Rare Decays and CP Violation in K and B Systems

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Abstract

The complementary roles played by K and B decays to check the Kobayashi-Maskawa mixing scheme and the mechanism of CP violation are discussed. The origin of the sizeable CP asymmetry in B decays is clarified, in comparison with the corresponding asymmetry in K system. While the theoretical prediction of such CP asymmetry in B decay is reliable, K rare decays still provide some useful information on m_t. For example, the recent data on $K_L \to \mu\bar{\mu}$, with some assumption, implies $60\,\mathrm{GeV} \lesssim m_t \lesssim 120\,\mathrm{GeV}$.

The purpose of this review talk is to discuss how the investigation of rare decays and CP violating processes, in both K and B meson systems, provides useful information on flavor mixing and quark masses. In particular, the importance of the measurement of CP asymmetries in B meson decays for the establishment of Kobayashi-Maskawa (K-M) model will be stressed, in comparison with the corresponding processes in the K meson system. It will, however, be also argued that the ongoing and the forthcoming experiments on K decays, especially $K_L \to \mu\bar{\mu}$, still play an important, complementary role in imposing a meaningful bound on m_t (the top quark mass). For convenience B and K systems will be treated separately.

I. B physics

(1) Why interested in?

Now the various projects of B meson factories have been actively discussed in several places in the world, including KEK. The interest in the rare decays and CP asymmetry of B mesons measured in such factories seems to stem from the following two points:

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(*a*) Sizeable *CP* asymmetry in K-M model.[1]

(*b*) A window to "beyond the standard theories."

The sizeable, $O(10\%)$, *CP* asymmetry in some typical decay modes is a unique prediction of the K-M model. One might wonder how one can predict such a large *CP* asymmetry with our poor knowledge on K-M mixing matrix elements of b quark, especially their phases. One may also ask the question why *CP* asymmetry can be large in B decay, but not in K decays. The clue to answer these questions lies in the unitarity of the K-M matrix, V. Namely, if we express the orthogonality condition between the columns of b and d quarks,

$$\sum_{i=u,c,t} V_{ib}V_{id}^* = 0 \,, \tag{1}$$

in a complex plane (Fig. 1), we will see that the 3 vectors corresponding to the 3 complex numbers in the sum in (1) form a closed triangle, often called as "unitarity triangle." Although by re-phasing of quark fields each vector rotates on the plane, the shape of the triangle, of course, does not change. Thus the shape itself should have some physical meaning. In fact, one can easily show that the area of the triangle, S, is related with the Jarlskog's parameter J, defined as

$$J = \pm\,\mathrm{Im}(V_{i\alpha}V_{j\alpha}^*V_{j\beta}V_{i\beta}^*) \qquad (\alpha \neq \beta,\, i \neq j)\,, \tag{2}$$

in the following way

$$S = \tfrac{1}{2}|J|\,. \tag{3}$$

The parameter J is a re-phasing invariant quantity, which always appears in *CP* violating observables in the K-M model. If, *e.g.*, $V_{ub} = 0$, then $S = J = 0$ and there would be no *CP* violation. In fact, there is an argument that the extent of *CP* violation, J, can be completely determined by the modulus of 4 elements of the K-M matrix,[2] or the rates of decays like $b \to u$ transition. (That is why the observation of charmless B decay is important in the view of *CP* violation.) We thus realize that any *CP* asymmetric quantity should depend on the shape of the triangle, *i.e.*, whether it is "well opened" or "squashed." In other words, it depends on the "opening angles," ϕ_1, ϕ_2, and ϕ_3 of Fig. 1 in the case of B decays.

To see how large these opening angles are, it is convenient to use the parametrization of K-M matrix by Wolfenstein,[3] which is a power expansion in terms of $\lambda \simeq \sin\theta_C \simeq 0.22$.

