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CP VIOLATION IN KAON DECAYS

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ABSTRACT

An updated analysis on CP violating rare K decays is presented. The CP violating muon polarization effects in $K_L \to \mu\bar{\mu}$, $K_{\mu 3}$, and $K^+ \to \pi^+\mu\bar{\mu}$ are discussed.

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INTRODUCTION

The CP violating effects such as a nonzero $K_L \to \pi\pi$ branching ratio and an asymmetry in $K_L \to \pi l \bar{\nu}$ semileptonic decay which are related to the CP violating parameter ϵ in the $K^0 - \bar{K}^0$ system and thus called "indirect" CP violation have been observed in experiments for years. But the origin of these effects remain unclear. In the standard model these phenomena come from the complex Kobayashi-Maskawa (KM) mixing matrix[1] in the quark sector where only one physical phase exists for three generations of quarks. To ensure that this KM model is indeed the source of CP violation, recently, a lot of experimentalists and theoretists have concerntrated their efforts on determing the parameter ϵ' which measures the "direct" CP violation in $K_L \to \pi\pi$ decay amplitude. However, the existence of this "direct" CP violation is still controversial since the experimental results on $Re(\epsilon'/\epsilon)$ from NA31 and E731 are given by $(2.3 \pm 0.7) \times 10^{-3}$ and $(0.6 \pm 0.7) \times 10^{-3}$, respectively, which are 1.5σ away from each other. Moreover, the theoretical predictions on this parameter are not yet precise because of the uncertainties of long-distance effects and m_t. It is fair to say that, presently, the inconclusive experimental measurements and theoretical calculations leave the use of ϵ'/ϵ as the test of the KM CP violation model in limbo. Therefore we should explore other CP violating processes beyond the decays of $K_L \to \pi\pi$. Within kaon physics, the most promising modes where CP violating effects would be accessible to future experiments are (I) rare K decays such as $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \nu\bar{\nu}$ and (II) muon polarizations in $K_L \to \mu\bar{\mu}$, $K \to \pi\mu\nu$ and $K^+ \to \pi^+\mu\bar{\mu}$. In this talk, I will present recent studies on these effects.

Before entering into the discussion on kaon decays, we review the KM mixing parameters. We write the KM matrix in terms of the Wolfenstein parametrization[2]

$$V \simeq \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}, \tag{1}$$

where $\lambda = 0.22$ is the Cabibbo angle, $A \simeq 1.0$ from the B-meson lifetime and the semileptonic decay of b into c final states, and ρ and η are constrained by the measurements of the ratio $|V_{ub}/V_{cb}|$, the CP violating parameter ϵ and the $B_d^0 - \bar{B}_d^0$ mixing (see Figs. 1–3 of Ref. 3).

Now let me turn to the subjects (I) and (II).

CP VIOLATION IN RARE KAON DECAYS

The study of kaon rare decays has played a pivotal role in formulating the standard model of electroweak interactions. It is now attracting renewed interest due to the prospect of significantly improved ongoing experiments and the possibility of a very large t-quark mass which has a very strong impact on the short distance part of rare kaon decay amplitudes. We shall concentrate on the following modes: $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \nu\bar{\nu}$. These decays involve flavor-changing neutral current interactions and therefore, in the standard model, are forbidden in the lowest order but they can occur radiatively through the loop diagrams.

$K_L \to \pi^0 e^+ e^-$: This decay has recently attracted much attention theoretically and experimentally since it may directly test the mechanism of CP violation in the standard KM model. It receives direct and indirect CP nonconserving as well as CP conserving contributions. The branching ratio for the CP conserving part of $K_L \to \pi^0 e^+ e^-$, which depends on the decay $K_L \to \pi^0 \gamma\gamma$, is estimated[4] to be order of 10^{-13} with the recent NA-31 experiment at CERN[5] which indicates that the observed distribution of the invariant $\gamma\gamma$ mass in the decay $K_L \to \pi^0 \gamma\gamma$ favors models involving ChPT. Using the recent measured branching ratio[6] of $Br(K^+ \to \pi^+ e^+ e^-) = (2.99 \pm 0.22) \times 10^{-7}$ and ChPT, the associated branching ratio due to the indirect CP violating contributions is given by $Br(K_L \to \pi^0 e^+ e^-)_{ind} = 1.6 \times 10^{-12}$. The direct CP violating part comes from the short-distance electroweak effects. One finds[3,7]

