PHYSICAL REVIEW D VOLUME 16, NUMBER 9 1 NOVEMBER 1977

# Conditions for natural suppression of *CP* violation*

Jihn E. Kim†
*Department of Physics, Brown University, Providence, Rhode Island 02912*
(Received 17 June 1977; revised manuscript received 7 July 1977)

We study the conditions for the natural suppression of $CP$ violation at the orders $G_F$ and $G_F\alpha$ of quark–gauge-boson couplings in the $SU(2)\times U(1)$ gauge-theory framework. For the natural suppression of $CP$ at the order $G_F$, the necessary and sufficient condition is that the quarks of the charges $q$ and $q-1$ do not belong to the same isomultiplets for at least one chirality. However, it is not generally possible to naturally suppress $CP$ at the order $G_F\alpha$ except for the limited class of models such as the standard four-quark model.

## I. INTRODUCTION

A few *extremely small* numbers have appeared in elementary-particle physics. They are the $K_L$-$K_S$ mass difference, the $K_L\to\mu\bar{\mu}$ branching ratio, upper bounds for the branching ratios of $\mu\to e\gamma$ and $\mu\to ee^+e^-$ decays, and $CP$-violating parameters in $K_L\to 2\pi$ decay. Do we understand why all these parameters are so small? The small or vanishing experimental numbers can be understood in two ways: by an *artificial* mechanism or by a *natural* mechanism.[1] The artificial mechanism implies that there is no alternative choice except one particular set of parameters in the theory to produce experimentally vanishing numbers. On the other hand, the natural mechanism implies vanishing experimental numbers however one may choose the parameters in the theory. Since the artificial mechanism is trivial, we pose the question to the *natural* scheme.

For the natural conservation of strangeness and muon number, the Glashow-Weinberg theorem should be satisfied.[1] But there does *not* exist an equally useful study for a naturally small $CP$ violation. Ever since the discovery of $CP$ nonconservation,[2] the mystery has not been why it is there,[3,4] but *why it is so weakly violated*.[5] The old idea for the feeble $CP$ violation with an imaginary coupling constant[6] cannot be incorporated within a gauge theory. If we stay in the standard four-quark scheme of Glashow, Iliopoulos, and Maiani[7] (GIM), we can introduce ingenious schemes through the spontaneous $CP$ violation[8] or $CP$-violating Higgs Lagrangian.[5] However, they do not solve the basic problem of the smallness of the violation in extended quark models. For example, the six-quark scheme of Kobayashi and Maskawa[9] introduces a complex parameter in $W$-boson–quark couplings, but there is no *a priori* reason that this parameter should be small.

At present, there is evidence that we need more quarks than the four quarks of GIM. The most serious phenomenological need arises when we try to fit the heavy lepton $\tau^-$ in the scheme. In this possible circumstance of extending quark and lepton models from the minimal four leptons and four quarks, we ask the following: *Is it possible to naturally suppress CP violation in gauge-boson–quark couplings*? We study this problem essentially in the perturbative treatment. Suppose that in a theory we have the maximum number of $CP$-violating parameters.[10] This is equivalent to the maximum number of unremovable imaginary phases through phase redefinition of quark fields. For example, the charged current

