

DIRECT CP VIOLATION IN RARE K DECAYS

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Abstract

After recent measurements the issue of the origin of CP violation in the K system has remained open. It is suggested that the rare $K \rightarrow \gamma\gamma$ decay mode might decide on the existence of direct CP violation.

1. Introduction

A brief historical study of discoveries in particle physics has revealed¹⁾ that

1/3 of discoveries have been achieved on the energy frontier,

1/3 on the accuracy frontier and

1/3 on the rarity frontier.

The neutral K-meson system, successively revealing strangeness, $K^0-\bar{K}^0$ mixing and CP violation, represents the best example for it. The K system has been a paradigm of the success of a low road (as opposed to collisions at highest energies) to "new physics". Presently we witness a rebirth of K physics owing to a new generation of high-precision

experiments at BNL, CERN, KEK and FERMILAB, approaching branching ratios $BR \sim 10^{-10}$ - 10^{-12} . These experiments have been made in search for two classes of processes:

- i) FORBIDDEN flavour-changing processes, exploring high-energy scale (above 10 TeV for $BR \sim 10^{-10}$),
- ii) RARE (allowed but suppressed) processes, providing a critical test of the standard-model predictions. Such processes, forbidden at lowest order in electroweak interactions, often proceed by a loop induced by gluon exchange. In this way one probes the interplay of electroweak and strong interactions. If these processes are, in addition, supplemented by signals of CP violation, they may elucidate the source of CP-violating phenomena.

2. CP violation 25 years after the discovery

While the discovery of CP violation appeared as a shock to the physical society, a quarter of a century later it would be a surprise if CP were not violated. In fact, only a very special choice ("fine tuning") of CP-violating phases may keep CP conserved. In addition to the most explored Kobayashi-Maskawa (KM) CP-violating phase δ_{KM} there are also two apparently independent (R.D. Peccei, ref. 2) phases, δ_{QCD} of strong CP violation and δ_{BAU} related to CP violation, needed to produce the observed baryon asymmetry of the universe (BAU). Exciting new signals for CP and T violation in the neutron electric dipole moment (K. Smith, ref. 2) have been indicated by two experimental groups:

$$\begin{array}{ll} -(1.4 \pm 0.6) \times 10^{-25} \text{ ecm} & \text{Leningrad,} \\ -(6 \pm 4 \pm 2) \times 10^{-26} \text{ ecm} & \text{ILL Grenoble,} \end{array} \quad (1)$$

where the latter limit could be improved up to 5×10^{-27} .

Note that these numbers exceed the 3-generation SM prediction of $NEDM \lesssim 10^{-31}$ by many orders of magnitude. (Short-distance (SD)³⁾ and long-distance (LD)⁴⁾ contributions are of comparable magnitude.)

Still, after 25 years the evidence for CP violation in particle physics has remained restricted to the K system, in particular to the $K^0 \rightarrow 2\pi$ decays. The ratios of the K-

decay amplitudes

$$\eta_{+-} = \frac{\langle \pi^+ \pi^- | H_{eff}^{\Delta S=1} | K_L \rangle}{\langle \pi^+ \pi^- | H_{eff}^{\Delta S=1} | K_S \rangle} = \epsilon + \epsilon' , \quad (2)$$

$$\eta_{00} = \frac{\langle \pi^0 \pi^0 | H_{eff}^{\Delta S=1} | K_L \rangle}{\langle \pi^0 \pi^0 | H_{eff}^{\Delta S=1} | K_S \rangle} = \epsilon - 2\epsilon'$$

are expressed by two CP-violating parameters:

ϵ - parameter of INDIRECT (mass-mixing) CP violation and
 ϵ' - parameter of DIRECT (amplitude) CP violation.

The experimental value $|\epsilon| = (2.27 \pm 0.03) \times 10^{-3}$ calls for a more precise theoretical prediction of ϵ in the SM⁵⁾. Concerning CP violation in the $K \rightarrow 2\pi$ decay amplitude there is a statistically significant measurement of a nonzero value at CERN (NA31):

$$|\epsilon'/\epsilon| = (3.3 \pm 1.1) \times 10^{-3} , \quad (3)$$

while the measurement at FNAL (E731) is consistent with zero:

$$\text{Re } \epsilon'/\epsilon = -(0.5 \pm 1.5) \times 10^{-3} . \quad (4)$$

In total, superweak CP violation is wounded, but the question of direct CP violation is still open. Therefore, a study of other (rare) K-decay modes might decide on direct CP violation.

