Rare Kaon Decays

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Abstract

Study of rare kaon decays supplies information to check the Standard Model from the viewpoints of lepton flavour violation and direct CP violation and to define parameters in the Standard Model. Rare kaon decays also give strong constraints on theories beyond the Standard Model. Experimental sensitivities on the branching ratios by existing accelerators will reach levels of 10^{-10} to 10^{-11} for various rare kaon decays. Future kaon factories proposed at BNL, FNAL and TRIUMF will improve these sensitivities by two or three orders of magnitude. Present status of rare kaon decay experiments and future kaon factories will be presented.

Introduction

Understanding kaon decays plays an important role to construct the Standard Mode in various aspects. After confirming the Standard Model rare kaon decays is used to check the Standard Model further and to test theories beyond the Standard Model. The $K_L^0 \rightarrow \mu e$ and $K^+ \rightarrow \pi^+ \mu e$, which are lepton flavor violating processes, were extensively studied recently. The second order weak processes, the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L^0 \rightarrow \mu^+ \mu^-$, give constraints on the Kobayashi-Maskawa matrix elements and the top quark mass. The $K_L^0 \rightarrow \pi^0 e^+ e^-$ is a good channel to search for direct CP violation. The $K^+ \rightarrow \pi^+ l^+ l^-$ and $K_L^0 \rightarrow \pi^0 l^+ l^-$ can be used to search for a Higgs boson with mass less than $m_K - m_\pi$, which could contribute through the decay sequence $K \rightarrow \pi$ H , H$\rightarrow l^+ l^-$.

For study of rare kaon decays present accelerators have been supplied abundant protons for kaon production and only a fraction of the full beam has been used by rare kaon decay experiments. Recently by technological development of detectors and electronics some rare kaon decay experiments can handle fully available proton beam and require more intense proton beam to get higher sensitivity. For this reason kaon factories were proposed at several laboratories in the world.

Rare kaon decay experiments have been done in different kaon energy regions. Parameters of accelerators which are used for kaon decay experiments are listed in Table 1. Experiments with kaon decay at rest prefer low energy beam to get a high kaon stopping rate. For experiments with kaon decay in flight the kaon momentum depends on the decay mode. The kaon decay rate is higher in lower energy but decay products have smaller spread in the downstream direction in higher energy. Smaller spread makes the geometrical acceptance of detectors larger. The momentum resolution for charged particles is better in lower energy but the energy resolution for neutral particles is better in higher energy. For this reason mainly kaon decay modes with charged decay products are studied at low energy and decay modes with neutral decay products are studied at high energy.

At the first part present status of rare kaon decay experiments will be presented and at the last part kaon factory proposals will be introduced.

1) Lepton Flavor Violating Processes

The $K_L^0 \rightarrow \mu e$ and $K^+ \rightarrow \pi^+ \mu e$ decays are lepton flavor violating processes which are forbidden by the Standard Model. These processes, which are different from the other lepton flavor violating processes, conserve the generation number. If these processes are mediated by a heavy boson which has the same coupling constant with a weak boson, the branching ratio level of 10^{-10} corresponds to the heavy boson mass scale of 100 TeV.

$K_L^0 \rightarrow \mu e$

To identify this decay momenta of the two decay particles are measured in a magnetic spectrometer and two particles are identified by following detectors. The $K_L^0 \rightarrow \pi e \nu$, whose branching ratio is 39%, is a serious background. A pion decay rate in a K_L^0 decay volume or in a spectrometer is about 10%. The background is not rejected by particle identification but this is rejected by calculating the effective mass whose maximum value is 8 MeV smaller than the K_L^0 mass. Then the mass resolution of the spectrometer is required to be excellent and momenta of muons have to be measured twice to reject muons from pions decay in flight.

