Stopped Kaon Experiment for $K^+ \to \pi^+ \nu\bar{\nu}$
- from E787 to E949 and the future -

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Abstract

The stopped kaon experiment is currently the best method to observe the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$. In this review, after introducing the theoretical motivation and the BNL E787 detector, reasons why the $K^+ \to \pi^+ \nu\bar{\nu}$ experiment is "difficult" are explained from the author's viewpoint. The prospects for the BNL E949 experiment from 2001 and for a possible new stopped-kaon experiment in the future facilities are discussed thereafter.

This review would be regarded as a point of departure for the Letter of Intent for new kaon-decay experiments at the 50-GeV Proton Synchrotron in the High-Intensity Proton Accelerator Facility by KEK and JAERI. Questions and comments are warmly welcome.

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1 Theoretical Motivation

The $K^+ \to \pi^+\nu\bar{\nu}$ decay is a flavor-changing neutral current process induced in the Standard Model (SM) by loop effects 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 V_{td} [1] in the Cabibbo-Kobayashi-Maskawa matrix. Long-distance contributions are negligible and the hadronic matrix element is extracted from the $K^+ \to \pi^0 e^+\nu$ decay. The theoretical uncertainty is 7% from the charm-quark contribution in the next-to-leading-logarithmic QCD calculations [1]. Efforts by theorists to understand and reduce the uncertainty continue, including recent discoveries of a small "overlooked" term from the box diagram (1999) [2] [3] and the effect of the subleading dimension-8 operators (2001) [4].

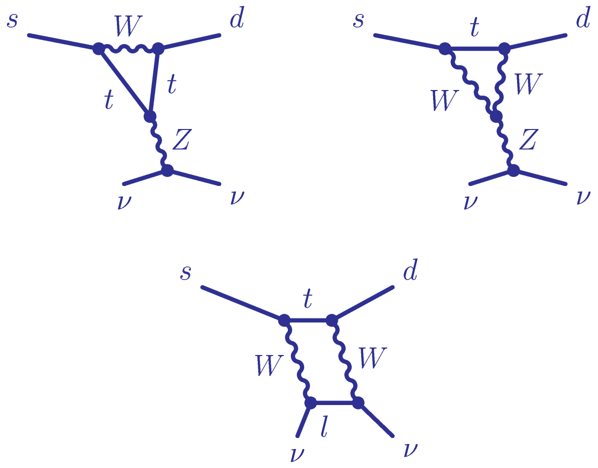

Figure 1: Penguin and box diagrams for $K^+ \to \pi^+\nu\bar{\nu}$ in the Standard Model.

The branching ratio is represented in the SM as [2] :

$$B(K^+ \to \pi^+\nu\bar{\nu}) = 4.11 \times 10^{-11} \times A^4 \times X(x_t)^2 \times [\ (\rho_0 - \rho)^2\ +\ \eta^2\ ] \tag{1}$$

in the Wolfenstein parameterization A, ρ and η. With the ρ-η constraints from other K and B decay experiments, the SM prediction of the branching ratio is, for example [6] [7], $(0.75 \pm 0.29) \times 10^{-10}$. Using only the results on $B_d - \bar{B}_d$ and $B_s - \bar{B}_s$ mixing [3], a branching ratio limit $< 1.15 \times 10^{-10}$ can be extracted. New physics beyond the SM could affect the branching ratio[8]. In addition, the two-body decay $K^+ \to \pi^+ X^0$, where the X^0 is a weakly-interacting light particle such as a familon [9], could also be observed as a 'π^+ plus nothing' decay with a monochromatic pion. Since the effects of new physics are not expected to be too large, a precise measurement of a decay at the level of 10^{-10} is required [3] .

[1] Exactly speaking, the $K^+ \to \pi^+\nu\bar{\nu}$ decay determines $|V_{ts}^*\ V_{td}|$. The uncertainties in $V_{ts}(= -A\lambda^2$ in the Wolfenstein parameterization) should be reduced by B-meson experiments.

[2] $X(x_t)$ is the Inami-Lim loop function [5] with the QCD correction, $x_t \equiv m_t^2/m_W^2$, and ρ_0 is due to the charm contribution.

[3] It is pointed out that a measurement at 1.5×10^{-10}, with reliable experimental precision, would be

2 BNL E787 Detector

Experiment 787 [4] at the Alternating Gradient Synchrotron (AGS) of BNL performed an initial search in 1989-91 and obtained the 90% confidence level (C.L.) upper limit of 2.4×10^{-9} [10]. Following major upgrades of the detector and the beam line, E787 took data from 1995 to 1998. The latest result [11] on $K^+ \to \pi^+\nu\bar{\nu}$ is from the 1995-97 datasets: the branching ratio is $1.5^{+3.4}_{-1.2} \times 10^{-10}$ based on one observed event and the background level of 0.08 ± 0.02 events. The result is consistent with the SM prediction and set a limit $1.07 \times 10^{-4} < |V^*_{ts}\, V_{td}| < 1.39 \times 10^{-3}$. The expected sensitivity from the entire E787 data is about 0.8×10^{-10}. Other byproduct modes [12] [13] [14] are also being studied.

