Rare Kaon Decays - a review of results

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Recent results and future prospects of rare kaon-decay experiments at KEK, BNL, CERN and FNAL are reviewed. Topics include lepton flavor violation, T-violating transverse muon polarization in $K^+_{\mu 3}$, exotic decays, $K^0 \to \pi^0 \ell^+ \ell^-$, and $K \to \pi \nu \overline{\nu}$.

1 Introduction

The branching ratio ($\mathcal{B}$) for a decay mode f of a particle is written as

$$\mathcal{B}(f) \equiv \frac{\Gamma_f}{\Gamma_{all}} = \tau \times \frac{2\pi}{\hbar} \int d(phase\ space) \cdot |M_f|^2 \tag{1}$$

in the S-matrix version of Fermi's Golden Rule No.2. K^0_S, K^+, and K^0_L decays with the branching ratio of 10^{-10} correspond to the partial widths of 0.73×10^{-15}, 5.3×10^{-18}, and 1.3×10^{-18}eV, respectively. Kaon decays at 10^{-7} or less are categorized as "rare" decays [1], and are the frontiers that no other heavy-flavor physics can reach at present. The smallest branching ratio yet measured in particle physics is $(8.7^{+5.7}_{-4.1}) \times 10^{-12}$ for the decay $K^0_L \to e^+e^-$ [4], and the most stringent upper limit is $< 4.7 \times 10^{-12}$ for $K^0_L \to \mu^\pm e^\mp$ [5]; both of these were achieved by the E871 experiment at BNL.

There should be reasons why a decay is particularly rare; except for the trivial case that the phase space is too small, the decay amplitude M_f must be small because 1) M_f is absolutely zero due to the symmetry in Theory of Everything, 2) the decay does exist at a tree level but the mass of the intermediate boson is too heavy, or 3) there is no tree diagram but are loop diagrams with suppression mechanisms such as GIM. We search for violations of the Standard Model (SM) in the second case, and study the flavor parameters and CP violations in and beyond the SM in the third case.

In this article, recent results and future prospects of rare kaon-decay experiments (table 1) are reviewed. For more information about this research field, the review in PDG-2004 [6] and latest talks in this summer [7, 8, 9] are recommended.

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

[1] In this conference, "medium" and "well-done" kaon decays were reviewed by F. Bossi [1] and S. Glazov [2] and theoretical issues were discussed by X-G He [3].

Lab	Accelerator		Experiment	Kaon decay
KEK	PS	(12 GeV)	E246 $\surd$	K^+ at rest
			E391a	K_L^0
KEK-JAERI	J-PARC PS	(50 GeV)	LoI's *	K_L^0, K^+ at rest
BNL	AGS	(25 GeV)	E787 $\surd$ / E949	K^+ at rest
			E865 $\surd$	K^+ in flight
			KOPIO *	K_L^0
CERN	SPS	(400 GeV)	NA48/1 $\surd$	K_S^0
			NA48/3 *	K^+ in flight
FNAL	Tevatron	(800 GeV)	KTeV $\surd$	K_L^0
	Main Injector	(120 GeV)	CKM-P940 *	K^+ in flight

Table 1: Rare kaon-decay experiments being reviewed in this article. The DAΦNE-KLOE experiment [1] is not included. "$\surd$" means data taking of the experiment is completed; "$*$" means construction of the experiment is not started.

2 Explicit violations of the Standard Model

Results of the searches for explicit SM violations are summarized in table 2. "FC" is the unified confidence intervals by Feldman and Cousins [10].

Mode	N_{obs}	n_{bgd}	Result	*Stat*	Experiment	Ref.
$K^+ \to \pi^+\mu^+e^-$	8	8.2±1.9	$< 2.2 \times 10^{-11}$	likelihood	E865-'98	
			$< 1.2 \times 10^{-11}$		E865 +E777	[11]
$K_L^0 \to \pi^0\mu^\pm e^\mp$			$< 3.37 \times 10^{-10}$	Poisson	KTeV	[12]
P_T in $K_{\mu 3}^+$			$\lvert P_T \rvert < 0.0050$		E246	[13]
$K^+ \to \pi^-\mu^+\mu^+$	5	5.3	$< 3.0 \times 10^{-9}$	FC	E865	[14]
$K^+ \to \pi^-e^+e^+$	0	negligible	$< 6.4 \times 10^{-10}$	FC	E865	[14]
$K^+ \to \pi^+\gamma$	0	negligible	$< 3.6 \times 10^{-7}$	FC	E787	[15]
$K^+ \to \pi^+X^0$	1		$< 7.3 \times 10^{-11}$	FC	E949-'02 +E787	[16]