The $K_L^0 \to \mu e$ is studied at KEK and BNL. The experimental setup of KEK-E137 is shown in Figure 1. The first round of data taking, which was one and half years, was finished in last July. The mass resolution of the spectrometer, which was determined by the $K_L^0 \to \pi^+\pi^-$, is 1.3 MeV. The group published results by half of the data[1]. They found no $K_L^0 \to \mu e$ or $K_L^0 \to e^+e^-$ events and found 54 $K_L^0 \to \mu^+\mu^-$ events. The upper limits of the $K_L^0 \to \mu e$ and $K_L^0 \to e^+e^-$ branching ratios are Br($K_L^0 \to \mu e$) $< 4.3 \times 10^{-10}$ and Br($K_L^0 \to e^+e^-$) $< 5.6 \times 10^{-10}$ (90% C.L.). The 54 $K_L^0 \to \mu^+\mu^-$ events correspond to an absolute branching ratio of ($8.4 \pm 1.1) \times 10^{-9}$. Extension of the experiment from Dec. 1989 to May 1990 was approved and finally the branching ratio sensitivity of the $K_L^0 \to \mu e$ decay will reach 1×10^{-10} (90% C.L.).

BNL-E791 constructed a single arm spectrometer. The spectrometer has a larger acceptance and events can be selected by calculating the effective mass of the decay products at an On-Line process. Their optimum beam intensity, which was determined by the tracking efficiency, is 5×10^{13} protons per pulse. They summarized their result based on the 1988 data[2]. They have observed 87 $K_L^0 \to \mu^+\mu^-$ events and no $K_L^0 \to \mu e$ and $K_L^0 \to e^+e^-$ events. The upper limits on the branching ratios are Br($K_L^0 \to \mu e$) $< 2.2 \times 10^{-10}$ and Br($K_L^0 \to e^+e^-$) $< 3.1 \times 10^{-10}$ (90% C.L.). They obtain the branching ratio (5.8 ± 0.6(stat.)± 0.4(syst.)) $\times 10^{-9}$. The absorptive part of the $K_L^0 \to \mu^+\mu^-$ amplitude can be estimated as the product of the experimentally known decay amplitude of the $K_L^0 \to \gamma\gamma$ and the pure QED $\gamma\gamma \to e^+e^-$ scattering amplitude. The $K_L^0 \to \gamma\gamma$ branching ratio is $(5.70 \pm 0.23) \times 10^{-4}$ [3]. The absorptive part gives an lower limit to the $K_L^0 \to \mu^+\mu^-$ branching ratio, ($6.8 \pm 0.27) \times 10^{-9}$. The branching ratio of E791 is smaller than this lower limit. In Figure 2 experimental results of the $K_L^0 \to \mu^+\mu^-$ branching ratios, the world average except new results and the unitary limit are shown. BNL-E791 ran this year and accumulated two times more data and next year they will accumulate the same amount of data.

Next year answer to existence of the $K_L^0 \to \mu e$ decay at 10^{-10} level will be made by two experimental groups. Also for the $K_L^0 \to \mu^+\mu^-$ decay consistency check between two experiments will be made with more statistics. If the branching ratio is greater than the unitary limit, constrains on the Kobayashi-Maskawa matrix elements and the top quark mass will be given. For future direction the KEK group is designing a new experiment with a ten times more intense K_L^0 beam and the BNL group is designing a new large solenoidal spectrometer with 2π geometrical acceptance.

$K^+ \rightarrow \pi^+ \mu e$

BNL-E777 is looking for this decay by a single arm double stage spectrometer. The $K^+ \rightarrow \pi^+\pi^+\pi^-$ whose branching ratio is 5.6% is a main background. They published an upper limit on the branching ratio, 1.1×10^{-9} (90% C.L.)[4], based on the 1987 data and they presented a preliminary upper limit, 2.3×10^{-10} (90% C.L.)[5] based on the 1988 data. The detector is also sensitive to the $K^+ \rightarrow \pi^+ e^+ e^-$ decay whose branching ratio is (2.7 ± 0.5) $\times 10^{-7}$ [6]. By this decay light neutral particles which decays into e^+e^- pair can be studied and rare neutral pion decay mode, the $\pi^0 \rightarrow e^+e^-$ can be studied. They accumulated about 800 and 1800 events of the $K^+ \rightarrow \pi^+ e^+ e^-$ in 1988 and 1989 respectively. The data in 1989 will yield $(5-6) \times 10^{-7}$ sensitivity for $m_\pi < m_x < 2m_\mu$ and 10^{-8} for $m_x <$ 100 MeV with better rejection of Dalitz decays and they hope to obtain 70 events of the $\pi^0 \rightarrow e^+e^-$ on 120 background events.