Analysis techniques developed in E787 from the $K^+ \to \pi^+\nu\bar{\nu}$ study are discussed elsewhere [15] in these Proceedings. This paper concentrates on the detector.

E787 measures the charged track emanating from K^+ decays at rest. The π^+ momentum from $K^+ \to \pi^+\nu\bar{\nu}$ is less than 227MeV/c as shown in Figure 2, while the major background sources of $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$, 21.2%) and $K^+ \to \mu^+\nu$ ($K_{\mu 2}$, 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 230MeV/c is adopted for the search. Background rejection is essential in this experiment, and we have the weapons for redundant kinematics measurement, μ^+ rejection, and extra-particle and photon veto. Each weapon should have a rejection of $10^5 \sim 10^6$, and we have reliable estimation of these rejections using real data.

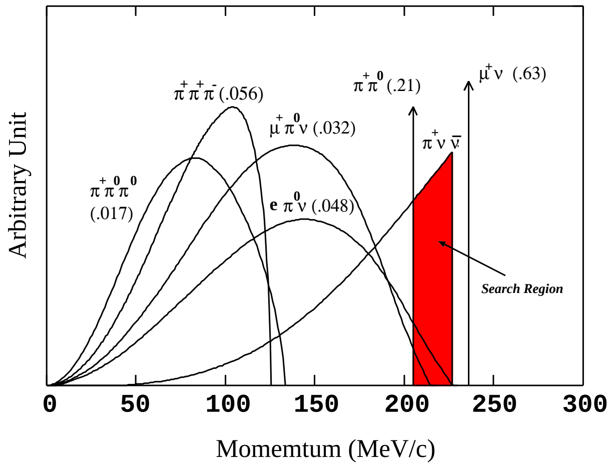

Figure 2: Momentum spectrum of the charged particles from kaon decays at rest.

The AGS delivered kaons of about 700 MeV/c [5] to the experiment at a rate of $(4-7) \times 10^6$ per 1.6-sec spill. The kaon beam line (LESB3 [16]) incorporated two stages of electrostatic particle separators which reduced the pion contamination to 25% at the

a sign of the physics beyond the SM [6].

[4] E787 is a collaboration of BNL, Fukui, KEK, Kyoto, Osaka, Princeton, TRIUMF and Alberta.

[5] This momentum was set to be below the threshold for hyperon production in the degrader.

entrance of the detector. Kaons were detected and identified by a Čerenkov counter, multi-wire proportional chambers and an energy-loss counter. After being slowed by a BeO degrader [6] , approximately 25% of the incident kaons reached an active target located at the center of the E787 detector [17] (see Fig. 3). The 12-cm diameter target, which consisted of 0.5-cm square plastic-scintillating fibers, provided initial tracking of the stopping kaon and its decay products. A delayed coincidence requirement (> 2 nsec) of the timing between the stopping kaon and the outgoing pion helps to reject backgrounds of pions scattered into the detector or kaons decaying in flight.

