BNL-E949 Technical Note K-031

Letter of Intent for Study of the Rare Decay $K^+ \to \pi^+\nu\bar{\nu}$ with Stopped Kaon Beam at J-PARC

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Abstract

This is a letter of intent for a new measurement of the branching ratio for the $K^+ \to \pi^+\nu\bar{\nu}$ decay with a low-energy DC-separated K^+ beam in the initial experimental hall [1] for the slow-extracted proton beams at J-PARC [2]. With the established experimental methods using K^+ decays at rest and a solenoidal magnetic spectrometer, we observe more than 50 $K^+ \to \pi^+\nu\bar{\nu}$ events in the Standard Model and measure the branching ratio with a precision $\leq$20%. This experiment determines a product of Kobayashi-Maskawa matrix elements $|V_{ts}^* \cdot V_{td}|$ with a precision $\leq$ 10% and enables us to search for the physics beyond the Standard Model by making a comparison between the results from Kaon decays and B-meson decays.

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Executive Summary

goals: We observe more than 50 $K^+ \to \pi^+\nu\bar{\nu}$ events in the Standard Model and measure the branching ratio with a precision $\leq$20%.

merits: We emphasize the following scientific merits.

1. One of the most important parameters in the Standard Model - i.e. $|V_{ts}^* \cdot V_{td}|$ is determined with a precision $\leq$ 10%.
2. The theoretical uncertainty of the branching ratio is small.
3. We search for the physics beyond the Standard Model by comparing $|V_{ts}^* \cdot V_{td}|$ to the results from B-meson decays.
4. The high-intensity proton beam available at J-PARC is suitable for studying rare processes such as the $K^+ \to \pi^+\nu\bar{\nu}$ decay.
5. The experimental methods proposed in this Letter of Intent are already established by the E787 and E949 experiments at BNL-AGS; we have had plenty of experience with them.
6. Medium-rare K^+ decay modes for studying chiral dynamics in low-energy QCD can be measured at the same time (see Appendix).

methods: We perform the experiment with the following beam and detector:

- slow-extracted proton beam of 30 GeV,
- low-energy (600-800 MeV/c in momentum) and DC-separated K^+ beam,
- K^+ decays at rest in an active stopping target, and
- solenoidal magnetic spectrometer with
  - 2π detection of charged particles and
  - 4π calorimetric coverage of all decay products except for ν.

We request a longer spill length and high duty factor to the accelerator operation, and a high K^+/π^+ ratio (> 3) to the

K^+ beam line. We are making a preliminary optics design of a shorter beam line with lower K^+ momentum.

urgency: To meet a lot of results on B decays and compete with the experiments proposed at other laboratories (e.g. the CKM experiment at FNAL), we want to do this as a "Day-1 experiment" of J-PARC.

manpower: About 30 to 50 physicists will be at work to construct and operate this type of experiment. We are making efforts to collaborate worldwide with physicists who are interested in the physics of this experiment.

funding: We roughly estimate that it costs 5M US$ and 10M US$ to construct a new beam line and a new detector for $K^+ \to \pi^+\nu\bar{\nu}$, respectively, from scratch. We are considering to use the resources in the existing beam lines and detectors.

Contents

1 Physics Motivation

The $K^+ \to \pi^+\nu\bar{\nu}$ decay is a process of flavor-changing neutral current from strange-quark to down-quark and is induced in the Standard Model (SM) of particle physics by the loop effects of W and Z bosons in the form of penguin and box diagrams (Fig. 1). The decay is sensitive to top-quark effects and provides an excellent route to determine the absolute value of the quantity λ_t:

$$\lambda_t \equiv V_{ts}^* \cdot V_{td} = A^2\lambda^5 \cdot (1 - \rho - i\eta) \tag{1}$$

in the Kobayashi-Maskawa matrix [3], where A, λ, ρ and η are the Wolfenstein parameterization [4]. Long-distance contributions to the decay are negligible, and the hadronic matrix element is extracted from the $K^+ \to \pi^0 e^+\nu$ decay; the theoretical uncertainty of the branching ratio $B(K^+ \to \pi^+\nu\bar{\nu})$ is 7% from the charm-quark contribution in the next-to-leading-logarithmic QCD calculations [5]. With the constraints on ρ-η (and λ_t) from other Kaon and B-meson experiments the SM predicts $B(K^+ \to \pi^+\nu\bar{\nu})$, which is proportional to $|\lambda_t|^2$, to be $(0.72 \pm 0.21) \times 10^{-10}$ [6]. The most part of the error in the prediction is from the ρ-η constraints, not from the theoretical uncertainty. The SM prediction is expected to narrow in near future once $B_s - \bar{B}_s$ mixing has been observed at Tevatron [7].

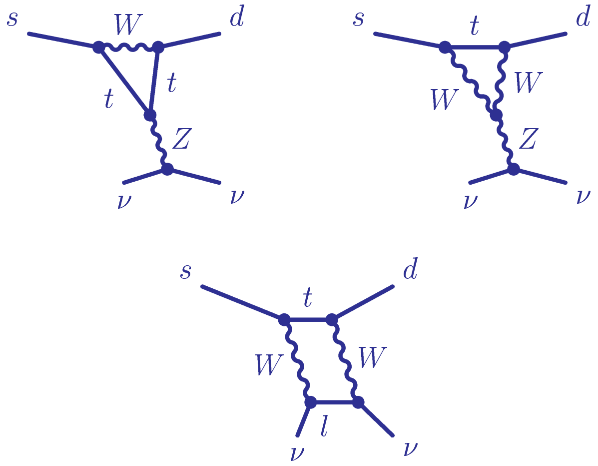

Figure 1: Penguin and box diagrams for $K^+ \to \pi^+\nu\bar{\nu}$ in the Standard Model.

CP violation in the SM is represented by so-called "Jarlskog invariant" J_{CP} [8]. The J_{CP} in Kaon sector is

$$J_{CP} = Im(V_{ts}^* \cdot V_{td} \cdot V_{us} \cdot V_{ud}^*) = \lambda(1 - \frac{\lambda^2}{2}) \times Im(\lambda_t). \tag{2}$$

A constraint on $|\lambda_t|$ from $K^+ \to \pi^+\nu\bar{\nu}$ sets an upper limit on $Im(\lambda_t)$. The branching ratio for a rare neutral-kaon decay $K_L^0 \to \pi^0\nu\bar{\nu}$ is directly related to $Im(\lambda_t)$ and, if both branching ratios are measured with good precision, J_{CP} is determined only from the information in Kaon sector [9]. By making a comparison between the results from K decays and B decays [10], it can be tested whether the source of CP violation is only from the phase of Kobayashi-Maskawa matrix elements or not.