Table 2: Summary of the searches for explicit SM violations. This table includes the number of observed events (N_{obs}), background estimation (n_{bgd}), and the statistical technique used to obtain the result (*Stat*). $K^+ \to \pi^+X^0$ is discussed in the next section.

2.1 Lepton flavor violation

Experimental search for lepton flavor (LF) violation in kaon decays ($K_L^0 \to \mu^\pm e^\mp$, $K^+ \to \pi^+\mu^+e^-$, $K_L^0 \to \pi^0\mu^\pm e^\mp$) has a long history. The kaon system is well suited to the investigation of LF-violating new processes involving both quarks and charged leptons [2] due to the high

[2] Assuming an additive quantum number for quarks and leptons in the same generation ("one" for down-quark and electron, "two" for strange-quark and muon, ...), the net number is conserved in the LF-violating

sensitivity achieved by experiments on this system. The mass of a hypothetical gauge boson for the tree-level effects should be in the scale of a few hundred TeV/c^2 [17, 18]. A drawback is that the LF-violating processes induced by Supersymmetric loop effects are not as promising as in $\mu^+ \to e^+\gamma$ decay and $\mu^- N \to e^- N$ conversion, because "Super-GIM" suppression mechanism is expected in both quark and lepton sectors [19]. Theoretical motivations for these decays are discussed in [20, 21, 22, 23].

Three-body decays $K \to \pi\mu e$ have to be explored in spite of the phase-space disadvantage, because they are sensitive to vector and scaler interactions. The best upper limit $\mathcal{B}(K^+ \to \pi^+\mu^+e^-) < 1.2 \times 10^{-11}$ was set by the E865 collaboration with their 1995-1998 data sets and the result of an earlier experiment E777 [24]. In the analysis of 1998 data set, eight observed events were examined with a general Likelihood from the combination of probability density functions for $K^+ \to \pi^+\mu^+e^-$; these events were not consistent with the signal [3], and an upper limit of 2.4 events was determined for calculating the limit of the branching ratio $< 2.2 \times 10^{-11}$. An upper limit $\mathcal{B}(K_L^0 \to \pi^0\mu^\pm e^\mp) < 3.37 \times 10^{-10}$ was set as a preliminary result from the KTeV collaboration with their 1997 and 1999 data sets.

2.2 T-violating transverse muon polarization in $K^+_{\mu 3}$

In the $K^+ \to \pi^0\mu^+\nu$ decay ($K^+_{\mu 3}$, $\mathcal{B}$=(3.27 ± 0.06)% [25]), the transverse muon polarization P_T (the perpendicular component of the muon spin vector relative to the decay plane determined by the momentum vectors of muon and pion in the K^+ rest frame) is a T-odd quantity and is an observable of CP violation. Any spurious effect from final-state interactions is small ($< 10^{-5}$), because no charged particle other than muon exists in the final state. P_T is almost vanishing ($\sim 10^{-7}$) [26] in the SM, while new sources of CP violation may give rise to P_T as large as 10^{-3}. P_T in $K^+_{\mu 3}$ has therefore been regarded as a sensitive probe of non-SM CP violation, and is a good example of looking beyond the SM by measuring a decay property with high statistics.

The E246 collaboration measured the charged track and photons from K^+ decays at rest with the superconducting toroidal spectrometer (consisting of 12 identical spectrometers arranged in rotational symmetry), which enabled the experiment to control possible sources of systematic uncertainties in polarization measurement. A new improved value $P_T = (-0.17 \pm 0.23(\text{stat}) \pm 0.11(\text{syst})) \times 10^{-2}$ was obtained by the total data sets of E246 from 1996 to 2000, giving an upper limit $|P_T| < 0.0050$.

