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Charged Higgs boson

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Assuming that there are more than one Higgs scalar doublet, we discuss the characteristics of the observable charged Higgs boson $H^{\pm}$ in the context of a vectorlike model of the $SU(2)\times U(1)$ gauge field theory. In particular, the production and the subsequent decay of $H^{\pm}$, the contribution to the muon magnetic-moment anomaly, and the contribution to the trimuon events in the neutrino reaction are surveyed.

I. INTRODUCTION

The renormalizable gauge-field model[1] that unifies the electromagnetic and the weak interactions opened the door to a computable weak-interaction theory. The detection of the vector bosons as a means of direct evidence of the theory, however, seems a remote possibility for some time to come because of their expected high masses (≈ 40 GeV or more). The Higgs scalar boson which generates the masses of various particles via spontaneous symmetry breaking is another key particle, the observation of which no doubt would give strong support for the gauge-field theory. (A gauge theory with a single Higgs scalar doublet predicts the existence of an observable neutral Higgs boson H^0.) The mass of such a particle is suggested[2] to be in the range of a few GeV to 10 GeV, and an extensive study of the neutral Higgs boson production is made[3] based on the original Weinberg-Salam (WS) model.[1] At this point, it is worthwhile to notice that the modes of production and decay of the Higgs bosons are strongly model dependent. Should the gauge-field model be modified in an esstential way, we have to reanalyze the processes which involve Higgs bosons. In fact, it seems that there is mounting evidence which suggests such a change.

The failure to detect the parity-violation effect in heavy atoms,[4] the observation of the y anomaly in the $\bar{\nu}$ reaction,[5] and the inadequacy of the pure vector model[6] generated an interest in the so-called vectorlike model[7,8] as an alternative to the naive WS model. Such modification inevitably introduces heavy neutral leptons which make some of the Higgs-particle couplings larger than in the WS model. A different mass-generation mechanism also implies a drastic change in the decay modes, e.g., the decay mode $H^0\to\mu^+\mu^-$, which is considered as a significant signature of the Higgs boson, does not exist in a vectorlike model, as will be seen later.

As to the number of Higgs scalars in the theory, there are no compelling reasons to have more than one Higgs scalar doublet from the point of view of mass generation. On the other hand, it is known that CP nonconservation can be introduced by spontaneous symmetry breaking, provided that there exist more than one Higgs doublet.[9] We adopt the latter view, or more explicitly, we assume that there are at least two Higgs scalar doublets, so that after absorbing three Goldstone bosons (two charged and one neutral) as the longitudinal components of the massive vector bosons, $W^{\pm}$ and Z^0, we are left with three massive neutral Higgs bosons and two charged Higgs bosons $H^{\pm}$ as observable objects. In particular, in this article, we discuss the decay modes and the production processes of the $H^{\pm}$ particle assuming that the mass $m_{H^{\pm}}$ ranges from 3 to 10 GeV. In an earlier communication, the author indicated that the trimuon events in the neutrino reaction may be explained by charged-Higgs-boson production, provided the value of $m_{H^{\pm}}$ is in the range mentioned above.

Finally, a comment on the observability of the Higgs bosons is in order. A great flexibility of the Higgs couplings, in contrast to the rigid restriction on the gauge-field coupling (unique once the group is decided), makes us wonder whether the Higgs scalrs may not be fundamental objects. Instead, they may be produced dynamically, say as bound states of the gauge fields, leptons, and quarks. This is an interesting suggestion, but it is extremely difficult to implement such an idea into a practical formalism. However, I believe that even if the Higgs scalars are dynamically derived objects, it still makes sense to use them as fields in the Lagrangian and the Higgs bosons should be observable as particles. The situation in that case is analogous to that of phonons in a solid. The phonons are definitely dynamically derived objects, originated from the electromagnetic interactions of the matter. Nevertheless, it is useful and practical to use them as fields which appear in the Lagrangian and, after all, one can observe them as particles which have attributes such as mass, energy, and momentum.

The plan of this article is the following: In Sec. II the model which we adopted is presented and the mixing of the neutral leptons as a result of the mass-generating mechanism and the decay of the neutral Higgs bosons are discussed. Assuming the existence of more than one kind of Higgs scalar doublet, we consider the characteristics of the charged Higgs boson in Sec. III. The contribution to the muon magnetic-moment anomaly, due to the $\mu^{\pm}-H^{\pm}$-neutral-lepton coupling, is estimated in Sec. IV. Section V deals with the trimuon events in the neutrino reaction and Sec. VI deals with the production of $H^{\pm}$.

II. A VECTORLIKE MODEL WITH NINE LEPTONS AND NINE QUARKS

In a recent paper,[8] the author adopted the principles of universality among leptons and the lepton-quark symmetry in the flavor degree of freedom to construct a vectorlike model. It consists of nine leptons (E^0, ν_e, e^-), (M^0, ν_μ, μ^-), (T^0, ν_τ, τ^-), and nine quarks (u, d, s), (u^c, d^c, s^c), (u^t, d^t, s^t). The latter, of course, has the color degree freedom of SU(3), too, which represents the strong interaction. The multiplets in the SU(2) × U(1) gauge group are the doublets