1.1 $K^+ \to \pi^+\nu\bar{\nu}$ beyond the Standard Model

New physics beyond the SM could affect $B(K^+ \to \pi^+\nu\bar{\nu})$ [11] [12] [13]. For example, new effects in supersymmetric models are induced through diagrams with new particles such as charged Higgs or charginos and stops replacing the W boson and quark in Fig. 1. It was pointed out recently [14] that the Kaluza-Klein modes in a model with extra dimensions would increase $B(K^+ \to \pi^+\nu\bar{\nu})$. A measurement of the branching ratio at 1.5×10^{-10} with reliable experimental precision would indicate a clear conflict with the SM and be a sign of new physics [6]. Fig. 2 shows a possible future comparison between $K \to \pi\nu\bar{\nu}$ branching ratios and theoretically-clean B-physics observables in the presence of new physics [13]; the (ρ, η) determined from the $|\Delta B| = 2$ mixing processes could be different from the (ρ, η) from the $|\Delta S| = 1$ rare decays.

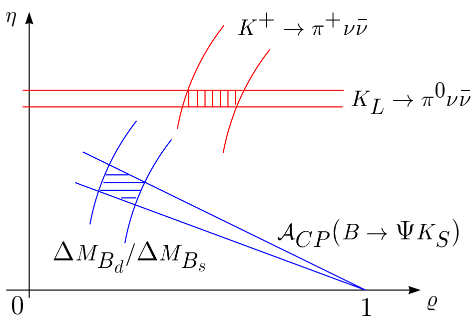

Figure 2: Schematic determination of (ρ, η) from the B system (horizontally hatched) and from $K \to \pi\nu\bar{\nu}$ (vertically hatched) [13].

2 Scientific Goals and Merits

Theoretical predictions give impetus for a precise measurement of the branching ratio for the rare $K^+ \to \pi^+\nu\bar{\nu}$ decay. The main goal of the experiment proposed in this Letter of Intent (LoI) is to **observe more than 50 $K^+ \to \pi^+\nu\bar{\nu}$ events** and **measure the branching ratio with a precision $\leq$ 20%**. $|\lambda_t|$ is determined with a precision $\leq 10\%$, which enables us to search for the physics beyond the SM by making a comparison between the results from K decays and B decays.

The high-intensity proton beam available at J-PARC is suitable for studying quark-flavor physics through rare processes of 10^{-10} or less such as the $K^+ \to \pi^+\nu\bar{\nu}$ decay. The experimental methods proposed in this LoI are the ones already established by the experiments E787 [15] and E949 [16] for $K^+ \to \pi^+\nu\bar{\nu}$ at the Alternating Gradient Synchrotron (AGS), which is the world's highest-intensity proton accelerator before J-PARC, of Brookhaven National Laboratory (BNL). We have had plenty of experience with the methods through E787 and E949 for more than 15 years and are confident that we achieve the physics results proposed in this LoI.

3 Review of Previous Results and Current Program

Fig. 3 shows the progress in the search and measurement of $K^+ \to \pi^+\nu\bar{\nu}$ [17].

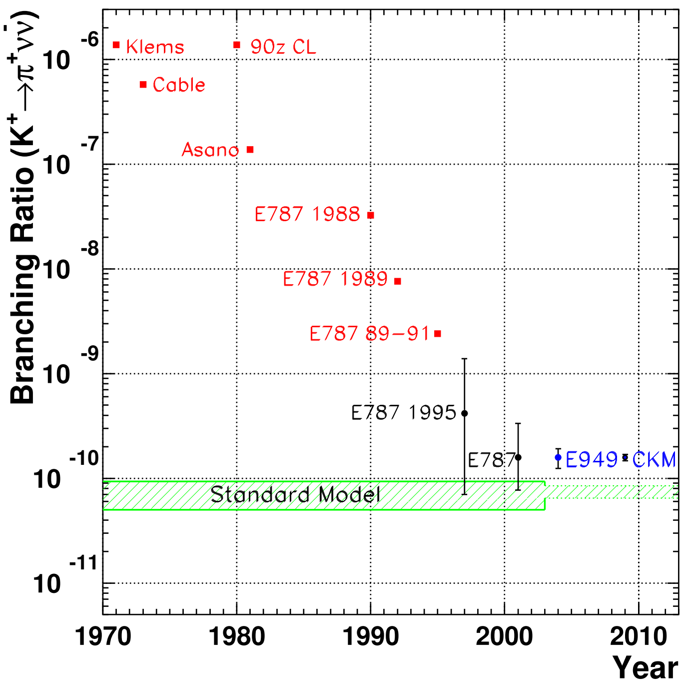

Figure 3: History of progress in the search and measurement of $K^+ \to \pi^+\nu\bar{\nu}$ [17]. The solid squares represent 90% C.L. upper limits. The solid circles are the E787 observation of this decay and the projections of the current central value of the branching ratio to the proposed sensitivities by the E949 and CKM experiments.

3.1 E787 and E949 Experiments at BNL

The E787 experiment measures the charged track emanating from K^+ decays at rest. E787 performed an initial search in 1989-91 and obtained the 90% confidence level (C.L.) upper limit of 2.4×10^{-9} [18]. Following major upgrades of the beam line and the detector, E787 took data from 1995 to 1998. The first evidence for $K^+ \to \pi^+\nu\bar{\nu}$ [19] was reported from the 1995 data set. Final results from E787 on $K^+ \to \pi^+\nu\bar{\nu}$ [20] were published in 2002; the total for the combined data set is two signal events in the pion momentum region examined, $211 < P < 229\text{MeV}/c$ (Fig. 4). Including all data taken, the backgrounds were estimated to contribute 0.15 ± 0.05 events. The branching ratio for the $K^+ \to \pi^+\nu\bar{\nu}$ decay was $1.57^{+1.75}_{-0.82} \times 10^{-10}$. A constraint $2.9 \times 10^{-4} < |\lambda_t| < 1.2 \times 10^{-3}$ was provided without reference to the B system. Although the results are consistent with the SM prediction, the possibility of a larger-than-expected branching ratio gives further impetus for measurements.