2) Direct CP Violation

The CERN and FNAL experiments have made efforts to extract direct CP violation effects by measuring $\epsilon'/\epsilon = 1/6(1 - |\eta_{00}|^2/|\eta_{+-}|^2)$ at the $K_L^0 \rightarrow \pi^0 e^+ e^-$ system. The ϵ'/ϵ should be zero for the superweak model and be small but non zero value for the Standard Model where CP is directly violated. The CERN group published the result, $\epsilon'/\epsilon = (3.3 \pm 1.1) \times 10^{-3}$ [7] based on the 1986 data and the FNAL group presented their preliminary result at the Lepton Photon conference, $\epsilon'/\epsilon = (-0.5 \pm 1.5) \times 10^{-3}$ [8] based on 20% of the data. So this time there is not a definite answer to existence on direct CP violation. These efforts will be continued further to get a definite answer.

The $K_L^0 \rightarrow \pi^0 e^+ e^-$ decay is interested as a new channel to study direct CP violation. The K_L^0 is almost CP odd state, $K_L \approx K_2 + \epsilon K_1$ but if the intermediated state is $\pi^0\gamma$ or π^0Z where CP is even, this decay process violate CP either directly, when the CP odd component decays, or indirectly when the small CP even component decays. For this decay there is also contribution from a CP conserving two photon intermediated state. The three contributions, which are theoretically calculated, are the same order of levels 10^{-10} to 10^{-11}. The direct CP violation effect can be extracted from the asymmetry of electron and positron spectrum.

Last year both experiments for ϵ'/ϵ published their upper limits on the branching ratio as the by-product that CERN-NA31 result is 4×10^{-8} [9] and FNAL-E731 result is 4.2×10^{-8} [10]. BNL-E780, which is mainly designed for the $K_L^0 \rightarrow \mu e$ has also reasonable acceptance for three body decay modes, published an upper limit for the $K_L^0 \rightarrow \pi^0 e^+ e^-$, 3.2×10^{-7} (90% C.L.)[11]. Then E780 rearranged the experiment setup and ran this year for the $K_L^0 \rightarrow \pi^0 e^+ e^-$. They are analyzing data and the branching ratio sensitivity is less than 10^{-9}. FNAL-E731 will run next year after modifying the beam line and installing a transition radiation detector for more stringent electron identification. This run will be two months and the sensitivity will reach 2×10^{-10}. And the second major five months run will be 1992 and the sensitivity will reach 1×10^{-11} [12].

KEK-E162, which is a new dedicated experiment for this decay, is constructing detectors (Fig. 3). They designed a large acceptance K_L^0 beam line and plan to use full extracted beam, 4×10^{12} protons per pulse. For this experiment the duty factor of 12 GeV PS will be increased from 20% to 50%. They will use a CeI calorimeter to get high energy resolution at low energy and fast response. The sensitivity will reach ($1 \sim 2) \times 10^{-10}$ [13].

The $K_L^0 \rightarrow \pi^0 e^+ e^-$ is a good place to look for a Higgs boson, because the background level is so small to this decay. CERN-NA31 got a preliminary result of an upper limit, Br($K \rightarrow \pi$ H) $\times$ Br(H $\rightarrow e^+ e^-$) $< 2 \times 10^{-8}$ (90% C.L.), through the range $20 < m_H < 350$ MeV, except the region of m_H within 15 MeV on either side of m_π where their limit of above Br products is $< 3 \times 10^{-8}$ [14]. This result eliminates all m_H value in $20 < m_H < 2m_\mu$ where the H $\rightarrow e^+ e^-$ is dominant.