2.3 Exotic decays

E865 reported the upper limits $\mathcal{B}(K^+ \to \pi^-\mu^+\mu^+) < 3.0 \times 10^{-9}$ and $\mathcal{B}(K^+ \to \pi^-e^+e^+) < 6.4 \times 10^{-10}$. The former decay is a neutrino-less "double muon" decay by changing total lepton number by two [27], and provides a unique channel to search for effects of Majorana neutrinos in the second generation of quarks and leptons [28, 29].

The decay $K^+ \to \pi^+\gamma$ is a spin 0→0 transition with a real photon and is thus forbidden by angular momentum conservation; this decay is also forbidden on gauge invariance

kaon decays.

[3]Reminder: since the likelihood analysis technique had been adopted, the background level 8.2 ± 1.9 in 1998 did not mean the search was background-limited.

grounds. An experimental signature of exotic physics, such as non-commutative QED and/or non-commutative SM [30], could appear in this decay mode. The E787 collaboration reported a new upper limit $\mathcal{B}(K^+ \to \pi^+\gamma) < 3.6 \times 10^{-7}$.

3 Flavor Changing Neutral Current processes

Results of the studies of Flavor Changing Neutral Current(FCNC) processes are summarized in table 3. "J" is the technique based on likelihood-ratio and modified Frequentist's approach, used to set limits on the Higgs mass from measurements at LEP, by Junk [31]. For the discussions in this section, the Wolfenstein parametrization of the Cabibbo-Kobayashi-Maskawa(CKM) matrix with $\lambda \equiv \sin\theta_C \simeq 0.22$, A, ρ, and η is used.

Mode	N_{obs}	n_{bgd}	Result	*Stat*	Experiment	Ref.
$K^0_S \to \pi^0 e^+ e^-$	7	$0.15^{+0.10}_{-0.04}$	$5.8^{+2.8}_{-2.3}$(stat)$\pm$0.8(syst) $\times 10^{-9}$	FC	NA48/1	[32]
$K^0_S \to \pi^0 \mu^+ \mu^-$	6	$0.22^{+0.18}_{-0.11}$	$2.9^{+1.5}_{-1.2}$(stat)$\pm$0.2(syst) $\times 10^{-9}$	FC	NA48/1	[33]
$K^0_L \to \pi^0 e^+ e^-$	2	1.06$\pm$0.41	$< 5.1 \times 10^{-10}$	FC	KTeV-'97	[34]
	1	0.99$\pm$0.35	$< 3.5 \times 10^{-10}$	FC	KTeV-'99	
			$< 2.8 \times 10^{-10}$		combined	[35]
$K^0_L \to \pi^0 \mu^+ \mu^-$	2	0.87$\pm$0.15	$< 3.8 \times 10^{-10}$	FC	KTeV-'97	[36]
$K^+ \to \pi^+ \nu\overline{\nu}$	3		$1.47^{+1.30}_{-0.89} \times 10^{-10}$	J	E949-'02 +E787	[16]
$\pi^+ \nu\overline{\nu}(2)$	1	1.22$\pm$0.24	$< 22 \times 10^{-10}$	FC	E787	[37]
$K^0_L \to \pi^0 \nu\overline{\nu}$	0	$0.12^{+0.05}_{-0.04}$	$< 5.9 \times 10^{-7}$	Poisson	KTeV	[38]
	(being analyzed)				E391a-'04	

Table 3: Summary of the studies of FCNC processes. This table includes the number of observed events (N_{obs}), background estimation (n_{bgd}), and the statistical technique used to obtain the result (*Stat*). n_{bgd} for $K^+ \to \pi^+\nu\overline{\nu}$ is explained in the text. "$\pi^+\nu\overline{\nu}(2)$" is a search in the π^+ momentum region < 195MeV/c.

The FCNC process in kaon decays is strange-quark to down-quark transition and is induced in the SM by the W and Z loop effects as Penguin and Box diagrams (figure 1). The top-quark in the loops dominates the transition because of its heavy mass, and the quantity:

$$V^*_{ts} \cdot V_{td} = -A^2\lambda^5 \cdot (1 - \rho - i\eta) = -|V_{cb}|^2 \cdot \lambda \cdot (1 - \rho - i\eta) \tag{2}$$

is measured. The decays are rare [4] due to $|V_{cb}|^2 \cdot \lambda$, and are precious because the important parameters ρ and η can be determined from them. The decay amplitude of K^0_L is a superposition of the amplitudes of K^0 and $\overline{K}^0$ and is proportional to η; observation of rare K^0_L decays, in particular the $K^0_L \to \pi^0\nu\overline{\nu}$ decay, is a new evidence for direct CP violation.