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L, \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L, \quad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L,$$
$$\begin{pmatrix}E^0\\ e^-\end{pmatrix}_R, \quad \begin{pmatrix}M^0\\ \mu^-\end{pmatrix}_R, \quad \begin{pmatrix}T^0\\ \tau^-\end{pmatrix}_R, \tag{2.1}$$

and singlets

$$(\nu_e)_R, \quad (\nu_\mu)_R, \quad (\nu_\tau)_R,$$
$$(E^0)_L, \quad (M^0)_L, \quad (T^0)_L \tag{2.2}$$

for leptons, and the doublets

$$\begin{pmatrix}u\\ d\end{pmatrix}_L, \quad \begin{pmatrix}u^c\\ \tilde{s}\end{pmatrix}_L, \quad \begin{pmatrix}u^t\\ d^t\end{pmatrix}_L,$$
$$\begin{pmatrix}u\\ d^c\end{pmatrix}_R, \quad \begin{pmatrix}u\\ s^c\end{pmatrix}_R, \quad \begin{pmatrix}u^t\\ s^t\end{pmatrix}_R, \tag{2.3}$$

and singlets

$$d_R, \quad s_R, \quad (d^t)_R,$$
$$(d^c)_L, \quad (s^c)_L, \quad (s^t)_L \tag{2.4}$$

for quarks. However, these forms of multiplets have only a symbolic meaning: The mass-generation mechansim inevitably induces mixing between the members in a triplet which have equal charges. We illustrate them for the (M_0, ν_μ, μ^-) triplet. In contrast to the original WS model, the masses of the charged leptons and the u-type quarks are generated without the Higgs scalar: The gauge-invariant mass term,

$$-\mathcal{L}^{(\mu)}_{\text{mass}} = m_\mu(\overline{\nu}_\mu, \overline{\mu}^-)_L \begin{pmatrix}M_0\\ \mu^-\end{pmatrix}_R + \text{H.c.}$$
$$= m_\mu(\overline{\mu}^-\mu^- + \overline{\nu}^L_\mu M^R_0 + \overline{M}^R_0 \nu^L_\mu), \tag{2.5}$$

then leads to a mixing of the neutral leptons ν_μ and M_0. In order to diagonalize the mass term, we define the doublets

$$\psi_L = \begin{pmatrix}M_1\\ \mu^-\end{pmatrix}_L, \quad \psi_R = \begin{pmatrix}M_2\\ \mu^-\end{pmatrix}_R \tag{2.6}$$

and the singlets

$$(N_1)_L, \quad (N_2)_R, \tag{2.7}$$

where M_i's and N_i's are linear combinations of ν_μ and M_0 and M_i is orthogonal to N_i. The gauge-invariant mass-generating terms in the Lagrangian are then given by

$$-\mathcal{L}^{(\mu)}_{\text{mass}} = m_\mu \overline{\psi}_L \psi_R + \rho \overline{N}^L_1 N^R_2 + \lambda_1 \overline{\psi}_L \hat{\varphi}_1 N^R_2$$
$$+ \lambda_2 \overline{\psi}_R \hat{\varphi}_1 N^L_1 + \text{H.c.}, \tag{2.8}$$

where $\rho, \lambda_1, \lambda_2$ are constants and the Higgs scalar doublet,

$$\varphi_1 = \begin{pmatrix}\varphi^+_1\\ \varphi^0_1\end{pmatrix} \quad \text{or} \quad \hat{\varphi}_1 = i\tau_2\varphi^*_1 = \begin{pmatrix}\overline{\varphi}^0_1\\ -\varphi^-_1\end{pmatrix}, \tag{2.9}$$

is used. The diagonalization of the mass matrix with the spontaneous symmetry breaking $\langle \varphi^0_1 \rangle = v_1/\sqrt{2}$ is attained by assuming

$$M_1 = \nu_\mu \cos\varphi + M_0 \sin\varphi, \quad M_2 = -\nu_\mu \sin\xi + M_0 \cos\xi,$$
$$N_1 = -\nu_\mu \sin\varphi + M_0 \cos\varphi, \quad N_2 = \nu_\mu \cos\xi + M_0 \sin\xi. \tag{2.10}$$

The requirement that

$$-\mathcal{L}^{(\mu)}_{\text{mass}} = m_\mu \overline{\mu}\mu + m_0 \overline{M}_0 M_0 \tag{2.11}$$

leads to the determination of the parameters

$$m_\mu = M_0 \sin\varphi \cos\xi,$$
$$\rho = M_0 \cos\varphi \sin\xi,$$
$$\lambda_1 \frac{v_1}{\sqrt{2}} = \rho \tan\varphi = M_0 \sin\varphi \sin\xi = m_\mu \tan\xi,$$
$$\lambda_2 \frac{v_1}{\sqrt{2}} = m_\mu \cot\varphi = M_0 \cos\varphi \cos\xi. \tag{2.12}$$

Since the absence of the right-handed ν_μ in low-energy weak-interaction phenomena implies that

$$\xi \ll 1, \tag{2.13}$$

we conclude that

$$\sin\varphi \cong \frac{m_\mu}{m_0} \tag{2.14}$$

and

$$\frac{\lambda_1}{\lambda_2} = \tan\varphi \tan\xi \ll \frac{m_\mu}{m_0}\,, \tag{2.15}$$

with good accuracy.