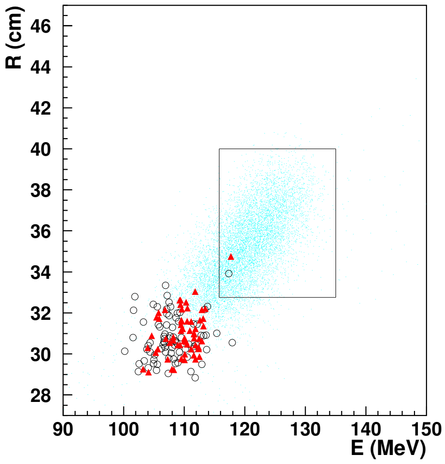

Figure 4: Range vs kinetic energy plot of the final sample of E787 [20]. The circles are for the 1998 data and the triangles are for the 1995-97 data set. The simulated distribution of expected events from $K^+ \to \pi^+ \nu \bar{\nu}$ is indicated by dots. The box indicates the signal acceptance region.

The E949 experiment continues the study at the AGS. 65-Tera(10^{12}) protons per 4.1-sec spill are extracted from the AGS every 6.4 sec to the kaon-production target. E949 is expected to reach a single-event sensitivity of $(8-14) \times 10^{-12}$, corresponding to up to 10 SM events (or 20 events at the branching ratio measured by E787), in 6000 hours or 2∼3 years of running and to determine $|\lambda_t|$ to $20-30\%$. Detector upgrades (explained later) and the engineering run was completed successfully, and the physics run started in 2002. In the first year the detector operated well at fluxes nearly twice as high as those typical of E787; the expected sensitivity was however comparable to the achievement of E787 due to limited beam hours of AGS for E949. The collaboration is waiting for funding of the remaining beam hours in their proposal.

3.2 CKM Experiment at FNAL

The "Charged Kaons at the Main Injector (CKM)" experiment [21] at Fermilab (FNAL) intends to study $K^+ \to \pi^+ \nu \bar{\nu}$ with in-flight K^+ decays for the first time. A RF-separated 22GeV$/c$ K^+ beam and Ring Imaging Čerenkov technique for particle identification are used. The goal of CKM is to collect 100 signal events in the SM with 10 background events (signal-to-noise(S/N) ratio of 10). CKM has been given Stage-1 scientific approval by FNAL in June 2001 [22] and is expected to start collecting data in 2007 or 2008 if the experiment is fully approved.

4 Experimental Methods

The π^+ momentum from $K^+ \to \pi^+\nu\bar{\nu}$ (Fig. 5) is less than 227MeV/c. The major background sources of $K^+ \to \pi^+\pi^0$ ($K_{\pi2}$, 21.2%) and $K^+ \to \mu^+\nu$ ($K_{\mu2}$, 63.5%) are two-body decays and have monochromatic momentum of 205MeV/c and 236MeV/c, respectively. The region "above the $K_{\pi2}$" between 211MeV/c and 229MeV/c has been adopted for the search [2] . Background rejection is essential in this experiment, and the weapons for redundant kinematics measurement, μ^+ rejection, and extra-particle and photon veto are employed. Each weapon should have a rejection of $10^5 \sim 10^6$, and reliable estimation of these rejections using real data is the key of the experiment.

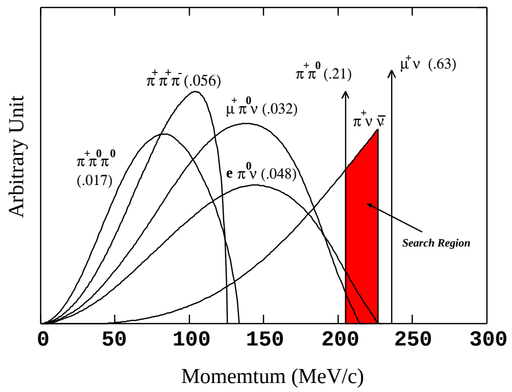

Figure 5: Momentum spectrum of the charged particles from K^+ decays at rest.

There are two approaches for the precise measurement of $K^+ \to \pi^+\nu\bar{\nu}$. One is a brand-new method with in-flight K^+ decays, with much better acceptance than previously achieved [3] , by the CKM collaboration. This LoI takes the other approach - i.e. to push ahead with a stopped kaon experiment in the style of E787-E949. An unbeatable merit is, we can make very realistic estimation of the sensitivity, acceptance and background level from the experiences of E787-E949 for many years; the real data, analysis codes and Monte Carlo simulations are available, and we can do many tests in the E949 experiment by regarding it as a pilot experiment for the future. A big issue is whether the beam line and detector can be improved further to compete with the CKM experiment.

In the following subsections, experimental methods of a stopped kaon experiment for $K^+ \to \pi^+\nu\bar{\nu}$ are explained. The prospects for the new experiment in the initial experimental hall (K-Hall) at J-PARC are discussed in the next section.

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[2] A search for $K^+ \to \pi^+\nu\bar{\nu}$ in the kinematic region with pion momentum below the $K_{\pi2}$ peak was reported recently by the E787 collaboration [23]; one event was observed, consistent with the background estimate of 0.73 ± 0.18, which implies an upper limit on $B(K^+ \to \pi^+\nu\bar{\nu}) < 4.2 \times 10^{-9}$ (90% C.L.). The possibility of measuring $B(K^+ \to \pi^+\nu\bar{\nu})$ in this kinematic region, which is being studied intensively by the E787 and E949 collaborations right now, is not included in this LoI.

[3] To be fair, it should be mentioned that the in-flight technique is not yet proved for the $K^+ \to \pi^+\nu\bar{\nu}$ experiment.

4.1 K^+ beam

Slow-extracted proton beam of 24 GeV can produce enough number of K^+'s. Kaons of about 700 MeV/c, which is set to be below the threshold for hyperon production in the material for slowing them, should be delivered to the experiment. A K^+ beam line incorporating two stages of electrostatic (DC) particle separation is indispensable for reducing the pion contamination and thereby the background due to beam pions scattered into the detector. A good example is the LESB3 channel [24] for E787-E949 at the AGS; the beam line provides a flux of $\sim 5 \times 10^5 K^+$/Tera-protons on the production target with a K^+/π^+ ratio of > 3. The channel views the 6-cm long platinum production-target at 0 degree and is 19.6 m long, including a 2.6-m drift from the last quadrupole magnet to the final focus at the center of the detector (Fig. 6).