$$B(K_L \to \pi^0 e^+ e^-)_{dir} = 2.6 \times 10^{-14} A^4 [C_V^2(m_t) + C_A^2(m_t)] \eta^2 \tag{2}$$

with the m_t dependent $C_V(m_t)$ and $C_A(m_t)$ functions given in Ref. 3. With the updated KM parameters[3] we find that the lower bound of $Br(K_L \to \pi^0 e^+ e^-)_{dir}$ is about $\sim 0.4 \times 10^{-12}$ which depends very weakly on the t quark mass, whereas the upper bound shows a stronger dependence with the maximum predicted $\sim 6.5 \times 10^{-12}$ for $m_t \sim 250\ GeV$. We note that the branching ratio from the direct CP contribution is lower than previously thought.[7] Furthermore, With the potential background coming from the recent observation of the decay $K_L \to \gamma\gamma e^+ e^-$, it is a challenge for the experiments to isolate the direct CP violating contribution.

$K_L \to \pi^0 \nu\bar{\nu}$: This mode is similar to the previous one but it only receives contributions from the CP violating amplitudes. The indirect CP violating contribution to the decay $K_L \to \pi^0 \nu\bar{\nu}$ is estimated[8] to be $\sim 4 \times 10^{-15}$, while for the direct one, we find[3]

$$Br(K_L \to \pi^0 \nu\bar{\nu})_{dir} \simeq 4.61 \times 10^{-11} A^4 |C_\nu(m_t^2/M_W^2)|^2 \eta^2 \tag{3}$$

which leads to $0.3 \times 10^{-11} \leq B(K_L \to \pi^0 \nu\bar{\nu})_{dir} \leq 5.5 \times 10^{-11}$ for $m_t \leq 250\ GeV$. Clearly, the branching ratio of the direct CP violating contribution is much larger than that of the indirect one. Albeit difficult to measure, this decay provides a very clean test for CP violation in the standard model.

CP VIOLATING MUON POLARIZATION EFFECTS

In two and three-body kaon decays such as $K_L \to \mu\bar{\mu}$, $K \to \pi\mu\nu$ and $K^+ \to \pi^+\mu\bar{\mu}$, the possible spin involved correlations are

	Correlation	*Symmetries violated*	*Decays*	
(i)	$\vec{s}_\mu \cdot \vec{p}_\mu$	P	$K_L \to \mu\bar{\mu}$, $K_{\mu 3}$, $K^+ \to \pi^+\mu\bar{\mu}$	(4)
(ii)	$\vec{s}_\mu \cdot (\vec{p}_1 \times \vec{p}_2)$	T	$K_{\mu 3}$, $K^+ \to \pi^+\mu\bar{\mu}$	
(iii)	$\vec{p}_i \cdot (\vec{s}_\mu \times \vec{s}_{\bar{\mu}})$	P, T	$K^+ \to \pi^+\mu\bar{\mu}$	

where $\vec{s}_{\mu(\bar{\mu})}$ is the muon (anti-muon) spin vector, $\vec{p}_i$ some momentum. The muon polarizations ralated to (i) and (ii) are the longitudinal and transverse muon polarizations, denoted as P_L and $P_\perp$, respectively. For (i) we will only discuss the effect in $K_L \to \mu\bar{\mu}$ since a nonvanishing P_L in this decay is also a result of CP violation. This is because the dimuon system is in C even states. Search for T odd correlations in (ii) and (iii) would imply CP violation based on CPT theorem in gauge theories. For the charged K decays it will provide a useful test on CP violation outside the neutral K system.

$K_L \to \mu\bar{\mu}$: In the standard model, the nonzero muon polarization arises from the indirect CP nonconservation induced by the parameter ϵ and the direct CP-violating decay amplitude via the standard neutral Higgs-boson exchange. It is estimated that[9] $|P_L(K_L \to \mu\bar{\mu})_{ind}| \sim 2 \times 10^{-3}$ and $|P_L(K_L \to \mu\bar{\mu})_{dir}| \ll 10^{-3}$ since the standard Higgs mass is larger than 57 GeV from the recent experimental searches at LEP. Recently we have systematically studied[10] various CP violation theories beyond the standard model and we have shown that sizable polarizations could be achieved in these theories. We summarize both experimental and theoretical expectations of $P_L(K_L \to \mu\bar{\mu})$ as follows:

Current expt. limit	*Future expt. sensitivety*	*Standard model*	*Non − standard models*	
0.5	10^{-2}	2×10^{-3}	10^{-2}	(5)

where the non-standard CP violation theories include the multi-Higgs, SUSY E_6, and left-right symmetric models. Clearly, measuring the muon polarization asymmetry in

$K_L \to \mu\bar{\mu}$ decay at a level of 1% will be a clear indication of CP violation beyond the standard model.