In addition to λ, we have one rather well determined parameter, $A \simeq 0.93 \pm 0.17$, and two parameters, ρ and η, on which we know little except for $\rho, \eta = O(1)$. As is seen in Fig. 1, in the triangle relevant for B^0 and $\bar{B}^0$, the lengths of all 3 edges are of $O(\lambda^3)$. Thus we have a well opened triangle. We, therefore, will expect sizeable CP asymmetry, since

$$CP \text{ asymm.} \sim \text{opening angles of triangle} \sim J/(\text{rates}) , \tag{4}$$

where the "rates" means the decay rates of the process in question and will be handled by the lengths of the edges. In fact, for the frequently discussed process, $B^0 \to \psi K_S$, the CP asymmetry turns out to be

$$a(B^0 \to \psi K_S) \simeq \sin(2\phi_1) , \tag{5}$$

which is estimated to be of $O(10\%)$. On the other hand, Eq. (4) implies a rather small decay rate. In fact we now know

$$\text{Br}(B^0 \to \psi K_S) \simeq 4 \times 10^{-4} , \tag{6}$$

which in turn demands high luminosity of e^+e^- beams in order to detect the CP asymmetry.

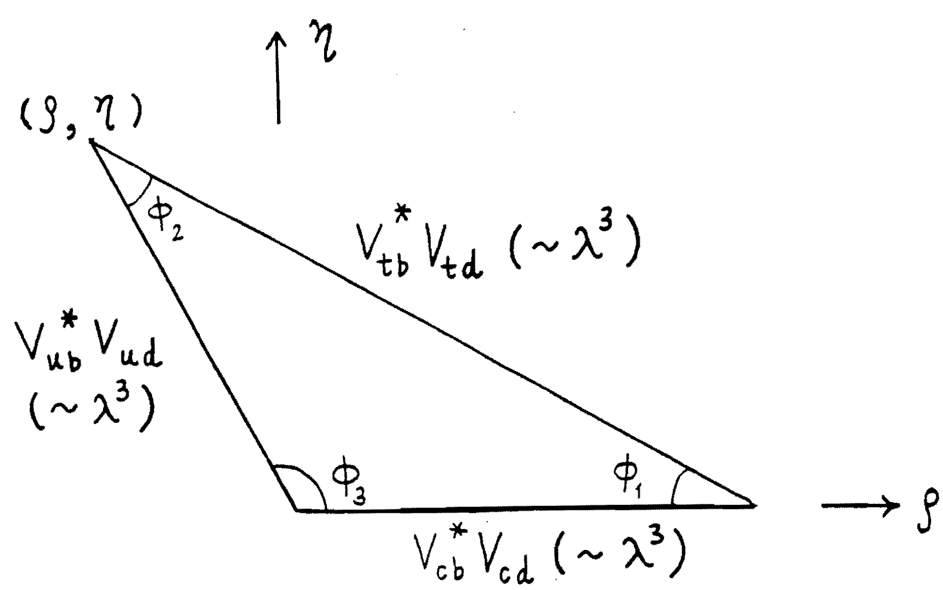

Fig. 1. The "unitarity triangle" for the $\bar{b}d$ system. When the lengths of all three edges are rescaled in the unit of $A\lambda^3$, the vertex with the angle ϕ_2 has the coordiate (ρ, η).

Then why can CP asymmetry not be large in the K system, while the parameter J is a unique quantity to describe CP violation? In Eq. (2), α, β, and i, j can take various combinations. Thus for $\alpha = s$ and $\beta = d$ we get another triangle, corresponding to the K^0 system, with the same area $|J|/2$. Since the modulus of $V_{ts}^* V_{td}$ is very small, $O(\lambda^5)$, while the lengths of the other edges are of $O(\lambda)$, the triangle for K^0 is a very squashed one. That is why CP asymmetry in K^0 system is very small:

$$a \sim \sin 2\theta \sim \lambda^4 \sim 10^{-3} \sim \varepsilon \,, \tag{7}$$

where θ denotes the smallest angle (we cannot get a large asymmetry even if we use another angle θ' since $\sin 2\theta' \sim \sin \pi \sim 0$), and ε is the famous quantity in $K^0 \to \pi\pi$ decays. We can actually show that the CP asymmetry discussed in $B \to \psi K$ decay just corresponds to $\mathrm{Im}(\varepsilon)$ in the K^0 decay. Though the asymmetry is very small, the decay rate has "no problem," $\mathrm{Br}(K_S \to \pi\pi) \simeq 100\%$. In this way the B and K factories are expected to play some complementary roles. The great advantage, however, in the B decay is that the theoretical prediction of the CP asymmetry is not expected to suffer from the uncertainty in the hadronic matrix element of the transition. This is essentially because such uncertainty will cancel out in the ratio, which defines the asymmetry, as long as only one amplitude is dominant in the decay.[1]