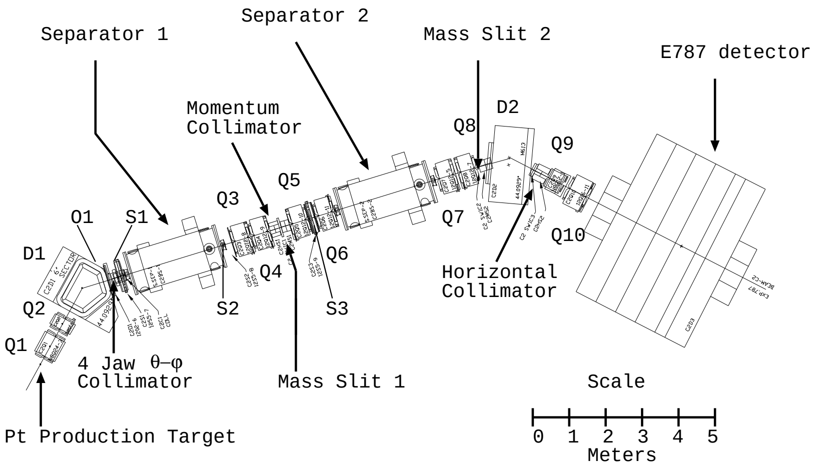

Figure 6: Layout of the LESB3 channel at BNL-AGS [24].

Kaons are detected and identified by a Fitch-type Čerenkov counter [25], multi-wire proportional chambers and an energy-loss counter. These counters are also used to remove backgrounds from multiple beam particles. After being slowed by a BeO degrader [4], approximately 25% of the incident kaons come to rest in an active stopping target; the remainder are lost or scattered out in the degrader. The target, which should consist of plastic-scintillating fibers, provides initial tracking of the stopping kaon and its decay products. A delayed coincidence requirement (typically > 2 nsec) of the timing between the outgoing pion and the incoming kaon in the target guarantees that the kaon actually decays at rest, and removes contributions from beam pions that are scattered into the detector and from kaons that decay in flight.

[4] BeO is a material with high density to slow kaons and with a low average atomic number to minimize their multiple Coulomb scattering.

4.2 Detector

The stopping target is located at the center of the detector for $K^+ \to \pi^+\nu\bar{\nu}$ [26] (Fig. 7). Particles emanating from K^+ decays at rest in the target were measured in a solenoidal spectrometer with a 1.0-T field directed along the beam axis. The magnet should be made large enough to contain all the active components within the yoke and coils; the inner volume of the E787-E949 detector, for example, is 2.2m long and 3.0m in diameter.

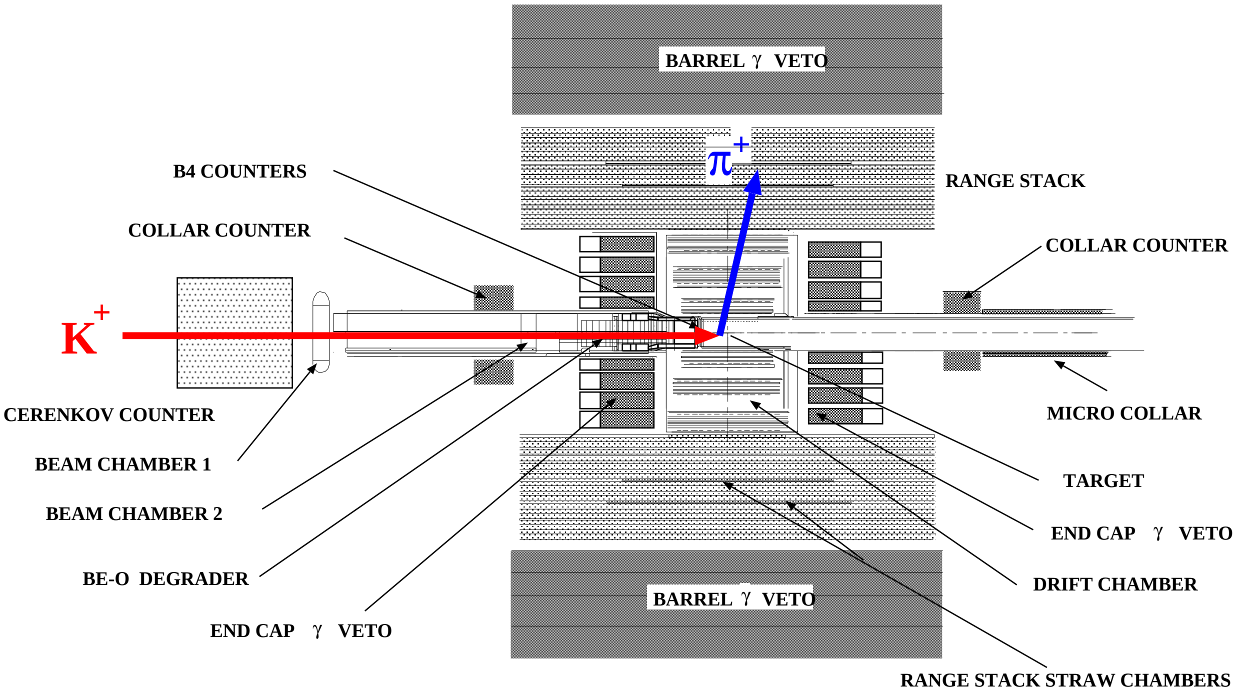

Figure 7: Schematic side-view of a solenoidal magnetic spectrometer for $K^+ \to \pi^+\nu\bar{\nu}$.

The charged decay products passed through a layer of trigger scintillators surrounding the target and a cylindrical low-mass central drift-chamber [27] and lost energy in an array of plastic scintillators called the "Range Stack (RS)". The drift chamber provides tracking information for momentum determination; the RS provides a measurement of range and kinetic energy of the π^+ track which comes to rest in it. The RS in the E949 detector is segmented into 24 azimuthal sectors and 19 radial layers. The RS counters in the first layer define the solid angle acceptance of 2π for the π^+ track in the RS. Two layers of low-mass tracking chambers were embedded within the RS to help range measurement. The RS counter in the sector and layer where the π^+ track comes to rest is called the "stopping counter". Scintillation light is brought out of the magnet at the upstream and downstream ends of the detector by ultraviolet-transmitting acrylic lightguides and is read out by phototubes. The output pulse shapes of the RS counters are recorded by 500-MHz sampling transient digitizers (TDs) [28]. In addition to providing precise time and energy information for reconstructing the π^+ track, the TDs enables us to observe the $\pi^+ \to \mu^+\nu$ decay at rest and the subsequent $\mu^+ \to e^+\nu\bar{\nu}$ decay in the RS stopping counter, and to remove muon and positron tracks as well as the π^+ tracks that decay in flight or undergo nuclear interaction before it comes to rest in the RS.

