Heavy-electron mass and CP violation in a gauge model

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A renormalizable $[SU(2)\times Y]$ weak gauge model is studied in which spontaneous breakdown generates masses for all fermions except neutrinos and gauge bosons except the photon and at the same time destroys the original P and CP invariance of the Lagrangian. A connection between the heavy-electron-to-electron mass ratio and the size of CP violation is pointed out. A free-quark-model calculation of lowest order CP violation in the $K^0 \leftrightarrow \bar{K}^0$ mass matrix is used to test whether the model can accommodate the measured CP violation ($|\epsilon| = 2\times 10^{-3}$) and the bound on heavy-lepton mass ($M_E > 1$ GeV). Assuming reasonable and consistent values of certain quark and Higgs-particle mass ratios, it is found that the model is consistent with known weak-interaction phenomenology if the mass of the heavy electron is *less* than about 6 GeV. The dominant leptonic decays of the heavy electron, E, are $E^- \to l^- + (\bar{\nu}_L^l) + \nu_R^e$, where $(\bar{\nu}_L^l)$ refers to the usual lepton ($l = e$ or μ) antineutrino but ν_R^e refers to a right-handed electron neutrino associated with the E.

I. INTRODUCTION

CP violation was introduced into renormalizable gauge models of weak and electromagnetic interactions soon after the upsurge in model building began in 1971 and 1972. Both explicit[1] and spontaneous[2] origins for CP-violating effects have been considered in detail in the literature.

In many of the models which have been proposed, with or without CP violation, new leptons are needed to fill in multiplets of the underlying gauge symmetries assumed.[3] Searches for heavy leptons have been under way for some time, and recent SLAC results[4] on anomalous $e\mu$ production in e^+e^- annihilation provide grounds for speculation that heavy leptons exist with a mass of approximately 2 GeV. If a heavy lepton exists, the ratio of the electron mass to heavy lepton mass is certainly very small, and one might ask whether this small ratio is related in any way to the small CP violation observed in K decays.

I suggest here that the small value of the ϵ parameter, which is characteristic of CP violation ($\epsilon \approx 2\times 10^{-3}$), and the necessarily small value of the ratio of electron mass, M_e, to heavy lepton mass, M_E (if the latter exist, $M_e/M_E < 5\times 10^{-4}$) have a common origin in the spontaneous breakdown of leptonic gauge symmetry, parity, and CP. In order to support this view, I present a model in which such a common origin of ϵ and M_e/M_E occurs.[5] The dominant leptonic decays of the heavy electron of this model are consistent with the observations at SLAC,[4] and read

$$E^- \to l^- + (\bar{\nu}_L^l) + \nu_R^e .$$

The *right*-handed counterpart of the electron neutrino is associated with the heavy electron and the usual right-handed electron (muon) antineutrino is associated with the electron (muon). This decay scheme gives the usual sequential $e^\pm\mu^\mp$ signature as in the events reported at SLAC.[4] The scheme which I present would require a three-body decay of each heavy particle—four missing neutral particles in all for $e^+e^- \to \mu^\pm e^\pm$ + missing neutrals. A distinctive feature is that the neutrinos have the same helicity in the final state of each decay particle.

The model is initially $[SU(2)\times Y]_{\text{weak}}$ gauge symmetric, parity-invariant, and CP-invariant and spontaneously breaks down to the residual electromagnetic gauge symmetry. The vacuum-breaking parameters supply masses to all particles except photon and neutrinos, and the relative phase between scalar and pseudoscalar vacuum expectation values supports all CP breaking. A close relationship is found between the CP-violating angle and the electron to heavy-electron mass ratio.

The model is described in Sec. II, where the couplings necessary for the $\bar{K}^0 \leftrightarrow K^0$ mass-mixing calculation of Sec. III are spelled out. The relationship derived in Sec. III between the measured CP parameter, ϵ, and the model's underlying spontaneous breaking CP parameter, θ, is discussed in Sec. IV. The conclusion is that the model accommodates known weak-interaction phenomenology if the heavy-electron mass, M_E, is in the range $1 \le M_E \le 6$ GeV.

II. THE MODEL

In this section, I define the gauge model of weak and electromagnetic interactions whose properties and consequences I wish to examine. The model is the same as the one previously discussed by McKay and Munczek[5] in a different context and without CP violation included. For ease of reference and in order to define all of the CP-violating parameters, I review the basic features of the model even though some of them have already been discussed in Ref. 5.

Leptons

The symmetry of the Lagrangian is chosen to be $[\mathrm{SU}(2)\times Y]_{\mathrm{weak}}$ with parity conservation before spontaneous breaking ensured by treating left and right symmetrically in the original Lagrangian, which is also CP-invariant. In the lepton sector, fermion fields are defined as[6]

$$\psi_e=\begin{pmatrix}\nu_{eL}+\nu_{eR}\\ e_L+E_R\end{pmatrix},\quad \xi_e=e_R+E_L\,, \tag{1}$$

and similarly for the muon μ, the heavy muon M, and the muon neutrino ν_μ. One needs at least two complex doublets of spin-zero particles in order to create parity-invariant Yukawa coupling to the leptons which, after spontaneous breakdown, provide masses for e, E, μ, and M. The choice of scalar fields is

$$s=\begin{pmatrix}s_1\\ s_2+\lambda_s/\sqrt{2g}\end{pmatrix},\quad t=\begin{pmatrix}t_1\\ t_2+\lambda_t e^{i\theta}/\sqrt{2g}\end{pmatrix}, \tag{2}$$

where the permitted relative phase between the vacuum expectation values of s and t is arbitrarily assigned to the t field (an account of the potential energy is given in Appendix A). Under parity transformation we choose $s\to s$, $t\to -t$. The general solution to the potential energy extremum problem admits this relative phase when there are two complex doublets with neutral members, as discussed by Lee.[7] This phase was arbitrarily set equal to zero in the study of Ref. 5. I wish to concentrate on parametrization of CP-violating effects via this phase in the present work.

