CP violation in a gauge model with right-handed charm current

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(Received 4 June 1976; revised manuscript received 6 January 1977)

A mechanism of CP violation including the nonleptonic $\Delta I = 1/2$ enhancement is discussed within the context of an $SU(2) \times U(1)$ gauge model of hadrons and leptons. The model is constructed so as to include a $V + A$ charm-changing charged current in addition to the conventional $V - A$ charged weak hadron current. The lepton-hadron-anomaly cancellation is achieved in this model by including a heavy lepton and its associated neutrino in addition to the known leptons. The $V + A$ current gives rise to additional contributions to the K_L- K_S mass difference and the CP-violation parameter, which do not contradict the experimental values.

I. INTRODUCTION

Following the discovery of ψ particles[1] evidence for charm[2] seems to be overwhelming in subsequent experiments.[3] Furthermore, an additional degree of freedom of quarks, namely color, introduced in a different context[4] appears to be necessary in order to explain the rise[5] in the ratio R $[=\sigma_{tot}(e^+e^- \to \text{hadrons})/\sigma_{tot}(e^+e^- \to \mu^+\mu^-)]$ from 2.5 to 5 as the energy increases from 3 GeV to 7 GeV. Thus a color-charm quark model with integrally charged quarks seems to be an attractive possibility. An interesting consequence of charm on weak interactions has been discussed by De Rújula *et al.*,[6] who have shown that a $V+A$ charm-changing current, in addition to the conventional weak charged current, can explain several experimental facts including $\Delta I = \frac{1}{2}$ enhancement in nonleptonic decays. This has renewed interest in gauge models with right-handed currents.[7] Furthermore, as the CP violation and $\Delta I = \frac{1}{2}$ enhancement in the nonleptonic neutral-kaon decays[8] appear to be closely related, it would be interesting to achieve these effects in a gauge model of hadrons involving four quark flavors $(\mathcal{P}, \mathcal{N}, \lambda, \mathcal{P}')$ with color tripling, and we have done that in the present paper. Although our model of CP violation is similar in spirit to that of Mahapatra,[8] it is somewhat comprehensive in its choice of quarks, and our work is more explicit in demonstrating the additional contribution to the K_L-K_S mass difference and CP-violation parameter resulting from the inclusion of the $V+A$ charm current. Although this contribution cannot be reliably estimated because of our ignorance about the hadronic factors in our model, a reasonable choice of these factors[9] yields an effect which is of the same order of magnitude as the experimental K_L-K_S mass difference[10] and which in no way can be used as a constraint to rule out the existence of the $V+A$ charm current.

The quark model with the CP-violating phases used in the present work is similar to that of Tomozawa and Yun[11] who, however, have not included the $V+A$ charm-changing current in their model. Consequently, while discussing weak interactions in the framework of $SU(2) \times U(1)$ gauge theory of Salam and Weinberg,[12] we have, unlike Tomozawa and Yun,[11] introduced a right-handed doublet involving $\mathcal{P}'$ and $\mathcal{N}$ quarks in order to incorporate a current of the type $\bar{\mathcal{P}}'\gamma_\mu(1-\gamma_5)\mathcal{N}$ in our model. This current gives rise to $\Delta I = \frac{1}{2}$ enhancement relative to $\Delta I = \frac{3}{2}$ due to the absence of Cabibbo suppression and the presence of the mass of $\mathcal{P}'$ quark in the $\Delta I = \frac{1}{2}$ matrix element as shown by De Rújula *et al.*[6] We have achieved the lepton-hadron-anomaly[13] cancellation by including, besides known leptons, a right-handed doublet involving a heavy lepton and its associated neutrino, which seems to be interesting in view of the dilepton events observed in the neutrino reactions.[14]

The plan of the paper is as follows. Our model and the principal results are presented in Sec. II and Sec. III, respectively. A brief discussion of the quark mass matrix is included in Sec. IV. Section V contains our summary and conclusions.

