $W_{4,5,6,7}^\mu$ and a linear combination of W_8^μ and B^μ , $\cos\gamma W^\mu + \sin\gamma B^\mu$, leaving $W_{1,2,3}^\mu$, $-\sin\gamma W^\mu + \cos\gamma B^\mu$ and all the fermions massless. At step two, we introduce an octet of scalars φ_i and an octet of pseudoscalars χ_i with the degeneracy of the vacuum broken such that

$$\langle \varphi_6 \rangle_0 = V_1 ; \langle \chi_7 \rangle_0 = V_2 ; V_1^2 = V_2^2 \ll V^2 \quad (4)$$

We will discuss later how this comes about.

The effect of this two-step symmetry breaking is to give all gauge bosons, except the photon, a mass and to lead to a neutral current

$$J_\mu^{HAD} = \frac{g}{(1+3\sin^2\alpha)^{1/2}} \left\{ \sin^2\alpha \bar{u} \gamma_\mu u + \bar{d} \gamma_\mu \left(-\frac{\sin^2\alpha}{2} + \frac{\gamma_5}{2} \right) d \right\} \quad (5)$$

$$J_\mu^{LEP} = \frac{g}{(1+3\sin^2\alpha)^{1/2}} \left\{ \bar{\nu}_L \gamma_\mu \nu_L + \bar{e} \gamma_\mu \left(\cos^2\alpha - \frac{\sin^2\alpha}{2} + \frac{\gamma_5}{2} \right) e \right\}$$

plus similar terms for the other fermions. The parameters in the theory are

$$\begin{aligned} e &= \frac{g\sqrt{3}}{2} \cos \alpha & \tan \alpha &= \frac{g}{g'} \\ \frac{g^2}{g_W^2} &= \frac{1}{8V_1^2} = \frac{G_F}{\sqrt{2}} & M_Z^2 &= \frac{4g^2V_1^2}{1+3\sin^2\alpha} \end{aligned} \quad (6)$$

where e is the electron charge and M_Z is the mass of the light neutral current mediating boson [because our group is $SU(3) \times U(1)$, in addition to the electromagnetic current there are two diagonal neutral currents, one mediated by Z and the other by a particle with mass squared of order $g^2V^2 \gg g^2V_1^2$]. The effective neutrino neutral current Hamiltonian is then

$$\begin{aligned} H_{\text{eff}}^{(\text{neutral}; \nu)} &= \frac{G_F}{\sqrt{2}} (\bar{\nu}_L \gamma^\mu \nu_L) (\bar{d} \gamma_\mu \gamma_5 d - \sin^2 \alpha \bar{d} \gamma_\mu d + 2 \sin^2 \alpha \bar{u} \gamma^\mu u) \\ &= \frac{G_F}{\sqrt{2}} (\bar{\nu}_L \gamma^\mu \nu_L) (2 \sin^2 \alpha \bar{u} \gamma_\mu u + \cos^2 \alpha \bar{d} \gamma_\mu d - \bar{d} \gamma_\mu (1 - \gamma_5) d) \end{aligned} \quad (7)$$

so we see that our parity violating neutral current is a mixture of V and $V-A$. The reason, of course, is the $SU(3) \times U(1)$ structure of the model and the fermion classification. Detailed fits will be presented in a longer version of this work.

At this point a few phenomenological comments are perhaps appropriate.

1) - We note that the model allows for decays via right-handed currents such as, e.g., $d_R \rightarrow u_R + e_R^- + \nu_R$. The magnitude of this transition compared to $d_L \rightarrow u_L + e_L^- + \nu_L$ is determined by $M_{W_1}^2/M_{W_4}^2$: even if corrections to the potential do not allow us to let the ratio V_1^2/V^2 be arbitrarily small⁵⁾, we may choose it small enough to not lead to observable consequences. The u_R to d_R transition may, however, be important in non-leptonic weak interactions.

2) - The value of the $\bar{\nu}$ to ν total cross-section in this model is $1/3$ below the b production threshold and rises to a limit of $4/3$.

- 3) - b production may be a source of dimuon events in ν collisions, whereas in $\bar{\nu}$ collisions one must excite $\bar{u}$ from the $\bar{u}u$ sea.
- 4) - Finally, we note that the parity violating term in the atomic physics experiment has the opposite sign ⁶⁾ from the Weinberg-Salam model.