[4] A new λ [2] that is higher than previously thought does not change $V^*_{ts} \cdot V_{td}$ so much if $|V_{cb}|$, a directly-measured quantity in B decay, is used.

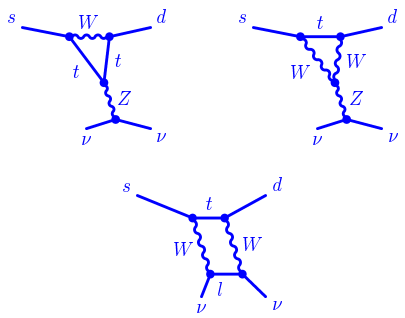

Figure 1: Penguin and Box diagrams in $K \to \pi\nu\overline{\nu}$.

3.1 $K^0 \to \pi^0\ell^+\ell^-$

Rare kaon decays with charged leptons should be easier to detect in experiments because the K^0 invariant mass can be fully-reconstructed. However, if the kaon decay accompanies charged leptons in the final state, the transition is also induced by long-distance effects with γ emission in hadronic interactions; their theoretical interpretations are not straightforward [5].

To the $K^0_L \to \pi^0\ell^+\ell^-$ decay, there are four contributions from direct CP violation (DIR), indirect CP violation due to the K_1 component of K^0_L (MIX), their interference (INT), and the CP conserving process (CPC) through the $\pi^0\gamma^*\gamma^*$ intermediate state. The CPC contribution can be obtained from the study of the decay $K^0_L \to \pi^0\gamma\gamma$ [40, 41]. The $K^0_S \to \pi^0\ell^+\ell^-$ decay, which is a CP conserving process of K^0_S , helps to do reliable estimation of MIX (and INT) and extract short-distance physics from $K^0_L \to \pi^0\ell^+\ell^-$ [42, 43].

The NA48 collaboration performed the data taking dedicated to K^0_S decays, named NA48/1, during 89 days in 2002 with a high-intensity K^0_S beam: 2×10^5 K^0_S decays per spill with a mean energy of 120 GeV. The rare decays $K^0_S \to \pi^0e^+e^-$ and $K^0_S \to \pi^0\mu^+\mu^-$ were observed for the first time (figure 2). The background levels ($0.15^{+0.10}_{-0.04}$ and $0.22^{+0.18}_{-0.11}$, respectively) were negligible. Using a vector matrix element and unit form factor, the measured branching ratios were $5.8^{+2.8}_{-2.3}$(stat)±0.8(syst) $\times10^{-9}$ and $2.9^{+1.5}_{-1.2}$(stat)±0.2(syst) $\times10^{-9}$, respectively. With these results, $\mathcal{B}(K^0_L \to \pi^0e^+e^-)\times10^{12} \simeq 5_{DIR}\pm9_{INT}+17_{MIX}+(negligible)_{CPC}$ and $\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)\times10^{12} \simeq 2_{DIR}\pm3_{INT}+9_{MIX}+5_{CPC}$ are predicted in the SM; the contribution from DIR is sub-dominant in these decays.

The $K^0_L \to \pi^0e^+e^-$ decay has been studied by KTeV. The limiting background was from the radiative Dalitz decay $K^0_L \to e^+e^-\gamma\gamma$ ($\mathcal{B}$=$(5.95\pm0.33)\times10^{-7}$ [25]) with invariant mass of the two photons consistent with the π^0 mass [44]. Phase space cuts, which were applied to the data to suppress the background, reduced the signal acceptance by 25%. The number of events observed in the signal region was consistent with the expected background for both of their 1997 and 1999 data sets. Combining these results, the KTeV final result was $\mathcal{B}(K^0_L \to \pi^0e^+e^-) < 2.8\times10^{-10}$. KTeV also studied the $K^0_L \to \pi^0\mu^+\mu^-$ decay, and has reported an upper limit $\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-) < 3.8\times10^{-10}$ from the 1997 data set (and is analyzing the 1999 data set). Both of the limits on $\mathcal{B}(K^0_L \to \pi^0e^+e^-)$ and $\mathcal{B}(K^0_L \to \pi^0\mu^+\mu^-)$ are still an order of magnitude larger than the SM predictions.