The Higgs-boson interaction is obtained by replacing φ_1 in Eq. (2.8) by

$$\varphi_1 = e^{i\vec{\tau}\cdot\vec{\xi}/v_1} \begin{bmatrix} 0 \\ \frac{v_1 + H^0}{\sqrt{2}} \end{bmatrix} \tag{2.16}$$

with the choice of gauge

$$\vec{\xi} = 0 \tag{2.17}$$

$$\mathcal{L}_{H_0} = -\lambda_1(\overline{\nu}_\mu \cos\varphi + M_0 \sin\varphi)_L(\nu_\mu \cos\xi + M_0 \sin\xi)_R H_0 - \lambda_2(-\overline{\nu}_\mu \sin\varphi + \overline{M}_0 \cos\varphi)_L(-\nu_\mu \sin\xi + M_0 \cos\xi)_R H_0 + \text{H.c.} \tag{2.18}$$

$$\begin{aligned} = [\, &-(\lambda_1 \sin\varphi \sin\xi + \lambda_2 \cos\varphi \cos\xi)\overline{M}_0 M_0 - (\lambda_1 \cos\varphi \cos\xi + \lambda_2 \sin\varphi \sin\xi)\overline{\nu}_\mu \nu_\mu \\ &+ (-\lambda_1 \cos\varphi \sin\xi + \lambda_2 \sin\varphi \cos\xi)(\overline{\nu}_\mu^L M_0^R + \overline{M}_0^R \nu_\mu^L) + (-\lambda_1 \sin\varphi \cos\xi + \lambda_2 \cos\varphi \sin\xi)(\overline{M}_0^L \nu_\mu^R + \overline{\nu}_\mu^R M_0^L)\,]H_0\,. \end{aligned} \tag{2.19}$$

From Eq. (2.15), it follows that (assuming that $m_0 \approx 2$ GeV)

$$\lambda_1 \lesssim 10^{-3}\lambda_2\,,$$

and therefore the λ_1 term may be negligibly small The dominant decay mode of H_0 is then

$$H_0 \to M_0 + \overline{M}_0 \tag{2.20}$$

followed by the successive decay

$$M_0 \to \mu^- + \begin{cases} \mu^+ + \nu_\mu \\ e + \nu_e \\ \text{hadrons} \end{cases} \tag{2.21}$$

and its charge-conjugate reaction. Using the relationship between the vector-boson mass m_W and the vacuum expectation value of the Higgs scalar,

$$\frac{1}{v_1^2} = \frac{1}{4}\frac{g^2}{m_W^2} = \sqrt{2}\,G_F\,, \tag{2.22}$$

where g and G_F are the SU(2) gauge field coupling constant and the Fermi coupling constant, respectively, we obtain the coupling strength of the reaction (2.20),

$$\begin{aligned} \frac{(\lambda_2)^2}{4\pi} &= \frac{2}{4\pi}\frac{m_0^2}{v_1^2} = \frac{10^{-5}}{\sqrt{2}\,\pi} \times (m_0/m_N)^2 \\ &= 1.0 \times 10^{-5} \quad (\text{for } m_0 \cong 2 \text{ GeV}), \end{aligned} \tag{2.23}$$

which is of the order of α^2. The rate of the decay (2.20) is then

$$\begin{aligned} \Gamma(H^0 \to M^0\overline{M}^0) &= \frac{\lambda_2^2}{8\pi} m_H \left(1 - \frac{4m_0^2}{m_H^2}\right)^{3/2} \\ &= 0.56 \times 10^{-5} \text{ GeV} \\ &= \frac{1}{1.3 \times 10^{-19} \text{ sec}}\,, \end{aligned} \tag{2.24}$$

for $m_H = 5$ GeV and $m_0 = 2$ GeV. On the other hand, the partial decay rate of the process (2.21) is typically

$$\begin{aligned} \Gamma(M^0 \to \mu^- \mu^+ \nu_\mu) &= \frac{G_F^2}{192\pi^3} m_0^5 \\ &= 0.69 \times 10^{-12} \text{ GeV} \\ &= \frac{1}{2.9 \times 10^{-12} \text{ sec}}\,. \end{aligned} \tag{2.25}$$

Considering the other decay modes such as

$$H^0 \to E^0\overline{E}^0, \quad T^0\overline{T}^0, \quad \text{etc.} \tag{2.26}$$

and

$$M^0 \to \mu^- + \begin{cases} e^+ + \nu_e \quad \text{etc.}, \\ \text{hadrons} \end{cases} \tag{2.27}$$

we would estimate the total decay lives

$$\tau_{H^0} \approx 10^{-19} \text{ sec}\,, \tag{2.28}$$

$$\tau_{M^0} \approx 10^{-12} \text{ sec} \tag{2.29}$$

for an arbitrary choice $m_{H^0} = 5$ GeV and $m_0 = 2$ GeV. The lifetime (2.28) is similar to that in the naive WS model, but the decay modes are entirely different in the two models. In the WS model, the

H^0 particle decays into charged-lepton pairs and u-type-quark pairs, while in the vectorlike model, it decays predominantly into heavy-neutral-lepton pairs and heavy-quark pairs $d^c\bar{d}^c$, $s^c\bar{s}^c$, and $s^t\bar{s}^t$, if energy conservation permits them.

