Enhancement of ϵ'/ϵ in the $SU(2)_L \times SU(2)_R \times U(1)$ model

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We explore the possible enhancement of the direct CP-violating parameter ϵ'/ϵ in the general left-right model based on the $SU(2)_L \times SU(2)_R \times U(1)$ gauge group. The mixing matrix of right-handed quarks, $V^R_{\rm CKM}$, is observable in the left-right model, and provides a new source of the CP-violating phase. We calculate the parameter ϵ'/ϵ in the left-right model and show that the new phases from $V^R_{\rm CKM}$ can yield a sizable contribution to the direct CP violation, enough to satisfy the recent measurements of $\mathrm{Re}(\epsilon'/\epsilon)$ from Fermilab KTeV and CERN NA48 experiments.

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I. INTRODUCTION

The quantity $\mathrm{Re}(\epsilon'/\epsilon)$ is a measure of direct CP violation in the neutral kaon system. The experimental situation of $\mathrm{Re}(\epsilon'/\epsilon)$ has settled down by the recent measurements by the KTeV [1] and NA48 [2] Collaborations. The present world average [2] including the earlier NA31 [3] and E731 [4] results reads

$$\mathrm{Re}(\epsilon'/\epsilon) = (19.3 \pm 2.4) \times 10^{-4}, \tag{1}$$

which leads to the conclusion that the parameter $\mathrm{Re}(\epsilon'/\epsilon)$ is nonzero and rules out the superweak model involving no direct CP violation. A more accurate value of ϵ'/ϵ will be obtained as NA48 and KTeV experiments further proceed and a new experiment, KLOE, at the Frascati Φ factory has started [5].

The theoretical prediction of the standard model (SM) originated in the Cabibbo-Kobayashi-Maskawa (CKM) phase is still controversial. Recently, Pallante and Pich have pointed out that the final-state interactions make it possible for the SM prediction to be fitted with the currently measured values of $\mathrm{Re}(\epsilon'/\epsilon)$ [6], while the earlier predictions show more than a 2σ deviation from the present measurements [7]. Since the hadronic matrix elements have large theoretical uncertainties, however it is not yet settled whether the measured ϵ'/ϵ originates only by the SM. Moreover, it is well known that the baryogenesis of our universe needs CP violation beyond that given by the SM. Therefore, it is interesting to consider the new source of CP violation from new physics beyond the SM and its implication on ϵ'/ϵ. The supersymmetric contribution to $\mathrm{Re}(\epsilon'/\epsilon)$ has been extensively studied in the literature [8] and other models are also attempted [9,10].

The left-right (LR) model based on the $SU(2)_L \times SU(2)_R \times U(1)$ gauge group is one of the natural extensions of the SM [11]. In the LR model, the right-handed CKM matrix $V^R_{\rm CKM}$ which describes mixing of right-handed quarks is an observable quantity while it is not observable in the SM. If we make a demand of manifest symmetry between left- and right-handed sectors, $V^R_{\rm CKM}$ should be identical to the usual CKM matrix. Then effects of the right-handed current interaction are suppressed by a large mass of the heavier charged gauge boson W_R and we cannot expect a sizable contribution to the CP-violating phenomena from the right-handed sector. Assigning no left-right symmetry manifested, meanwhile, $V^R_{\rm CKM}$ contains three mixing angles and six phases in general, and it may result in exotic CP violations in various processes. The kaon decay amplitudes generically accompany the product of CKM matrix elements $\lambda_i = V^*_{is}V_{id}$ with $i=u,c,t$. In the SM, the CP phase dominantly appears in (13) elements of the CKM matrix for the kaon system and the CP-violating effects are suppressed by the smallness of $|V_{td}| \sim 10^{-3}$ in spite of the order 1 phase, $\delta_{\rm CKM}$. Thus it is possible to enhance the CP-violating effect in the general LR model if $|\lambda^R_t| \gg |\lambda^L_t|$, although suppressed by m_{W_R}.

In this work, we consider the general version of the LR model assuming no symmetry between left- and right-handed sectors. We find that the enhancement of $\mathrm{Re}(\epsilon'/\epsilon)$ in the LR model is consistent with the present experiments and show the corresponding parameter space. This paper is organized as follows: In Sec. II, the basic formalism of the $\Delta S=1$ effective Hamiltonian in the LR model is presented. We calculate the contribution of the right-handed sector to the parameter ϵ'/ϵ in Sec. III and perform the numerical study under the constraints from measured ϵ_K and Δm_K in Sec. IV. Finally, we conclude in Sec. V.