As for the issue (b) listed above, I would just point out that among the interesting ideas of the beyond standard model, only in the four (or higher) generation model some dramatic change may occur in the rare processes and the CP asymmetry.[4] This is essentially because the processes of our present interest are handled by the generation mixing matrix. Of course, for some siutable choices of parameters, there are chances to get some remarkable deviations from the standard model prediction in other kinds of models as well, like L-R symmetric model,[5] SUSY models,[6] *etc.* Though one interesting possibility in the four generation model is to get very different x_s/x_d ($x = \Delta m_B/\Gamma$, Δm_B: B^0, $\bar{B}^0$ mass difference, $\Gamma = 1/\tau_B$), with $x_{d,s}$ corresponding to $B_{d,s}$ mesons, from the standard model prediction ($\sim /\lambda^2$), the recent LEP result seems to disfavor the existence of the fourth family.

(2) B rare processes

The advantage of the B rare decays, in the view of checking the standard model, is that the expected decay rates are not so small as in K rare decays. The reason is twofold. First, b quark couples with t quark in full strength, $V_{tb} \sim 1$, and secondly, the top quark mass is now known to be quite large, as the recent CDF result $m_t \gtrsim 80\,\mathrm{GeV}$ tells us. The expected branching ratios for the typical rare decays are[7]

$$\mathrm{Br}(b \to s\ell^+\ell^-),\ \mathrm{Br}(b \to s\nu\bar{\nu}) \sim O(10^{-6} \text{ to } 10^{-5}) \tag{8}$$

while $\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) = O(10^{-10})$ in the standard model. In the literature, it has been shown that a short-distance QCD enhancement makes the radiative decay process $b \to s\gamma$ or $B \to K^*\gamma$ the most promising candidate to be seen in the B factories in near future, $\mathrm{Br}(b \to s\gamma) \gtrsim 1 \times 10^{-4}$ for $m_t \gtrsim 100\,\mathrm{GeV}$,[8] which is close to the upper bound, $\mathrm{Br}(b \to s\gamma) < (6\text{–}50)\times 10^{-4}$, derived from the present experimental bound $\mathrm{Br}(B \to K^*\gamma) < 2\times 10^{-4}$ with some uncertainty in evaluating the ratio of branching ratios of the exclusive and the inclusive decays.

Another interesting process to be observed in the B factories is $B_s \leftrightarrow \bar{B}_s$ mixing. As we saw in Fig. 1, once every length of the three edges are rescaled in the unit of $A\lambda^3$, a set of parameters (ρ, η) completely determine the triangle. Therefore, a precise measurement of $B_s \leftrightarrow \bar{B}_s$ mixing will facilitate the precise prediction of *CP* asymmetry, since

$$\frac{x_s}{x_d} \simeq \left|\frac{V_{ts}}{V_{td}}\right|^2 \simeq \frac{1}{\left[(1-\rho)^2 + \eta^2\right]\lambda^2}\,, \tag{9}$$

if we ignore a possible SU(3) breaking effect.

(3) *CP* asymmetry in *B* decays

One remarkable feature of B decays is that a state with almost definite *CP* eigenvalue, like K_L in K decays, cannot be extracted, because of the fact that the two eigenstates of the Hamiltonian have very close lifetimes. Thus, in considering the *CP* asymmetry we always have to take $B \leftrightarrow \bar{B}$ mixing effect into account. The mixing has two implications in the *CP* asymmetry: (i) It "dilutes" the asymmetry, as is shown in the factor $x/(1+x^2)$ which appears in "time-integrated asymmetry." (ii) It enables us to get a sizeable *CP* asymmetry, of order 10% or so, through the interference of two possible amplitudes for a B decay, $B \to f$ and $B \to \bar{B} \to f$, where f is a final state into which both B and $\bar{B}$ can decay, such as ψK_S. Let us recall that the *CP* asymmetry in pure $\Delta B = 2$ process, as in the so-called charge asymmetry, is quite small, $O(10^{-3})$.