$$J_\mu^+=\bar{u}_L\gamma_\mu U d_L \tag{1}$$

defines a unitary matrix $U$ in the flavor basis (in the flavor basis, the mass matrix is diagonal). Here $U$ is $n\times n$ and $u$ and $d$ are $n\times 1$ column vectors of quarks of charge $\frac{2}{3}$ and $-\frac{1}{3}$, respectively. As usual, we identify $d_1=d$, $d_2=s$, $u_1=u$, and $u_2=c$. Then we study the following problem: How many columns of $U$ can be made real while maintaining the maximum number of independent parameters in $U$ by the phase transformation $V^\dagger UW$, where $V$ and $W$ are diagonal unitary? In this specific example (1), we can make only *one* column of $U$ be real for $n\geq 3$, but cannot make two or more columns real. (For $n=2$ we can make both of the columns real.) This means we can remove any $CP$ violation from the order $G_F$ but should include it at the order $G_F\alpha$. Suppose we could make two columns of $U$ be real. Then we can remove $CP$ violation up to the order $G_F\alpha$ since we can redefine the quark field phases such that any desired two columns (or two rows) are real. In this case, the $K_L$-$K_S$ mass difference which occurs at the one-loop level does not have any imaginary component and $CP$ violation in $K_L \to 2\pi$ through gauge-boson coupling is expected to occur at the level of $(\alpha m_q^4/\pi M_W^4)G_F\alpha$, i.e., $\eta_{+-}$ is order of $\alpha m_q^2/M_W^2$.

We assume an $SU(2)\times U(1)$ gauge theory.[11] In Sec. II, we show that the quarks of charge $q$ and $q-1$ do not belong to the same weak isomultiplets for at least one chirality for the natural $CP$ conservation at the order $G_F$. This is equivalent to the condition for the microweak $CP$ violation of Lee.[10] Then we show that it is not generally possible to have natural $CP$ conservation at the order $G_F\alpha$. In Sec. III, we present a few models which can have natural $CP$ conservation in the $K_L$-$K_S$ mass matrix up to the one-loop level. None of these models can successfully interpret the high-$y$ anomaly.[12]

## II. CONDITION FOR NATURAL SUPPRESSION OF CP VIOLATION

In this section we assume an $SU(2)\times U(1)$ gauge theory,[11] and define the quark fields in the weak-interaction basis

$$\xi_L, \quad \xi_R \tag{2a}$$

and the flavor basis

$$q_L, \quad q_R \tag{2b}$$

for each chirality. If necessary, $q$ is decomposed to charge eigenstates

$$q=\{\ldots,f,u,d,v,\ldots\}, \tag{3}$$

where $f,u,d,v$, have $Q=\frac{5}{3}$, $\frac{2}{3}$, $-\frac{1}{3}$, and $-\frac{4}{3}$, respectively. In the weak-interaction basis gauge-boson coupling is diagonal and in the flavor basis the mass matrix is diagonal. The weak-interaction basis and the flavor basis are related by unitary transformations,

$$\begin{aligned} q_L &= V_L\xi_L\,,\\ q_R &= V_R\xi_R\,. \end{aligned} \tag{4}$$

The mass matrix

$$\bar{\xi}_L M\xi_R+\bar{\xi}_R M^\dagger\xi_L \tag{5}$$

is diagonalized by $V_L$ and $V_R$,

$$\bar{q}M_Dq=\bar{q}_LM_Dq_R+\bar{q}_RM_Dq_L\,, \tag{6}$$

where

$$M_D=V_LMV_R^\dagger\,. \tag{7}$$

Equation (6) can be decomposed to

$$\bar{q}M_Dq=\bar{u}M_uu+\bar{d}M_dd+\cdots, \tag{8}$$

where $M_u$ and $M_d$ are diagonal. The gauge-boson coupling is defined in the weak-interaction basis as

$$\mathcal{L}=gJ_W^\mu W_\mu^- +(g^2+g'^2)^{1/2}J_Z^\mu Z_\mu\,, \tag{9}$$

where

$$J_\mu^W=\bar{\xi}_L\gamma_\mu T_+^L\xi_L+\bar{\xi}_R\gamma_\mu T_+^R\xi_R \tag{10}$$

and

$$\begin{aligned} J_\mu^Z={}&\bar{\xi}_L\gamma_\mu(T_3^L-\sin^2\theta_WQ^L)\xi_L\\ &+\bar{\xi}_R\gamma_\mu(T_3^R-\sin^2\theta_WQ^R)\xi_R\,, \end{aligned} \tag{11}$$

where

$$Q=Q^L\frac{1-\gamma_5}{2}+Q^R\frac{1+\gamma_5}{2}\,. \tag{12}$$

Since $[Q,M]=0$, we have[13]