In addition to the local $\mathrm{SU}(2)\times Y$ gauge transformations, an additional global γ_5 transformation is assigned and the Lagrangian is required to be invariant under this transformation. The choice of transformations is

$$\psi'=e^{i\alpha\gamma_5}\psi\,,\quad \xi'=e^{-i\alpha\gamma_5}\xi\,,\quad s'=s\,,\quad t'=t\,.$$

The weak-leptonic couplings of the fermions and scalar mesons are then limited to the form

$$\mathcal{L}_{(\text{weak-Yukawa})}=\sqrt{2}\,ga_e\bar{\xi}_e s^\dagger\psi_e+\sqrt{2}\,gb_e\bar{\xi}_e\gamma_5 t^\dagger\psi_e +\mathrm{H\,c.}+e\to\mu\,. \tag{3}$$

After spontaneous breakdown, as assigned in Eq. (2), mass terms for e, E, μ, and M emerge, but the ν_e and ν_μ fields remain massless. The mass terms are

$$\bar{e}(a_e\lambda_s-b_e\lambda_t\cos\theta-ib_e\lambda_t\sin\theta\gamma_5)e +\bar{E}(a_e\lambda_s+b_e\lambda_t\cos\theta-ib_e\lambda_t\sin\theta\gamma_5)E+e\to\mu\,, \tag{4}$$

which can be put in standard form by redefining the fermion fields and requiring that the mass terms not contain the γ_5 bilinear form. The CP-violating effects will then be shifted entirely to the physical Higgs-particle couplings (in the unitary gauge). If one makes the substitution

$$e\to e^{i(\alpha_e/2)\gamma_5}e\,,\quad E\to e^{i(\alpha_E/2)\gamma_5}E \tag{5}$$

and requires that the mass terms in Eq. (4) have the form $m\bar{\psi}\psi$, one finds that

$$\tan\alpha_e=\frac{\lambda_t b_e\sin\theta}{a_e\lambda_s-b_e\lambda_t\cos\theta},\qquad \tan\alpha_E=\frac{\lambda_t b_e\sin\theta}{a_e\lambda_s+b_e\lambda_t\cos\theta}, \tag{6}$$

where

$$M_e=[(a_e\lambda_s)^2+(b_e\lambda_t)^2-2a_eb_e\lambda_s\lambda_t\cos\theta]^{1/2}\,,\qquad M_E=[(a_e\lambda_s)^2+(b_e\lambda_t)^2+2a_eb_e\lambda_s\lambda_t\cos\theta]^{1/2}\,. \tag{7}$$

The relationship among the masses and CP-violating phases θ,α_e,α_E is represented geometrically in Fig. 1. A similar set of relations holds for muon parameters. From Fig. 1 we see that if $M_e/M_E\ll 1$, then $b_e\lambda_t\approx a_e\lambda_s$ and $\theta\ll 1$ is necessary. The lower bound on charged lepton masses has been established to be ~1 GeV,[8] so that if E-type leptons exist at all, the condition $M_e/M_E\ll 1$ is certainly true phenomenologically. It is this connection between the small electron to heavy-electron mass ratio and a small CP-violation angle and a "maximal P violation," $b_e\lambda_t\approx a_e\lambda_s$, which makes a more thorough study of CP-violation effects in the model of interest. I turn directly, then, to quark representation and CP-phase-angle choices in order to lay the groundwork for an estimate of the CP-violation effects in the kaon system within the framework of this model. A discussion of CP-violating effects in μ decay is relegated to Appendix B.

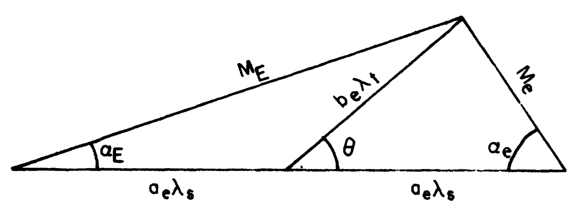

FIG. 1. Geometrical representation of the relationships among the quantities M_e, M_E, α_E, $\lambda_S a_e$, and $\lambda_t b_e$ defined in the text.

Quarks

The quarks are assigned to four singlets and two doublets of $[\mathrm{SU}(2)\times Y]_{\mathrm{weak}}$, and each singlet transforms as $S'=e^{-i\gamma_5\alpha'}S$ and each doublet as $D'=e^{i\gamma_5\alpha'}D$ under the global γ_5 group. Anticipating that the quark mass terms, which are all generated by the coupling to the scalar fields, will be CP-violating combinations of $\bar\psi\psi$ and $\psi\gamma_5\psi$ bilinear forms, I define doublets

$$Q=\begin{pmatrix}\mathcal{P}_L+\mathcal{P}'_R e^{-i\alpha_1}\\ \mathfrak{N}_L\cos\theta_C+\lambda_L\sin\theta_C+\mathfrak{N}'_R\cos\theta_C e^{i\alpha_2}+\lambda_R\sin\theta_C e^{i\alpha_3}\end{pmatrix},$$
$$Q_c=\begin{pmatrix}c_L+c'_L e^{-i\alpha_4}\\ -\mathfrak{N}_L\sin\theta_C+\lambda_L\cos\theta_C-\mathfrak{N}'_R\sin\theta_C e^{i\alpha_2}+\lambda'_R\cos\theta_C e^{i\alpha_3}\end{pmatrix},$$

and singlets (8)

$$\sigma=\mathfrak{N}_R e^{i\alpha_5}+\mathfrak{N}'_L\,,\quad \sigma_s=\lambda_R e^{i\alpha_6}+\lambda'_L\,,$$
$$\rho=\mathcal{P}_R e^{-i\alpha_7}+\mathcal{P}'_L\,,\quad \rho_c=c_R e^{-i\alpha_8}+c'_L\,.$$

The phases $\alpha_1\cdots\alpha_8$ are chosen in such a way that the fields $\mathcal{P}$, $\mathcal{P}'$, etc. have real masses and all CP-violation effects are contained in the quark couplings to the scalar fields. In the unitary gauge, which is the gauge I shall use in calculations of perturbation theory amplitudes, the physical Higgs-particle couplings to quarks and leptons carry the CP violation. The angle θ_C in Eq. (8) is the Cabibbo angle, and the familiar charmed quark mechanism[9] for canceling $\Delta S=1$ neutral currents has been invoked.