II. SU(2) × U(1) MODEL WITH RIGHT-HANDED CHARM CURRENT

We consider the three triplets of colored quarks

$$q_i = \begin{pmatrix} \mathcal{P}_i \\ \mathcal{N}_i \\ \lambda_i \end{pmatrix}, \quad i = 1, 2, 3, \tag{1}$$

and three charmed colored quarks $\mathcal{P}'_i$. The electric charges of the quarks $\mathcal{P}'_i$, $\mathcal{P}_i$, $\mathcal{N}_i$, and λ_i are, respectively,

$$Q_i = \begin{cases} 1,1,0,0 & \text{for } i = 1,2 \\ 0,0,-1,-1 & \text{for } i = 3. \end{cases} \tag{2}$$

Following Tomozawa and Yun[11] we introduce the respective mixing of the first two triplets of quarks and the first two charmed quarks:

$$q^{(1)}=\begin{pmatrix}\mathcal{P}^{(1)}\\ \mathfrak{N}^{(1)}\\ \lambda^{(1)}\end{pmatrix}=\begin{pmatrix}\mathcal{P}_1\cos\theta'+\mathcal{P}_2\sin\theta'\\ \mathfrak{N}_1\cos\theta'+\mathfrak{N}_2\sin\theta'\\ \lambda_1\cos\theta'+\lambda_2\sin\theta'\end{pmatrix}=q_1\cos\theta'+q_2\sin\theta' , \tag{3a}$$

$$q^{(2)}=\begin{pmatrix}\mathcal{P}^{(2)}\\ \mathfrak{N}^{(2)}\\ \lambda^{(2)}\end{pmatrix}=\begin{pmatrix}-\mathcal{P}_1\sin\theta'+\mathcal{P}_2\cos\theta'\\ -\mathfrak{N}_1\sin\theta'+\mathfrak{N}_2\cos\theta'\\ -\lambda_1\sin\theta'+\lambda_2\cos\theta'\end{pmatrix}=-q_1\sin\theta'+q_2\cos\theta' . \tag{3b}$$

Similarly,

$$\begin{aligned}\mathcal{P}'^{(1)}&=\mathcal{P}'_1\cos\theta'+\mathcal{P}'_2\sin\theta' ,\\ \mathcal{P}'^{(2)}&=-\mathcal{P}'_1\sin\theta'+\mathcal{P}'_2\cos\theta' .\end{aligned} \tag{3c}$$

It is to be noted that such a mixing may influence observables in the $\Delta S=0$ and $\Delta C=0$ interactions. In order to construct the conventional charged weak current as well as the $V+A$ charm-changing charged current we define the following doublets and singlets:

$$L_1=\begin{pmatrix}\mathcal{P}_L^{(1)}\\ \mathfrak{N}_L^{(1)}(\theta_1)\end{pmatrix},\quad \begin{matrix}Q=1\\ Q=0,\end{matrix}$$
$$L'_1=\begin{pmatrix}\mathcal{P}_L'^{(1)}\\ \lambda_L^{(1)}(\theta_1)\end{pmatrix},\quad \begin{matrix}Q=1\\ Q=0,\end{matrix} \tag{4}$$

where

$$\mathfrak{N}_L^{(1)}(\theta_1)=\mathfrak{N}_L^{(1)}\cos\theta_1+\lambda_L^{(1)}\sin\theta_1 \tag{5}$$

and

$$\lambda_L^{(1)}(\theta_1)=-\mathfrak{N}_L^{(1)}\sin\theta_1+\lambda_L^{(1)}\cos\theta_1 , \tag{6}$$

$$L_2=\begin{pmatrix}\mathcal{P}_L^{(2)}\\ \mathfrak{N}_L^{(2)}(\theta_2,\varphi_h,\psi_h)\end{pmatrix},\quad \begin{matrix}Q=1\\ Q=0,\end{matrix}$$
$$L'_2=\begin{pmatrix}\mathcal{P}_L'^{(2)}\\ \lambda_L^{(2)}(\theta_2,\varphi_h,\psi_h)\end{pmatrix},\quad \begin{matrix}Q=1\\ Q=0,\end{matrix} \tag{7}$$

where

$$\mathfrak{N}_L^{(2)}(\theta_2,\varphi_h,\psi_h)=\mathfrak{N}_L^{(2)}\cos\theta_2\,e^{i\varphi_h}+\lambda_L^{(2)}\sin\theta_2\,e^{i\psi_h} \tag{8}$$

and

$$\lambda_L^{(2)}(\theta_2,\varphi_h,\psi_h)=-\mathfrak{N}_L^{(2)}\sin\theta_2\,e^{i\varphi_h}+\lambda_L^{(2)}\cos\theta_2\,e^{i\psi_h} , \tag{9}$$