$$[Q^L,V_L]=[Q^R,V_R]=0\,, \tag{13}$$

which guarantees the flavor conservation in $Q^{L,R}$ terms in $J_\mu^Z$. For the natural conservation of flavors in neutral currents, $T_3^{L,R}$ should be the multiple of identity for the equally charged quarks, and $Z_\mu$ coupling to quarks conserves $CP$. If we require flavor conservation only between $d$ quarks, the $Z_\mu$ coupling can violate $CP$ but the $K_L$-$K_S$ mass difference picks up an imaginary component only at the two-loop level of Feynman diagrams. Hence, the contribution to a possibly large $CP$ violation in $K_L\to 2\pi$ can come only from the charged-current coupling (10). This charged current (10) can be decomposed into components,

$$\begin{aligned} J_\mu^W={}&\bar{u}_L\gamma_\mu U^Ld_L+\bar{u}_R\gamma_\mu U^Rd_R+\bar{d}_L\gamma_\mu X^Lv_L\\ &+\bar{d}_R\gamma_\mu X^Rv_R+\bar{f}_L\gamma_\mu Y^Lu_L+\bar{f}_R\gamma_\mu Y^Ru_R\\ &+\cdots, \end{aligned} \tag{14}$$

where $U^{L,R}$, $X^{L,R}$, $Y^{L,R}$, etc. are unitary matrices and $u_{L,R}$, $d_{L,R}$, etc. are column vectors with quark fields.

Now we investigate systematically the conditions for $CP$ conservation at the order $G_F$ and the order $G_F\alpha$. For this we also *assume that the quark mass matrix is completely arbitrary.*

### A. Natural CP conservation at the order $G_F$

Any unitary transformation $A^{L,R}$, $B^{L,R}$, etc. which is needed for making a particular element of $U^{L,R}$, $X^{L,R}$, etc. real should leave the diagonal quark mass matrix $M_D$ unchanged,

$$\bar{q}M_Dq=\bar{u}_LM_uu_R+\bar{u}_RM_uu_L+\bar{d}_LM_dd_R+\bar{d}_RM_dd_L+\cdots. \tag{8'}$$

Namely,

$$\begin{aligned} M_u&=A^{L\dagger}M_uA^R=A^{R\dagger}M_uA^L\,,\\ M_d&=B^{L\dagger}M_dB^R=B^{R\dagger}M_dB^L\,, \end{aligned} \tag{15}$$

etc., where $A^{L,R}$ and $B^{L,R}$ redefine the quark fields

$u_{L,R}$ and $d_{L,R}$, respectively. Since $M$ is completely arbitrary, $A^{L,R}$, $B^{L,R}$, etc. are diagonal unitary (i.e., only the phase redefinition of quark fields is allowed) and left- and right-unitary matrices are equal,

$$A^L = A^R\,, \quad B^L = B^R\,, \quad \text{etc.} \tag{16}$$

As an illustration, let us take $U^L$ and $U^R$ in Eq. (14). By phase transformations $A^{L,R}$ and $B^{L,R}$, we want, without loss of generality, to make the first elements of $U^{L,R}$ be real,

$$(A^{L\dagger}U^L B^L)_{11} = \text{real}\,,$$

$$(A^{R\dagger}U^R B^R)_{11} = (A^{L\dagger}U^R B^L)_{11} = \text{real}\,,$$

which is equivalent to

$$A_{11}^{L*}U_{11}^L B_{11}^L = \text{real}\,, \tag{17a}$$

$$A_{11}^{L*}U_{11}^R B_{11}^L = \text{real}\,. \tag{17b}$$

Equations (17a) and (17b) imply that

$$\text{phase of } U_{11}^L = \text{phase of } U_{11}^R = \text{phase of } A_{11}^L B_{11}^{L*}\,, \tag{18}$$