II. $\Delta S=1$ EFFECTIVE HAMILTONIAN IN THE LR MODEL

The $K \to \pi\pi$ processes are described by the $\Delta S=1$ effective Hamiltonian written by

$$\mathcal{H}^{\Delta S=1}_{\rm eff} = \frac{G_F}{\sqrt{2}} \Bigg[\sum_{i=1}^{2} [\lambda^L_u C_i(\mu) Q_i(\mu) + \lambda^R_u C'_i(\mu) Q'_i(\mu)] - \sum_{j=3}^{10} [\lambda^L_t C_j(\mu) Q_j(\mu) + \lambda^R_t C'_j(\mu) Q'_j(\mu)] \Bigg], \tag{2}$$

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where Q_i are the SM operators, Q_i' their chiral conjugate operators, and C_i and C_i' are corresponding Wilson coefficients. We follow the convention of Refs. [12,13] for the explicit form of operators Q_i. For simplicity, we set the left-right mixing to be zero in this work. The new Wilson coefficients C_i' at the scale $\mu = m_{W_R}$ are determined by matching the Feynman diagrams with W_R boson exchanges to the effective Hamiltonian (2). The relevant Feynman rules involved in the diagrams of γ-penguin and gluon-penguin are obtained by the $(L\leftrightarrow R)$ exchange of their chiral conjugates of the SM. Consequently, we have the effective γ- and gluon-penguin vertices as

$$(\overline{s}\gamma d)_R = -i\lambda_i^R \frac{G_F}{\sqrt{2}} \frac{e}{8\pi^2} \frac{g_R^2}{g_L^2} D_0(x_i') \times \overline{s}(q^2\gamma_\mu - q_\mu \not{q})(1+\gamma_5)d, \tag{3}$$

$$(\overline{s}G^a d)_R = -i\lambda_i^R \frac{G_F}{\sqrt{2}} \frac{g_s}{8\pi^2} \frac{g_R^2}{g_L^2} E_0(x_i') \times \overline{s}_\alpha(q^2\gamma_\mu - q_\mu \not{q})(1+\gamma_5)T^a_{\alpha\beta} d_\beta, \tag{4}$$

where $x_i' = m_i^2/m_{W_R}^2$ and $i = u,c,t$. The loop functions $D_0(x)$ and $E_0(x)$ are the same as those of the SM and given in Ref. [13]. In addition, the effective Z-penguin vertex with the internal W_R boson exchanges is given by

$$(\overline{s}Zd)_R = i\lambda_i^R \frac{G_F}{\sqrt{2}} \frac{e}{2\pi^2} m_Z^2 \frac{\cos\theta_W}{\sin\theta_W} \frac{g_R^2}{g_L^2} C_R(x_i') \overline{s}\gamma_\mu(1+\gamma_5)d, \tag{5}$$

with the new loop function

$$C_R(x) = \frac{x}{16}\left(\frac{3}{1-x} + \frac{4-2x+x^2}{(1-x)^2}\ln x\right) \tag{6}$$

in the leading order of the suppression by m_{W_R}. Since the $Zf\overline{f}$ and ZW^+W^- vertex is left-right asymmetric, the loop function of the $(\overline{s}Zd)_R$ vertex is different from that of the Z-penguin vertex in the SM. We do not include the contributions from the charged Higgs boson here, which is acceptable because we have the freedom to let the charged Higgs boson be sufficiently heavy.

The relative strength of new effective vertices to the SM ones is generically given by

$$\left|\frac{(\overline{s}Vd)_R}{(\overline{s}Vd)_{\rm SM}}\right| = \left|\frac{\lambda_i^R}{\lambda_i^L}\right| \frac{g_R^2}{g_L^2} \frac{F_V^R(x_i')}{F_V^L(x_i)}, \tag{7}$$

where $F(x)$ is a generic loop function. Actually, the generic suppression factor involved in the right-handed sector is given by $\beta_g \equiv (g_R^2/g_L^2)(m_{W_L}^2/m_{W_R}^2)$ in the LR model. Note that the ratio of Eq. (7) goes to the generic suppression factor $\sim|\lambda_i^R/\lambda_i^L|\beta_g$ if $F(x)\sim x$. We point out that the new vertices can be enhanced by the factor $|\lambda_i^R/\lambda_i^L|$ while suppressed by the large mass of W_R. The loop functions $D_0(x')$, $E_0(x')$, and $C_R(x')$ behave like logarithmic functions when $x' \ll 1$ so that the suppression by the m_{W_R} is weaker than β_g.