III. THE CHARGED HIGGS BOSON

Although the minimum set of Higgs scalars required for mass generation is a single doublet, there is no limitation as the number of Higgs scalars which can be used in the theory. Should there exist two or more Higgs scalar doublets by some reason, then the model would predict charged Higgs bosons as well as a few more neutral particles. This is indeed the case if the observed CP violation in the weak decays of the K^0-$\bar{K}^0$ system is a spontaneously broken symmetry: The introduction of two kinds of Higgs scalar doublets inevitably requires a phase factor for one of the vacuum expectation values of the Higgs scalar, thus leading to a milliweak CP violation.[9]

Following such an idea, we assume that there exist at least two Higgs scalar doublets,

$$\varphi_i = \begin{pmatrix} \varphi_i^+ \\ \varphi_i^0 \end{pmatrix} \quad \text{or} \quad \varphi_i = i\tau_2\varphi_i^* = \begin{pmatrix} \bar{\varphi}_i^0 \\ -\varphi_i^- \end{pmatrix}, \quad i = 1, 2 \tag{3.1}$$

which have the vacuum expectation values

$$\langle\varphi_1^0\rangle = \frac{v_1}{\sqrt{2}} \text{ and } \langle\varphi_2^0\rangle = \frac{v_2}{\sqrt{2}}\, e^{i\theta}\,. \tag{3.2}$$

Since three out of eight degrees of freedom of the two doublets are absorbed into the longitudinal modes of the massive vector bosons (two charged and one neutral), we are left with three neutral Higgs bosons, H_i^0 $(i = 1, 2, 3)$, and two charged Higgs bosons, $H^\pm$, as observable objects. In this and subsequent sections, we investigate the important characteristics of the $H^\pm$ particle.

According to the analysis of T. D. Lee,[9] the charged Higgs boson can be expressed in terms of the $\varphi_i^\pm$ fields in the following way:

$$H^\pm = \frac{1}{(v_1^2 + v_2^2)^{1/2}}\, (v_2\varphi_1^\pm - v_1\varphi_2^\pm e^{\mp i\theta})\,, \tag{3.3}$$

while the massless charged Goldstone bosons which are to be absorbed into the $W_\mu^\pm$ bosons are

$$G^\pm = \frac{1}{(v_1^2 + v_2^2)^{1/2}}\, (v_1\varphi_1^\pm + v_2\varphi_2^\pm e^{\mp i\theta})\,. \tag{3.4}$$

Inverting Eqs. (3.3) and (3.4), we have

$$\varphi_1^\pm = \frac{1}{(v_1^2 + v_2^2)^{1/2}}\, (v_2 H^\pm + v_1 G^\pm) \tag{3.5}$$

and

$$\varphi_2^\pm = \frac{1}{(v_1^2 + v_2^2)^{1/2}}\, (-v_1 H^\pm + v_2 G^\pm) e^{\pm i\theta}\,. \tag{3.6}$$

The vacuum expectation values are related to the vector-boson mass by

$$\frac{1}{v_1^2 + v_2^2} = \frac{1}{4}\frac{g^2}{m_W^2} = \sqrt{2}\, G_F \tag{3.7}$$

in lieu of Eq. (2.22).

First, for the sake of simplicity, let us assume that only one of the Higgs doublets, say φ_1, can couple to the muon fields. In this case, formulas (2.5)–(2.15) are valid, and the interaction involving the $H^\pm$ particle is given by

$$\begin{aligned}\mathcal{L}_{H^\pm} = {} & \frac{\lambda_1 v_2}{(v_1^2 + v_2^2)^{1/2}}\, \bar{\mu}_L^-(\nu_\mu \cos\xi + M_0 \sin\xi)_R H^- \\ & + \frac{\lambda_2 v_2}{(v_1^2 + v_2^2)^{1/2}}\, \bar{\mu}_R^-(-\nu_\mu \sin\varphi + M_0 \cos\varphi)_L H^- \\ & + \text{H.c.}\,.\end{aligned} \tag{3.8}$$

A more general case where both Higgs scalar doublets couple to the muon fields is discussed in the Appendix, giving the interaction Lagrangian

$$\begin{aligned}\mathcal{L}_{H^\pm} = {} & \frac{\lambda_1 v_2}{(v_1^2 + v_2^2)^{1/2}}\, \bar{\mu}_L^-(\nu_\mu e^{i\alpha_1}\cos\xi + M_0 e^{i\beta_1}\sin\xi)_R H^- \\ & + \frac{\lambda_2 v_2}{(v_1^2 + v_2^2)^{1/2}}\, \bar{\mu}_R^-(-\nu_\mu e^{-i\alpha_2}\sin\varphi + e^{-i\beta_2}M_0\cos\varphi)H^- \\ & + \text{H.c.}\,.\end{aligned} \tag{3.9}$$

where

$$\begin{aligned}\lambda_1 &= \lambda_{11} - \lambda_{12}\frac{v_1}{v_2}\, e^{-i\theta}\,, \\ \lambda_2 &= \lambda_{21} - \lambda_{22}\frac{v_1}{v_2}\, e^{-i\theta}\,,\end{aligned} \tag{3.10}$$

with the constraint

$$e^{i(\beta_1 + \alpha_2)} = 1\,. \tag{3.11}$$

The definition of the λ's and the phase parameters are given in the Appendix.