3) $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

This mode, which is strangeness changing neutral current process, induced by the second order weak interaction. The Standard Model prediction, which depends on the

Kobayashi-Maskawa matrix elements and the top quark mass, is (1 - 8) $\times 10^{-10}$ [15], where long distance effect is small. The present branching ratio limit is 1.4×10^{-7} (90% C.L.)[16], which was obtained by KEK-E10 in 1981. There is a large window for nonstandard physics between the experimental limit and the predicted level. The $K^+ \to \pi^+ \nu\bar{\nu}$ is an excellent place to search for variety of neutral, light and weakly interacting particles such as axion, familon, hyperphoton, Higgs and the supersymmetric photino, goldstino, scaler Higgs, predicted by beyond the Standard Model. Also by measuring the branching ratio with reasonable statistics, constrains on the Kobayashi-Maskawa matrix elements and the top quark mass can be given.

The experimental signal is just one pion from a stopped K^+. For this decay BNL-E787 constructed a large solenoidal spectrometer as shown in Figure 4. In the center of the spectrometer there is a kaon stopping target. The kaon stopping rate is 300×10^3 per 7×10^{12} protons per pulse. The detector is nearly hermetic for gamma and charged particle vetoing around the target and the geometrical acceptance for a pion is 50%. They took the equivalent of about ten days worth of data in 1988 and about this data they presented an upper limit on the $K^+ \to \pi^+ \nu\bar{\nu}$, 3×10^{-8} (90% C.L.)[17] and the decay with a single massless particle such as axion or familon, 6×10^{-9}. They obtain three $K^+ \to \pi^+ \mu^+ \mu^-$ events. By low statistics they set an upper limit on the branching ratio of the $K^+ \to \pi^+ \mu^+ \mu^-$, 2.3×10^{-7} (90% C.L.)[18]. Also this gives an upper limit of the branching ratio of the decay $K^+ \to \pi^+$H, H $\to \mu^+ \mu^-$, 1.5×10^{-7} for Higgs boson mass in interval $220 < m_H < 320$ MeV.

This year they accumulated successfully ten times more data and next year they will accumulate the same amount of data. Then their branching ratio sensitivity will reach around 1×10^{-9}. After that they will upgrade both the kaon beam line and the detectors in order to obtain more than 10 candidates. The new beam line will transfer much more intense K^+ beam and its pion flux will be reduced by installing one more DC separator. Also they are trying to switch the lead scintillator sandwich calorimeter to a CeI calorimeter in order to get better energy resolution and to upgrade the spectrometer to get better momentum, energy and range resolution.

Future Kaon Factory

In order to supply much more intense proton beam for kaon production kaon factories were proposed in the world as listed in Table 2.

1) KEK

At KEK construction of a new experimental hall will be completed at the end of this year. To the hall a primary proton beam is efficiently extracted from 12 GeV PS. In the hall high intensity beam lines will be constructed. Also next year the duty factor of slow extraction will be improved from 20% to 50%. Based on these modifications new kaon decay experiments are being discussed.

2) BNL

Several upgrade projects are going on at BNL. A new preinjector line was installed and a new 1.5 GeV booster will be installed next to 200 MeV linac in order to overcome a space charge limit at injection to AGS. At AGS new vacuum system and radio frequency cavities will be installed. By these upgrades the proton intensity will be increased to 6×10^{13} per pulse in 1993. Also design of a stretcher ring is going to get 100% duty factor. By using this amount of beam more than ten $K^+ \to \pi^+ \nu \bar{\nu}$ events are expected to be observed.

3) FNAL

The new Main Injector has been proposed to increase the luminosity for FNAL collider experiments. Also the new Main Injector can produce high energy, high intensity proton beam for fixed target experiments. By the Main Injector both collider experiments and fixed target experiments can run simultaneously. The Main Injector provides 3.0×10^{13} protons every 2.9 sec at 120 GeV and the duty factor is 35%. An experiment for the $K_L^0 \to \pi^0 e^+ e^-$ decay has been mainly concerned at this high energy. A clean high intensity K_L^0 beam line, where neutron to K_L^0 ratio is one, was designed. By a preliminary design sensitivity on a branching ration of the $K_L^0 \to \pi^0 e^+ e^-$ reached level of 10^{-13}.