We also have an extra neutral gauge boson in the LR model and the corresponding $\overline{s}Z'd$ vertex. Due to the Z' propagator, its contribution to the Wilson coefficients is additionally suppressed by the factor of $m_Z^2/m_{Z'}^2 < 0.02$ from the present bound on $m_{Z'}$ [14]. Hence we ignore the $\overline{s}Z'd$ vertex in this work.

There are two kinds of box diagram contributing to the terms $C_i'Q_i'$; one has two W_R exchanges and the other one W_R and one ordinary W_L exchange. The box diagram containing two W_R bosons is computed as

$$[(\overline{s}d)(\overline{q}q)]_{RR} = -i\lambda_i^R \frac{G_F}{\sqrt{2}} \frac{g_L^2}{4\pi^2} |V_{jq}^R|^2 \beta_g \frac{g_R^2}{g_L^2} \tilde{B}(x_i', x_j') \times (\overline{d}P_L\gamma_\mu s)(\overline{q}P_L\gamma^\mu q), \tag{8}$$

where the function $\tilde{B}(x_i', x_j')$ $(i,j = u,c,t)$ is found in Ref. [13]. We find that this contribution is additionally suppressed by β_g as well as the loop function factor $(g_R^2/g_L^2) \times[\tilde{B}(x_i', x_j')/\tilde{B}(x_i, x_j)]$. For the box diagram with one W_R boson and one W_L boson exchange, the chiral structure makes the contributions proportional to the masses of internal quarks as well as the CKM factors such that $[(\overline{s}d) \times(\overline{d}d)]_{LR} \propto \lambda_i^R |V_{id}^L|^2 m_i^2$. Thus this is additionally suppressed by the mass ratio $m_i^2/m_W^2 \sim (10^{-4} - 10^{-8})$ $(i = u,c)$ or the CKM factor $|V_{id}^L|^2 \sim 10^{-5}$ $(i=t)$. Consequently, the contributions from box diagrams are much smaller than those from penguin diagrams and are not considered in this work.

Matching the full theory to the effective theory given by Eq. (2) at the scale $\mu = m_W$, we have the Wilson coefficients at next-to-leading order (NLO):

$$\begin{aligned}
C_1'(m_W) &= \frac{11}{2}\frac{\alpha_s(m_W)}{4\pi}\beta_g,\\
C_2'(m_W) &= \left(1 - \frac{11}{6}\frac{\alpha_s(m_W)}{4\pi} - \frac{35}{18}\frac{\alpha}{4\pi}\right)\beta_g,\\
C_3'(m_W) &= -\frac{\alpha_s(m_W)}{24\pi}\frac{g_R^2}{g_L^2}\tilde{E}_0(x_t'),\\
C_4'(m_W) &= C_6'(m_W) = \frac{\alpha_s(m_W)}{8\pi}\frac{g_R^2}{g_L^2}\tilde{E}_0(x_t'),\\
C_5'(m_W) &= \left(-\frac{\alpha_s(m_W)}{24\pi}\tilde{E}_0(x_t') + \frac{1}{\sin^2\theta_W}\frac{\alpha}{6\pi}C_R(x_t')\right)\frac{g_R^2}{g_L^2},\\
C_7'(m_W) &= \frac{\alpha}{6\pi}\frac{g_R^2}{g_L^2}\left[4C_R(x_t') + \tilde{D}_0(x_t') - \frac{4}{\sin^2\theta_W}C_R(x_t')\right],\\
C_9'(m_W) &= \frac{\alpha}{6\pi}\frac{g_R^2}{g_L^2}[4C_R(x_t') + \tilde{D}_0(x_t')],\\
C_8'(m_W) &= C_{10}'(m_W) = 0.
\end{aligned} \tag{9}$$