The dominant decay model of the $H^\pm$ particle is then

$$H^+ \to \mu^+ + M_0, \tag{3.12}$$

with the coupling strength

$$\begin{aligned}\frac{|f|^2}{4\pi} &= \frac{|\lambda_2|^2 v_2^2}{4\pi(v_1^2 + v_2^2)} \\ &= \frac{1}{4\pi}\frac{2m_0^2}{v_1^2 + v_2^2}\, R^2 \\ &= \frac{10^{-5}}{\sqrt{2}\pi}\left(\frac{m_0}{m_N}\right)^2 R^2 \\ &= 1.0\times 10^{-5}R^2 \quad (\text{for } m_0 = 2\text{ GeV}),\end{aligned} \tag{3.13}$$

where

$$R^2 = \begin{cases} \left(\dfrac{v_2}{v_1}\right)^2 & \text{(for the single Higgs coupling)} \\ \left| \dfrac{\lambda_{21} v_2 - \lambda_{22} v_1 e^{-i\theta}}{\lambda_{21} v_1 + \lambda_{22} v_2 e^{-i\theta}} \right|^2 & \text{(for the general case)}. \end{cases} \tag{3.14}$$

Since the quantity R is an arbitrary parameter, we cannot predict the decay rate of the process (3.12) with certainty. With the assumption $R^2 = 1$, the decay rate of (3.12) is estimated to be $1/(5 \times 10^{-20}\ \text{sec})$ and the decay life to $H^\pm$ is expected to be

$$\tau_{H^\pm} \approx 10^{-20}\ \text{sec} \tag{3.15}$$

for the assumed value of $m_H = 5$ GeV and $m_0 = 2$ GeV, in view of the competing decay modes

$$H^+ \to e^+ + E^0\,, \quad \tau^- + T^0\,, \quad \text{hadrons } (b + \bar{u})\,, \quad \text{etc.} \tag{3.16}$$

The branching ratio of the latter two in Eq. (3.16) may be small because of smaller available energies.

The neutral heavy leptons, M^0 or E^0, subsequently decay into

$$M^0 \to \mu^- + \begin{cases} \mu^+ + \nu_\mu \\ e^+ + \nu_e \\ \text{hadrons} \end{cases} \tag{3.17}$$

or

$$E^0 \to e^- + \begin{cases} \mu^+ + \nu_\mu \\ e^+ + \nu_e \\ \text{hadron} \end{cases} \tag{3.18}$$

with the lifetime

$$\tau_{M^0, E^0} \approx 10^{-12}\ \text{sec}\,. \tag{3.19}$$

The branching ratio may be estimated to be

$$\begin{aligned} B(M^0 \to \mu^- \mu^+ \nu_\mu) &\approx B(M^0 \to \mu^- e^+ \nu_e) \\ &\approx B(E^0 \to e^- \mu^+ \nu_\mu) \\ &\approx B(E^0 \to e^- e^+ \nu_e) \\ &\approx 0.2\,. \end{aligned} \tag{3.20}$$

The charged Higgs boson H^+ quickly decays into $\mu^+\mu^-$ or e^+e^- + something with the branching ratio $\approx \frac{1}{2}$, $\mu^+\mu^-\mu^+, \mu^+\mu^-e^+, e^+e^-e^+, e^+e^-p^+$ with the branching ratio $\approx \frac{1}{10}$. All these multileptons should come out at the target where the $H^\pm$ particles are produced, which should be a very distinctive signature of the charged Higgs bosons.

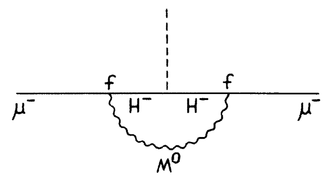

FIG. 1. The diagram for the muon magnetic-moment anomaly due to the charged Higgs boson $H^\pm$.

IV. THE MUON MAGNETIC-MOMENT ANOMALY

The interaction (3.12) obviously contributes to the anomaly a_μ of the muon magnetic moment. [The contribution to the electron anomaly is small by a factor $(m_e/m_\mu)^2 = 2.3 \times 10^{-5}$]. We calculate the a_μ by the diagram of Fig. 1, obtaining

$$\begin{aligned} (a_\mu)_{H^\pm} &= \left(\frac{g_\mu - 2}{2}\right)_{H^\pm} \\ &= -\frac{f^2}{16\pi^2} m_\mu^2 \int_0^1 \frac{x^2(1-x)\,dx}{m_H^2 x + m_0^2(1-x) - m_\mu^2 x(1-x)} \\ &= -\frac{10^{-5}}{4\sqrt{2}\pi^2}\left(\frac{m_\mu}{m_N}\right)^2 R^2 g(r) \\ &= -2.3 \times 10^{-9} R^2 g(r)\,, \end{aligned} \tag{4.1}$$

where R^2 is defined in Eq. (3.14) and

$$g(r) = \frac{r}{1-r}\left[\frac{1}{6} - \frac{1}{2}\frac{r}{1-r} - \left(\frac{r}{1-r}\right)^2 + \frac{r_2}{(1-r)^3} \ln \frac{1}{r}\right], \tag{4.2}$$

with

$$r = (m_0/m_H)^2\,.$$

In the integration of Eq. (4.1), we assumed that $m_\mu \ll m_H, m_0$. The consistency of the experiment[10] and the QED prediction to the accuracy 10^{-8} puts the limit on the parameter R^2, which is shown in Table I. It is obvious from Table I that the anomaly of the muon magnetic moment will not give a useful bound on the arbitrary parameter R^2 at the present level of accuracy.

TABLE I. The upper bound on R^2 [defined by Eq. (3.14)] from the muon magnetic-moment anomaly.