[5] The case of the decay $K^0_L \to \mu^+\mu^-$ ($\mathcal{B}$=$(7.27\pm0.14)\times10^{-9}$ [25]) is discussed in [39].

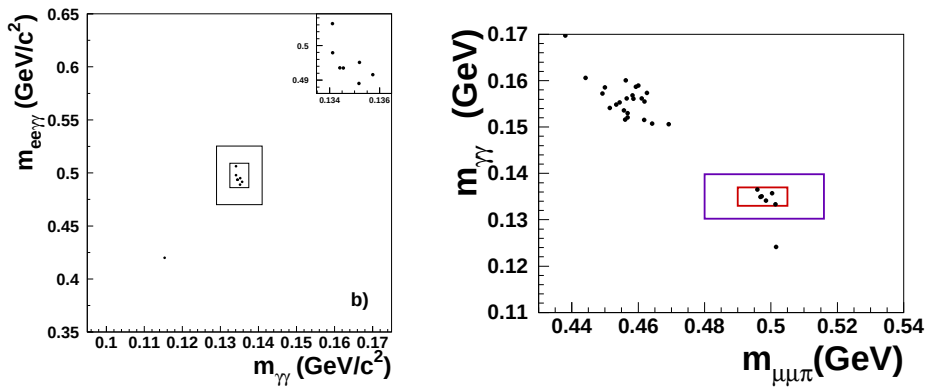

Figure 2: First observation of $K_S^0 \to \pi^0 e^+ e^-$ [32] (left) and $K_S^0 \to \pi^0 \mu^+ \mu^-$ [33] (right).

3.2 $K \to \pi\nu\overline{\nu}$

Branching ratios for the $K^+ \to \pi^+\nu\overline{\nu}$ and $K_L^0 \to \pi^0\nu\overline{\nu}$ decays [45] are represented in the SM as

$$\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) \;=\; (\,5.30 \times 10^{-11}\,) \cdot C_{\pi\nu\overline{\nu}} \quad\times\quad [\,(\rho_0 - \rho)^2 \;+\; \eta^2\,] \tag{3}$$

and

$$\mathcal{B}(K_L^0 \to \pi^0\nu\overline{\nu}) \;=\; (\,23.2 \times 10^{-11}\,) \cdot C_{\pi\nu\overline{\nu}} \quad\times\quad [\,\eta^2\,]\,, \tag{4}$$

respectively, where

$$C_{\pi\nu\overline{\nu}} \;\equiv\; [\,\frac{\mathcal{B}(K^+ \to \pi^0 e^+\nu)}{4.87 \times 10^{-2}}\,] \;\times\; [\,\frac{|V_{cb}|}{0.0415}\,]^4 \;\times\; [\,\frac{X(x_t)}{1.529}\,]^2\,, \tag{5}$$

$X(x_t)$ is the Inami-Lim loop function [46] with the QCD correction, x_t is the square of the ratio of the top to W masses. ρ_0 in $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ [6] is estimated to be ≈ 1.37. Long-distance contributions are negligible, and the hadronic matrix elements are extracted from the $K^+ \to \pi^0 e^+\nu$ decay. The theoretical uncertainty in $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ is 7% from the charm-quark contribution in the next-to-leading logarithmic(NLO) QCD calculations in ρ_0 and would be reduced by performing a next-to-NLO calculation, while the theoretical uncertainty in $\mathcal{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ is only 1-2%. With the ρ-η constraints from other kaon and B decay experiments, the SM prediction is $(7.8 \pm 1.2) \times 10^{-11}$ for $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ and $(3.0 \pm 0.6) \times 10^{-11}$ for $\mathcal{B}(K_L^0 \to \pi^0\nu\overline{\nu})$. New physics beyond the SM could affect these branching ratios [47, 48, 49], and the ρ and η (and $\sin 2\phi_1$) determined from $K \to \pi\nu\overline{\nu}$ and those from the B system would be different [50]. Since the effects of new physics are not expected to be too large, a precise measurement of a decay at the level of 10^{-11} is required.