$$L_3=\begin{pmatrix}\mathcal{P}_{3L}\\ \mathfrak{N}_{3L}(\theta_3)\end{pmatrix},\quad \begin{matrix}Q=0\\ Q=-1,\end{matrix}$$
$$L'_3=\begin{pmatrix}\mathcal{P}'_{3L}\\ \lambda_{3L}(\theta_3)\end{pmatrix},\quad \begin{matrix}Q=0\\ Q=-1,\end{matrix} \tag{10}$$

where

$$\mathfrak{N}_{3L}(\theta_3)=\mathfrak{N}_{3L}\cos\theta_3+\lambda_{3L}\sin\theta_3 \tag{11}$$

and

$$\lambda_{3L}(\theta_3)=-\mathfrak{N}_{3L}\sin\theta_3+\lambda_{3L}\cos\theta_3 , \tag{12}$$

$$R_1=\mathcal{P}_R^{(1)},\ Q=1,\quad R_2=\mathcal{P}_R^{(2)},\ Q=1,\quad R_3=\mathcal{P}_{3R},\ Q=0, \tag{13}$$

$$R_1^\lambda=\lambda_R^{(1)},\ Q=0,\quad R_2^\lambda=\lambda_R^{(2)},\ Q=0,\quad R_3^\lambda=\lambda_{3R},\ Q=-1, \tag{14}$$

$$R'_1=\begin{pmatrix}\mathcal{P}_R'^{(1)}\\ \mathfrak{N}_R^{(1)}\end{pmatrix},\quad \begin{matrix}Q=1\\ Q=0,\end{matrix} \tag{15}$$

$$R'_2=\begin{pmatrix}\mathcal{P}_R'^{(2)}\\ \mathfrak{N}_R^{(2)}\end{pmatrix},\quad \begin{matrix}Q=1\\ Q=0,\end{matrix} \tag{16}$$

where

$$\mathfrak{N}_R^{(2)}=\mathfrak{N}_R^{(2)} \tag{17}$$

and

$$R'_3=\begin{pmatrix}\mathcal{P}'_{3R}\\ \mathfrak{N}_{3R}\end{pmatrix},\quad \begin{matrix}Q=0\\ Q=-1.\end{matrix} \tag{18}$$

It is to be noted that $\mathcal{P}_R'^{(1)}$, $\mathcal{P}_R'^{(2)}$, and $\mathcal{P}'_{3R}$ are members of the right-handed doublets in our model but they are singlets in the model proposed by Tomozawa and Yun.[11] We have made this choice in order to include the $V+A$ charm-changing charged current in our model.

The necessary and sufficient condition for the cancellation of the lepton-hadron anomaly is $Q_L=Q_R$, where Q_L and Q_R are the sum of the electric charges for the left- and right-handed fermion doublets, respectively. This is achieved in the present model by introducing the following right-handed doublet and a left-handed singlet of leptons:

$$\begin{pmatrix}\nu_L\\ L^-\end{pmatrix}_R,\quad \begin{matrix}Q=0\\ Q=-1\end{matrix}\quad \text{and } L_L^-,\ Q=-1 \tag{19}$$

in addition to those (L_e, L_μ, R_e, R_μ) defined in Ref. 11. In our model $Q_L=Q_R=0$, which is same as expected[6] for the conventional current.

From now on we concentrate on the hadronic interactions, and the relevant hadronic Lagrangian in our SU(2)×U(1) gauge model is

$$\begin{aligned}\mathcal{L} = {}&\tfrac{1}{2} ig[(\bar{L}_1\gamma_\mu \vec{\tau} L_1 + \bar{L}_1'\gamma_\mu \vec{\tau} L_1') + (\bar{L}_2\gamma_\mu \vec{\tau} L_2 + \bar{L}_2'\gamma_\mu \vec{\tau} L_2') + (\bar{L}_3\gamma_\mu \vec{\tau} L_3 + \bar{L}_3'\gamma_\mu \vec{\tau} L_3') + (\bar{R}_1'\gamma_\mu \vec{\tau} R_1') + (\bar{R}_2'\gamma_\mu \vec{\tau} R_2') + (\bar{R}_3'\gamma_\mu \vec{\tau} R_3')]\cdot \vec{A}^\mu \\ &+ \tfrac{1}{2} ig'[(\bar{L}_1\gamma_\mu L_1 + \bar{L}_1'\gamma_\mu L_1') + (\bar{L}_2\gamma_\mu L_2 + \bar{L}_2'\gamma_\mu L_2') - (\bar{L}_3\gamma_\mu L_3 + \bar{L}_3'\gamma_\mu L_3') + (\bar{R}_1'\gamma_\mu R_1') + (\bar{R}_2'\gamma_\mu R_2') - (\bar{R}_3'\gamma_\mu R_3') \\ &\quad + 2(\bar{R}_1\gamma_\mu R_1 + \bar{R}_2\gamma_\mu R_2) - 2(\bar{R}_3^\lambda\gamma_\mu R_3^\lambda)] B^\mu\,, \end{aligned} \tag{20}$$