A hermetic calorimeter system surrounding the central region is designed to detect photons and all decay products (except for ν) from $K_{\pi 2}$ and other decay modes. Good resolution for timing and energy is critical for reducing acceptance loss by the accidental hits in a high counting-rate environment. The barrel calorimeter, which is a cylindrical detector located immediately outside the RS, covers about two thirds of the solid angle. Two endcap calorimeters and additional calorimeters for filling minor openings along the beam direction, as well as any active parts of the detector not hit by the π^+ track, are also used for detecting extra particles. In E949, the barrel calorimeter consists of sampling shower-counter modules constructed of alternating layers of lead and plastic-scintillator sheets totaling 14.3 radiation lengths, and the endcap calorimeters [29] consisted of undoped-CsI crystals (with 13.5 radiation lengths), which are read out by fine-mesh phototubes in the 1.0-T field into 500-MHz TDs based on charged coupled devices (CCDs) [30]. Plastic-scintillating fibers of the target are also read out by the CCD-based TDs.

The two $K^+ \to \pi^+ \nu\bar{\nu}$ signal events by E787 are shown in Fig 8.

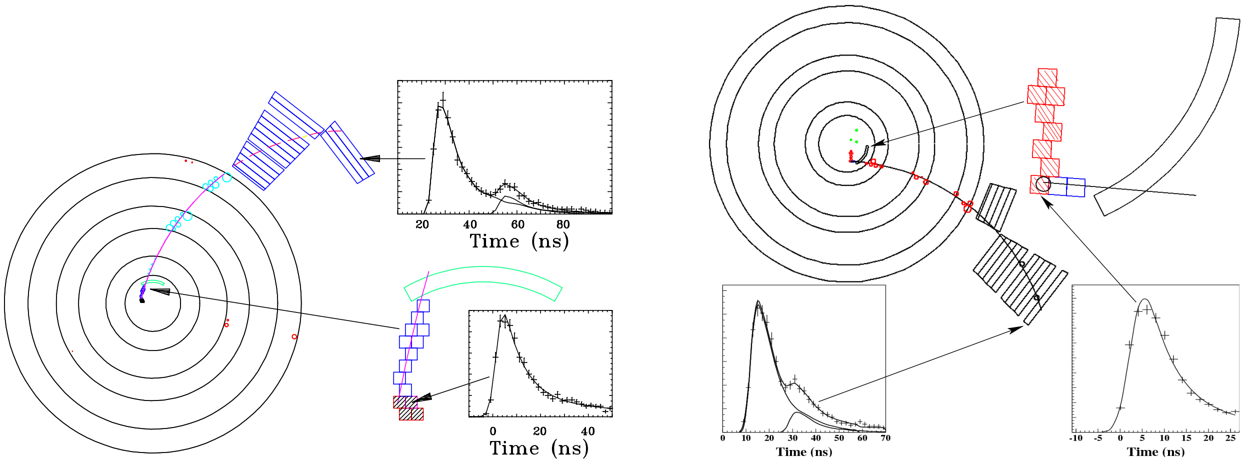

Figure 8: Displays of the two $K^+ \to \pi^+ \nu\bar{\nu}$ events by E787 [19] [20].

5 Prospects for the New Experiment

The total acceptance in the $K^+ \to \pi^+ \nu\bar{\nu}$ measurement by E787 is 0.2% [20], including the factors of K^+ stop efficiency (0.702), K^+ decay after 2 nsec (0.851), the solid angle acceptance to the π^+ track (0.409), and π^+ stop without nuclear interaction nor decay-in-flight in the RS (0.527); most of these factors cannot be improved so much, as long as we stick to the concept of stopped kaon decay. The factor of $K^+ \to \pi^+ \nu\bar{\nu}$ phase space is 0.136 because the kinematic region is limited to be above the $K_{\pi 2}$. The factors of

π^+ reconstruction efficiency (0.969) and other kinematic constraints for π^+ identification (0.554) are reasonable in a particle physics experiment.

Main reasons why the remaining acceptance factors: "$\pi - \mu - e$ decay acceptance (0.392)", "beam and target analysis (0.706)" and "accidental loss (0.751)" get to be small in the $K^+ \to \pi^+\nu\bar{\nu}$ measurement are discussed in [31]. To summarize,

1. While the π^+ and μ^+ tracks from kaon decays at rest should be reconstructed and measured in a non-destructive way, the target and RS, made of plastic scintillators, work as "destructive devices" in some cases and create backgrounds. π^+ identification in the RS stopping counter with the pulse-shape information is indispensable.

2. There are four "times" in each event: the kaon-incident time, the kaon-decay time, pion-decay time and muon-decay time. The rates of the counters located in or close to the beam line are particularly high, and an accidental hit at any of the times could veto a signal event and reduce the acceptance.

3. We need to wait the $\pi^+ \to \mu^+ \to e^+$ decay-chain in the stopping counter for a few μsec. The RS, target and endcap signals are recorded by waveform digitizers, which follows huge event size and non-negligible DAQ deadtime.

The E949 experiment has made efforts to improve them by a larger K^+ exposure, new beam counters, replacement of RS scintillators at the inner layers, additional calorimeters in the barrel and beam regions to improve photon detection, new trigger and monitor systems, RS readout by TDCs in order to tag the $\mu^+ \to e^+$ chain in the stopping counter without using TDs and to reduce DAQ deadtime, and optimization of the trigger, DAQ etc. By the new experiment in this LoI, we push for these improvements and optimizations.

5.1 Requirements to the Accelerator

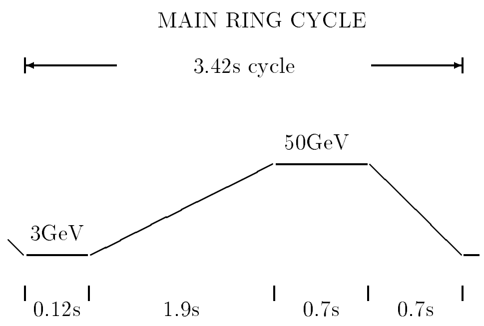

Figure 9: Typical machine cycle of JHF-PS for slow extraction.