$r = \left(\dfrac{m_0}{m_H}\right)^2$	$g(r)$	The upper bound on R^2
0.1	0.0144	390
0.2	0.0262	210
0.3	0.0363	150
0.4	0.0451	120
0.5	0.0530	110
1	$\frac{1}{12} = 0.0833$	67

V. TRIMUON EVENTS IN THE NEUTRINO REACTION

Recent experiments[11] in the neutrino reaction (on the nuclear targets) showed that three muons are produced in the lepton sector with the branching ratio

$$R_{3\mu}=\frac{\Gamma(\nu_\mu+Z\to 3\mu+X)}{\Gamma(\nu_\mu+Z\to \mu+X)}\approx(1-5)\times 10^{-4}\,. \tag{5.1}$$

A typical explanation[12] of such phenomena is to assume the existence of a charged heavy lepton L^- of the mass ≈ 7 GeV which is produced by the incident ν_μ and subsequently decays into the muons

$$\begin{aligned}\nu_\mu+Z\to\ & L^-+X\\ & \searrow M^0\mu^-\bar\nu_\mu\\ & \quad\searrow \mu^-\mu^+\nu_\mu\,.\end{aligned} \tag{5.2}$$

In the vectorlike model considered in this article, the above explanation requires new triplets of leptons and quarks, and also the mixing among all d- or s-type quarks should be introduced (via the Higgs mechanism) in order not to have absolutely stable heavy hadrons. Although the condition for an asymptotically free theory[13] admits up to five flavor triplets of quarks, it would be esthetically more appealing to have the fewest possible number of fields. Besides, the scheme (5.2) would have difficulty since the small mixing angles would be used in two places: in the production vertex $\nu_\mu\to L^-+W^+$ and in the decay $L^-\to M^0\mu^-\bar\nu_\mu$. As was indicated in an earlier communication,[14] we show that the observed trimuon events can be explained without introducing the new charged heavy lepton.

The interaction of the charged Higgs boson (3.8) or (3.9) contains the vertex

$$\nu_\mu\to\mu^-+H^+ \tag{5.3}$$

with coupling strength

$$\frac{|f'|^2}{4\pi}=\frac{|f|^2\sin^2\varphi}{4\pi}=\frac{10^{-5}}{\sqrt{2}\pi}\left(\frac{m_\mu}{m_N}\right)^2R^2$$
$$=2.87\times10^{-8}R^2\,. \tag{5.4}$$

The process which we proposed as an explanation for the trimuon events is the associate production of μ^-H^+ by neutrinos via the electromagnetic interaction with nuclei. Since H^+ predominantly decays into 2μ or $2e+(\mu\nu$ or $e\nu$ or hadrons) we could account for the trimuon events, provided that the production cross section is sizable. The alleged process is written schematically,

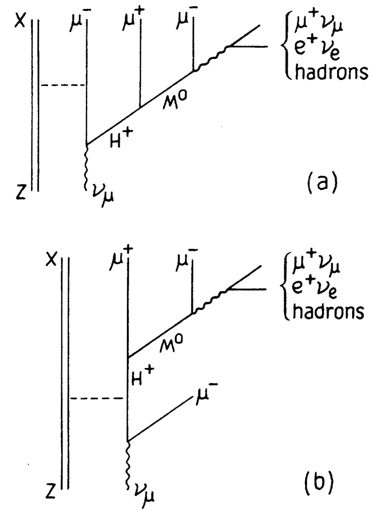

FIG. 2. Trimuon events due to the production of the charged Higgs boson and its successive decay.

$$\begin{aligned}\nu_\mu+Z\to\mu^-+\ & H^++X\\ & \searrow \mu^++M^0\\ & \qquad\quad\searrow \mu^-+\begin{cases}\mu^++\nu_\mu\\ e^++\nu_e\\ \text{hadrons}\end{cases}\end{aligned} \tag{5.5}$$

or

$$\begin{aligned}\nu_\mu+Z\to\mu^-+\ & H^++X\\ & \searrow e^++E^0\\ & \qquad\quad\searrow e^-+\begin{cases}\mu^++\nu_\mu\\ e^++\nu_e\\ \text{hadrons}\end{cases}\end{aligned} \tag{5.6}$$

The Feynman diagrams of (5.5) are given in Fig. 2.

If the mass of the charged Higgs boson is ~ 5 GeV, then one might assume that the processes (5.5) and (5.6) dominate over $H^-\to\tau^-+T^0$ or $b+\bar u$ because the phase space available for the latter may be small. Then the branching ratio

$$B_\mu=\frac{\Gamma(H^+\to\mu^++M^0)}{\Gamma(H^+\to\text{all})}\approx\tfrac{1}{2} \tag{5.7}$$

as was mentioned earlier, and

$$R_{3\mu}=\frac{\sigma(\nu_\mu Z\to\mu^-+H^++X)}{\sigma(\nu_\mu Z\to\mu^-+X)}B_\mu$$
$$\cong\frac{1}{2}\,\frac{\sigma(\nu_\mu Z\to\mu^-+H^++X)}{\sigma(\nu_\mu Z\to\mu^-+X)}\,. \tag{5.8}$$

In evaluating (5.8), $\sigma(\nu_\mu Z\to\mu^-+X)$ is taken from Ref. 15 (multiplied by 0.8 to eliminate the neutral-current component), and $\sigma(\nu_\mu+Z\to\mu^-+H^++X)$ is estimated from the calculation of Refs. 16 and 17 neglecting the effect of spin. The results thus

TABLE II. Estimate of the ratio $R_{3\mu}$ of the trimuon cross section to the single-muon cross section.