where each notation has its usual meaning. $\mathcal{L}$ is expressed in terms of the quark and vector-boson fields as follows:

$$\begin{aligned}\mathcal{L} = {}&\mathcal{L}_{\mathrm{con}} + \frac{1}{2\sqrt{2}} ig[(\bar{\mathcal{P}}_1'\cos\theta' + \bar{\mathcal{P}}_2'\sin\theta')\gamma_\mu(1-\gamma_5)(\mathfrak{N}_1\cos\theta' + \mathfrak{N}_2\sin\theta') \\ &+ (-\bar{\mathcal{P}}_1'\sin\theta' + \bar{\mathcal{P}}_2'\cos\theta')\gamma_\mu(1-\gamma_5)(-\mathfrak{N}_1\sin\theta' + \mathfrak{N}_2\cos\theta') + \bar{\mathcal{P}}_3'\gamma_\mu(1-\gamma_5)\mathfrak{N}_3]W^\mu\,. \end{aligned} \tag{21}$$

The angles $(\theta_1, \theta_2, \theta_3)$ and the CP-violating phases (φ_h, ψ_h) together define the Cabibbo angle through the relations[11]

$$\tan^2\theta_C = \frac{|\sin\theta_1 + \sin\theta_2 e^{i\psi_h} + \sin\theta_3|^2}{|\cos\theta_1 + \cos\theta_2 e^{i\varphi_h} + \cos\theta_3|^2}\,, \tag{22}$$

$$\cos\frac{\theta_1-\theta_3}{2}\left(\cos\frac{\theta_1-\theta_3}{2} + \cos\varphi_h\cos\theta_2\cos\frac{\theta_1+\theta_3}{2} + \cos\psi_h\sin\theta_2\sin\frac{\theta_1+\theta_3}{2}\right) = 0\,. \tag{23}$$

The CP-violating phases are genuine, as can be seen from their appearance in the quark mass matrix discussed in Sec. IV. A simple choice, which satisfies both Eqs. (22) and (23), is as follows:

$$\theta_1 = \pi,\ \ \theta_2 = \pi/12,\ \theta_3 = 0,\ \ \varphi_h = 0,\ \text{ and } \psi_h \simeq 10^{-3}\,. \tag{24}$$

III. RESULTS

To estimate the contribution to the K_L-K_S mass difference we approximate the vector-boson propagator by $-ig^{\alpha\beta}/p^2 - M_W{}^2$ and neglect the external momenta compared to the internal momentum for simplifying the integration. The contribution to the mass difference due to diagrams 1(c) and 1(d) resulting from the conventional charged current is given by

$$\begin{aligned}(\Delta m)_{\mathrm{con}} = {}&\frac{g^4}{M_W{}^4}\,\frac{f_K{}^2}{128\pi^2}\,\Delta m_{\mathcal{P}\mathcal{P}'}{}^2 m_K \\ &\times \mathrm{Re}(\sin\theta_1\cos\theta_1 + \sin\theta_2\cos\theta_2\, e^{i(\varphi_h - \psi_h)} + \sin\theta_3\cos\theta_3)^2\,, \end{aligned} \tag{25}$$

where $\Delta m_{\mathcal{P}\mathcal{P}'}{}^2 = m_{\mathcal{P}'}{}^2 - m_{\mathcal{P}}{}^2$ and f_K is the vector form factor. The additional contribution to the K_L-K_S mass difference due to diagrams 1(a) and 1(b) resulting from the $V+A$ current is

$$\begin{aligned}(\Delta m)_{\mathrm{add}} = {}&\frac{g^4}{M_W{}^4}\,\frac{4f_S{}^2 + f_T{}^2}{128\pi^2}\, m_K(m_{\mathcal{P}'}{}^2)\left(\ln\frac{M_W{}^2}{m_{\mathcal{P}'}{}^2} - 2\right) \\ &\times \mathrm{Re}(\cos\theta_1 + \cos\theta_2\, e^{i(-\psi_h)} + \cos\theta_3)^2\,, \end{aligned} \tag{26}$$