A typical machine cycle of the 50-GeV proton synchrotron (JHF-PS) [32] at J-PARC is to accelerate 200-Tera protons every 3.42 sec (Fig. 9), which means the average current is 9.5 μA. Slow-extracted proton beam (0.7-sec spill, with the duty factor of 0.20) is transported to the K-Hall. The beam energy at the initial operation phase (Phase 1) of JHF-PS will be 30 GeV.

It must be pointed out that the slow-extraction described above is unsuitable and unoptimized for kaon decay experiments or any particle-physics experiment with time-coincidence techniques [33]. Table 1 shows a comparison of the PS operation between the AGS (optimized to the E949 experiment) and the JHF-PS. While the amount of protons per spill available at JHF-PS is $\times 3$ larger, the instantaneous proton rate in the spill is $\times 18$ higher than AGS, due to the poor duty cycle of JHF-PS, and is hardly ever tolerable by taking into account the acceptance loss due to accidental hits.

PS operation		AGS for E949	JHF-PS Phase 1	
proton energy	GeV	24	30	
protons on Tgt	10^{12}/spill	65	200	$\times$ 3.1
machine cycle	sec	6.4	3.42	$\times$ 1/1.87
average current	μA	1.63	9.5	$\times$ 6
slow extraction	sec	4.1	0.7	$\times$ 1/6
duty factor		0.64	0.20	$\times$ 0.31
instantaneous rate	10^{12}/sec	16	286	$\times$ 18

Table 1: Comparison of the PS operation between the AGS to the E949 experiment and the JHF-PS.

We therefore request, for the experiment of this LoI, a longer spill length and high duty factor to the operation of JHF-PS rather than upgrading the proton energy to 40 GeV or 50 GeV [5] . It has been suggested that the duty-cycle can be improved from 0.20 to 0.39 (1.7-sec spill every 4.42 sec) when the JHF-PS is operated at 30 GeV [35].

It has also been suggested that the energy for accelerating protons at JHF-PS is limited, to the lower side, to be 30 GeV by the beam aperture at the slow extraction. Still, if the machine cycle are kept and the beam is accelerated only upto 24 GeV, for example, the spill length can be extended and the duty factor is improved [36]. At the same time it is necessary to decrease the protons per spill and reduce the total beam loss at the extraction, but a better running condition might be achieved by this.

5.2 Requirements to the Beam Line

In the original layout [37] of the K-Hall at J-PARC, there were two primary beam lines (A and B). The A line had two production targets (T1 and T2) in cascade, and the secondary particles from the T2 target were extracted to "K1.1" beam line for low-energy kaons ($0.5 \sim 1.1$ GeV/c in momentum). The experiment in this LoI was originally supposed to

[5] There is no significant change to the K^+ yields below 1 GeV/c between the proton energies of 30 GeV and 50 GeV [34].

be performed with the K1.1 beam line optimized for $K^+ \to \pi^+ \nu\bar{\nu}$. The limited Phase 1 budget allows, however, one primary line and one production-target in the K-Hall [1]. An example of preliminary layout of the K-Hall is shown in Fig. 10. A low-energy, two-stage separated K^+ beam line, viewing the T1 target at 6 degree and in 24-m long, is considered.

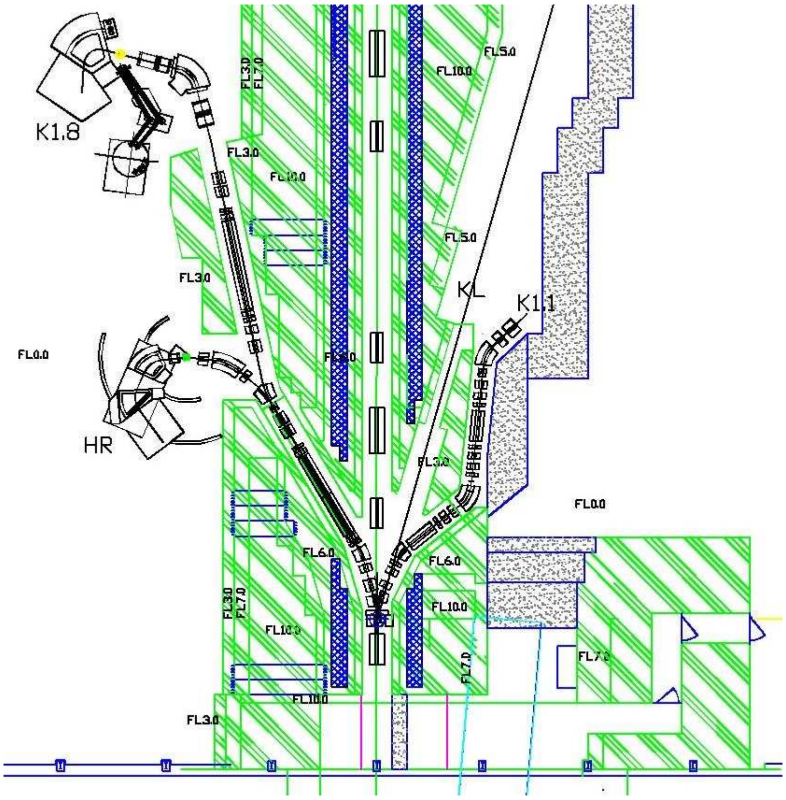

Figure 10: Preliminary layout of the K-Hall. "K1.1" to the right is for low-energy K^+'s.

To reduce the pion contamination and the background to $K^+ \to \pi^+ \nu\bar{\nu}$ due to beam pions scattered into the detector, **a $\mathbf{K^+}$ beam line with a high K^+/π^+ ratio (>3) should be constructed at K-Hall**. The K^+ momentum must be low (600-800 MeV/c). Right now we are investigating the optimization of the kaon beam line for $K^+ \to \pi^+ \nu\bar{\nu}$ at the K-Hall, based on the experience of E787 and E949. An idea is **a shorter beam line with lower $\mathbf{K^+}$ momentum**.

- The counting-rates in the most subsystems related to the beam analysis and photon veto analysis in the E787 and E949 detectors were proportional to the incident kaons, not to the kaons at rest in the target [38]. That means, with the same incident flux and by lowering the beam momentum (and reducing the amount of material in the degrader), the kaon stopping fraction increases while accidental hits decrease [6] .

[6] Also, using additional proton intensity to extend the spill length without increasing the instantaneous rate raises the number of kaon decays per hour without impacting the acceptance.