4) TRIUMF

The Kaon Factory was designed to accelerate $100 \mu A$ proton beam from 520 MeV H^- TRIUMF cyclotron to 30 GeV. This intensity is about a hundred times more than available at present accelerators. The TRIUMF cyclotron would be followed by two fast-cycling synchrotrons, interleaved with three storage rings. By this arrangement cyclotron output is accepted without a break, and two synchrotrons run continuous acceleration cycles without wasting time on flat bottoms or flat tops. By the high intensity beam simply hundred time better sensitivity can be reach at various decay modes. This project is planed to be done by international collaboration of several countries including our country. This project has got some money for pre-construction work and full approval will be early in 1990.

Summary

By present accelerators branching ratio sensitivities of rare kaon decay modes will reach levels of 10^{-10} to 10^{-11}. This progress mainly owes technological development of detectors and electronics. These sensitivities are very important to check the Standard Model and to test various theories beyond the Standard Model. Also experimental results on the second order weak processes will further constraints on the Kobayashi-Maskawa matrix elements and the top quark mass. Future kaon factories will improve sensitivities on branching ratios two or three orders of magnitude and will realize to extract direct CP violation in the $K_L^0 \to \pi^0 e^+ e^-$ decay and to observe the branching ratio of the $K^+ \to \pi^+ \nu\bar{\nu}$ decay with statistical significance.

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Table .1: Present Accelerators for Rare Kaon Decays

Accelerator	Energy	Intensity	Cycle	Duty Factor
KEK-PS	12 GeV	4.5×10^{12}ppp	2.5 sec	20%
BNL-AGS	30 GeV	1.6×10^{13}ppp	2.5 sec	35%
CERN SPS	450 GeV	3.0×10^{13}ppp	12 sec	25%
FNAL-TEV	800 GeV	2.8×10^{13}ppp	60 sec	30%

Table .2: Future Kaon Factories

Accelerator	Energy	Intensity	Cycle	Duty Factor
BNL-AGS (booster)	30 GeV	6×10^{13}ppp	2.5 sec	35%
BNL-AGS (stretcher)	30 GeV	5×10^{13}pps		100%
EHF	30 GeV	6×10^{14}pps		100%
TRIUMF	30 GeV	6×10^{14}pps		100%
FNAL (Main Injector)	120GeV	3×10^{13}ppp	2.9 sec	35%

ppp = protons per pulse

pps = protons per second

EHF = The European Hadron Facility

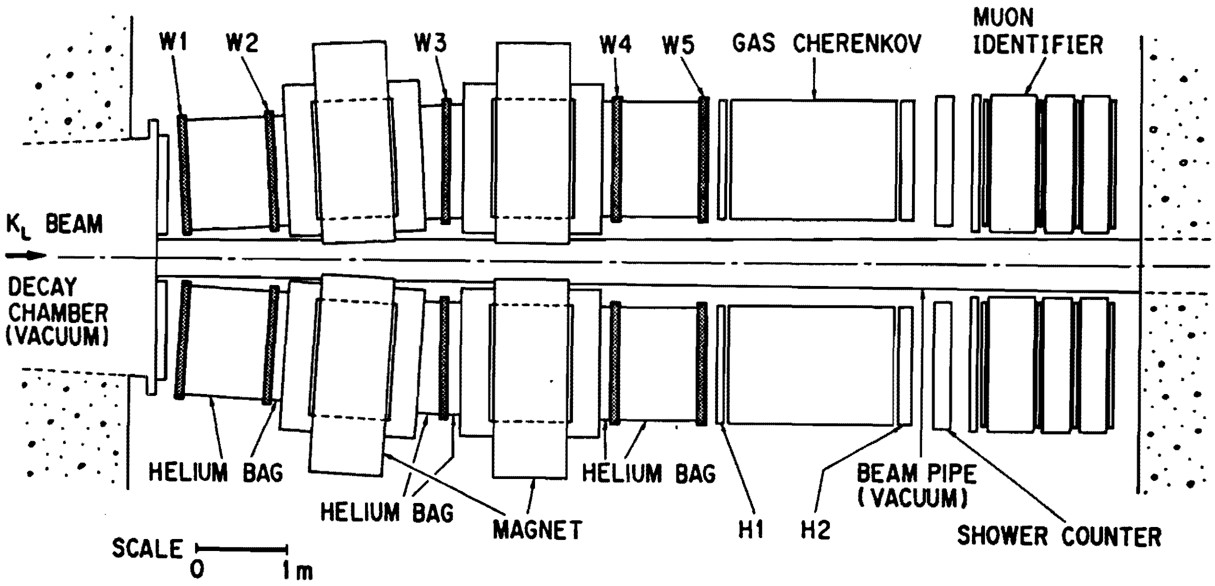


Fig. 1. Apparatus of KEK-E137 search for the $K_L^0 \to \mu e$.

