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Review

Experiments with K-meson decays

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ABSTRACT

Recent results and future prospects of particle physics experiments with neutral and charged K-meson (kaon) decays are reviewed. Topics include CP violation, rare decays, leptons in kaon decays, tests of CPT and quantum mechanics, radiative decays, hadrons in kaon decays, basic observables, V_{us} and CKM unitarity, and exotic searches. Experimental techniques developed for the kaon decay experiments are discussed.

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1. Introduction

K-mesons (kaons) were discovered in 1947 in "two (cloud-chamber) photographs (of cosmic ray showers) containing forked tracks of a very striking character" [1]. They were the first heavy-flavor particles, which can be produced by strong interactions but have only weak decays. Through the decays they had major contributions [2] toward establishing the

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Table 1
Kaon decay experiments being reviewed in this article.

Lab	Accelerator		Experiment	Kaon decay
KEK	KEK-PS	(12 GeV)	E246 √	K^+ at rest
			E391a √	K_L^0
BNL	AGS	(25 GeV)	E949 √, E787 √	K^+ at rest
KEK - JAEA[a]	J-PARC Main Ring	(30 GeV)	K^{O}TO	K_L^0
			TREK	K^+ at rest
IHEP, Protvino	U-70	(70 GeV)	ISTRA + √	K^- in flight
			OKA	$K^\pm$ in flight
CERN	SPS	(400 GeV)	NA48 √	K_L^0, K_S^0
			NA48/1 √	K_S^0
			NA48/2 √	$K^\pm$ in flight
			NA62	K^+ in flight
FNAL	Tevatron	(800 GeV)	KTeV √	K_L^0, K_S^0
INFN, Frascati	DAΦNE	($\sqrt{s} \sim 1.02$GeV)	KLOE√	$K_L^0 + K_S^0$, $K^+ + K^-$
			KLOE-2	$K_L^0 + K_S^0$, $K^+ + K^-$

[a] JAEA is the abbreviation of Japan Atomic Energy Agency.
√ Data taking of the experiment is completed.

Standard Model (SM) of particle physics. In the modern experiments, with millions of kaon decays per second by high-intensity accelerators, searches and measurements with the sensitivity of $10^{-8} \sim 10^{-12}$ are performed and the flavor parameters in and beyond the SM are studied.

In this article,[1] recent results and future prospects of kaon decay experiments (Table 1) are reviewed. Emphasis is placed on the achievements in the first decade of this century. Theoretical kaon physics is not fully covered because comprehensive reviews are available (e.g. [6–9]).

Reminder: the experimental upper limits in this article are at the 90% confidence level (C.L.).

2. CP violation

2.1. Overview

The CP-violating $K_L^0 \to \pi^+\pi^-$ decay was discovered [10], unexpectedly, in 1964 at the sensitivity of 10^{-3}. After the CP asymmetry in the K^0 - $\overline{K^0}$ mixing, with the parameter ϵ, was established [11,12], a long-standing problem has been its origin; the first question was whether it was due to the $\Delta S = 2$ *superweak* transition [13] or not. In 1973, Kobayashi and Maskawa [14] accommodated CP violation in the electroweak theory with six quarks (and a single complex-phase in the mass-eigenstate mixing matrix under the charged-current interactions). The Kobayashi–Maskawa theory [15,16], including the prediction of *direct* CP violation in the decay process from the CP-odd component (K_2) to the CP-even state ($\pi\pi$), was verified by the observations of time-reversal non-invariance (CPLEAR [17] at CERN) and, finally, due to the determination of ϵ'/ϵ (NA48 at CERN and KTeV at FNAL) as well as the discoveries of top quark and CP-violating *B*-meson decays.

In the modern classification (e.g. [18]) CP violation is grouped into three: in *mixing*, *decay*, and *interference between decays with and without mixing* (Table 2). All of these have been extensively studied in the *B* Factory experiments. Experimental studies in neutral-kaon decays have a long history, while the study of CP violation in the charged-kaon decay modes started recently. The CP-violating processes in *mixing* and *decay* suffer from hadronic uncertainties. A rare decay $K_L^0 \to \pi^0\nu\overline{\nu}$ [19], which will be discussed in Section 3.2, is known to be a golden mode in this category [20] because the branching ratio can be calculated with very small theoretical uncertainties in the SM as well as in its extensions.

The rest of this section is devoted to the kaon results of the CP violation in *decay*.

2.2. CP violation in decay

The NA48 collaboration at CERN and the KTeV collaboration at FNAL published the final measurement of $Re(\epsilon'/\epsilon)$ as $(14.7 \pm 2.2) \times 10^{-4}$ [24] and $(19.2 \pm 2.1) \times 10^{-4}$ [22], respectively, where $Re(\epsilon'/\epsilon)$ is obtained from the double ratio of decay rates:

$$\frac{\Gamma(K_L^0 \to \pi^0\pi^0) \,/\, \Gamma(K_S^0 \to \pi^0\pi^0)}{\Gamma(K_L^0 \to \pi^+\pi^-) \,/\, \Gamma(K_S^0 \to \pi^+\pi^-)} \approx 1 - 6\, Re(\epsilon'/\epsilon) \tag{1}$$

or

$$\frac{\Gamma(K_L^0 \to \pi^+\pi^-) \,/\, \Gamma(K_S^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \pi^0\pi^0) \,/\, \Gamma(K_S^0 \to \pi^0\pi^0)} \approx 1 + 6\, Re(\epsilon'/\epsilon). \tag{2}$$

[1] The materials in my previous reviews [3–5] are expanded and updated.