We ignore the running from the scale $\mu = m_{W_R}$ to m_W for simplicity and perform the matching only at $\mu = m_W$. The complete renormalization-group (RG) evolution of the Wilson coefficients (C_i, C_i') from the scale $\mu = m_W$ to $\mu = m_c$ is governed by a 20×20 anomalous dimension matrix. Since the strong interaction preserves chirality, new operators Q_i' are not mixed with the SM operators and evolve separately. Thus the anomalous dimension matrix is decomposed into two 10×10 matrices which are identical to each other. The 10×10 anomalous dimension matrix has been calculated by several authors at NLO [15]. Here we use the numerical values listed in Ref. [12], obtained under the naive dimensional reduction (NDR) scheme. Finally, the values of the Wilson coefficients at the scale $\mu = m_c$ are determined after solving the RG equation.

III. ϵ'/ϵ IN THE LR MODEL

The complex parameter ϵ' is defined as

$$\epsilon' = \frac{1}{\sqrt{2}} \mathrm{Im}\left(\frac{A_2}{A_0}\right) e^{i(\pi/2 + \delta_2 - \delta_0)}, \tag{10}$$

where $A_{I=0,2}$ are the isospin amplitudes in $K \to \pi\pi$ decays and $\delta_{0,2}$ are the corresponding strong phases. The ratio $\mathrm{Re}(\epsilon'/\epsilon)$ is obtained from the measured ratio $\eta_{00} \equiv A(K_L \to \pi^0\pi^0)/A(K_S \to \pi^0\pi^0)$ and $\eta_{\pm} \equiv A(K_L \to \pi^+\pi^-)/A(K_S \to \pi^+\pi^-)$ as

$$\left|\frac{\eta_{00}}{\eta_{\pm}}\right|^2 \approx 1 - 6 \ \mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right), \tag{11}$$

where the deviation of $|\eta_{00}/\eta_{\pm}|$ from 1 indicates the direct CP violation in $K \to \pi\pi$ decays. Using the Hamiltonian in Eq. (2), we can express the parameter $\mathrm{Re}(\epsilon'/\epsilon)$ with the CKM factors,

$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = N_t^L \mathrm{Im}\lambda_t^L + N_t^R \mathrm{Im}\lambda_t^R - N_u^R \mathrm{Im}\lambda_u^R, \tag{12}$$

where the coefficients $N_i^{L(R)}$'s are given by

$$N_i^{L(R)} = \frac{G_F \omega}{2|\epsilon| \mathrm{Re}A_0} \left(\sum_i C_i^{(\prime)} \langle Q_i^{(\prime)} \rangle_0 - \frac{1}{\omega} \sum_i C_i^{(\prime)} \langle Q_i^{(\prime)} \rangle_2 \right), \tag{13}$$

in terms of the evolved Wilson coefficients $C_i^{(\prime)}(\mu = m_c)$ and hadronic matrix elements $\langle Q_i^{(\prime)} \rangle_{0,2}$. The explicit form of hadronic matrix elements $\langle Q_i \rangle_I$ is listed in Refs. [13,16]. The parameter ω is defined by the ratio of isospin amplitudes, as $\omega \equiv \mathrm{Re}A_2/\mathrm{Re}A_0$. The $(-)$ sign of the last term in Eq. (12) is owing to the convention of the effective Hamiltonian of Eq. (2). The value of N_t^L predicted in the SM is reduced by cancellation between $\Delta I = 1/2$ and $\Delta I = 3/2$ contributions, as the electroweak penguin contributions are enhanced by large top quark mass. In the LR model, W_R is much heavier than the top quark and the electroweak penguin contributions are relatively small as $x_t' \ll 1$. Thus there is less cancellation between $\Delta I = 1/2$ and $\Delta I = 3/2$ contributions in this model, which yields enhancement of the coefficients N_i^R. We note that λ_u^R may be the complex number, and contributions of the right-handed sector to $\mathrm{Re}(\epsilon'/\epsilon)$ depend on two CKM parameters $\mathrm{Im}\lambda_t^R$ and $\mathrm{Im}\lambda_u^R$ as a result, while the SM contribution consists of the $\mathrm{Im}\lambda_t^L$ alone. This means that direct bounds on right-handed CKM elements are hardly obtained.