The Yukawa couplings of these eight quarks—the three usual quarks $\mathcal{P},\mathfrak{N},\lambda$ of SU(3), the charmed quark c, and heavy counterparts for each—are chosen to be

$$\begin{aligned}\mathcal{L}_{(\text{weak-hadronic-Yukawa})}&=\sqrt{2}g[\sigma(As^\dagger+B\gamma_5t^\dagger)(\cos\theta_CQ-\sin\theta_CQ_c)+\text{H.c.}\\&\quad+\bar\sigma_s(Cs^\dagger+D\gamma_5t^\dagger)(\sin\theta_CQ+\cos\theta_CQ_c)+\text{H.c.}\\&\quad+\bar\rho(\bar A\bar s^\dagger+\bar B\gamma_5\bar t^\dagger)Q+\bar\rho_c(\bar C\bar s^\dagger+\bar D\gamma_5\bar t^\dagger)Q_c\\&\quad+\text{H.c.}].\end{aligned}\tag{9}$$

These couplings ensure that, after spontaneous breakdown of the weak $\mathrm{SU}(2)\times Y$ to $\mathrm{U}(1)_{\mathrm{em}}$, all quarks acquire mass. The $\bar s$ and $\bar t$ representations are defined by $\bar s=i\tau_2(s^\dagger)^T$ and $\bar t=i\tau_2(t^\dagger)^T$ and are SU(2) (but not Y) equivalent to s and t.

The masses and coupling parameters are real if the angles α_i are chosen to be

$$\begin{aligned}\tan\alpha_{1,7}&=\lambda_t\bar B\sin\theta/(\bar A\lambda_s\pm\bar B\lambda_t\cos\theta)\,,\\ \tan\alpha_{2,5}&=\lambda_t\bar B\sin\theta/(\bar A\lambda_s\pm B\lambda_t\cos\theta)\,,\\ \tan\alpha_{3,6}&=\lambda_t\bar D\sin\theta/(C\lambda_s\pm D\lambda_t\cos\theta)\,,\\ \tan\alpha_{4,8}&=\lambda_t\bar D\sin\theta/(\bar C\lambda_s\pm\bar D\lambda_t\cos\theta)\,,\end{aligned}\tag{10}$$

where θ, λ_s, and λ_t are again the vacuum parameters defined in Eq. (2). The relationships between the masses and the (real) coupling constants are determined to be

$$\begin{aligned}M_{\mathcal{P},\mathcal{P}'}&=[(\lambda_s\bar A)^2+(\lambda_t\bar B)^2\mp2\lambda_s\lambda_t\bar A\bar B\cos\theta]^{1/2}\,,\\ M_{\mathfrak{N},\mathfrak{N}'}&=[(\lambda_sA)^2+(\lambda_tB)^2\mp2\lambda_s\lambda_tAB\cos\theta]^{1/2}\,,\\ M_{\lambda,\lambda'}&=[(\lambda_sC)^2+(\lambda_tD)^2\mp2\lambda_s\lambda_tCD\cos\theta]^{1/2}\,,\\ M_{c,c'}&=[(\lambda_s\bar C)^2+(\lambda_t\bar D)^2\mp2\lambda_s\lambda_t\bar C\bar D\cos\theta]^{1/2}\,,\end{aligned}\tag{11}$$

and diagrams akin to Fig. 1 can be drawn for each of the unprimed-primed quark pairs with their corresponding phase angles (e.g., $\alpha_e,\alpha_E,m_e,m_E\to\alpha_5,\alpha_2,M_{\mathfrak{N}},M_{\mathfrak{N}'}$).

The Yukawa couplings (9) will, with phases chosen as in (8) and (10), produce CP-violating terms whose contribution to the $K^0\to\bar K^0$ transition amplitude will give a handle on the relation between θ, the fundamental CP parameter in this model, and ϵ, the modulus of the phenomenological CP-violation parameter in the neutral kaon system. Before turning to the description of the $K^0\to\bar K^0$ amplitude calculation, described in the following section, I shall define the unitary gauge and spell out the couplings of the charged, physical Higgs scalar to the quark fields. These will be the couplings of interest in the approximation employed in the next section.

The gauge-covariant derivatives of the scalar fields are defined as

$$\begin{aligned}D_\mu s&=\partial_\mu s-igL_\mu s+i(g'/2)B_\mu s\,,\\ D_\mu t&=\partial_\mu t-igL_\mu t+i(g'/2)B_\mu t\,,\end{aligned}\tag{12}$$

where L and B are the triplet and singlet gauge fields of $[\mathrm{SU}(2)\times Y]_w$ and $L_\mu=\vec{L}_\mu\cdot\frac{1}{2}\vec\tau$. From the invariant kinetic-energy terms $(D_\mu s)^\dagger D^\mu s+(D_\mu t^\dagger)D^\mu t$ there arises a mixing

$$-\partial_\mu s_1^\dagger W \lambda_s - \partial_\mu t_1^\dagger W \lambda_t e^{i\theta} + \text{H.c.}\,, \qquad (13)$$

with s_1 and t_1 the destruction operators for the positive component of the scalar and pseudoscalar doublets, respectively, and with $W=(L^1 - iL^2)/\sqrt{2}$ the destruction operator for the positive W boson. To remove the mixing (13), the physical charged Higgs particle M_1 is defined as

$$\sin\beta M_1 \equiv s_1\,, \quad \cos\beta\, M_1 e^{i\theta} \equiv -t_1\,, \qquad (14)$$

where $\cos\beta = \lambda_s/(\lambda_s^{\,2}+\lambda_t^{\,2})^{1/2}$ and $\sin\beta = \lambda_t/(\lambda_s^{\,2}+\lambda_t^{\,2})^{1/2}$ will be used for brevity in a number of subsequent expressions. The choice of physical neutral Higgs fields is discussed in Appendix A. The complete condition for unitary gauge, which determines the choice of Higgs fields, reads

$$t\langle t^\dagger\rangle_0 + s\langle s^\dagger\rangle_0 - \text{H.c.} = 0\,. \qquad (15)$$

In the unitary gauge, defined by Eq. (15), the masses of the charged gauge boson, W, and the neutral one, Z, are given by

$$M_W = \tfrac{1}{2}(\lambda_s^{\,2}+\lambda_t^{\,2})^{1/2}$$

and (16)

$$M_Z = \frac{(g^2+g'^2)^{1/2}}{g} M_W\,,$$

which is the same relationship between M_Z and M_W as in the Weinberg-Salam[10] model.