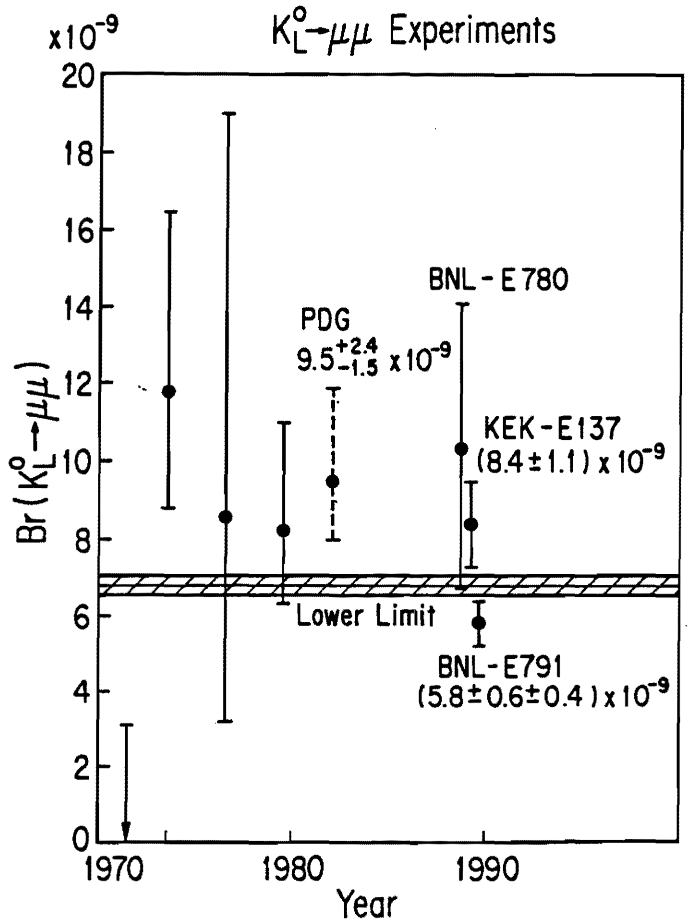


Fig. 2.