$K_{\mu 3}$: We only study $K^+_{\mu 3}$, *i.e.*, $K^+ \to \pi^0\mu^+\nu$ mode in which we can ignore the effects from the electromagnetic final-state interactions. It is straightforward to show that[11] there is no muon transverse polarization for theories with purely effective V and A interactions such as the standard, left-right-symmetric, and horizontal-symmetry models. The existence of a non-zero value of $P_\perp(K^+_{\mu 3})$ will be a definite signature of new physics beyond these models. However, $P_\perp$ is sensitive to some multi-Higgs and leptoquark models. In particular, we estimate that[11] in the Weinberg three Higgs doublets model, $P_\perp \sim 2.6 \times 10^{-4} v_2^2/v_3^2$ which yields an upper bound around 8.4×10^{-3}. For the multi-Higgs models in which the KM matrix has a non-zero phase we find that it can easily reach to a level of 10^{-3} without conflicting with experimental constraints. In some classes of leptoquark models a large $P_\perp$ would also be achieved. The muon polarization effects predicted from these models are accessible with the recently approved KEK experiment[12] in which a sensitivity of 0.09% in $P_\perp(K^+_{\mu 3})$ will be obtained.

$K^+ \to \pi^+\mu\bar{\mu}$: This decay has not been observed yet and the current experimental limit[13] is $Br(K^+ \to \pi^+\mu\bar{\mu}) < 2.3 \times 10^{-7}$. In the standard model it occurs at the one-loop level via the electroweak penguin and box diagrams. As is well known, the decay is dominated by the one-photon piece, which has large albeit uncertain long-distance corrections. The decay branching ratio is expectd to be around 6×10^{-8}. To compute the T violating correlations for this process, we write the most general amplitude as[14]

$$\mathcal{M} = \bar{u}(p_\mu, s_\mu)[F_S + iF_P\,\gamma_5 + F_V\,p_K{}^\mu\gamma_\mu + F_A\,p_K{}^\mu\gamma_\mu\gamma_5]v(p_{\bar{\mu}}, s_{\bar{\mu}})\ , \tag{6}$$

and define A^{1s}_{CPV} and A^{2s}_{CPV} to be the coefficient of the one and two-spin correlations in (i) and (ii) in the differential decay rate, respectively. We find that $A^{1s}_{CPV} \propto [-Im(F_S F_V^*) + Re(F_P F_A^*)]$ and $A^{2s}_{CPV} \propto [m_\mu Re(F_P F_V^*) + C \cdot Im(F_V F_A^*)]$. In the standard model, the penguin and box diagrams do not contribute to the form factor F_S and the contributions to F_V and F_A (F_P) are dominated by the one photon exchange diagram which is fixed by the measurement of $K^+ \to \pi^+ e\bar{e}$ and by the Z-penguin and W-box diagrams involving t-quark, respectively. Thus A^{1s}_{CPV} is vanishingly small whereas A^{2s}_{CPV}, depending on the parameters m_t and η, could be at a level of 10^{-2}. We note that for $A^{1,2s}_{CPV}$, the contributions from the final state electromagnetic interactions between the pion and the muons are at a level of 10^{-3}. Therefore, from the point of

view of probing KM mechanism, the measurement of two-spin correlations of the outgoing muon is necessary. However, it is very difficult to measure the μ^- polarization experimentally but it may not be impossible.[15]

CONCLUSIONS

We have reviewed the theoretical aspects of the CP violation in the rare K decay modes: $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \nu\bar{\nu}$ and CP violating muon polarization effects in $K_L \to \mu\bar{\mu}$, $K^+ \to \pi^0 \mu^+ \nu$ and $K^+ \to \pi^+ \mu\bar{\mu}$ decays. We have shown that most of the CP violating effects are accessible to the ongoing or future kaon experiments. Clearly, kaon physics may open again a new frontier in particle physics.

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