The E787 and E949 collaborations for $K^+ \to \pi^+\nu\overline{\nu}$ and related decays measure the charged track emanating from K^+ decays at rest. The π^+ momentum from $K^+ \to \pi^+\nu\overline{\nu}$ is less than 227MeV/c, while the major background sources of $K^+ \to \pi^+\pi^0$ ($K^+_{\pi 2}$, $\mathcal{B}$=21.2%) and $K^+ \to$

[6] The departure of ρ_0 from unity, without which the branching ratio should be proportional to $|V_{td}|^2$, measures the relative importance of the internal charm-quark contributions.

$\mu^+\nu$ ($\mathcal{B}$=63.5%) are two-body decays and have monochromatic momentum of 205MeV/c and 236MeV/c, respectively. The region "above the $K^+_{\pi 2}$" between 211MeV/c and 229MeV/c is adopted for the search [7]. Background rejection is essential in this experiment, and the weapons for redundant kinematics measurement, μ^+ rejection, and extra-particle and photon veto are employed.

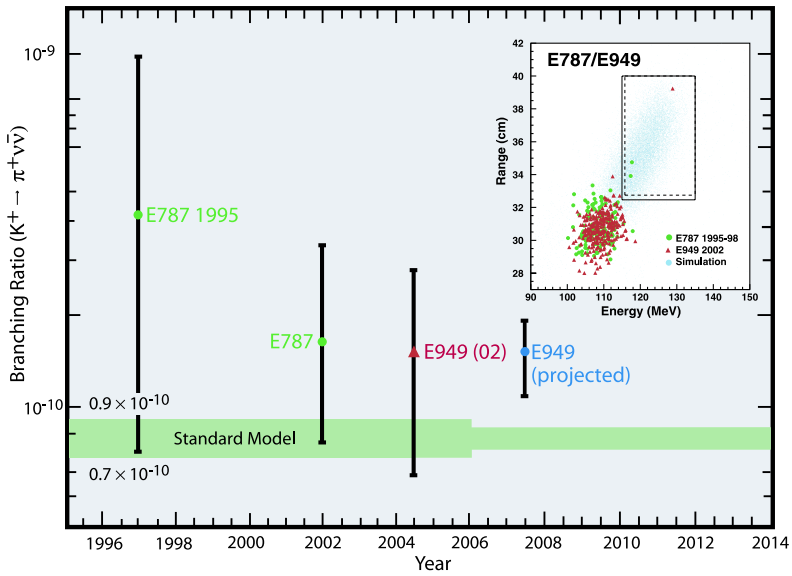

Figure 3: History of the study of $K^+ \to \pi^+\nu\overline{\nu}$, with the plot [16] of E949-'02 +E787 at the top right. "E949 (02)" represents the branching ratio by combining the E949 and E787 data sets; "E949 (projected)" represents the measured central value with the precision expected to E949 after running for 60 weeks. The SM prediction would be narrowed down if the B_s-$\overline{B}_s$ mixing is measured in the near future.

E787 had reported two events consistent with the $K^+ \to \pi^+\nu\overline{\nu}$ decay giving $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ $= 1.57^{+1.75}_{-0.82}$ $\times 10^{-10}$ with the 1995-1998 data sets [51]. The backgrounds were estimated to contribute 0.15 ± 0.05 events. In the first data set of E949 for 12 weeks in 2002 with the upgraded detector [52], an additional event near the upper kinematic limit for $K^+ \to \pi^+\nu\overline{\nu}$ was observed. A total number of background events expected in the signal region was 0.30 ± 0.03. Combining the E949 and E787 data sets, the branching ratio $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) = 1.47^{+1.30}_{-0.89}$ $\times 10^{-10}$, in the 68% confidence interval including statistical and systematic uncertainties, was obtained by a likelihood ratio technique based on the three observed events (figure 3). At the measured central value of the branching ratio, the additional event had a signal-to-background ratio of 0.9; the estimated probability that background alone gave rise to the three events (or to any more signal-like configuration) was 0.001. The upper limit for $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ was $< 3.22 \times 10^{-10}$, from which a model-independent bound on $K^0_L \to \pi^0\nu\overline{\nu}$: $\mathcal{B}(K^0_L \to \pi^0\nu\overline{\nu}) < 4.4 \times \mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) < 1.4 \times 10^{-9}$ (Grossman-Nir limit [53]) can be extracted. The E949 and

[7] E787 reported a new upper limit $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu}) < 22 \times 10^{-10}$ from a search for $K^+ \to \pi^+\nu\overline{\nu}$ in the π^+ momentum region < 195MeV/c. E949 continues the search in the same region.