Due to the mixing effect, the *CP* asymmetry depends on time,

$$A(t) \equiv \frac{\Gamma(B(t) \to f) - \Gamma(\bar{B}(t) \to f)}{\Gamma(B(t) \to f) + \Gamma(\bar{B}(t) \to f)}\,, \tag{10}$$

where $B(t)$ denotes a state at time t, which was B^0 at $t = 0$, the time of its production.

After neglecting some small corrections, the asymmetry (on the $\Upsilon(4S)$ peak) is given as

$$A(t) \simeq a(f) \cdot \sin(\Delta m_B\, t)\,, \tag{11}$$

with

$$a(f) \simeq -\Im m\{(q/p)(A(\bar{B} \to f)/A(B \to f))\}\,, \tag{12}$$

where p, q are parameters to define the two eigenstates:

$$B_{1,2} \propto (p\,|B\rangle \pm q\,|\bar{B}\rangle)\,. \tag{13}$$

If $f = \bar{f}$ and if only one diagram gives dominant contribution to the decay, $a(f)$ is determined unambiguously in terms of K-M mixing angles only, *i.e.*, it is free from uncertainty due to the strong interaction, like strong phases. A typical candidate for such final states is $f = \psi K_S$ and we can estimate the asymmetry as

$$-a(\psi K_S) = \frac{2(1-\rho)\eta}{(1-\rho)^2 + \eta^2} = 0.1 \text{ to } 0.6\,, \tag{14}$$

where the uncertainty of the numerical value comes from our poor knowledge on ρ and η, though some constraints can be put[9] by use of the data on ε and $B_d \leftrightarrow \bar{B}_d$.

The presence of $B \leftrightarrow \bar{B}$ mixing, on the other hand, makes the detection of the *CP* asymmetry in e^+e^- machine very nontrivial. The definition of the asymmetry, (10), clearly tells us that if we misidentify B as $\bar{B}$, we will get an asymmetry with a wrong sign. The $B \leftrightarrow \bar{B}$ mixing and also the fact that the wave function of the $B\bar{B}$ system, *e.g.*, on the $\Upsilon(4S)$ peak, is the antisymmetric admixture of "forward B"–"backward $\bar{B}$" and its opposite make the identification of B or $\bar{B}$ hard. The antisymmetriticity of the wave function, on the other hand, provides a tool for the identification, since, once we can "tag" one of the $B\bar{B}$ as, *e.g.*, a $\bar{B}$ at some given time, then at the same time the other cannot be a $\bar{B}$, but should be a B. Unfortunately, such tagging is still not enough to observe *CP* asymmetry. As we saw, by tagging we can in some sense fix the origin of time, the time of production of another B or $\bar{B}$ meson. The problem, however, is that the "successive" decay like $B \to \psi K_S$, which is of our interest, may occur before the tagging. So the signal may be earlier than the production of decaying particle! Namely, not only $t > 0$ but also $t < 0$ may happen in Eq. (11), and if we do not identify the decay time t we will get zero *CP* asymmetry.[1] That is why one argues the necessity to devise an "asymmetric collider." Even if the identification of time t is possible, we still need some very high luminosity, $L = O(10^{33}$ to $10^{34}/\,\mathrm{cm}^2\cdot\mathrm{s})$, in order to measure the CP asymmetry in the decay into ψK_S. Another idea to tag B or $\bar{B}$ is to use polarized electron beam on the Z peak,[10] which might be relevant for LEP. By the use of the polarized beam we will have a large forward-backward asymmetry in the decay into $b\bar{b}$, which may help to tag B or $\bar{B}$.

II. K Physics

The K meson physics is not a new field at all, but there is some renewed interest in the subject. First we should notice that now the K rare decay experiments in KEK (PS) and BNL (AGS) have started to provide their new data on the decays $K_L \to \mu\bar{e}$ ($K_L \to \mu\bar{\mu}$), $K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0 e^+ e^-$, *etc.* In addition, now the famous quantity ε'/ε, the measure of the so-called direct CP violation in $K \to \pi\pi$ decays, is a very hot topic; the NA31 experiment at CERN has claimed the observation of nonvanishing ε' for the first time. We will briefly discuss some topics separately in the following.