As mentioned above, the quark couplings to the charged Higgs particles are of special interest. In particular, the $\lambda\mathcal{P}M_1$, $\lambda c M_1$, $\mathcal{N}\mathcal{P}M_1$, and $\mathcal{N}cM_1$, couplings determine the CP-violation effects in the $K^0-\bar{K}^0$ system in the approximation used. One finds the following expressions for these couplings from examination of Eqs. (8), (9), (10), and (14):

$$\mathcal{L}(M_1\mathcal{N}\mathcal{P}) = \frac{g}{\sqrt{2}}\cos\theta_C M_1^*\bar{\mathcal{N}}[(A\sin\beta + Be^{-i\theta}\cos\beta)e^{-i\alpha_5}(1-\gamma_5) - (\bar{A}\sin\beta + \bar{B}e^{-i\theta}\cos\beta)e^{-i\alpha_7}(1+\gamma_5)]\mathcal{P} + \text{H.c.}\,,$$

$$\mathcal{L}(M_1\mathcal{N}c) = -\frac{g}{\sqrt{2}}\sin\theta_C M_1^*\bar{\mathcal{N}}[(A\sin\beta + Be^{-i\theta}\cos\beta)e^{-i\alpha_5}(1-\gamma_5) - (\bar{C}\sin\beta + \bar{D}e^{-i\theta}\cos\beta)e^{-i\alpha_8}(1+\gamma_5)]c + \text{H.c.}\,,$$

(17)

$$\mathcal{L}(M_1\lambda\mathcal{P}) = \frac{g}{\sqrt{2}}\sin\theta_C M_1^*\bar{\lambda}[(C\sin\beta + De^{-i\theta}\cos\beta)e^{-i\alpha_6}(1-\gamma_5) - (\bar{A}\sin\beta + \bar{B}\cos\beta e^{-i\theta})e^{-i\alpha_7}(1+\gamma_5)]\mathcal{P} + \text{H.c.}\,,$$

$$\mathcal{L}(M_1\lambda c) = \frac{g}{\sqrt{2}}\cos\theta_C M_1^*\bar{\lambda}[(C\sin\beta + De^{-i\theta}\cos\beta)e^{-i\alpha_6}(1-\gamma_5) - (\bar{C}\sin\beta + \bar{D}e^{-i\theta}\cos\beta)e^{-i\alpha_8}(1+\gamma_5)]c + \text{H.c.}$$

Armed with these interactions and the W-meson interactions, which are the same as in the usual Weinberg-Salam model, one can compare CP-conserving amplitudes to CP-violating amplitudes in lowest order for the reaction $\bar{\lambda}\mathcal{N}\to\lambda\bar{\mathcal{N}}$ which, in the free-quark picture, can be related to $K^0\to\bar{K}^0$. The construction and comparison of these amplitudes is the problem addressed in the next section.

III. *CP* VIOLATION IN THE $\bar{\lambda}\mathcal{N}\to\lambda\bar{\mathcal{N}}$ TRANSITIONAL AMPLITUDE

In the spirit of Lee, Primack, and Treiman[11] and Gaillard and Lee,[12] I shall evaluate the lowest-order free-quark model graphs for $\bar{\lambda}\mathcal{N}\to\lambda\bar{\mathcal{N}}$. Then I shall simulate the $|K^0\rangle$ and $|\bar{K}^0\rangle$ states by the appropriate $J^P=0^-$ $|\mathcal{N}\bar{\lambda}\rangle$ and $|\bar{\mathcal{N}}\lambda\rangle$ free-quark states at rest, as done by Lee[7] in discussing the ϵ parameter in the context of the same 8-quark version of the George-Glashow[13] model which was studied by Lee, Primack, and Treiman.

The diagrams of interest are shown in Figs. 2 and 3. I adopt the point of view that graphs which involve an M_1, the charged Higgs scalar, are suppressed by at least an order of magnitude. Therefore, the CP-conserving amplitude is approximated by the W-meson graphs of Fig. 2. The CP-conserving amplitude $T^{CP=+}$, which is the same as in the Weinberg-Salam model and has been calculated by Gaillard and Lee,[12] can be expressed in the following form:

$$T^{CP=+} = 2(\tfrac{1}{2}g^2\sin\theta_C\cos\theta_C)^2 I(M_W, M_W, M_c, M_{\mathcal{P}}) \times \bar{V}_\lambda\gamma_\mu\frac{(1-\gamma_5)}{2}U_{\mathcal{N}}\bar{U}_\lambda\gamma^\mu\frac{(1-\gamma_5)}{2}V_{\mathcal{N}}\,. \qquad (18)$$

The approximation has been made that high-internal-momentum contributions dominate the integral

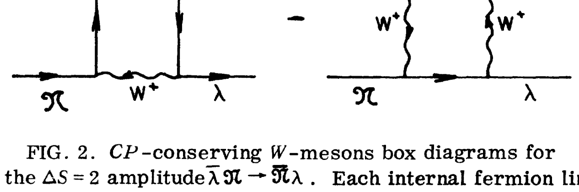

FIG. 2. CP-conserving W-mesons box diagrams for the $\Delta S=2$ amplitude $\bar{\lambda}\mathcal{N}\to\bar{\mathcal{N}}\lambda$. Each internal fermion line can be either a $\mathcal{P}$ quark or a c quark; so each diagram shown summarizes four possibilities.

$I(M_W, M_W, M_c, M_{\mathcal{P}})$, whose form is

$$I(M_W, M_W, M_c, M_{\mathcal{P}}) \simeq \int \frac{d^4q}{(2\pi)^4} \frac{q^2}{(q^2-M_W{}^2)^2}\left(\frac{1}{q^2-M_c{}^2}-\frac{1}{q^2-M_{\mathcal{P}}{}^2}\right)^2, \quad (19)$$

which has the value[12]

$$I(M_W, M_W, M_c, M_{\mathcal{P}}) = \frac{i}{16\pi^2}\frac{1}{M_W{}^2}\frac{M_c{}^2}{M_W{}^2}$$

when $M_c{}^2 \gg M_{\mathcal{P}}{}^2$. Equation (19) does not include contributions to $I(M_W, M_W, M_c, M_{\mathcal{P}})$ which come from the $q^\mu q^\nu/M_W{}^2$ part of the unitary-gauge propagator. These (finite) terms each bring in an additional factor of $M_c{}^2/M_W{}^2$ or $M_{\mathcal{P}}{}^2/M_W{}^2$ and can be safely ignored. This will also be the case for the following CP-violating amplitude which results from the graphs of Fig. 3. Using the couplings listed in Eq. (17) and the usual W-meson gauge couplings, one obtains the expression