- There is already an optics design of a 550 MeV/c two-stage separated K^+ beam called "K550" by J. Doornbos (TRIUMF) [39] [7]. K550 has a twice as high solid angle and momentum acceptance as LESB3 and the same beam purity. In contrast to the stopping fraction of 0.26 for 730-MeV/c kaons by the LESB3 (19.6m), the stopping fraction for 550-MeV/c kaons by the K550 (14.7m) is 0.40 and is 50% better.
- To handle lower-momentum kaons, the beam line should have shorter length. There are many difficulties, in the real case, in constructing a shorter K^+ beam line with high solid angle as K550 to the K-Hall: heat capacity of the vacuum duct, radiation hardness and stability of the magnets and separators, radiation shield of the experimental area etc. We are making a preliminary optics design of the K^+ beam line for $K^+ \to \pi^+\nu\bar{\nu}$ within these constraints.

Table 2 shows a comparison of the operation between the AGS to E949 and the JHF-PS, with one-half proton beam [8] and the optimizations above, to a new stopped kaon experiment. Assuming there is no loss to the K^+ yields, the instantaneous proton rate in the spill is 3.7 times higher than E949 (and is more or less consistent with the increase of the average current [9]) and the acceptance is increased by 1.5 due to the stopping fraction.

PS operation		AGS to LESB3 for E949	JHF-PS mod · 1/2 to K550 for new exp.	
proton energy	GeV	24	30	
protons on Tgt	10^{12}/spill	65	100	× 1.54
machine cycle	sec	6.4	4.42	× 1/1.45
average current	μA	1.63	3.6	× 2.2
slow extraction	sec	4.1	1.7	× 1/2.4
duty factor		0.64	0.39	× 0.60
instantaneous rate	10^{12}/sec	16	59	× 3.7
K^+ momentum	MeV/c	730	550	(no lose)
stopping fraction		0.26	0.4	× 1.5

Table 2: Comparison of the PS operation between the AGS to the BNL-E949 experiment and the JHF-PS, with one-half proton beam and the optimizations in the text, to a new stopped kaon experiment.

[7] The K550 was originally designed for E949 as a replacement of the present line LESB3 at AGS.
[8] "one-half" means the proton beam is shared with other beam lines or the experiment starts when the accelerator complex is doing commissioning studies with lower intensity.
[9] For reference, the JHF-PS with one-sixth proton beam gives numbers comparable to the AGS.

5.3 Detector and Experiment

The goal of the new experiment is to collect more than 50 $K^+ \to \pi^+\nu\bar{\nu}$ events in the SM from K^+ decays at rest. In other words, the single-event sensitivity proposed by E949 should be improved, **by a factor of at least 5**, to 2×10^{-12} in the environment that the instantaneous rate is higher.

First, in this subsection, we discuss an experiment based on incremental improvements of the E949 methods. We expect to achieve the goal by optimizing the JHF-PS operation and the K^+ beam line, improving the detector, and relaxing selection criteria ("cuts") in the analysis.

- Running mode ($\times 1.5$):
  - stopping fraction and duty factor ($\times 1$) [10] and
  - beam hours of ~ 3 years ($\times 1.5$).
- New, rate-capable detector ($\times 2$).
- Re-optimization of the detector and analysis ($\times 2$):
  - S/N=5 by relaxing the TD cuts identifying π^+ with the $\mu^+ \to e^+$ chain etc. ($\times 1.2$),
  - brighter detector and better energy resolution ($\times 1.4$), and
  - pipeline trigger, faster DAQ etc ($\times 1.2$).

Major upgrades of the stopping target and the RS to achieve better resolutions and rate capabilities are the key, and ideas are:

- more segmentation ("chopping") of the RS scintillators by at least four,
- brighter plastic scintillators to get more light outputs, and
- RS readout with wavelength-shifting fibers or readout directly in the magnetic field [40], with advanced phototubes or photodiodes, for better light-collection.

In addition, beam counters with better segmentation, a new Silicon-strip energy-loss counter (for better dE/dx measurement and K^+/π^+ separation) [41] in the beam line, and new calorimeters, with fast response, to the subsystems close to the beam line are being considered; their R&D works are already started at KEK. Waveform digitizing, as well as the trigger, DAQ and monitor systems, will be developed based on modern technologies [42]. A design of a prototype 500-MHz waveform digitizer is underway by the KEK Electronics group.

[10] We hope for keeping the beam conditions to be comparable to E949 by a JHF-PS duty factor of at least 0.5 or a K^+ beam line with a better stopping fraction.

5.4 New Spectrometer

We also seek a stopped kaon experiment for $K^+ \to \pi^+ \nu \bar{\nu}$ with new techniques. A concept of "higher-field ($\geq$2.0-T) spectrometer" (with a superconducting solenoidal magnet) has been discussed by E787 collaborators [43]. The merits are:

1. Improved π^+-momentum resolution.
2. "Compact detector": since the curvature of the π^+ tracks get smaller, the size of the drift chamber, RS and magnet is reduced.
3. "Fiber Stack": since the size of the RS is small, finer RS segmentation (in particular to the region where the π^+ track comes to rest) with plastic-scintillating fibers can be realized, which makes the RS tracking easier and a loss of $\pi - \mu - e$ decay acceptance due to accidental hits in the stopping counter smaller.
4. "Crystal Barrel": since the detector is compact, the size of the calorimeter system surrounding the central region is also reduced; the barrel calorimeter located immediately outside the RS can be made of fully-active scintillating crystals (undoped-CsI or faster ones), rather than sampling shower-counters, and achieve much-improved photon detection.

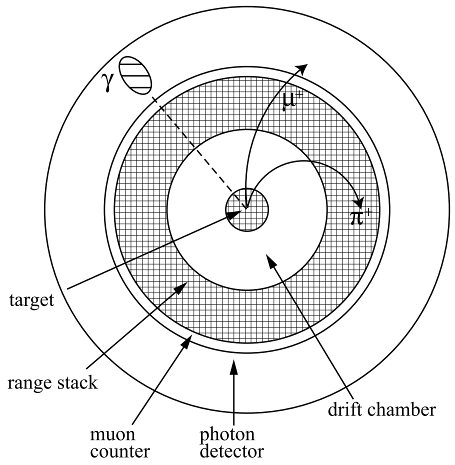

Figure 11: Schematic endview of a new spectrometer.