(1) K rare decays

A few typical rare decays will be chosen. First of all, if $K_L \to \mu\bar{e}$ is observed, it clearly indicates the presence of new physics beyond the standard model, and it will be a great discovery by itself.[11] Next, in the decay of $K^+ \to \pi^+\nu\bar{\nu}$, the following point should be stressed. Namely, the branching ratio of this decay can be reliably calculated as a function of m_t:[12,13]

$$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) \simeq N_g \times 1.5 \times 10^{-5} \left| \sum_{i=c,t} V_{is}^* V_{id}\, D(m_i^2/M_W^2) \right|^2 , \qquad (15)$$

where the top quark mass dependence has been contained in the function D defined in Ref. 12, and N_g is the number of generations. Equation (15) simply comes from the short distance contribution, *i.e.*, one-loop diagrams in the quark picture, while possible long-distance contribution has been estimated to be small.[13] A part of the reason is that the photon exchange is irrelevant in this case, in contrast to the cases of $K_L \to \mu\bar{\mu}$ and $K_L \to \pi^0 e^+ e^-$ where the amplitudes of the photon exchange diagrams have much uncertainty due to the long-distance effects. Equation (15) leads to a range of the branching ratio for, say, $60\,\mathrm{GeV} \lesssim m_t \lesssim 180\,\mathrm{GeV}$,

$$\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu}) = (1 \text{ to } 4) \times 10^{-10} , \qquad (16)$$

where the constraint on the K-M elements[9] has been used. We find that the branching ratio depends on m_t rather mildly, and the "stable" prediction should be checked in near future as the test of the standard model, though on the other hand the measurement may not be a good way to constrain m_t.

As is seen in Fig. 2, which shows the result of Ref. 12 on the ratio of $\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$ to the short-distance contribution to $K_L \to \mu\bar{\mu}$, the amplitude of $K_L \to \mu\bar{\mu}$ is more sensitive to m_t, compared with that of $K^+ \to \pi^+\nu\bar{\nu}$. The recent results from experiments KEK-137[11] and AGS-791,[14] are very interesting and rather surprising; the measured branching ratios tend to be smaller than the PDB value, and the result from AGS-791 is even lower than the "unitarity bound." They, anyway, may impose some meaningful bound on m_t, once the dispersive part of the two-photon process, $K_L \to \gamma\gamma \to \mu\bar{\mu}$, is fixed. For example, the KEK result $\mathrm{Br}(K_L \to \mu\bar{\mu}) = (8.4 \pm 1.1) \times 10^{-9}$ leads to a bound

$$60\,\mathrm{GeV} \lesssim m_t \lesssim 120\,\mathrm{GeV}\,, \tag{17}$$

if we relate the ratio of the dispersive to the absorptive parts of the two-photon process to the corresponding ratio in the process $\eta \to \gamma\gamma \to \mu\bar{\mu}$.[15] The uncertainty in the above