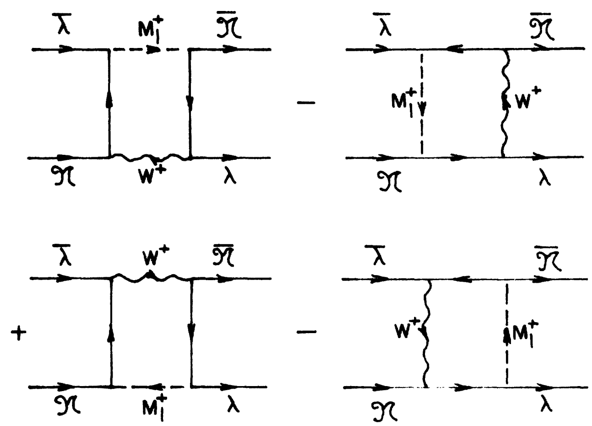

FIG. 3. Mixed W and M_1 (Higgs-particle) box diagrams. These diagrams contribute to CP violation in $\bar{\lambda}\mathfrak{N} \to \bar{\mathfrak{N}}\lambda$ and consequently in $K^0 \to \bar{K}^0$.

$$T^{CP=-} = 2i\sin(\alpha_3+\alpha_6-\alpha_2-\alpha_5)\frac{M'_\lambda M'_{\mathfrak{N}}}{4M_W{}^2}\left(\tfrac{1}{2}g^2\sin\theta_C\cos\theta_C\right)^2$$
$$\times I(M_W, M_{M_1}, M_c, M_{\mathcal{P}})(2\bar{V}_\lambda U_{\mathfrak{N}}\bar{U}_\lambda V_{\mathfrak{N}} - 2\bar{V}_\lambda\gamma_5 U_{\mathfrak{N}}\bar{U}_\lambda\gamma_5 V_{\mathfrak{N}} - \bar{V}_\lambda\gamma_\mu U_{\mathfrak{N}}\bar{U}_\lambda\gamma^\mu V_{\mathfrak{N}} + \bar{V}_\lambda\gamma_\mu\gamma_5 U_{\mathfrak{N}}\bar{U}_\lambda\gamma^\mu\gamma_5 V_{\mathfrak{N}}). \quad (20)$$

In arriving at expression (20), I have assumed that $\tan\beta = 1$ $(\lambda_t = \lambda_s)$ because the dependence on quark masses simplifies in this case. The CP violation is supported by the θ-dependent factor

$$\sin(\alpha_3+\alpha_6-\alpha_2-\alpha_5) = \frac{\tan\theta}{4}\left\{\left(\frac{M'_\lambda}{M_\lambda}-\frac{M_\lambda}{M'_\lambda}\right)\left[\left(\frac{M_{\mathfrak{N}}}{M'_{\mathfrak{N}}}+\frac{M'_{\mathfrak{N}}}{M_{\mathfrak{N}}}\right)^2-\left(\frac{M'_{\mathfrak{N}}}{M_{\mathfrak{N}}}-\frac{M_{\mathfrak{N}}}{M'_{\mathfrak{N}}}\right)^2\Big/\cos^2\theta\right]^{1/2}\right.$$
$$\left.-\left(\frac{M'_{\mathfrak{N}}}{M_{\mathfrak{N}}}-\frac{M_{\mathfrak{N}}}{M'_{\mathfrak{N}}}\right)\left[\left(\frac{M_\lambda}{M'_\lambda}+\frac{M'_\lambda}{M_\lambda}\right)^2-\left(\frac{M'_\lambda}{M_\lambda}-\frac{M_\lambda}{M'_\lambda}\right)^2\Big/\cos^2\theta\right]^{1/2}\right\}, \quad (21)$$

where the angles α_3, α_6, α_2, and α_5 are defined in Eqs. (8) and (10). The reality of the coupling constants in Eqs. (17) and (3) imposes the following conditions:

$$\text{For quarks,}\quad 1 \geq \cos\theta \geq \frac{M_i'^2 - M_i{}^2}{M_i'^2 + M_i{}^2}, \quad i = \mathfrak{N}, \mathcal{P}, \lambda, c; \quad (22a)$$

$$\text{For leptons,}\quad 1 \geq \cos\theta \geq \frac{M_{E,M}{}^2 - M_{e,\mu}{}^2}{M_{E,M}{}^2 + M_{e,\mu}{}^2}. \quad (22b)$$

To make the effect of this factor (21) more transparent, one notes that the quartet of unprimed quarks will dominate the known hadron structure if $M' \gg M$, which implies that $\cos\theta \approx 1$ when combined with (22a). Assuming that $M_\lambda \neq M_{\mathfrak{N}}$, one can show that $\sin(\alpha_3+\alpha_6-\alpha_2-\alpha_5)$ has no extremum in the range (22a), and simply changes monotonically by a small fraction. It is reasonable, then, to replace the expression in braces by its value at $\cos\theta = 1$ and to obtain

$$\sin(\alpha_3+\alpha_6-\alpha_2-\alpha_5) \approx \frac{\tan\theta}{2}\left(\frac{M'_\lambda}{M_\lambda}-\frac{M'_{\mathfrak{N}}}{M_{\mathfrak{N}}}\right), \quad (23)$$

where M/M' terms have been neglected. Putting all this together and using the fact that $I(M_W, M_{M_1}, M_c, M_{\mathcal{P}})/I(M_W, M_W, M_c, M_{\mathcal{P}}) = M_W{}^2/M_{M_1}{}^2$, I obtain[14]

$$|\epsilon| \simeq \frac{1}{\sqrt{8}}\left|\frac{T^{CP=-}(\bar{\lambda}\mathfrak{N}\to\bar{\mathfrak{N}}\lambda)}{T^{CP=+}(\bar{\lambda}\mathfrak{N}\to\bar{\mathfrak{N}}\lambda)}\right|$$
$$\approx \frac{3}{\sqrt{8}}\frac{1}{2}\left|\tan\theta\frac{M'_\lambda M'_{\mathfrak{N}}}{M_{M_1}{}^2}\left(\frac{M'_\lambda}{M_\lambda}-\frac{M'_{\mathfrak{N}}}{M_{\mathfrak{N}}}\right)\right|. \quad (24)$$

This is the principal result of the present section. In obtaining this estimate of the relationship be-

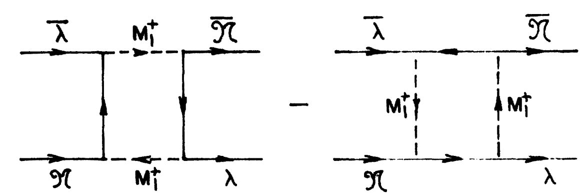

FIG. 4. CP-violating charged Higgs-particle (M_1) box graphs. These are assumed to be suppressed by M_1 mass as discussed in the text.

tween the phenomenological CP parameter ϵ and the spontaneous CP-violation parameter θ of the model, I have maintained the results for CP-conserving effects in rare K decays obtained by Gaillard and Lee.[12] The condition to do this is that

$$M'^2/M_{M_1}{}^2 \ll 1\,, \tag{25}$$

where M'^2 is the square of (or product of any two) heavy quark masses. One finds the constraint (25) by comparing the CP-conserving parts of graphs shown in Fig. 3 and Fig. 4 with the W-meson graphs, Fig. 2, in the approximation that external momenta are ignored.