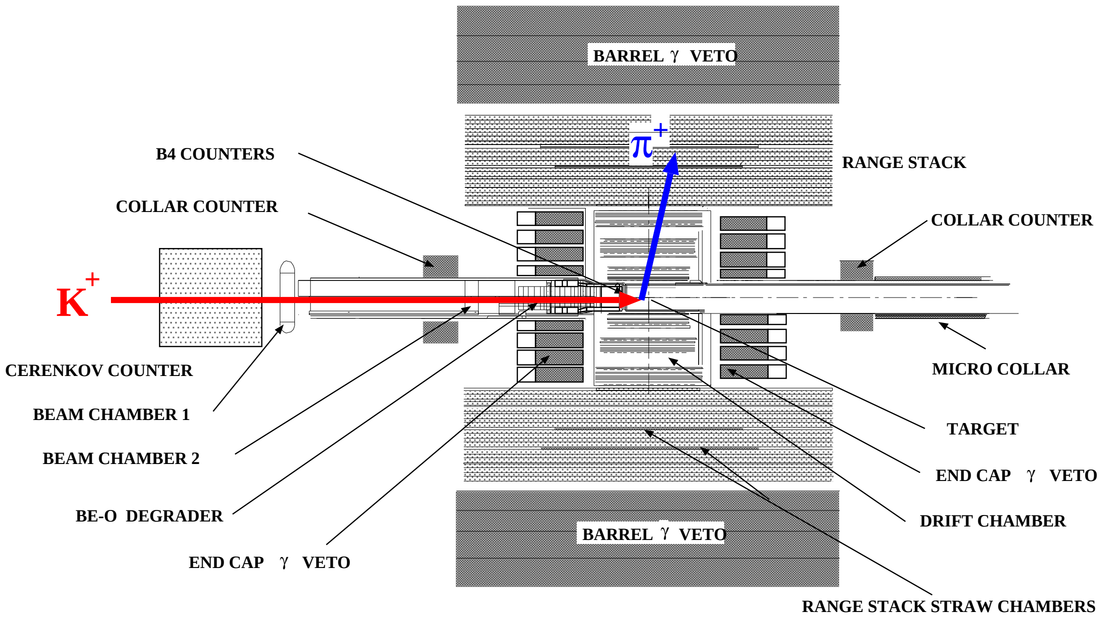

Figure 3: Schematic side-view of the E787 detector.

Particles emanating from kaon decays at rest in the target were measured in a solenoidal spectrometer with a 1.0-T field directed along the beam axis. The charged decay products passed through a layer of trigger scintillators surrounding the target (I-counter) and a cylindrical drift chamber [18], and lost energy and stopped in a Range Stack (RS) made of plastic scintillators. The drift chamber, with a total mass of 3×10^{-2} radiation lengths, provided tracking information from 12 layers of axial anode-wire cells and six layers of thin spiral-strip cathode foils. The RS filled the radial region between 45.1 cm and 89.6 cm and was segmented into 24 azimuthal sectors and 21 radial layers totalling one radiation length. The first RS layer (T-counter) defined the solid angle acceptance for the π^+ track in the RS. Two layers of straw tube tracking chambers were embedded within the RS. The output pulse shapes of the RS counters were recorded by 500-MHz sampling transient digitizers (TDs) [19], each of which was based on two interleaved 250-MHz flash analog-to-digital converters (ADCs). Momentum, kinetic energy and range are measured to reject the backgrounds by kinematic requirements. In addition to providing precise

[6] BeO is s material with high density to degrade and with a low average atomic number to minimize multiple Coulomb scattering.

time and energy information for reconstructing the π^+ track, the TDs provided rejection of muon and electron tracks by detecting the $\pi^+ \to \mu^+ \to e^+$ decay chain in the RS stopping counter.

A hermetic calorimeter system surrounded the central region, and $K_{\pi 2}$ and other decay modes with extra particles (γ, e, ...) are vetoed by the in-time signals in the system. The barrel (BL) calorimeter, which was a cylindrical detector being located immediately outside the RS, covered about two thirds of the solid angle. It was made of alternating layers of lead (0.1 cm) and plastic scintillator (0.5 cm) sheets and was segmented azimuthally into 48 sectors, whose boundaries were tilted so that the inter-sector gaps did not project back to the target. In each sector, four radial groups of lead-scintillator layers added up to a total of 14.3 radiation lengths. About 29% of the shower energy was deposited in the scintillators. The two endcap (EC) calorimeters [20] 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, were also used for vetoing extra particles. The two endcap calorimeters consisted of 143 undoped-CsI crystals, which were read out by 500-MHz CCD-based TDs [21] [7] .

The first evidence for the $K^+ \to \pi^+ \nu\bar{\nu}$ decay reported in [22] is shown in Figure 4.

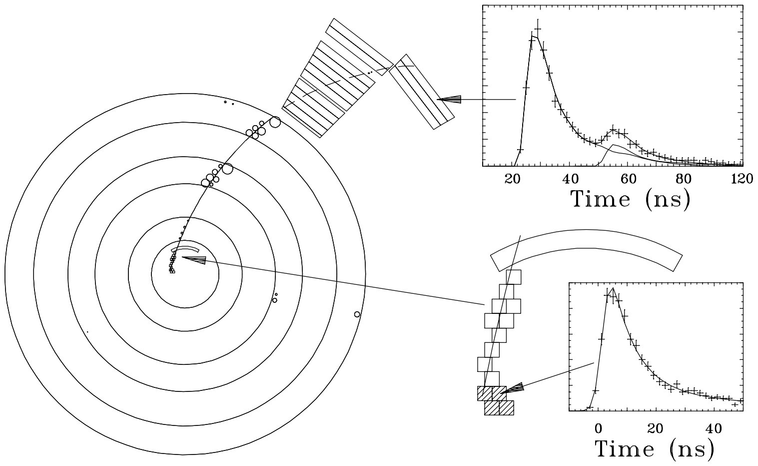

Figure 4: Evidence for the decay $K^+ \to \pi^+ \nu\bar{\nu}$.

3 Why the $K^+ \to \pi^+ \nu\bar{\nu}$ Experiment is Difficult ?

Figure 5 shows the range versus momentum [8] plot of the events which met the $K^+ \to \pi^+ \nu\bar{\nu}$ trigger requirements and succeeded in the first-pass reconstruction. In this plot we can see the categories of the charged tracks in the E787 detector.