IV. NUMERICAL STUDY

It is well known that the K-$\bar{K}$ mixing puts stringent constraints on the LR model [17]. The parameter ϵ_K and the mass difference Δm_K are obtained from the off-diagonal element M_{12} in the neutral kaon mass matrix. The leading contribution of the LR model to M_{12} comes from the box diagram with one W_L and one W_R gauge boson as internal lines. One can find the relevant $\Delta S = 2$ effective Hamiltonian and related formulas in Ref. [18]. If the left-right symmetry manifests, the mass of the W_R boson should be greater than 1.6 TeV [19] to satisfy the experimental Δm_K and ϵ_K data [13,20],

$$\Delta m_K = 3.51 \times 10^{-15} \ \mathrm{GeV},$$

$$\epsilon_K = (2.280 \pm 0.013) \times 10^{-3}. \tag{14}$$

The bound on m_{W_R} can be lowered by assuming $V_{\mathrm{CKM}}^R \neq V_{\mathrm{CKM}}^L$ [21,22] and it is the case considered here.

In the general LR model, the gauge couplings of $SU(2)_L$ and $SU(2)_R$ groups are not necessarily the same but are expected to be of the same order to avoid the fine-tuning and maintain the perturbativity. For the numerical analysis, we let $g_L^2/g_R^2 = 1$ here. We limit the contribution of the LR model to

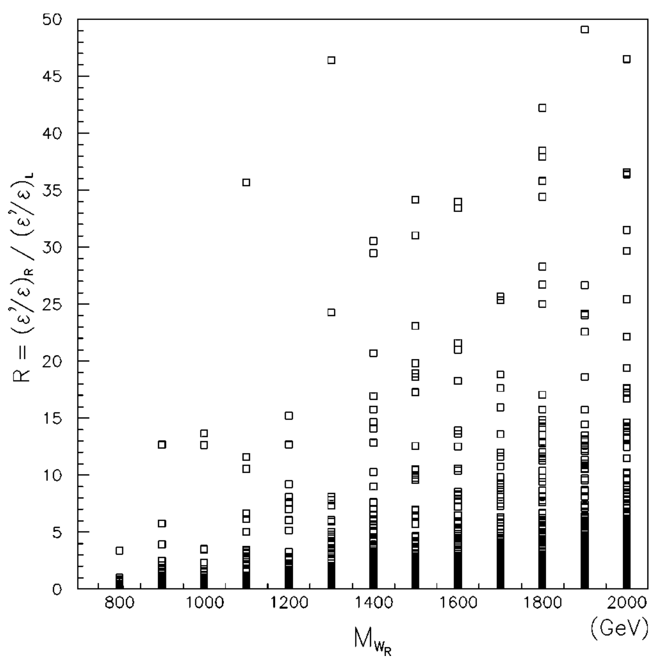

FIG. 1. The ratio of the ϵ'/ϵ from the right-handed sector to that of the standard model with respect to the mass of W_R boson in the vacuum saturation limit under the assumption that $\mathrm{Im}\lambda_u^R = 0$.

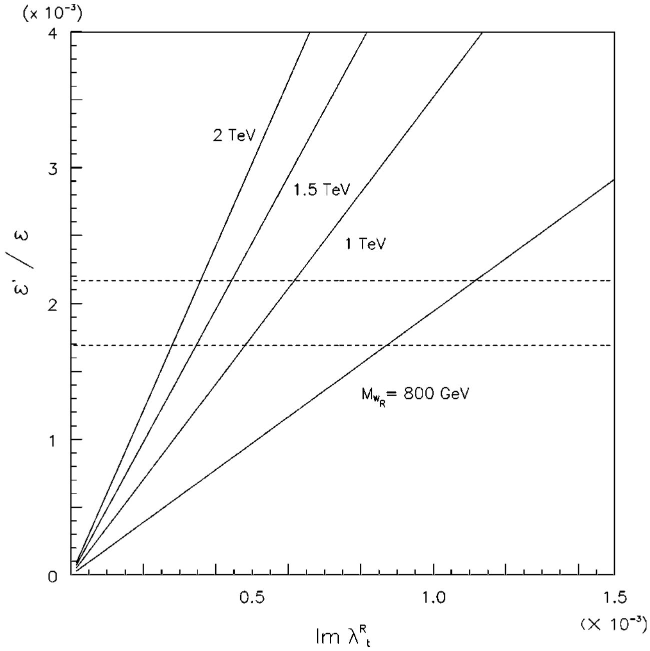

FIG. 2. Dependences of ϵ'/ϵ on the CKM parameter Imλ_t^R for each value of m_{W_R} in the vacuum saturation limit under the assumption that Im$\lambda_u^R = 0$.