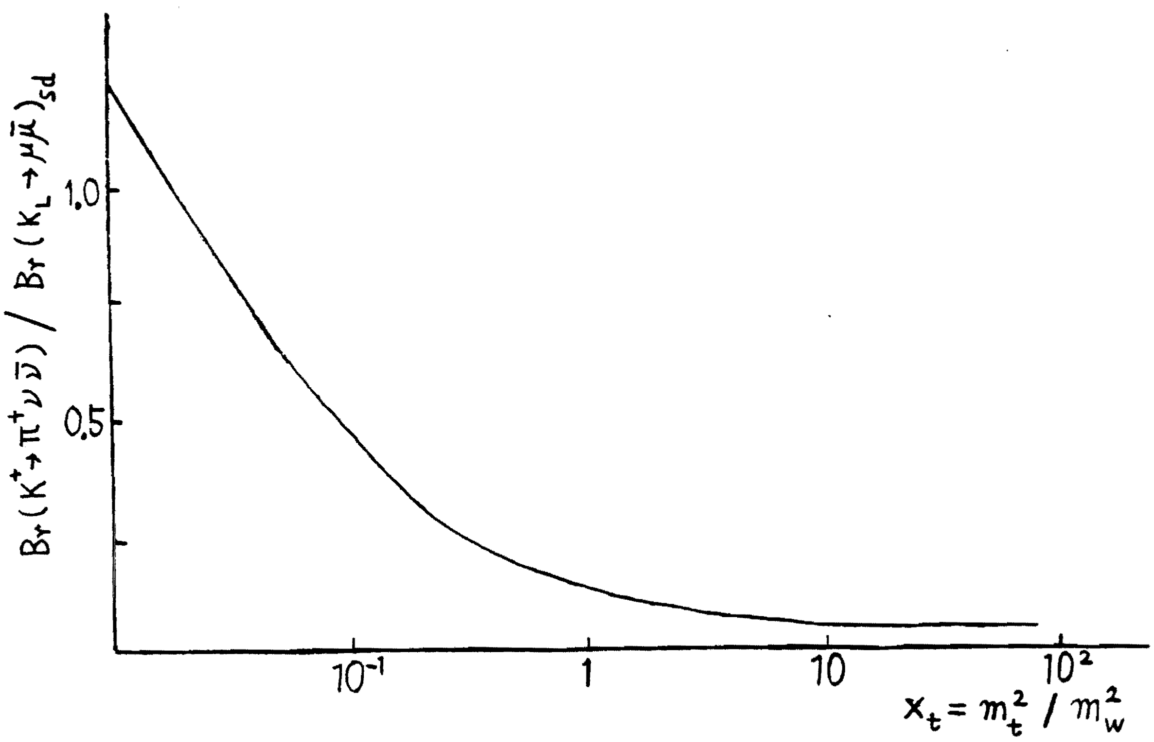

Fig. 2. The ratio $\mathrm{Br}(K^+ \to \pi^+\nu\bar{\nu})/[\mathrm{Br}(K_L \to \mu\bar{\mu})]_{\mathrm{sd}}$ as a function of the top quark mass ($x_t = m_t^2/m_W^2$), where the subscript sd denotes the short distance contribution.

bound on m_t is due to the lack of our knowledge on the K-M parameters, ρ and η. We find that only destructive interference between the dispersive parts of the short-distance[12] and the two-photon amplitudes is allowed. Thus a smaller experimental value on the branching ratio implies a larger m_t.[16]

(2) *CP* violation in *K* decay

We will discuss two topics, ε'/ε and $K_L \to \pi^0 e^+ e^-$. The measure of "direct *CP* violation," ε'/ε, is now in controversy; there exist two contradictory (in 1σ level) experimental data,[14] $(3.3 \pm 1.1) \times 10^{-3}$ (CERN, NA31) and $(-0.5 \pm 1.5) \times 10^{-3}$ (FNAL, E731). One may argue that once ε'/ε is fixed to some finite value, m_t cannot be arbitrarily large.[17] The essence of the argument is that ε'/ε weakly depends on m_t, since the penguin contribution to ε' behaves like $\ln(m_t/m_c)$, while ε grows up as m_t^2/M_W^2 as m_t goes up. Namely,

$$\begin{aligned} &\varepsilon'/\varepsilon \simeq 1.1\,(150\,\mathrm{MeV}/m_s)^2 \times 10^{-2}\eta\,, \\ &\varepsilon \propto \eta\, E(m_t^2/M_W^2)\,, \end{aligned} \tag{18}$$

where $E(x)$ is a monotonically increasing function of x; $E(x) \simeq x$ for $x \ll 1$ and $E(x) \simeq x/4$ for $x \gg 1$.[12] In this way a bound $m_t \simeq 90\,\mathrm{GeV}$ was obtained,[17] relying on the NA31 result. However, it should be emphasized that the first equation in Eq. (18) is not quite correct when top is very heavy, $m_t \gtrsim M_W$, as has been suggested by recent experiments. In fact, when m_t is large, terms which are power in $(m_t/M_W)^2$ start to play important roles, in addition to the famous penguin contribution, $\sim \ln(m_t/m_c)$, in the flavor changing gluon vertex $\bar{s}dg$. Furthermore, we note[12] that $\bar{s}dZ$ vertex grows up as m_t^2/M_W^2 for a limit $m_t \to \infty$, while $\bar{s}dg$ (or $\bar{s}d\gamma$) vertex approaches to a constant (except for some log correction). It thus seems to be a hot topic now to re-examine ε'/ε for a heavy top, paying some attention to the role played by the Z-exchange through the $\Delta I = 3/2$ piece of *CP* violating amplitude.[18] It has been pointed out[18] that for a large m_t there is a substantial cancellation between the QCD penguin and the "Z-penguin" diagrams, making ε'/ε considerably small.