3. Direct CP violation in $K_{L,S} \rightarrow 2\gamma$

A distinguished feature of CP-violating K-decay amplitudes is that they probe the SD scale: since K contains only quarks of the first and second generation, CP violation requires the appearance of (heavy) quarks of the third generation in loops. From several promising candidate decays ($K \rightarrow 3\pi$, $K \rightarrow \pi \ell^+ \ell^-$, $K \rightarrow \pi \nu \bar{\nu}$, $K \rightarrow \pi \eta \gamma$) we select $K \rightarrow \gamma \gamma$ as the theoretically most appealing candidate that might stand the best chance of providing further evidence for direct CP violation in view of the prospects of the LEAR at CERN and the ϕ factories. This decay stimulated our interest⁶⁾ after recent measurements of partial decay widths:

$$\begin{aligned} \text{BR}(K_L \rightarrow \gamma\gamma) &= (6.05 \pm 0.04 \pm 0.08 \pm 0.20) \times 10^{-4}, \\ R &= \Gamma(K_S \rightarrow \gamma\gamma) / \Gamma(K_L \rightarrow \gamma\gamma) = 2.3 \pm 1 \pm 0.4. \end{aligned} \quad (5)$$

Since $K_S \rightarrow \gamma\gamma$ does not overwhelm $K_L \rightarrow \gamma\gamma$, it is possible to distinguish the effect of direct CP violation from the superweak prediction in measuring the time-dependent asymmetry of intensities:

$$\Delta(\tau) = \frac{\Gamma(K^0 \rightarrow \gamma\gamma)(\tau) - \Gamma(\bar{K}^0 \rightarrow \gamma\gamma)(\tau)}{\Gamma(K^0 \rightarrow \gamma\gamma)(\tau) + \Gamma(\bar{K}^0 \rightarrow \gamma\gamma)(\tau)}. \quad (6)$$

This asymmetry is expressed by the CP-violating parameters ϵ and $\epsilon'_{\gamma\gamma}(-)$ through the ratio (which is the counterpart of eq. (2)):

$$\eta_- = \frac{A(K_S \rightarrow \gamma\gamma(-))}{A(K_L \rightarrow \gamma\gamma(-))} = \epsilon + \epsilon'_{\gamma\gamma}(-). \quad (7)$$

In ref. 6) we found an entirely new, gluonic monopole- ("penguin"-) induced loop contribution to the CP-violating amplitude:

$$\begin{aligned} M_P(s\bar{d} \rightarrow \gamma\gamma) &= \sqrt{2} G_F \epsilon^{\mu\nu\alpha\beta} (\bar{d}_L \gamma_\alpha t^a t^b s_L) (k_1 - k_2)_\beta \epsilon^*(2)_\mu \epsilon^*(1)_\nu \\ &\times \frac{e_d^2}{4\pi^2} \frac{\alpha_s}{12\pi} \ln \frac{m_t^2}{m_c^2} \left[\ln \frac{m_t^2}{m_c^2} + \text{const} \right]. \end{aligned} \quad (8)$$

This amplitude is characterized by a relaxed (logarithmic) GIM cancellation and a dominant logxlog term, leading to the prediction

$$\left| \frac{\epsilon'_{\gamma\gamma}(-)}{\epsilon} \right|_P^{\text{SD}} \sim \frac{1}{30} - \frac{1}{10}. \quad (9)$$

This value is comparable with the somewhat uncertain LD prediction⁷⁾.

However, this is not the end of the story. We have recently noticed⁸⁾ that for the heavy top ($m_t \sim M_W$), the previously neglected⁹⁾ diagrams with W- and unphysical-Higgs exchange may appear. In fact, owing to incomplete GIM cancellation, such diagrams lead to sizeable CP-violating amplitudes, even exceeding the value in (9). Unless there is accidental cancellation of various SD and LD contributions, our predictions encourage measurements of a new direct CP violation in $K_{L,S} \rightarrow \gamma\gamma$

at the LEAR and at the forthcoming ϕ factories.

References

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