the ϵ_K to be within the measured error, which implies that the indirect CP violation is originated principally by the left-handed sector. The box diagrams of the SM are known to describe about 70% of the measured K_L-K_S mass difference and the remaining part is attributed to unknown contributions including nonperturbative effects. So we assume that the new

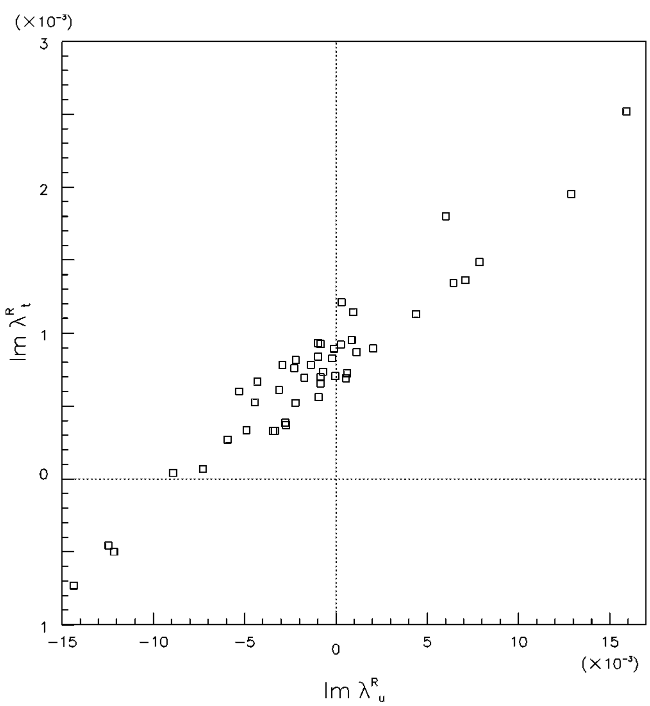

FIG. 3. Parameter set of (Imλ_u^R,Imλ_t^R) which satisfy the present $\Delta m_K, \epsilon_K$ data and the recent ϵ'/ϵ data for $m_{W_R} = 800$ GeV.

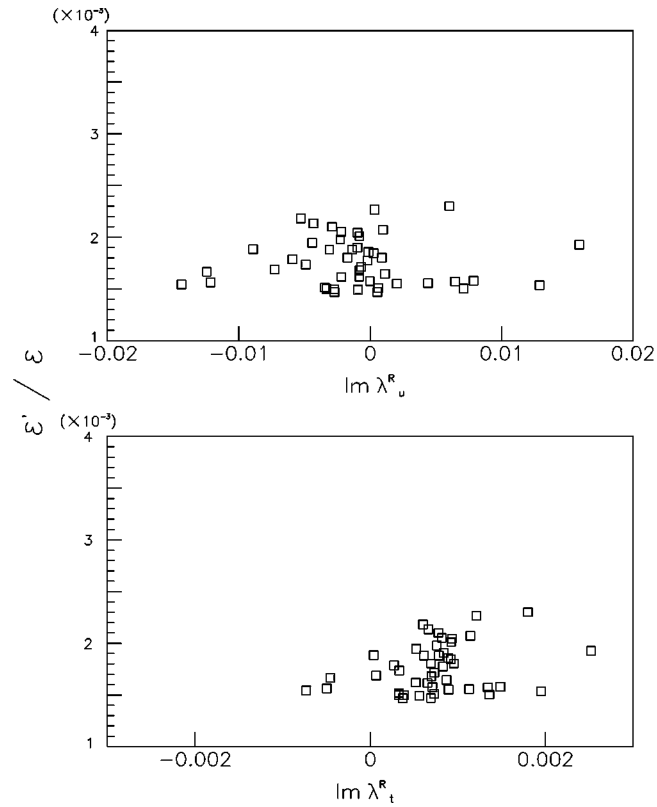

FIG. 4. Distributions of the ϵ'/ϵ prediction with respect to λ_u^R and λ_t^R which satisfy the Δm_K and ϵ_K data for $m_{W_R} = 800$ GeV.

contributions Δm_K^R are required not to exceed 30% of the measured Δm_K here.