m_H (GeV) \ E (GeV)	100	150	200
3	2.0×10^{-4}	3.0×10^{-4}	3.6×10^{-4}
4	0.41×10^{-4}	0.70×10^{-4}	1.0×10^{-4}
5	0.12×10^{-4}	0.19×10^{-4}	0.27×10^{-4}
8	0.61×10^{-6}	1.7×10^{-6}	2.3×10^{-6}
10	2.5×10^{-8}	2.9×10^{-7}	0.60×10^{-6}

obtained are summarized in Table II, with the assumption $R=1$. Although the $\nu_\mu \mu^- H^+$ coupling constant contains an arbitrary factor R, it is evident from Table II that for the mass range $m_H = 3$–5 GeV and $R=O(1)$, the process (5.5) can account for the observed value of $R_{3\mu}$ reasonably well. The value of $m_H = 10$ GeV may not be excluded if $R \cong 10$. Detailed calculations of the production cross section $\sigma(\nu_\mu + Z \to \mu^- + H^+ + X)$, the momentum distribution of μ's, and the angular correlation of 2μ's are in progress, to be compared with this experiment.

VI. PRODUCTION OF THE CHARGED HIGGS BOSONS

Assuming that the mass of the charged Higgs bosons $H^\pm$ is 3–10 GeV, we suggest that intensive searches for such particles should be made, since, once produced, the detection is easy. As is mentioned earlier, the lifetimes of $H^\pm$ and M^0 or E^0 are 10^{-20} and 10^{-12} sec, respectively, and hence, the leptons, as the decay products, will be emitted at the target.

Upon completion of the PETRA or PEP machine, it is definitely desirable to look for

$$e^- + e^+ \to H^- + H^+ \tag{6.1}$$

$$H^+ \to \begin{cases} \mu^+ + M^0, & M^0 \to \mu^- + \begin{cases} \mu^+ + \nu_\mu \\ e^+ + \nu_e \\ \text{hadrons} \end{cases} \\ e^+ + E^0, & E^0 \to e^- + \begin{cases} \mu^+ + \nu_\mu \\ e^+ + \nu_e \\ \text{hadrons} \end{cases} \end{cases}$$

$$H^- \to \begin{cases} \mu^- + \bar{M}^0, & \bar{M}^0 \to \mu^+ + \begin{cases} \mu^- + \bar{\nu}_\mu \\ e^- + \bar{\nu}_e \\ \text{hadrons} \end{cases} \\ e^- + \bar{E}^0, & \bar{E}^0 \to e^+ + \begin{cases} \mu^- + \bar{\nu}_\mu \\ e^- + \bar{\nu}_e \\ \text{hadrons} \end{cases} \end{cases}$$

The resultant particles to be observed in this process are typically 4–6 leptons. Since there is no known particle which could decay into the multicharged lepton state, this will be a clear signature. Of course heavy-charged-lepton pairs could be produced if such a particle exists and each particle could decay into multilepton states with a small branching ratio. However, the main decay mode of such a heavy lepton is a single charged lepton + neutrals. We should stress that the decay scheme (6.1) is the main decay mode of the charged-Higgs-boson pair. With the assumption of the branching ratio

$$\frac{\Gamma(M^0 \to \mu^- \mu^+ \nu_\mu)}{\Gamma(H^+ H^- \to \text{all})} \approx \frac{1}{5}\,, \tag{6.2}$$

we would estimate

$$\frac{\Gamma(H^+ H^- \to 6\mu)}{\Gamma(H^+ H^- \to \text{all})} \approx \frac{1}{100}\,. \tag{6.3}$$

Therefore it seems to be possible to observe the 6μ events, should the $H^\pm$ particle exist. The momentum distributions of the muon, and the angular correlation of the μ's should also tell us whether scalar particle pairs are really produced or not.

The pair production of the charged Higgs boson can also occur via electromagnetic interaction in any reaction such as

$$\begin{aligned} &p + p \to H^+ + H^- + X\,, \\ &\pi + p \to H^+ + H^- + X, \\ &\bar{p} + p \to H^+ + H^- + X, \\ &\gamma + p \to H^+ + H^- + X, \text{ etc. .} \end{aligned} \tag{6.4}$$

Although the magnitude of the production cross section is smaller by the fine-structure constant α compared with the hadronic processes, the multilepton decay product is a decisive signature, so that it should be observable without any difficulty. The only problem could be the energy available if the mass of $H^\pm$ is close to 10 GeV. In this case, we have to wait for higher-energy beams than those of the accelerators at Fermilab or CERN II.

Note added. (1) If one wishes to avoid the mixing of ν_μ and M_0 in the model proposed in this article, one may assume the existence of a doublet and a triplet of Higgs scalars and a special interaction form for the triplet Higgs scalar $\vec{\eta}$,

$$-\mathcal{L}^{(\mu)}_{\text{mass}} = m_\mu \bar{\psi}_L \left(1 - \frac{\vec{\tau}\vec{\eta}}{\langle \eta_0 \rangle}\right) \psi_R + \text{H.c.}\,,$$

instead of Eq. (2.5). This possibility was explored by Deshpande and Ma.[18] They showed that the dominant decay modes of the charged Higgs bosons in such a model are hadronic ones which makes the detection of the Higgs bosons difficult.[19] (Their model does not lead to the spontaneous breaking of CP symmetry unless another set of doublet Higgs scalars is introduced.) On the other hand, our model predicts that the Higgs bosons $H^{\pm}$ predominantly decay into multilepton states as is explained in Sec. III [Eqs. (3.8) and (3.16)], provided that the masses of the quarks d^c, s^c, and s^t are heavy. This would give a very clear signature in detecting the charged Higgs bosons.