Fig. 11 shows a schematic endview of a new spectrometer being considered. While π^+ tracks are contained in the RS region, μ^+ tracks from $K_{\mu 2}$ (with a larger curvature) pass through the RS and hit the muon counter, which makes the online μ^+ rejection easier. The barrel calorimeter detects photons as well as μ^+ tracks. Higher counting-rates in the compact detector is overcome by the much finer segmentation (than the E949 detector) in all the subsystems.

Intensive Monte Carlo studies are being prepared for its conceptual-design works.

6 Urgency, Manpower, Funding etc.

In the first decade of this century, a lot of experimental results on B decays are expected from BELLE, BABAR, Tevatron, LHC-b, BTEV etc. Particularly important is a first measurement of $B_s - \bar{B}_s$ mixing and a determination of $|V_{td}|$ from B decays, which is expected at Tevatron [7]. To meet the big opportunity of quark-flavor physics, many K-decay experiments are currently in analysis, under construction or being prepared (Table 3). The CKM experiment at FNAL is pursuing the same physics goal, with two times better sensitivity than ours and using a brand-new (and not-yet-proved) technique. Since $B(K^+ \to \pi^+\nu\bar{\nu})$ is very important to search for the physics beyond the SM in Kaon sector, we believe two experiments with different methods would be performed. To compete with the CKM experiment, which may start collecting data as early as 2007-08, we want to do the experiment in this LoI as a "Day-1 experiment" of J-PARC.

lab	accelerator		experiment	kaon decay
KEK	PS	(12 GeV)	E246 $\checkmark$	stopped K^+
			E391a	K_L^0
BNL	AGS	(24 GeV)	E787 $\checkmark$ / E949	stopped K^+
			E865 $\checkmark$	in-flight K^+
			E871 $\checkmark$	K_L^0
			KOPIO *	K_L^0
CERN	SPS	(450 GeV)	NA48	K_L^0, K_S^0
FNAL	Tevatron	(800 GeV)	KTEV $\checkmark$	K_L^0
	Main Injector	(120 GeV)	CKM *	in-flight K^+

Table 3: Rare kaon-decay experiments. "$\surd$" means data taking of the experiment is completed. "$*$" means detector construction of the experiment is not started.

From the experience of E787 and E949, about 30 to 50 physicists will be at work to construct and operate this type of experiment. We are making efforts to collaborate worldwide with particle and nuclear physicists who are interested in the physics of $K^+ \to \pi^+\nu\bar{\nu}$ as well as the physics of "chiral dynamics in low-energy QCD", which can be studied with the same spectrometer (see Appendix).

We roughly estimate that it costs 5M US$ and 10M US$ to construct a new beam line and a new detector for this experiment, respectively, from scratch. At present we have a computing resource and are funded in part by Grant-in-Aid for Scientific Research [44] in Priority Areas: "Mass Origin and Supersymmetry Physics" [45] from the MEXT Ministry of Japan [11] , which enables us to push R&D for new detectors and electronics forward in time. Additional funds are needed to construct the beam line and complete the detector. We are considering usage of the resources in the existing beam lines (e.g. the K5 chan-

[11] KAKENHI TokuTei RyouIki: "ShitsuRyou KiGen" from Monbu-Kagaku-Shou.

nel [46] [12] at the 12-GeV PS of KEK and the LESB3 channel at AGS) and detectors as much as possible.

We are also committing ourselves to the current program of kaon physics experiments and to other LoI's for rare kaon-decay experiments at J-PARC.

7 Conclusion

The stopped kaon experiment is currently the best method to observe the $K^+ \to \pi^+\nu\bar{\nu}$ decay. This LoI pushes ahead with a stopped kaon experiment at J-PARC, in the style of BNL E787-E949, to observe more than 50 $K^+ \to \pi^+\nu\bar{\nu}$ events in the SM.

All the needed information in LoI, requested by "Call for Letters of Intent" [1] from the Director of Project Office of High Intensity Proton Accelerators, is included in the "Executive Summary" at the beginning of this LoI.

Acknowledgments

We would like to thank D.A. Bryman (University of British Columbia), L.S. Littenberg (BNL), T. Numao (TRIUMF) and S. Sugimoto (KEK) for valuable comments.

[12] The K5 channel is a low-momentum (550-650 MeV/c) single-stage separated bean line and provides a flux of $\sim 1 \times 10^5 K^+$/Tera-protons on the production target with a K^+/π^+ ratio of 1/10. The channel views the 6-cm long platinum production-target at $0 - \pm 3$ degrees and is 12.5 m long.

A Byproduct Physics

We point out that, with the same solenoidal magnetic spectrometer for $K^+ \to \pi^+\nu\bar{\nu}$, many medium-rare K^+ decay modes for studying chiral dynamics in low-energy QCD (e.g. Chiral Perturbation Theory (ChPT) [47] and large-N_c QCD [48]) can be measured at the same time. Table 4 is a list of the physics of kaon decays from the E787 experiment; most of these are three- or four-body decays to the final states consisting of π^+, μ^+ and γ (including the γ's from π^0) [13] . These decay modes can be measured with better sensitivities by the experiment proposed in this LoI, and possible CP and T violations in the correlation of momentum vectors in the final states can be pursued. This would potentially be a new experimental program of J-PARC that both particle and nuclear physicists are interested in.

decay mode	result	year	physics
$K^+ \to \pi^+\nu\bar{\nu}$	observed	2000	SM flavor dynamics
$K^+ \to \pi^+ f$	limit	2000	familon [49], beyond the SM
$K^+ \to \pi^+ H,\ H \to \mu^+\mu^-$	limit	1989	SM light Higgs
$K^+ \to \pi^+\gamma\gamma$	observed	1997	ChPT
$K^+ \to \pi^+\mu^+\mu^-$	observed	1997	ChPT
$K^+ \to e^+\nu\mu^+\mu^-$	limit	1998	ChPT
$K^+ \to \mu^+\nu\gamma$	measured	2000	ChPT
$K^+ \to \pi^+\pi^0\gamma$	measured	2000	ChPT, analysis in progress
$K^+ \to \pi^+\pi^0\nu\bar{\nu}$	limit	2001	SM, initial search
$K^+ \to \pi^+\gamma$	limit	2002	Angular momentum conservation [50]
$K^+ \to \mu^+\pi^0\nu\gamma$			ChPT, analysis in progress

Table 4: Physics of kaon decays from E787.

[13] Reconstructing electron tracks from kaon decays at rest is not easy, because they could start showering in the stopping target before entering the drift chamber.

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