Finally, I reiterate that expression (24) follows from the free-quark model amplitude (18) and (20) after mocking-up the K^0 and $\overline{K}^0$ states by free $|\mathfrak{N}\overline{\lambda}\rangle$ and $|\overline{\mathfrak{N}}\lambda\rangle$ quark states with $J^P=0^-$ at rest, in the manner of Ref. 7.

IV. DISCUSSION OF RELATIONSHIP BETWEEN PHENOMENOLOGICAL AND VACUUM CP-VIOLATION PARAMETERS

In Sec. III, I obtained the formula, Eq. (24), which related the measured parameter ϵ to the CP-violating phase angle θ between the complex scalar and pseudoscalar field vacuum expectation values as introduced in Sec. II. The angle θ depends on the electron to heavy-lepton mass ratio, a number on the order of 10^{-3}–10^{-4} or less. This observation motivated the effort to link M_e/M_E with the phenomenological ϵ parameter, which is of the same order of magnitude ($\epsilon \approx 2\times 10^{-3}$) as the experimental upper bound on M_e/M_E. The difficulty now is that hadronic parameters M'_λ/M_λ, $M'_{\mathfrak{N}}/M_{\mathfrak{N}}$, and $M'_\lambda M'_{\mathfrak{N}}/M_{M_1}{}^2$ have been necessarily introduced into the formula which relates θ with ϵ. These quark mass parameters are difficult to estimate, and I shall conclude by discussing some plausible values for them and the consequences for the value of M_e/M_E.

As mentioned in the preceding section, a consistency requirement on the ratio of heavy quark masses, M', to charged Higgs-particle mass M_{M_1} is that $M'^2/M_{M_1}{}^2 \ll 1$. To relax this restriction would require a complete reworking of the analysis of the Gaillard-Lee[12] type, where only W-boson effects were accounted for. A rather prominent role for the Higgs particles in weak interactions might be possible in the framework of the present model. For example, it was noted in Ref. 5 that only a surprisingly weak statement, $M_E M_M/M_{M_1}{}^2 \lesssim \frac{1}{2}$,[15] followed from analysis of the M_1 effects in μ decay. However, such a complete reanalysis is not the point of the present study. Therefore, in the spirit of the Sec. III calculation, a lower limit on $\tan\theta$ is obtained by setting[16]

$$M'_\lambda M'_{\mathfrak{N}}/M_{M_1}{}^2 = \tfrac{1}{100}\,. \tag{26}$$

This assumed value yields a lower limit on $\tan\theta$ for a given value of $M'_\lambda/M_\lambda - M'_{\mathfrak{N}}/M_{\mathfrak{N}}$ in the sense that larger values of $M'_\lambda M'_{\mathfrak{N}}/M_{M_1}{}^2$ would be inconsistent with the neglect of CP-conserving M_1 effects of this order and neglect of CP-violating effects of order $(M'/M_{M_1})^4$ in Sec. III.

Finally, we need some estimate of the factor $M'_\lambda/M_\lambda - M'_{\mathfrak{N}}/M_{\mathfrak{N}}$ in Eq. (24). Clearly, $M'_i/M_i \gg 1$, $i=\mathfrak{N},\mathcal{P},\lambda,c$ is required if this model is to accommodate the popular picture that known hadronic structure arises from four types of relatively light-weight quarks bound by color-SU(3) gauge gluons. Therefore, as a guess at the minimum value for this ratio, we take[17]

$$M'_\lambda/M_\lambda = 100\,. \tag{27}$$

As mentioned by Gaillard, Lee, and Rosner,[18] SU(4) chiral symmetry mass formulas for the pseudoscalar mesons when $M_{\mathcal{P}} = M_{\mathfrak{N}}$ require that

$$M_{\mathcal{P}} \approx M_{\mathfrak{N}} \approx M_\lambda/25 \ll M_c\,. \tag{28}$$

Finally, one notes that if $M'_{\mathfrak{N}} = M'_{\mathcal{P}} = M'_{\mathfrak{N}} = M'_c$, then the light quark couplings to M_1 are all the same and the quark couplings to the neutral Higgs particles are SU(4) singlet, and only SU(3) [SU(4)] singlet hadronic states are formed below (above) charm threshold in decay of neutral Higgs scalars. If the neutral Higgs scalar contributions to nonleptonic weak decays could be enhanced, then their SU(3) singlet coupling to quarks would allow a Lee-Treiman[19] type of $\Delta I = \frac{1}{2}$ mechanism. The modifications of the model needed to achieve this are under study, and I mention it here simply to provide motivation for the assumption that all *heavy* quark masses are equal. This latter assumption combined with the values (26), (27), and (28) leads us to the estimate

$$\begin{aligned} |\epsilon| &\approx \frac{1}{\sqrt{8}}\,\frac{3}{2}\left|\tan\theta\,\frac{M'_\lambda M_{\mathfrak{N}}}{M_{M_1}{}^2}\left(\frac{M'_\lambda}{M_\lambda}-\frac{M'_{\mathfrak{N}}}{M_{\mathfrak{N}}}\right)\right| \\ &\approx \frac{3}{4\sqrt{2}}\,\tan\theta \times 25 \end{aligned} \tag{29}$$

or

$$\tan\theta \approx \theta \approx \frac{8\sqrt{2}}{75}\times 10^{-3} = 1.5\times 10^{-4}\,.$$

If the estimate (29) is combined with the reality condition on the L (weak-Yukawa) coupling constants

$$1 \geq \cos^2\theta \geq \frac{(1-M_e{}^2/M_E{}^2)^2}{(1+M_e{}^2/M_E{}^2)^2}$$

one obtains

$$\theta \approx 1.5 \times 10^{-4} \leq 2M_e/M_E$$

or

$$M_E \leq 6 \text{ GeV},$$

where the equality holds when the scalar and pseudoscalar couplings of electron to Higgs particles are exactly equal (recall that $\lambda_s = \lambda_t$ has already been assumed).