which *cannot* be generally satisfied for arbitrary $U^L$ and $U^R$. Hence, one of $U^L$ and $U^R$ is not allowed for natural $CP$ conservation at the order $g$. The physical implication of Eqs. (17a) and (17b) is that we can redefine quark field phases such that the interaction $\bar{u}\gamma_\mu(a+b\gamma_5)dW^\mu$ conserves $CP$. Therefore, the decay $W^+ \to u\bar{d}$ conserves $CP$. This argument can be applied to any final state of the quark and antiquark combinations, and Eqs. (17a) and (17b) guarantee the $CP$ conservation at the order $g$ in the decays $W^+ \to u_i\bar{d}_j$. Further, we note that if one of $U^R$ or $U^L$ were forbidden, we could make any one row (or column) of $U^L$ of $U^R$ real by appropriate phase matrices $A^L$ and $B^L$, i.e.,

$$\text{phase of } U_{j1}^L = \text{phase of } A_{jj}^L B_{11}^{L*}$$

if $U^R$ were forbidden.

Therefore, we obtain a *necessary condition* for the natural $CP$ conservation at the order $G_F$: *The quarks of charge q and q − 1 do not belong to the same weak isomultiplets for at least one chirality.* This is also a *sufficient* condition since we can make any one element real for any *one* unitary matrix by appropriate phase transformations similar to Eq. (17). Further, if the above condition is satisfied, the one-$W$-boson-exchange diagrams, e.g.,

$$u_i\bar{d}_j \to W^+ \to u_k\bar{d}_l \text{ or } f_k\bar{u}_l \text{ or } d_k\bar{v}_l\,, \text{ etc.}\,,$$

can contain at most the overall phase factors which cannot be tested experimentally. Namely, the above condition is necessary and sufficient for the natural conservation of $CP$ at the order $g$ and $G_F$.

If this condition for natural $CP$ conservation at the order $G_F$ is satisfied, it is easy to see that the electric dipole moment of quarks cannot arise in the second order of $g$ since the electromagnetic coupling of fermions conserve $CP$ and flavor. The electric dipole moment of the quark in this theory is estimated by Lee[10] to be of the order of $10^{-27}$ $e$ cm for $m_W \approx 60$ GeV and $m_q \approx 3$ GeV. (Here we have not considered the factor $\epsilon \approx 10^{-3}$ of Ref. 10.)

We note that the vector models[14] do not have natural $G_F$-order $CP$ conservation. But the Kobayashi and Maskawa six-quark model[9] conserves $CP$ at the order $G_F$.

### B. Condition for natural $CP$ conservation at the order $G_F\alpha$

The feeble $CP$ violation observed in $K_L \to 2\pi$ decay, viz., $\eta_{+-} \approx \eta_{00} \approx 2\times 10^{-3}$, suggests that $CP$ is also suppressed at the one-loop level of the $s+s \to d+d$ amplitude due to the fact that the $CP$-conserving $K_L$-$K_S$ mass difference is consistent with the one-loop calculation.[15] Since we can use the freedom of redefining quark field phases, the necessary and sufficient condition for the natural $CP$ conservation at the order $G_F\alpha$ *is the existence of two unitary diagonal matrices, say A and B, which removes all the complex numbers from two columns (or two rows) from an arbitrary unitary matrix U* in addition to the condition for the natural $G_F$-order $CP$ conservation. (This kind of argument can be extended to the natural $CP$ conservation at higher orders.) Note that if this condition on the order $G_F\alpha$ is satisfied, the $K_L$-$K_S$ mass difference does not get an imaginary part up to $G_F\alpha(m_q^2/M_W^2)$ due to the GIM suppression since the dominant contribution to the mass difference comes from the one-loop calculation which is known to be suppressed by quark mass terms. Without loss of generality, let us transform $U^L$ by phase matrices $A^L$ and $B^L$ such that the first two columns are real, i.e.,

$$A_{jj}^{L*}U_{j1}^L B_{11}^L = \text{real}\,, \tag{19a}$$

$$A_{jj}^{L*}U_{j2}^L B_{22}^L = \text{real} \tag{19b}$$

($j$ is not summed) namely,

$$\text{phase of } U_{j1}^L B_{11}^L = \text{phase of } U_{j2}^L B_{22}^L \tag{20}$$

and the phase of $A_{jj}^L$ is determined from (19a) or (19b).