where f_S and f_T are scalar and tensor form factors, respectively. The contributions $(\Delta m)_{\mathrm{con}}$ and $(\Delta m)_{\mathrm{add}}$ cannot be reliably estimated because of our ignorance of the form factors and the angles. However, a simple choice of angles as given in Eq. (24) and a reasonable choice of form factors

$$f_K \simeq 1.2 m_\pi,\quad f_S/f_K \leq 0.04,\quad \text{and } f_T/f_K \leq 0.23 \tag{27}$$

leads to

$$(\Delta m)_{\mathrm{con}} \simeq 1.26\times 10^{-14} m_K$$

and $\qquad$ (28)

$$(\Delta m)_{\mathrm{add}} \leq 4.8\times 10^{-14} m_K\,,$$

which are not in conflict with the experimental values.

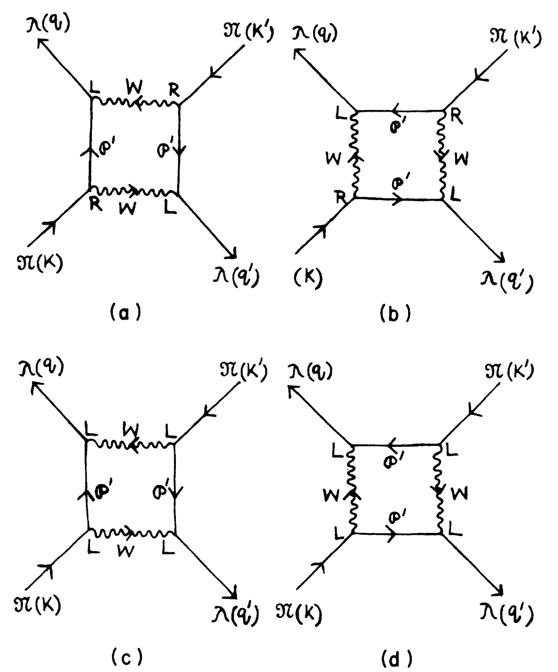

FIG. 1. The relevant diagrams of order g^4 for K_0-$\bar{K}_0$ transition.

In other words, the constraining role of the K_L-K_S mass difference cannot be exercised in discarding the model if the inequality in Eq. (28) is satisfied. The CP-violation parameters arising from the usual $V-A$ and $V+A$ charm currents are given by

$$(\mathcal{E})_{\text{con}} \simeq \frac{\sin(\varphi_h - \psi_h)}{1+\sin 2\theta_1/\sin 2\theta_2 + \sin 2\theta_3/\sin 2\theta_2} \tag{29}$$

and

$$(\mathcal{E})_{\text{add}} \simeq \frac{-\sin\psi_h}{1+\cos\theta_1/\cos\theta_2 + \cos\theta_3/\cos\theta_2}\,. \tag{30}$$

Experimentally $(\mathcal{E})_{\text{con}} + (\mathcal{E})_{\text{add}} = 10^{-3}$, which implies the small difference between the CP-violating phases. The CP violation disappears completely if $\phi_h = \psi_h = 0$, although the CP violation due to the conventional current vanishes if $\phi_h = \psi_h$. It is interesting to note that for the simple choice of angles given in Eq. (24) our model predicts

$$(\mathcal{E})_{\text{con}} = (\mathcal{E})_{\text{add}} = 10^{-3}\,. \tag{31}$$

IV. QUARK MASS MATRIX AND CP-VIOLATING PHASES

To construct the quark mass matrix we require two Higgs multiplets

$$T = \begin{pmatrix} T^+ \\ T^0 \end{pmatrix} \text{ and } \pi = \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix}, \tag{32}$$

and let T^0 and π^0 develop nonzero vacuum expectation values

$$\langle T^0 \rangle = \kappa \text{ and } \langle \pi^0 \rangle = \rho\,. \tag{33}$$