[7] Plastic-scintillating fibers in the target were also read out by the CCD-based TDs.
[8] The momentum is chosen because it contains the kinematic information of the track before entering the RS scintillators.

- $K_{\pi 2}$ peak events:
  The range and momentum are consistent with $K_{\pi 2}$.

- pion band events:
  The range and momentum are consistent with the π^+ range-momentum relation.

- $K_{\mu 2}$ peak events:
  The range and momentum are consistent with $K_{\mu 2}$.

- $K_{\mu 2}$ range tail events:
  While the momentum is consistent with $K_{\mu 2}$ the range is shorter than expected, which indicates the $K_{\mu 2}$ muons had inelastic scattering in the RS.

- muon band events:
  The range and momentum are consistent with the μ^+ range-momentum relation [9] .

The pion band events are beam pions being scattered into the detector, kaons decaying in flight, or multiple beam particles. The muon band events are kaons decaying in flight, pions decaying in flight, or $K^+ \to \mu^+\nu\gamma/K^+ \to \mu^+\pi^0\nu$ decays whose muon momentum is lower than $K_{\mu 2}$.

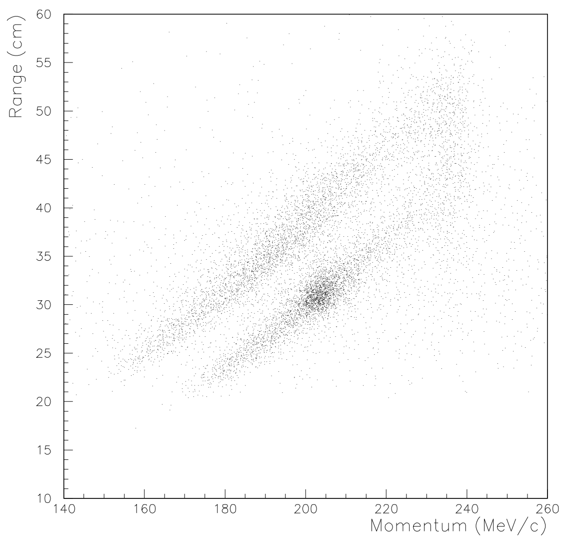

Figure 5: Range versus momentum plot of the events which met the $K^+ \to \pi^+\nu\bar{\nu}$ trigger requirements and succeeded in the first-pass reconstruction. The kinematic values of the charged tracks are calculated with a pion hypothesis.

The acceptance factors in the $K^+ \to \pi^+\nu\bar{\nu}$ measurement [11] are summarized in Table 1; the total acceptance is only 0.21%. It includes the factors of the solid angle

[9] The range is longer than expected for pions with the same momentum.

acceptance to the charged track (0.407), π^+ stop without nuclear interaction nor decay-in-flight in the RS (0.513), K^+ stop efficiency (0.704) and K^+ decay after 2 nsec (0.850); I do not think we can build a much better detector in these factors, as long as we stick to the concept of stopped kaon decay. Also the factors of the reconstruction efficiency (0.959) and other kinematic constraints (0.665) look reasonable.

Acceptance factors	method	
Solid angle acceptance	M.C.	0.407
π^+ nucl. int., decay-in-flight	M.C.	0.513
K$^+$ stop efficiency	$K_{\mu 2}$	0.704
K$^+$ decay after 2 ns	$K_{\mu 2}$	0.850
Reconstruction efficiency	$K_{\mu 2}$	0.959
Other kinematic constraints	π_{scat},$K_{\pi 2}$	0.665
$\pi - \mu - e$ decay acceptance	π_{scat}	0.306
Beam and target analysis	$K_{\mu 2}$	0.699
Photon veto analysis	$K_{\mu 2}$	0.785
$K^+ \to \pi^+ \nu\bar{\nu}$ phase space	M.C.	0.155
Total acceptance		0.21%

Table 1: Acceptance factors used in the measurement of $K^+ \to \pi^+\nu\bar{\nu}$ [11], and the methods to determine them. The "K^+ stop efficiency" is the fraction of kaons entering the target that stopped and was measured using an analysis of the $K^+ \to \mu^+\nu$ data and its known branching ratio, and "other kinematic constraints" includes kinematic particle identification and dE/dx cuts. "M.C.", "$K_{\pi 2}$", "$K_{\mu 2}$" and "π_{scat}" mean the sample generated by Monte Carlo simulation and the data samples of $K^+ \to \pi^+\pi^0$ decays, $K^+ \to \mu^+\nu$ decays and scattered beam pions accumulated by calibration triggers, respectively.

I am going to explain the reasons why the remaining acceptance factors get to be small in the $K^+ \to \pi^+\nu\bar{\nu}$ measurement and why it is hard to increase them so much from the achievements in E787.