It is worth noting here that, because the W boson couples heavy electron and muon only to *right*-handed neutrinos, one does not expect charged heavy-lepton production via conventional neutrino beams in this model.[8]

In summary, I suggest that the small CP-violation parameter and a small ratio of electron to heavy-electron mass can both arise from the same spontaneous vacuum breaking of local gauge symmetry, parity, and CP. In the specific model studied in this paper, I find that a heavy lepton in the mass range $1 \leq M_E \leq 6$ GeV would be in agreement with known weak phenomenology. The upper limit was found by calculating CP violation in the $K^0 \leftrightarrow \bar{K}^0$ mass mixing in a free-quark approximation, and then making plausible estimates of and consistency requirements on quark mass parameters. The bound is reached when $\lambda_s = \lambda_t$ and $a_e = b_e$, which means equal magnitude of scalar and pseudoscalar vacuum breaking and equal scalar and pseudoscalar couplings to Higgs fields.

The recently reported anomalous $e\mu$ signal in e^+e^- annihilation experiments[4] now allows room for interpretation as heavy-lepton production with mass at about 2 GeV. Althouh a clean lepton mass prediction in this model has not been obtained, the calculations presented here show that the quantities $\epsilon = 2 \times 10^{-3}$ and $M_e/M_E \approx 2.5 \times 10^{-4}$ could have the same spontaneous-breaking origin.

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APPENDIX A

The potential energy of the scalar fields and the choice of physical Higgs fields are summarized in this appendix.

The unitary gauge conditions on the scalar fields read

$$-\operatorname{Im}t_1 \operatorname{Re}\langle t\rangle_0 + \operatorname{Re}t_1 \operatorname{Im}\langle t\rangle_0 - \operatorname{Im}s_1 \operatorname{Re}\langle s\rangle_0 + \operatorname{Re}s_1 \operatorname{Im}\langle s\rangle_0 = 0 \quad \text{(A1)}$$

for the charged components, and

$$\operatorname{Re}t_2 \operatorname{Im}\langle t\rangle_0 + \operatorname{Im}t_2 \operatorname{Re}\langle t\rangle_0 + \operatorname{Re}s_2 \operatorname{Im}\langle s\rangle_0 + \operatorname{Im}s_2 \operatorname{Re}\langle s\rangle_0 = 0 \quad \text{(A2)}$$

for the neutral ones. The relative $s \leftrightarrow t$ phase is chosen to make a and b, the scalar and pseudoscalar couplings, relatively real. The phases of singlet fermion fields are then chosen to make the scalar couplings real. The phases of the doublet fermion fields and scalar fields are chosen so that the vacuum expectation of s is real. The vacuum expectation values then have the form shown in Eq. (2). The choice of charged Higgs field has been given in Eq. (14), which satisfies (A1) when $\operatorname{Im}\langle s\rangle_0 = 0$. The neutral sector is more complicated. One finds that a properly normalized, diagonal kinetic energy is produced by the field choices

$$\begin{aligned}
F_1 &= \sqrt{2}\,(-\sin\theta \operatorname{Im}t_2 + \cos\theta \operatorname{Re}t_2),\\
F_2 &= \sqrt{2}\,(\cos\theta \operatorname{Im}t_2 + \sin\theta \operatorname{Re}t_2)/\cos\beta, \qquad \text{(A3)}\\
F_3 &= \sqrt{2}\operatorname{Re}s_2.
\end{aligned}$$

However, mixings among F_1, F_2, and F_3 result from the potential-energy Lagrangian, which I discuss next.

Masses are guaranteed for the independent fields M_1, F_1, F_2, and F_3 by including in the Lagrangian the terms σ^2, τ^2, Λ^2, and $\chi^\dagger\chi$, where

$$\begin{aligned}
&\sigma \equiv s^\dagger s - \lambda_s^2/2g^2, \quad \tau \equiv t^\dagger t - \lambda_t^2/2g^2\\
&\Lambda \equiv s^\dagger t - t^\dagger s - 2i\,\sin\theta\,\lambda_s\lambda_t/2g^2, \quad \chi \equiv \bar{t}^\dagger s.
\end{aligned} \qquad \text{(A4)}$$

Mixing terms such as $\sigma\tau$ can also occur. As a sufficient potential-energy expression, I offer

$$V/g^2 = A\sigma^2 + B\tau^2 + C\Lambda^2 + D\chi^\dagger\chi + E\sigma\tau. \qquad \text{(A5)}$$

The charged Higgs particle M_1 gains mass

$$M_{M_1}{}^2 = D(\lambda_s{}^2 + \lambda_t{}^2) \qquad \text{(A6)}$$

from the $D\chi^\dagger\chi$ term of (A5).

The neutral fields are completely mixed by the interactions (A5), and a diagonalization which preserves the kinetic-energy from is effected by the orthogonal transformation

$$\begin{aligned}
F_1 &= (-\sin\phi\,\sin\psi + \cos\theta'\,\cos\phi\,\cos\psi)f_1\\
&\quad - (\sin\phi\,\cos\psi + \cos\theta'\,\cos\phi\,\sin\psi)f_2\\
&\quad + \sin\theta'\,\cos\phi f_3,\\
F_2 &= (\cos\phi\,\sin\psi + \cos\theta'\,\sin\phi\cos\psi)f_1 \qquad \text{(A7)}\\
&\quad + (\cos\phi\cos\psi - \cos\theta'\,\sin\phi\,\sin\psi)f_2\\
&\quad + \sin\theta'\,\sin\phi f_3,\\
F_3 &= -\sin\theta'\,\cos\psi f_1 + \sin\theta'\,\sin\psi f_2 + \cos\theta' f_3.
\end{aligned}$$

Diagonalization of the mass matrix for f_1, f_2, and f_3, defined in (A7), results in three complicated equations for θ', ϕ, and ψ in terms of A, B, C, E, θ, and β, and they can be solved in principle for these independent, orthogonal neutral fields f_1, f_2, and f_3. In the absence of the term $E\sigma\tau$ in

Eq. (A5), all mixings would be of order $\sin\theta$ and could be treated perturbatively. Neutral Higgs-particle effects are not dealt with in this paper, so I shall not dwell further on the details of their diagonalizations and couplings.