We choose the following interaction between the Higgs scalars and the left- and right-handed quark multiplets:

$$\begin{aligned}\mathcal{L}_I = {} & \frac{f_1}{\kappa}\sum_{i=1}^{3} \bar{L}_i \begin{pmatrix} T^+ \\ T^0 \end{pmatrix} R_i^{\lambda} + \frac{f_2}{\kappa}\sum_{i=1}^{3} \bar{L}_i \begin{pmatrix} T^0 \\ -T^- \end{pmatrix} R_i + \frac{f_3}{\rho}\sum_{i=1}^{3} \bar{L}_i' \vec{\tau}\cdot\vec{\pi} R_i' + \frac{f_4}{\rho}\sum_{i=1}^{3} \bar{L}_i \vec{\tau}\cdot\vec{\pi} R_i' \\ & + \frac{f_5}{\kappa}\sum_{i=1}^{3} \bar{L}_i' \begin{pmatrix} T^0 \\ -T^- \end{pmatrix} R_i + \frac{f_6}{\kappa}\sum_{i=1}^{3} \bar{L}_i' \begin{pmatrix} T^+ \\ T^0 \end{pmatrix} R_i^{\lambda} + f_7 \sum_{i=1}^{3} \bar{L}_i R_i' + f_8 \sum_{i=1}^{3} L_i' R_i' \\ & + \text{H.c.}\,,\end{aligned} \tag{34}$$

where f_i's ($i=1,\ldots,8$) are arbitrary constants which in general may be complex. Thus we obtain mass terms likes

$$\bar{\psi}_{iL}\, m_{ij}\, \psi_{jR} + \bar{\psi}_{jR}\, m_{ij}^{\dagger}\, \psi_{iL}\,, \tag{35}$$

where i and $j=1,\ldots,12$ run over the twelve quark fields. Some of the off-diagonal mass terms turn out to be zero because of the condition given in Eq. (33). Following Mahapatra[8] the mass matrix is diagonalized by choosing the appropriate f_i's so that all the off-diagonal matrix elements vanish. The masses of the twelve colored quarks are determined by the relevant diagonal elements. The CP-violating phases appear in the diagonal mass terms of $\mathfrak{N}_1$, $\mathfrak{N}_2$, λ_1, and λ_2 quarks, which are given by

$$\begin{aligned} m_{\mathfrak{N}_1} &= \text{Re}\{\cos^2\theta'[(2f_7+f_3)\cos\theta_1 - f_8\sin\theta_1] \\ &\qquad + \sin^2\theta'\, e^{-i\varphi_h}[(f_3-f_8)\sin\theta_2 + 2f_7\cos\theta_2]\}, \\ m_{\mathfrak{N}_2} &= \text{Re}\{\sin^2\theta'[(2f_7+f_3)\cos\theta_1 - f_8\sin\theta_1] \\ &\qquad + \cos^2\theta'\, e^{-i\varphi_h}[(f_3-f_8)\sin\theta_2 + 2f_7\cos\theta_2]\}, \\ m_{\lambda_1} &= \text{Re}[(f_1\sin\theta_1 + f_6\cos\theta_1)\cos^2\theta' \\ &\qquad + (f_1\sin\theta_2 + f_6\cos\theta_2)\sin^2\theta'\, e^{-i\psi_h}], \\ m_{\lambda_2} &= \text{Re}[(f_1\sin\theta_1 + f_6\cos\theta_1)\sin^2\theta' \\ &\qquad + (f_1\sin\theta_2 + f_6\cos\theta_2)\cos^2\theta'\, e^{-i\psi_h}]. \end{aligned} \tag{36}$$

Thus we see that the CP-violating phases are genuine because they survive in the diagonal mass matrix and hence they cannot be transformed away.

V. CONCLUSIONS

We have discussed a mechanism of CP violation including the nonleptonic $\Delta I = \frac{1}{2}$ enhancement within the framework of an $SU(2)\times U(1)$ gauge model of hadrons involving four quark flavors with color tripling. The $V+A$ charm current of the type $\bar{\mathcal{P}}'\gamma_\mu(1-\gamma_5)\mathfrak{N}$ is incorporated in our model by defining a right-handed doublet involving $\mathcal{P}'$ and $\mathfrak{N}$ quarks, which leads to the nonleptonic $\Delta I = \frac{1}{2}$ enhancement as shown by De Rújula *et al.*[6] We achieve the lepton-hadron-anomaly cancellation by introducing a new heavy lepton and its associated neutrino, the existence of which is subject to experimental verification. The CP-violating phases are introduced in the hadronic sector and shown to be genuine because of their distinctive appearance in the diagonal quark mass matrix. The presence of the right-handed charm current in our model gives rise to an additional contribution to the K_L-K_S mass difference and the CP-violation parameter, which are not in conflict with the experimental values. It is to be noted that our model leads to a milliweak[15] type CP violation with consequences of the superweak theory[16] for $K_L^0 \to 2\pi$.

ACKNOWLEDGMENTS

We are grateful to Dr. B. Dutta Roy and D. Bhaumik for helpful discussions.

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