3.1 Muon rejection by the TD cuts

$K_{\mu 2}$ is harder to be handled in the trigger among the two major background sources [10]. The $K_{\mu 2}$ events have the same topology as the $K^+ \to \pi^+\nu\bar{\nu}$ events and cannot be easily removed by ordinary combinations of counter signals online. $K_{\mu 2}$'s branching ratio is more than 10^9 times higher than $K^+ \to \pi^+\nu\bar{\nu}$'s; we cannot even make the DAQ running without introducing a special function to the trigger system.

In the E787 $K^+ \to \pi^+\nu\bar{\nu}$ trigger, the Level-0 cuts such that:

[10] $K_{\pi 2}$ has extra photons and can be reduced by the online photon veto cuts to the BL, EC and RS counters.

- tracks reaching the outer three RS layers (19 – 21) were vetoed, and
- tracks whose "refined range", being calculated online from combining the RS stopping layer, the polar opening angle to the beam axis from the RS timing information and the energy deposit in the target, was longer than criteria were vetoed,

were applied. Furthermore, based on the pulse shape information from the TDs on the RS,

- events with a $\pi^+ \to \mu^+$ decay in the RS stopping counter were tagged online by a double-pulse algorithm demanding that the RS pulse had a larger area (due to the μ^+) than expected from its height

This function, called the Level-1.1 trigger, was realized by the TD control board with ASICs (Application Specific Integrated Circuits). The performance of the Level-1.1 trigger was: π^+ acceptance of 0.6, μ^+ rejection of about 20, and the trigger decision time of 10-20 μsec.

In the offline analysis, a double-pulse fit [11] to the TD pulse shape recorded in the stopping counter was made to ensure $\pi^+ \to \mu^+$ decay. The $\mu^+ \to e^+$ decay was reconstructed as well, and many TD cuts to identify the $\pi^+ \to \mu^+ \to e^+$ chain in the RS stopping counter were imposed. The total acceptance of π^+ identification online and offline, using the TD information, was 0.306 and was inevitably small to achieve the μ^+ rejection of 10^5.

3.2 Accidental loss by the beam, target and photon veto cuts

The offline cuts of:

- no extra hits in the Čerenkov counter, multi-wire proportional chambers, energy-loss counter and target, to remove events triggered by kaon decays in flight or by multiple beam particles, and
- no extra hits in the calorimeter system, to remove events by $K_{\pi 2}$, $K^+ \to \mu^+\nu\gamma$, and etc

at the decay times (the kaon decay time in the target and the pion and muon decay times in the RS stopping counter) were applied in the analysis, which is the main limitation costing around 40% of the acceptance and suffers directly from the high counting-rate environment in or close to the beam line. The strategy of the stopped kaon experiment, and what the E787 experiment really did in the post-1995 runs [23], were therefore to limit the instantaneous rates and attempt to gain in the overall number of stopped kaons.

[11] The MINUIT package for function minimization and error analysis in the CERN Program Library has been used in the E787 analysis.

In the E787 experiment, only 25% of the kaons in the beam were slowed down and stop in the target while the remainder were lost or scattered out in the degrader. The rates in the most subsystems related to the beam analysis and photon veto analysis in the E787 detector were proportional to the incident kaons, not to the stopped kaons in the target. That means, with the same incident flux and a lower beam-momentum, the kaon stopping fraction increases while accidental hits decrease. 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. By reducing the beam-momentum from 790MeV/c in 1995 to 710MeV/c in 1997-98 the fraction of incident kaons stopping in the target was improved by 44%. The AGS spill length was extended from 1.6sec to 2.2sec and furthermore to 2.8sec in 1998. Other improvements in the trigger and readout provided acceptance gains of about 20%.

3.3 $K^+ \to \pi^+\nu\bar{\nu}$ in the region below the $K_{\pi2}$

The current best E787 sensitivity on $K^+ \to \pi^+\nu\bar{\nu}$ [11] utilizes a limited momentum region above the $K_{\pi2}$, and the phase-space acceptance is 0.155. To increase the acceptance as well as to confirm the SM prediction of the π^+ spectrum, the $K^+ \to \pi^+\nu\bar{\nu}$ study below the $K_{\pi2}$ ("$\pi^+\nu\bar{\nu}$-2") is strongly demanded. The latest result on $\pi^+\nu\bar{\nu}$-2 is the upper limit 1.7×10^{-8} (90%C.L.) from the old E787 dataset [24]. Analysis of the $\pi^+\nu\bar{\nu}$-2 data taken after the major upgrades of the detector and the beam line is being performed.