APPENDIX B

Muon decay parameters are peculiarly insensitive to the presence of lowest-order M_1 contributions in this model. The relevant couplings, which can be extracted from Eqs. (3), (5), (6), and (7) are[20]

$$\begin{aligned}\mathcal{L} = & g\bar{e}_R\nu_e M_1^*\left(\frac{M_E}{M_W}\right)e^{i(\alpha_e/2-\alpha_E)} + \text{H.c.}\\ & + g\bar{\mu}_R\nu_\mu M_1^*\left(\frac{M_M}{M_W}\right)e^{i(\alpha_e/2-\alpha_E)} + \text{H.c.}\\ & + \frac{g}{\sqrt{2}}\bar{e}_L \not{W}\nu_e + \text{H.c.} + \frac{g}{\sqrt{2}}\bar{\mu}_L\not{W}\nu_\mu + \text{H.c.}\end{aligned} \tag{B1}$$

The effective Lagrangian for $\mu\to e\nu\bar{\nu}$ decay is, in second order,

$$\begin{aligned}\mathcal{L}_{\text{eff}} = \frac{G}{\sqrt{2}}[&\bar{e}(1-\gamma_5)\gamma_\lambda\nu_e\bar{\nu}_\mu\gamma^\lambda\mu - \bar{e}(1-\gamma_5)\gamma_\lambda\nu_e\bar{\nu}_\mu\gamma_5\gamma^\lambda_\mu\\ & - \omega e^{i\Delta}\bar{e}(1+\gamma_5)\nu_e\bar{\nu}_\mu\mu + \omega e^{i\Delta}\bar{e}(1+\gamma_5)\nu_e\bar{\nu}_\mu\gamma_5\mu],\end{aligned} \tag{B2}$$

where $\omega \equiv M_E M_M/M_{M_1}{}^2$ and where $\Delta \equiv \alpha_e/2 - \alpha_E - \alpha_\mu/2 + \alpha_\mu$. The parameter Δ can be expressed in terms of M_e, M_μ, M_E, M_M, and θ, but its specific form will not be needed. Following the notation of Commins[20], one finds that

$$\begin{aligned}& A_V = 1,\ A_V' = -1,\ A_A = -1,\ A_A' = 1,\\ & A_S = -\omega e^{i\Delta},\ A_S' = -\omega e^{i\Delta},\ A_P = \omega e^{i\Delta},\ A_P' = \omega e^{i\Delta},\end{aligned} \tag{B3}$$

and consequently that

$$\begin{aligned}& C_V = C_A' = -(1+\tfrac{1}{2}\omega e^{i\Delta}),\\ & C_A = C_V' = (1-\tfrac{1}{2}\omega e^{i\Delta}).\end{aligned} \tag{B4}$$

All other c_i and c_i' are zero. The decay parameters K, h, ρ, δ, η, and ξ take on the values

$$\begin{aligned}& K = 16(1+\tfrac{1}{4}\omega^2)\\ & h = \frac{-1+\frac{1}{4}\omega^2}{1+\frac{1}{4}\omega^2},\quad \xi = -1\\ & \rho = \delta = \tfrac{3}{4},\quad \eta = 0.\end{aligned} \tag{B5}$$

Thus, only K and h are affected by the presence of the M_1 exchange amplitude. The experimental value $|h| = 1.00 \pm 0.14$ puts a weak constraint on ω, $\omega \lesssim \frac{1}{2}$, as mentioned in Ref. 5. We see that *CP-violation effects do not show up at all to this order.*

The muon decay case has been considered in detail because the situation is relatively clean, and any constraints on parameters are free of uncertainties of the strong-interaction effects. Because the neutrino momenta are not measured and are therefore integrated out in the phenomenological analysis of muon decay, any *CP*-violating effects show up only indirectly. For example, $\xi \neq -1$ if $C_V = C_A'^*$ and $C_V' = C_A^*$. Direct tests of *CP* violation in decays of baryons require a detailed analysis of quark models. In a free-quark picture, the T violation in neutron β decay will be proportional to the T violation amplitude in the free $\mathfrak{N}$ quark decay, $G_F \tan\theta(M_{\mathfrak{N}}' M_E/M_{m_1}{}^2)M_{\mathfrak{N}}'/M_{\mathfrak{N}}$. Using the estimates in the text and $M_E < M_n'$, this T-violation amplitude is less than $4\times 10^{-3}G_F$. The present limit in neutron β decay is at the 1% level and in $N_e^{19}\beta$ decay the limit is at the 0.1% level. This free-quark estimate is small enough to be compatible with present limits, but large enough to motivate detailed estimates of T violation in hadronic weak decays. This problem and the problem of the electric dipole moment of the neutron are under study.

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ton decays of the type searched for at ADONE as well as at SLAC (Ref. 4). The interaction reads

$$\frac{g}{\sqrt{2}}\left[\bar{E}\not{W}^{+}\left(\frac{1+\gamma_5}{2}\right)\nu^{e}\right]+\text{H.c.},$$

which, when combined with a conventional electron or muon coupling, yields a second-order W-exchange effective Lagrangian

$$\mathcal{L}_{\text{eff}}=\frac{G_F}{\sqrt{2}}[\bar{e}\gamma_\lambda(1-\gamma_5)\nu^e\bar{\nu}^e(1-\gamma_5)\gamma^\lambda E + \bar{\mu}\gamma_\lambda(1-\gamma_5)\nu^\mu\bar{\nu}^e(1-\gamma_5)\gamma^\lambda E].$$

The heavy lepton couples via the W-gauge boson to the *right*-handed component of the ν^e field while the electron couples via W to the *left*-handed component.

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[16]This value ensures that M_1 contributions to semileptonic decays, which contain one factor of M'/M_{M_1}, are suppressed by at least a factor of 10. By using the experimental branching ratios of $\pi\to\nu e$ to $\pi\to\mu\nu$ and similarly for kaons [Particle Data Group, Phys. Lett. 50B, 1 (1974)] one can obtain the bound

$$\frac{M'_\lambda M'_\eta}{M_1{}^2}\lesssim 0.07\left(\frac{M_e}{M_\pi}\right)^2\frac{M_{M_1}{}^2}{M_E{}^2}$$

by evaluating the M_1 contribution to the π and leptonic decays with $M_E=M_M$. Unfortunately, this bound involves the unknown ratio of $(M_1/M_E)^2$, where $(M_1{}^2/M_E{}^2)>2$ (Ref. 15), and is not helpful in evaluating Eq. (24).

[17]In view of (28) and the estimates of Refs. 12 and 18 that $M_c\approx 2$ GeV, one needs a ratio this large to ensure that *all* of the primed quark masses can be an order of magnitude larger than *all* of the unprimed ones.

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