For an arbitrary $n\times n$ unitary matrix $U^L$, there are $n$ equations corresponding to (20), i.e., $j=1, \ldots, n$, to solve for two parameters $B_{11}^L$ and $B_{22}^L$. Therefore, for $n \geq 3$, there do not exist phase matrices $A^L$ and $B^L$ such that (19a) and (19b) are true. On the other hand, if $n=1$ or 2, $CP$ is conserved to all orders in gauge-boson–quark couplings. This is the original observation of Kobayashi and Maskawa.

Since it is hard to observe $CP$ violation outside the neutral $K$ system, we may relax the condition on natural $CP$ conservation at the one-loop level in other channels, which will be the case for the second and third models in Sec. III.

At this point, it is worthwhile to examine the consequences of the flavor-changing neutral currents. In this case the matrix $U^L$ in Eqs. (19a) and (19b) is $m\times n$, where $m\neq n$. Corresponding to Eqs. (19a) and (19b), there are $2m$ equations for the phase, and we have $m$ adjustable phases in $A^L_{ij}$ and two adjustable phases in $B^L_{11}$ and $B^L_{22}$. Therefore, the case $m\leq 2$ admits solutions without restricting the value of $n$. However, the case $m=2<n$ which corresponds to two $Q=\frac{2}{3}$ quarks and $n$ $Q=-\frac{1}{3}$ quarks presents other disastrous problems such as the ones in $Q=-\frac{1}{3}$ neutral currents which violate both flavors and $CP$.

## III. MODELS

In this section we shall give several examples of natural $G_F\alpha$-order $CP$ conservation in $d$-quark–gauge-boson couplings. This ensures the reality of the $K_L$-$K_S$ mass matrix up to the one-loop level.

The first example is the four-quark model of GIM,[7]

$$\begin{pmatrix}u'\\ d\end{pmatrix}_L,\ \begin{pmatrix}c'\\ s\end{pmatrix}_L,\ \begin{matrix}u_R\ ,\ c_R\ ,\\ d_R\ ,\ s_R\ ,\end{matrix} \tag{21}$$

where

$$\begin{pmatrix}u'\\ c'\end{pmatrix}_L=U^{L\dagger}\begin{pmatrix}u\\ c\end{pmatrix} \tag{22}$$

Any complex parameter in $U^L$ can be removed by redefining quark field phases, and $CP$ is conserved to all orders of gauge-boson couplings.

The second example is[16]

$$\begin{gathered}f_{1L}, f_{2L}, \begin{pmatrix}f_1\\ u''\end{pmatrix}_R,\ \begin{pmatrix}f_2\\ c''\end{pmatrix}_R,\\ \begin{pmatrix}u'\\ d\end{pmatrix}_L,\ \begin{pmatrix}c'\\ s\end{pmatrix}_L, d_R, s_R,\end{gathered} \tag{23}$$

where

$$\begin{pmatrix}u'\\ c'\end{pmatrix}_L=U^{L\dagger}\begin{pmatrix}u\\ c\end{pmatrix}_L \tag{24}$$

and

$$\begin{pmatrix}u''\\ c''\end{pmatrix}_R=Y^R\begin{pmatrix}u\\ c\end{pmatrix}_R. \tag{25}$$