Unfortunately, it was found that the $\pi^+\nu\bar{\nu}$-2 analysis needed tighter target cuts and photon veto cuts to control the $K_{\pi2}$ background, and the total acceptance would be a little bit lower than the acceptance above the $K_{\pi2}$. The reason is as follows [25]. The trigger for $\pi^+\nu\bar{\nu}$-2, which requires the range of the π^+ track is shorter than that from $K_{\pi2}$, collects in the real cases the $K_{\pi2}$ events whose π^+ is scattered in the target with some energy loss in it. The solid angle acceptance for the π^+ track in the RS T-counter does not guarantee that the π^+ tracks emanate from kaon decays to the RS direction. Imagine the case that a π^+ from $K_{\pi2}$ decay is emitted to the direction of the beam axis and scattered into the RS, the photons from the $\pi^0 \to \gamma\gamma$ decay in $K_{\pi2}$ go to the beam direction, which is not well covered by the calorimeter system.

3.4 Particle interactions in the detector

We detect low energy π^+'s, μ^+'s and γ's from kaon decays at rest (below 200MeV) in the E787 detector. In addition to

- multiple Coulomb scattering (with non-Gaussian tail) of π^+'s and μ^+'s, and
- electromagnetic shower of γ's,

which can be well reproduced by Monte Carlo simulation, there are:

- π^+ hadronic interactions in plastic scintillators (elastic, pseudo-elastic, quasi-elastic, absorption, spallation),
- μ^+ elastic and inelastic scattering (hard scattering, μ^+-^{12}C Giant Dipole Resonance), and
- photo-nuclear absorption, which could subsequently produce slow neutrons,

whose cross section, energy loss, scattering angle and etc are not well known and uncertain from nuclear experiments and theories. We can put some formula into the Monte Carlo codes but we cannot rely on them; we must work on and learn from the real data. That means it takes time and man-power to do background studies and acceptance calculations.

3.5 A résumé

The E787 detector is a large solenoidal spectrometer and measures the particles in the center-of-mass system, like the 4π detectors in the high energy collider experiments. In the E787 detector, however, there are at least three big differences, which makes the experiment much more difficult than imagined.

1. While the charged particles from kaon decays at rest (π^+ and μ^+) should be reconstructed and measured in a non-destructive way, the target and RS, made of scintillators, work as "destructive" devices in some cases and create backgrounds.
2. There are three times in each event: the kaon decay time, pion decay time and muon decay time. An accidental hit at any could veto the event and reduce the acceptance.
3. We need to wait the $\pi^+ \to \mu^+ \to e^+$ decay chain for a few μsec. The RS, target and EC signals are recorded by waveform digitizers, which follows huge event size and non-negligible DAQ deadtime [26].

It should also be noted that, in contrast to the $K_L^0 \to \pi^0\nu\bar{\nu}$ experiments [27] whose photon veto to the $K_L^0 \to \pi^0\pi^0$ background is of great concern, the most serious issue of the $K^+ \to \pi^+\nu\bar{\nu}$ experiments is to control the muon backgrounds.

4 BNL E949 Experiment

Experiment E949 [28], which is going to start taking data in 2001, continues the study of the $K^+ \to \pi^+\nu\bar{\nu}$ decay with the stopped kaon decay at the AGS of BNL with a larger K^+ exposure, improved photon detection capability [12] and optimization of the trigger, DAQ and etc. 65-Tera(10^{12}) protons per 4.1-sec spill are extracted from the AGS every 6.4 sec to the kaon-production target. The LESB3 kaon beam line, the same one as in E787, is

[12] This is a key to pursue the $\pi^+\nu\bar{\nu}$-2 analysis in E949.