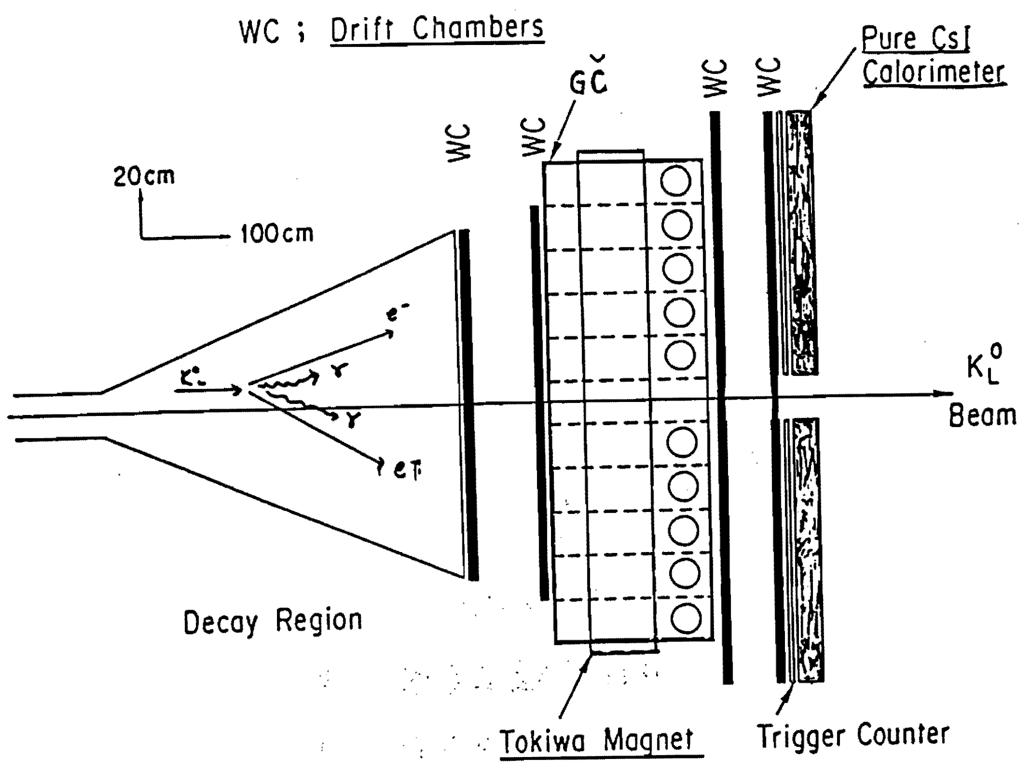


Fig. 3. Apparatus of KEK-E162 search for the $K_L^0 \to \pi^0 e^+ e^-$.