E787 data sets were also used to set a limit on the branching ratio for $K^+ \to \pi^+ X^0$, where X^0 is a neutral weakly-interacting massless particle [54], to be $< 7.3 \times 10^{-11}$ based on the one event from E949 [8]. E949 was approved to run for 60 weeks and is waiting to take more data. A cosmic-ray run with the E949 detector was performed in August 2004, and the collaboration is ready to resume $\pi^+\nu\overline{\nu}$ data collection.

The current best upper limit on $\mathcal{B}(K_L^0 \to \pi^0\nu\overline{\nu}) < 5.9 \times 10^{-7}$ was set by KTeV; the Dalitz decay mode $\pi^0 \to e^+e^-\gamma$ ($\mathcal{B}$=1.2%) for the final state of $K_L^0 \to \pi^0\nu\overline{\nu}$ was used in this search. To reach the SM sensitivity, reconstructing $\pi^0 \to \gamma\gamma$ from $K_L^0 \to \pi^0\nu\overline{\nu}$ has to be considered. To beat the major background from $K_L^0 \to \pi^0\pi^0$ in case two out of four photons are missed, photon detection with low inefficiency ($< 10^{-3} \sim 10^{-4}$) is required to the detector. A search using $\pi^0 \to \gamma\gamma$ had been performed with KTeV's one-day special run [55]; a limit on the branching ratio was determined to be $< 1.6 \times 10^{-6}$ based on one event in the signal region with the background estimate of 3.5 ± 0.9 events.

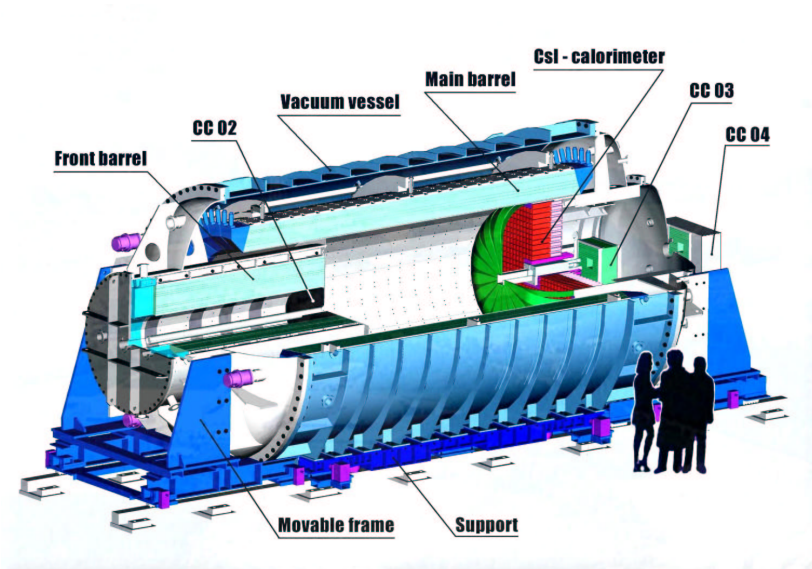

Figure 4: E391a detector for $K_L^0 \to \pi^0\nu\overline{\nu}$.

The E391a experiment [56] (figure 4) is the first dedicated search for the $K_L^0 \to \pi^0\nu\overline{\nu}$ decay. A collimated "pencil" neutral beam was newly designed, and an endcap calorimeter with undoped CsI crystals detected two photons from π^0 and measured their energy and position. The K_L^0-decay vertex position along the beam line was determined from the constraint of π^0 mass. Calorimeters that covered the decay region did hermetic photon detection. Charged particles were removed by their energy deposits in plastic scintillators in front of each calorimeter. Beam line survey and detector construction were performed from 2001 to 2003 and the first physics run was carried out in 2004 with 2.5×10^{12} protons per spill. The goal of E391a is to achieve a sensitivity below the Grossman-Nir limit and to reach the level predicted by new physics [48, 49]; the 2004 data set is now being analyzed, and the next physics run is scheduled

[8] This event was observed within 2 standard deviations of the expected π^+ momentum (227MeV/c).

in 2005.