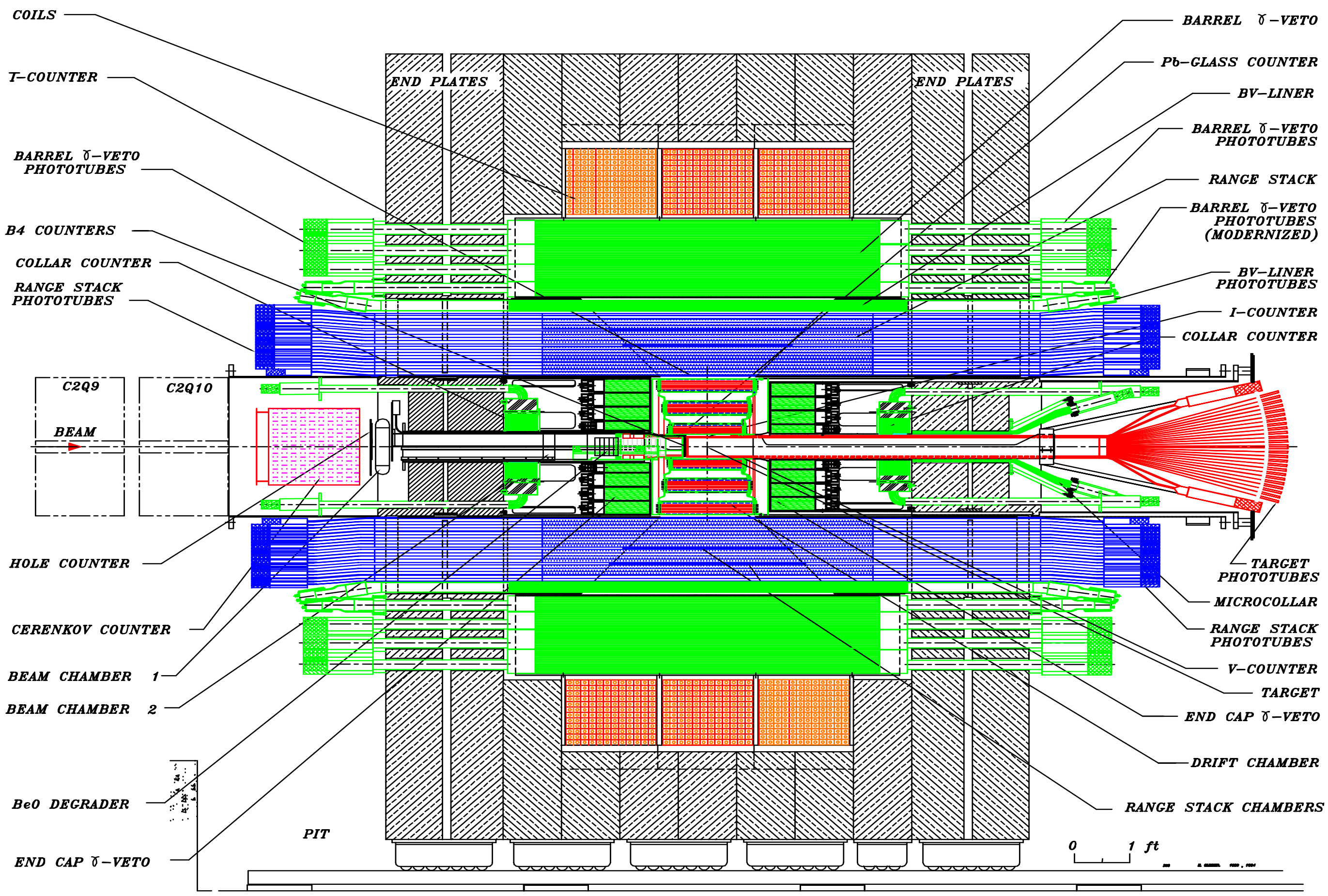

Figure 6: Side-view of the E949 detector.

used. The E949 detector is shown in Fig. 3. The upgrades [13] from the E787 detectors include:

- new Barrel Liner shower counter, which fills the radial region between the RS [14] and the BL calorimeter,
- new or improved calorimeters for further filling minor openings along the beam direction,
- new energy-loss counter and degrader [15] ,
- replacement of the RS T-counter and introducing scintillating fiber readout to it,
- replacement of the RS scintillators in the layers 2 –5,

[13] More information on E949 detector subsystems is available through http://www.phy.bnl.gov/e949/ .

[14] The RS scintillators in the layer 20 and layer 21 are removed, and the scintillators in the layer 19 are replaced to thinner ones.

[15] R&D studies of GSO and PWO crystals [29] [30] for new beam instruments are being performed.

- new trigger system with a programmable Level-0 board and mean timers [31] [32],
- RS readout with TDCs, in order to tag the $\mu^+ \to e^+$ chain in the stopping counter without using TDs [16] to reduce DAQ deadtime, and
- RS gain monitoring system using LEDs [33].

By optimization of the running mode (beam momentum, AGS duty factor, ...) and the analysis scheme, we hope to reach the sensitivity of $(8-14) \times 10^{-12}$ in 6000 hours of the beam time, which corresponds to about two years of running with RHIC (BNL's Relativistic Heavy Ion Collider)[17] , and determine $|V_{ts}^* \, V_{td}|$ to 20 – 30%.

5 The Future

In the first decade of the 21st century the season of B-factory experiments (BELLE, BABAR, LHC-b, BTEV, ...) has come. Theorists already predicted possible signals for physics beyond the SM by comparing the results by kaon decays and B-meson decays [34] [35]. To meet the opportunity of quark-flavor physics, the keyword of the future $K^+ \to \pi^+\nu\bar{\nu}$ experiments should certainly be **precise measurement**. The physics reach expected from the E949 experiment is not far enough, and we desire a new experiment targeting a sensitivity of 1×10^{-12}, about 100 signal events or a branching ratio measurement with 10% precision, by the year around 2010.