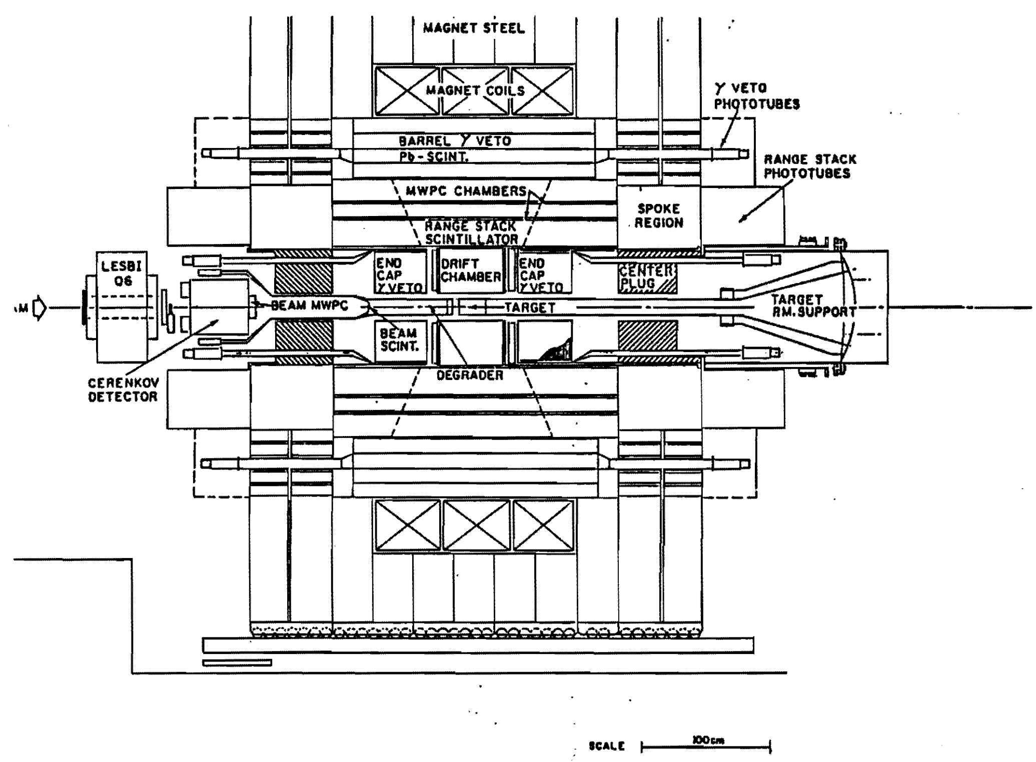
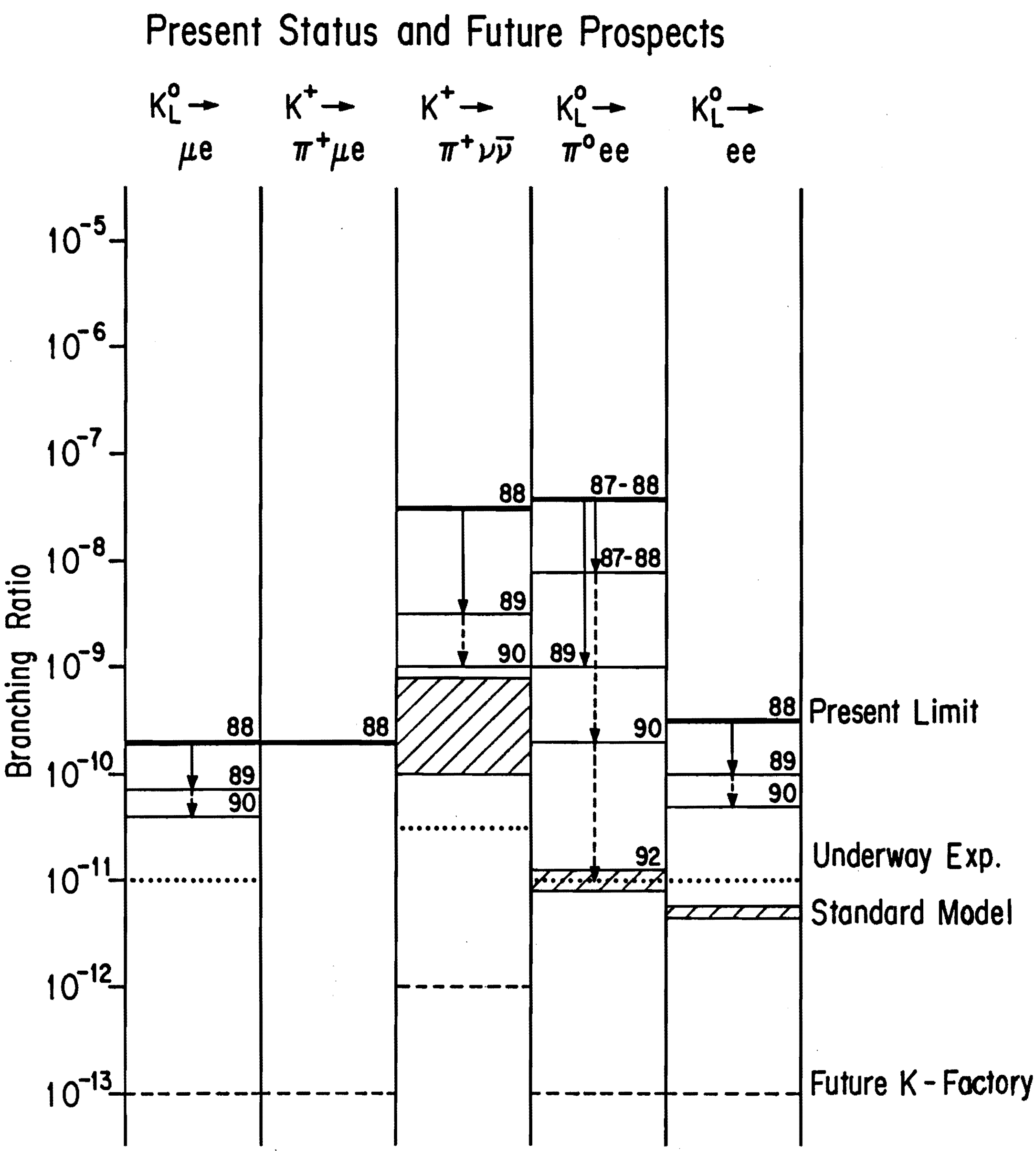


Fig. 4. Apparatus of BNL-E787 search for the $K^+ \to \pi^+ \nu \bar{\nu}$.



Present Status and Future Prospects
$K_L^0 \to \mu e$
$K^+ \to \pi^+ \mu e$
$K^+ \to \pi^+ \nu \bar{\nu}$
$K_L^0 \to \pi^0 ee$
$K_L^0 \to ee$
Branching Ratio
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
88
89
90
87-88
92
Present Limit
Underway Exp.
Standard Model
Future K-Factory

Fig. 5.