4 Future kaon programs

All the kaon laboratories have their own project of high-intensity proton accelerator facilities: J-PARC of KEK-JAERI, AGS of BNL, SPS of CERN and Main Injector of FNAL. The workshops, in which new kaon programs were discussed earnestly, were held in the last 6 months; please visit the Web sites [57, 58, 59, 60] for details.

J-PARC, which stands for Japan Proton Accelerator Research Complex [61], in the joint project of Japan Atomic Energy Research Institute (JAERI) and KEK. The accelerators consisting of Linac, 3GeV rapid-cycle Synchrotron and 50GeV Synchrotron are under construction at the Tokai site of JAERI located at 50km northeast of KEK. The construction of the Phase-1 facilities will be finished in 2008 and, with the very intense proton beam (300×10^{12} protons per spill) from the 50GeV PS, great opportunities for various research in nuclear and particle physics, including kaon experiments with much higher sensitivities than ever, would be opened. A call for Letters of Intent (LoI's) was issued in July 2002, and thirty LoI's were submitted. There were five LoI's for kaon experiments with a neutral beam and with a K^+ beam of low momentum (0.6-0.8 GeV/c); these are regarded as a natural extension of the kaon experiments that have been worked out (E391a, E949 and E246). See [62] for more information.

KOPIO [63], which is a part of the Rare Symmetry Violating Processes (RSVP) experiments, is a study of $K_L^0 \to \pi^0 \nu\overline{\nu}$ with new concepts and techniques. An RF-bunched proton beam from BNL-AGS with a large targeting angle produces K_L^0's of low momentum (around 0.8 GeV/c), so that with the TOF technique the momentum of each kaon is measured and the decay can be analyzed in the K_L^0 rest frame. A combination of the pre-radiator and Shashlik calorimeter intends to measure the timing, energy, position and angle of low energy photons and fully reconstruct the decay. The RSVP construction start is in the FY05 Congressional budget of the US, and the first physics run is expected to be performed in 2010.

There is a FNAL experiment named CKM [64] to construct an RF-separated K^+ beam of 22 GeV/c from Main Injector and measure the $\pi^+ \nu\overline{\nu}$ decay in flight for the first time. The CKM experiment was granted scientific (Stage 1) approval in 2001 but was not endorsed by the P5 Subpanel of HEPAP for cost reasons; the experiment is being re-designed as P940 to use an un-separated K^+ beam of 45 GeV/c to the KTeV experimental hall. At CERN-SPS a new initiative called NA48/3 [65], which uses an un-separated K^+ beam of 75 GeV/c for the $K^+ \to \pi^+ \nu\overline{\nu}$ decay in flight, is in progress. Beam tests for the detectors in NA48/3 were performed in August 2004, and data to address the issues of drift chambers, a new beam spectrometer ("gigatracker") based on hybrid technology with thin-and-fast silicon micro-pixel layers plus a micromegas-based TPC, and photon hermeticity were collected. Their LoI (SPSC-I-229) was submitted in October.

5 Conclusions

The study of kaon physics continues to make great strides. Though no explicit violation of the SM is observed, certain new-physics scenarios have been excluded. Experimental sensitivities

have reached 10^{-9}-10^{-12}. "Blind analysis" has already been de facto; in the rare-decay searches where both Signal and Noise are in small statistic, we started using Likelihood techniques instead of a simple cut-and-count method. Future kaon programs will be "almost $\pi\nu\overline{\nu}$" [9]; $\mathcal{B}(K^+ \to \pi^+\nu\overline{\nu})$ and $\mathcal{B}(K_L^0 \to \pi^0\nu\overline{\nu})$ would be measured in $\sim$10% precision ($\sim$100 signal events) with highly sophisticated and special-purpose detectors, and it will be tested whether the source of CP violation is only from the CKM phase or not.

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