Let us now turn to the problem of generating fermion masses. We do this by considering the Yukawa couplings of the fermions to the $\vec{\varphi}$, $\vec{\chi}$ fields. We impose on the whole Lagrangian, in addition to the SU(3) symmetry, a discrete symmetry which interchanges right and left fermion components and $\vec{\varphi}$ and $\vec{\chi}$ fields

$$\begin{aligned} q_R &\rightarrow \frac{1+i\gamma_5}{2} q_L \\ \varphi &\rightarrow \chi \quad \chi \rightarrow -\varphi \end{aligned} \quad (8)$$

where $\varphi = \vec{\lambda} \cdot \vec{\varphi}$, $\chi = \vec{\lambda} \cdot \vec{\chi}$ and q' , ℓ , ℓ' transform as q does. This discrete symmetry forbids the appearance of SU(3) invariant mass terms such as $m_0 \bar{q} \cdot q$ and restricts the Yukawa couplings to

$$\begin{aligned} L_{\text{YUKAWA}} = & f_1 \bar{q} \{ \varphi + i\gamma_5 \chi \} q + f_2 \bar{q}' \{ \varphi + i\gamma_5 \chi \} q' \\ & + f_3 \bar{q}' \{ \varphi + i\gamma_5 \chi \} q + g_1 \bar{\ell} \{ \varphi + i\gamma_5 \chi \} \ell \\ & + g_2 \bar{\ell}' \{ \varphi + i\gamma_5 \chi \} \ell' + h.c. \end{aligned} \quad (9)$$

If the vacuum breaks the symmetry as shown in Eq. (4), picking $V_1 = -V_2$, and the fermions in the representations shown in Eqs. (1) and (2), the fermion mass matrix becomes

$$\begin{aligned} M = & 2V_1 f_1 \bar{b} b + 2V_1 f_2 \bar{h} h + V_1 f_3 (\bar{b} h + \bar{h} b) \\ & + 2V_1 g_1 \bar{E} E + 2V_1 g_2 \bar{M} M \end{aligned} \quad (10)$$

i.e., we can give arbitrary masses to E , M , b and h since the f 's and g 's are free parameters. This is a very attractive first stage of fermion mass generation.

Our symmetry breaking mechanism works as follows : we consider the scalar and pseudoscalar field potential $P(\Phi, \varphi, \chi)$ and write the most general form keeping terms up to fourth order in the fields, preserving parity and $SU(3)$ invariance. Imposing the discrete symmetry which interchanges $\varphi \rightarrow \chi, \chi \rightarrow -\varphi$ limits the form of P such that it in fact has a larger invariance group $SU(3) \times SU(3)$, allowing separate rotations of Φ and of φ, χ . This allows us to choose $\langle \Phi \rangle_0 = (0, 0, V)$ by rotating the vacuum expectation value of Φ ; as for the φ, χ fields, let us assume CP is conserved so that χ can only have a non-vanishing seventh component and φ third, sixth and eight components

$$\begin{aligned} \langle \vec{\varphi} \rangle_0 &= \vec{V}_1 = a_1 \hat{x} + a_2 \hat{z} + a_3 \hat{Q} \\ \langle \vec{\chi} \rangle_0 &= \vec{V}_2 = V_2 \hat{y} \end{aligned} \quad (11)$$

where $\hat{x}, \hat{y}, \hat{z}$ are three unit vectors in $SU(3)$ space along the three U spin axes $(\lambda_6, \lambda_7, (\lambda_3 - \sqrt{3}\lambda_8)/2)$ while $\hat{Q}$ is along the charge direction $(\frac{1}{2}(\lambda_3 + (\lambda_8/\sqrt{3})))$. Minimization of the potential leads to $a_3 = 0$ and the $SU(3) \times SU(3)$ invariance of P allows us to rotate φ and χ about the y axis, leaving $\vec{V}_2$ unchanged and bringing $\vec{V}_1$ to lie along the x axis. We then also find $V_1^2 = V_2^2$, so we have completed our task.

In our longer publication, we will present a complete discussion of the potential and its symmetries. At that time we will also discuss the one-loop corrections ⁷⁾ to the potential, which break the symmetries.

An obvious shortcoming of the model at this stage is the masslessness of the charmed quark c . If we break the natural symmetry by

$$\mathcal{L} \rightarrow \mathcal{L} + m_c \bar{q}' q' \quad (12)$$

this problem is removed. By s - h mixing s acquires a mass $\sim (m_c^2/m_h)$; pursuing a phenomenological line as this may well be fruitful, though care must be exercised so that the neutrinos do not acquire masses.

It is clear that there is still a great deal of theoretical and phenomenological work to be done on the model. At this stage it possesses a high degree of symmetry between leptons and hadrons and an intriguing underlying dynamical structure ; some sort of natural symmetry is probably necessary if one is to ever obtain a true calculation of lepton and hadron masses (or mass differences) and the model has some promise along these lines without blatantly contradicting present phenomenology.

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