In this model the $G_F\alpha$-order $CP$ problem in the neutral $K$ system depends only on the matrix $U^L$ which can be made real following the arguments of Sec. II. The same conclusion can be drawn for $Y^R$. But we cannot make both $U^L$ and $Y^R$ real, simultaneously. The reason is that the phase freedom is restricted for the $u$ quark field due to Eq. (16). For example, if we made $Y^R$ real, the freedom for $A^L$ is exhausted and only two parameters in $U^L$ can be removed by $B^L$ [refer to Eq. (19)], leaving one complex parameter. Hence, $CP$ is conserved in $K_L\to 2\pi$ up to the order $G_F\alpha$ of the gauge-boson couplings and $\eta_{+-}$ from this source is expected to be of order of $(\alpha/\pi)m_q^2/M_W^2$. (In this model other sources of $CP$ violation such as the ones discussed in Refs. 5 and 8 play a more important role in $K_L\to 2\pi$ decay.) The same degree of $CP$ conservation is expected for mesons, $(\bar f_1 f_2\pm f_1\bar f_2)/\sqrt{2}$. However, $D_{1,2}\equiv(u\bar c\pm\bar u c)/\sqrt{2}$ is expected to substantially violate $CP$ unless it is suppressed by real or imaginary (or both) Cabibbo angles.

As the third example, we consider

$$\begin{pmatrix}f_1'\\ u'\\ d\end{pmatrix}_L,\begin{pmatrix}f_2'\\ c'\\ s\end{pmatrix}_L,\ \begin{matrix}f_{1R}, f_{2R},\\ u_R,\ c_R,\\ d_R,\ s_R,\end{matrix} \tag{26}$$

The phenomenological implication of this model is similar to that of the second model. The three models have the same unfortunate fate for the high-$y$ anomaly.[12] But this model is the simplest one to include the $\tau^-$ lepton in the scheme,[17]

$$\begin{pmatrix}\nu_e\\ e^-\\ E^=\end{pmatrix}_L,\begin{pmatrix}\nu_\mu\\ \mu^-\\ M^=\end{pmatrix}_L,\begin{pmatrix}\nu_\tau\\ \tau^-\\ T^=\end{pmatrix}_L,\begin{pmatrix}\nu_l\\ l^-\\ L^=\end{pmatrix}_L,\ \text{and } V+A \text{ singlets.} \tag{27}$$

We note that (26) and (27) do not produce the Adler-Bell-Jackiw anomaly.[18]

## IV. CONCLUSION

The natural suppression of $CP$ violation in gauge-boson–quark couplings in the SU(2) × U(1) theory has been studied. We have obtained a necessary and sufficient condition for the order-$G_F$ suppression of $CP$: The quarks of charge $q$ and $q-1$ should not belong to the same weak isomultiplets for at least one chirality. However, we could *not* remove the $CP$ phase at the order $G_F\alpha$ except for the special cases of Sec. III.

## ACKNOWLEDGMENTS

The author is greatly indebted to Professor Benjamin Lee for his valuable comments. He also acknowledges the discussions with H. Harari, P. Langacker, and R. E. Shrock. He also thanks Professor Benjamin Lee for his kind hospitality at Fermilab.

*Work supported in part by the U. S. Energy Research and Development Administration.

†Present address: University of Pennsylvania, Philadelphia, Pennsylvania 19174.

[1]S. L. Glashow and S. Weinberg, Phys. Rev. D 15, 1958 (1977). See also, K. Kang and J. E. Kim, Phys. Lett. 64B, 93 (1976); E. A. Paschos, in *Proceedings of the International Neutrino Conference, Aachen, West Germany, 1976*, edited by H. Faissner, H. Reithler, and P. Zerwas (Vieweg, Braunschweig, 1977), p. 501. Phys. Rev. D 15, 1966 (1977); J. E. Kim, *ibid.* 16, 172 (1977); K. Kang, J. E. Kim, and R. Nabavi, Phys. Rev. D 16, 911 (1977).

[2]J. H. Christensen, J. W. Cronin, V. L. Fitch, and R. R. Turlay, Phys. Rev. Lett. 13, 138 (1964).