(2) A two-doublet Higgs scalar model was proposed by Ma, Pakvasa, and Tuan[20] to explain Perl events.

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APPENDIX: MASS GENERATION OF THE MUON FAMILY WITH TWO HIGGS SCALAR DOUBLETS

The mass matrix, which is a generalization of Eq. (2.8), can be written as

$$-\mathcal{L}_{\text{mass}} = m_\mu \bar{\psi}_L \psi_R + \rho \bar{N}_1^L N_2^R + \bar{\psi}_L(\lambda_{11}\hat{\varphi}_1 + \lambda_{12}\hat{\varphi}_2)N_2^R + \bar{\psi}_R(\lambda_{21}\hat{\varphi}_1 + \lambda_{22}\hat{\varphi}_2)N_1^L + \text{H.c.}, \tag{A1}$$

where definitions (2.6), (2.7), and (3.1) are used. The diagonalization of (A1) is achieved by postulating

$$\begin{aligned} M_1 &= \nu_\mu e^{i\alpha_1}\cos\varphi + M_0 e^{i\beta_1}\sin\varphi, \\ M_2 &= -\nu_\mu e^{-i\beta_2}\sin\xi + M_0 e^{-i\alpha_2}\cos\xi, \\ N_1 &= -\nu_\mu e^{-i\beta_1}\sin\varphi + M_0 e^{-i\alpha_1}\cos\varphi, \\ M_2 &= \nu_\mu e^{i\alpha_2}\cos\xi + M_0 e^{i\beta_2}\sin\xi. \end{aligned} \tag{A2}$$

The requirement

$$-\mathcal{L}_{\text{mass}} = m_\mu \mu\bar{\mu} + m_0 \bar{M}_0 M_0 \tag{A3}$$

leads to

$$\begin{aligned} & e^{i\beta_1 + i\alpha_2} = 1, \\ & m_\mu = m_0 \sin\varphi\cos\xi, \\ & \rho = e^{-i\alpha_1 - i\beta_2} m_0 \cos\varphi \sin\xi, \\ & \lambda_{11}v_1 + \lambda_{12}v_2 e^{-i\theta} = \sqrt{2}\,\rho e^{i(\alpha_1+\beta_1)}\tan\varphi \\ & \qquad = \sqrt{2}\, m_0 e^{i(\beta_1-\beta_2)}\sin\varphi\sin\xi, \\ & \lambda_{21}v_1 + \lambda_{22}v_2 e^{-i\theta} = \sqrt{2}\, m_\mu e^{i(\alpha_1+\beta_1)}\cot\varphi \\ & \qquad = \sqrt{2}\, m_0 e^{i(\alpha_1+\beta_1)}\cos\varphi\cos\xi \end{aligned} \tag{A4}$$

($e^{i\beta_1 + i\alpha_2} = -1$ is also a solution, but this case will be reduced to the one which we obtained above by redefining the angle φ, ξ appropriately). The same reasoning as before gives the conditions

$$|\xi| \ll 1$$

and

$$\sin\varphi \approx \frac{m_\mu}{m_0} \ll 1\,. \tag{A5}$$

The ratio of the last two equations in (A4) is

$$\left|\frac{\lambda_{11}v_1 + \lambda_{12}v_2 e^{-i\theta}}{\lambda_{21}v_1 + \lambda_{22}v_2 e^{-i\theta}}\right| = |\tan\varphi\tan\xi| \ll \frac{m_\mu}{m_0} \tag{A6}$$

and is of the order of $<10^{-3}$. Except for a case of accidental cancellation, it is natural to assume that

$$|\lambda_{11}|,\ |\lambda_{12}| \ll |\lambda_{21}|,\ |\lambda_{22}|, \tag{A7}$$

and thus we may neglect the effect of the λ_{11} and λ_{12} terms. Using Eqs. (3.5) and (3.6), we obtain the interaction Lagrangian (3.9) in the text, which gives the coupling of the charged Higgs boson $H^{\pm}$ and the $\mu^-\bar{\nu}_\mu$ and $\mu^-\bar{M}^0$ pairs.

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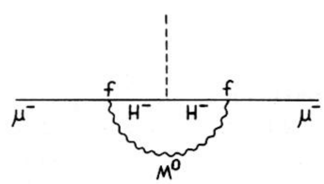

FIG. 1. The diagram for the muon magnetic-moment anomaly due to the charged Higgs boson $H^{\pm}$.

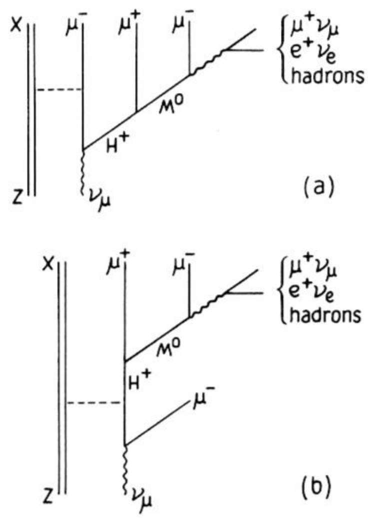

FIG. 2. Trimuon events due to the production of the charged Higgs boson and its successive decay.