Next let us consider $K_L \to \pi^0 e^+ e^-$. There are planned experiments dedicated to the decay, KEK-162 and FNAL-799. This decay process is special in the sense that in the lowest order, $O(\alpha G_F)$, or at the one-loop level, the process is possible only through *CP* violating amplitudes; for instance, in the typical process $K_L \to \pi^0\gamma^* \to \pi^0 e^+ e^-$ we easily find that the intermediate $\pi^0\gamma^*$ state has $CP = +1$. Actually, the above statement is true in the standard model provided only the gauge interactions are taken into account. A Higgs-exchange process $K_L \to \pi^0 H \to \pi^0 e^+ e^-$, however, is a *CP* conserving process, and if the Higgs can be on-shell the branching ratio beats that of the "signal." Furthermore in a general class of gauge models, such scalar type couplings may occur even through gauge interactions, as in the left-right symmetric model. Here we will just focus our attention to the consequence of the standard model with a rather heavy Higgs.

There are three competing amplitudes which contribute to the decay, $K_2 \to \pi^0 e^+ e^-$, $\varepsilon K_1 \to \pi^0 e^+ e^-$ and $K_2 \to \pi^0 \gamma\gamma \to \pi^0 e^+ e^-$. The last process, though being of higher order $O(\alpha^2 G_F)$, is CP conserving and gives a contribution to the branching ratio of around 2×10^{-11}.[19] As for the first "direct CP violation" amplitude, there has been some improvement of the argument. Just as in ε'/ε, here again the importance of the Z-exchange diagram for a heavy top quark has been stressed.[20] In particular, the axial-vector coupling of Z to e^+e^- yields an amplitude C_A, which behaves as $(m_t/M_W)^2$, roughly speaking; $0.1 \lesssim C_A \lesssim 0.8$ for $50 \lesssim m_t \lesssim 180\,\text{GeV}$ for instance. The vector coupling partner is accidentally suppressed by a factor of $1/4 - \sin^2\theta_W$. A nice thing here is that the amplitude C_A does not interfere with the amplitude of "indirect CP violation," $\varepsilon K_1 \to \pi^0 e^+ e^-$, which is dominated by the γ-exchange or so-called QED penguin diagram. Thus the direct CP violation piece has a lower bound on its prediction[20]

$$\text{Br} \gtrsim 10^{-11} \left|(s_2 s_3 s_\delta / 10^{-3}) C_A\right|^2 , \tag{19}$$

where s_2 *etc.* correspond to the original K-M parameters. The remaining problem is how to reliably estimate the amplitude $K_1 \to \pi^0 e^+ e^-$, responsible for the indirect CP violation. Since the decay amplitude is a CP conserving one, the intermediate u and c quark contributions are dominant in the QED penguin. When we consider the u quark contribution, quark picture would not be suitable, since the long-distance contribution seems to be important there. We thus need to look for a model, where not only the pseudoscalars are included, but also the vector meson dominance is realized in the γ exchange. A sophisticated way to introduce the vector mesons based on the so-called hidden $\text{SU}(3)_V$ symmetry has been proposed,[21] where the vector meson dominance (*i.e.*, no direct $\pi^+\pi^-\gamma$ coupling) is realized. It, however, seems that the SU(3) breaking effect has not been fully worked out. Thus, we have been trying to utilize the model in a direction proposed by Ebert and Reinhardt,[22] where both spontaneous and explicit breakings of SU(3) can be incorporated on an equal footing, while the vector meson dominance is maintained. As the first step, we recently adopted the model in calculating the $K \to \pi\pi$ amplitudes and have found an additional enhancement of $\Delta I = 1/2$ amplitude due to the proper treatment of SU(3) breaking.[23]

To close our discussion, we would like to notice that both K and B meson decay processes play very important complementary roles in the confirmation of the Kobayashi-

Maskawa scheme of flavor mixing and *CP* violation, or even in finding some signature of a beyond-standard model.

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