[3]Pre-gauge-theory attempts to incorporate *CP* violation include L. Wolfenstein, Phys. Rev. Lett. 13, 562 (1964); T. T. Wu and C. N. Yang, *ibid.* 13, 380 (1964); S. L. Glashow, *ibid.* 14, 35 (1965); L. Wolfenstein, Nuovo Cimento 42, 17 (1966). For more phenomenological models, see L. Wolfenstein, in *Theory and Phenomenology in Particle Physics*, edited by A. Zichichi (Academic, New York, 1969). For a recent experimental survey, see K. Kleinknecht, in *Proceedings of the XVII International Conference on High Energy Physics, London, 1974*, edited by J. R. Smith (Rutherford Laboratory, Chilton, Didcot, Berkshire, England, 1974), p. III-23.

[4]Early works on *CP* violation in the gauge theory include R. N. Mohapatra, Phys. Rev. D 6, 2023 (1972); M. A. B. Beg and A. Zee, *ibid.* 8, 1460 (1973); A. Pais, *ibid.* 8, 625 (1973); T. D. Lee, *ibid.* 8, 1226 (1973); Phys. Rep. 9C, 148 (1974); A. Zee, Phys. Rev. D 4, 1772 (1974); R. N. Mohapatra and J. C. Pati, *ibid.* 11, 566 (1975); J. Frenkel and M. E. Ebel, Nucl. Phys. B83, 177 (1974). For a review on these subjects, see R. N. Mohapatra, in *Particles and Fields—1974*, edited by C. E. Carlson (AIP, New York, 1974), p. 127. For gauge theories of superweak *CP* violation, see R. N. Mohapatra, J. C. Pati, and L. Wolfenstein, Phys. Rev. D 11, 3319 (1973); P. Sikivie, Phys. Lett. 65B, 141 (1976).

[5]S. Weinberg, Phys. Rev. Lett. 37, 657 (1976).

[6]S. Okubo, Nuovo Cimento 54A, 491 (1968).

[7]S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[8]T. D. Lee, Ref. 4; H. Georgi and A. Pais, Phys. Rev. D 10, 1246 (1974); H. Georgi and A. Pais, Harvard Univ. Report No. HUTP-77/A041, 1977 (unpublished).

[9]M. Kobayashi and K. Maskawa, Prog. Theor. Phys. 49, 652 (1973); for an analysis of this model, see S. Pakvasa and M. Sugawara, Phys. Rev. D 14, 305 (1976); J. Ellis, M. K. Gaillard, and D. V. Nanopoulos, Nucl. Phys. B109, 213 (1976).

[10]B. W. Lee, Phys. Rev. D 15, 3394 (1977).

[11]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*, edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.

[12]A. Benvenuti *et al.*, Phys. Rev. Lett. 36, 1478 (1976); 37, 189 (1976).

[13]This argument has been given by S. L. Glashow and S. Weinberg, Ref. 1; B. W. Lee, Ref. 10; B. W. Lee and R. E. Shrock, Fermilab Report No. PUB-77/24-THY (unpublished).

[14]H. Fritzsch, M. Gell-Mann, and P. Minkowski, Phys. Lett. 59B, 256 (1975); A. De Rújula, H. Georgi, and S. L. Glashow, Phys. Rev. D 12, 3589 (1975); S. Pakvasa, W. Simmons, and S. Tuan, Phys. Rev. Lett. 35, 702 (1975); F. Wilczek, A. Zee, R. Kingsley, and S. Treiman, Phys. Rev. D 12, 2768 (1975).

[15]M. K. Gaillard and B. W. Lee, Phys. Rev. D 10, 897 (1974).

[16]This has been also considered by B. W. Lee, Ref. 10.

[17]M. Perl *et al.*, Phys. Rev. Lett. 35, 195 (1975); Phys. Lett. 63B, 466 (1976).

[18]S. L. Adler, in *Lectures on Elementary Particles and Quantum Field Theory*, edited by S. Deser, M. Grisaru, and H. Pendleton (MIT Press, Cambridge, Mass., 1970); R. Jackiw, in S. B. Treiman, R. Jackiw, and D. J. Gross, in *Lectures on Current Algebra and Its Applications* (Princeton Univ. Press, Princeton, N.J., 1972).