The vacuum insertion method with $B_i^{(\Delta I)} = 1$ provides a good approximation of ϵ'/ϵ in the SM. But the parameters $B_1^{(1/2)}$, $B_2^{(1/2)}$, $B_1^{(3/2)}$ show large deviations from the values expected in the vacuum saturation limit. In the SM, $B_{i=1,2}$ do not play roles in CP violation since Imλ_u^L is extremely small. However, the term Imλ_u^R from the right-handed sector is not necessarily small and it can contribute to ϵ'/ϵ considerably. Here, we consider the special case of Im $\lambda_u^R = 0$ for the time being in order to investigate the enhancement of ϵ'/ϵ. We calculate the ratio $R \equiv \mathrm{Re}(\epsilon'/\epsilon)_R / \mathrm{Re}(\epsilon'/\epsilon)_{\mathrm{SM}}$ in the vacuum saturation limit and plot it with varying m_{W_R} from 800 GeV to 2 TeV in Fig. 1. Constraints by the Δm_K and ϵ_K data are considered. This plot indicates the enhancement by the CKM factor Im λ_t^R/Im λ_t^L since contributions to Re(ϵ'/ϵ) come from the CKM elements Im $\lambda_t^{L,R}$ alone in this case. We show the dependence of ϵ'/ϵ on Im λ_t^R with respect to m_{W_R} in Fig. 2.

For the realistic prediction without the assumption that Im $\lambda_u^R = 0$, we calculate ϵ'/ϵ by scanning all the angles and phases of V_{CKM}^R which are constrained by the Δm_K and ϵ_K data. In this paper, we adopt the values of $B_1^{(1/2)}$, $B_2^{(1/2)}$, and $B_1^{(3/2)}$ extracted in Refs. [12,13] by a phenomenological approach

$$B_1^{(1/2)} = 16.5, \quad B_2^{(1/2)} = 6.6, \quad B_1^{(3/2)} = 0.453, \qquad (15)$$

and those of $B_6^{(1/2)}$ and $B_8^{(3/2)}$ summarized by [12,13,16]

$$B_6^{(1/2)}=1, \quad B_8^{(3/2)}=1. \tag{16}$$

Figure 3 plots the all possible parameter sets of $(\mathrm{Im}\lambda_u^R, \mathrm{Im}\lambda_t^R)$ which satisfy the recent ϵ'/ϵ data of Eq. (1) at the 2-σ level under the Δm_K and ϵ_K constraints for $m_{W_R}=800$ GeV, which is close to the present lower bound of the extra W gauge boson from experiment. Correlations of the parameters $\mathrm{Im}\lambda_u^R$ and $\mathrm{Im}\lambda_t^R$ with ϵ'/ϵ are shown in Fig. 4. We find that the values of $\mathrm{Im}\lambda_t^R$ center on a nonzero value, while the values of $\mathrm{Im}\lambda_u^R$ are distributed centering on zero. Thus we conclude that $\mathrm{Im}\lambda_t^R$ is principally responsible for the new contributions to the ϵ'/ϵ. We note that there exist a few points far from the accumulated region, which indicate the fine-tuned combinations of parameters, and they should be less meaningful.

V. CONCLUSION

We explore the possibility that the LR model provides sizable direct CP violation of the kaon system without affecting the K-$\bar{K}$ mixing system. It implies the scenario that the ϵ_K is explained by the SM sector and the ϵ'/ϵ is explained by the right-handed sector. In conclusion, we show that the recent measurement of ϵ'/ϵ is explained in the framework of the general left-right model without fine-tuning. We pointed out the possibility that the contributions of the LR model can be larger than expected; (i) enhancement by CKM factors, (ii) the weaker suppressions for the effective vertices than the tree level suppression factor β_g, and (iii) less cancellation between $\Delta I=1/2$ and $\Delta I=3/2$ contributions. On the other hand, it is likely for the LR model to give interesting predictions on other observables, i.e., hyperon CP violation [23], $K\to\pi\nu\bar{\nu}$ decays, etc. in the parameter space studied here. Measurements of these observables enable us to obtain more information on V_{CKM}^R and test the LR model.

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