There are two approaches for the precise measurement of $K^+ \to \pi^+\nu\bar{\nu}$. One is a brand-new experiment with in-flight K^+ decays, with much better acceptance than previously achieved [18] . In this approach the CKM experiment [36] at the Main-Injector of FNAL, presented by B.Tschirhart in this workshop [37] and recently granted Scientific (Stage I) approval [38], aims to collect $\sim$ 100 event sample with the expected signal acceptance of $\sim$2% and total backgrounds of less than 10 events (signal-to-noise (S/N) ratio of 10).

The other approach is to continue a stopped kaon experiment in the style of E787-E949. A big issue is whether the detector can be improved further to compete with the CKM experiment. An unbeatable merit, however, 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 in E787-E949 are available, and we can do many tests in the E949 experiment by regarding it as a pilot experiment for the future.

In this section [19] , I explain an initial design for a possible new stopped kaon experi-

[16] The electron energy is estimated from the pulse width recorded in the TDCs.
[17] The AGS is an injector for RHIC in the complex.
[18] 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.
[19] This section is based on my presentation at the JHF high energy physics workshop [39] [40], 7-Jan-2000, KEK, by the Japan Association of High Energy Physicist. It should be noted that there are already many discussions (E.g., [23] [41] [42] [43] [44] [45]) on the future $K^+ \to \pi^+\nu\bar{\nu}$ experiments by E787 collaborators and I owe much to them.

ment using the new High-Intensity Proton Accelerator Facility [46] [47] [20] by KEK and JAERI, Japan, which start construction in the fiscal year 2001.

5.1 50-GeV PS operation and K^+ beam

The "Phase 1" accelerator complex of the High-Intensity Proton Accelerator Facility consists of the 400-MeV Linac, 3-GeV synchrotron and 50-GeV synchrotron. A typical machine cycle of the 50-GeV proton synchrotron (PS) is to accelerates 320-Tera protons every 3.42 sec, which means the average current is 15.6 μA and the beam power is 0.75 MW. Slow-extracted 50-GeV proton beam (0.7-sec spill, with the duty cycle of 0.20) is transported to the Nuclear & Particle Physics Facility (K-Hall), and fast-extracted beam is transported to the Neutrino beam line to Super-Kamiokande.

In this initial design, it is assumed that the one-third of the proton beam [21] is extracted to the "K1.1" beam line, which is one of the three secondary beam lines being planned to the K-Hall [46] and is for low-energy kaons in 0.5 $\sim$ 1.1 GeV/c.

First of all, it must be pointed out that the machine cycle of the 50-GeV PS is not suitable and unoptimized for kaon decay experiments [40] (or any particle-physics experiment with time-coincidence techniques). Table 2 shows a comparison of the PS operation between the AGS to the BNL-E949 experiment and the 50-GeV PS (with the one-third proton beam) to a new stopped kaon experiment. While the amount of protons available in the new experiment is three times larger, the instantaneous proton rate in the spill is almost one order of magnitude higher than E949, due to its poor duty cycle, and is hardly ever tolerable by taking into account the acceptance loss due to accidental hits.

PS operation		AGS to LESB3	50GeV-PS $\cdot$ 1/3 to K1.1	
proton energy	GeV	24	50	
protons on Tgt	10^{12}/spill	65	100	$\times$ 1.54
machine cycle	sec	6.4	3.42	$\times$ 1/1.87
average current	μA	1.63	4.68	$\times$ 2.88
slow extraction	sec	4.1	0.7	$\times$ 1/6
duty factor		0.64	0.20	$\times$ 0.83
instantaneous rate	10^{12}/sec	16	143	$\times$ 9

Table 2: Comparison of the PS operation between the AGS to the BNL-E949 experiment and the 50-GeV PS, with the one-third proton beam, to a new stopped kaon experiment.

However, there are some ideas to optimize the PS operation and the kaon beam line

[20] A feasibility of using the high-intensity proton driver at the front-end of a muon storage ring complex of Neutrino Factory or Muon Collider is discussed in [48] [49].

[21] "one-third" means the proton beam is shared with other two beam lines or the experiment starts when the accelerator complex is doing commissioning studies.

for a stopped kaon experiment and beat the difficulties. These are the strong requests to the new facility and there is no room for compromise.

Improve the duty cycle by operating the PS at 30 GeV :
If the machine cycle (every 3.42 sec) and the protons per spill (100 Tera) are kept [22] and the beam is accelerated only upto 30 GeV, the spill length can be extended from 0.7 sec to 1.8 sec and the duty cycle is improved from 0.20 to 0.53 [50]. Concerning the K^+ yields below 1 GeV/c [51], there is no significant change between the proton energies of 50 GeV and 30 GeV.

Shorter beam line with lower K^+ momentum (K550) :
There is already an optics design of a 550 MeV/c two stage separated K^+ beam called "K550" by J.Doornbos (TRIUMF) [52] [23] . K550 has a twice as high solid angle and momentum acceptance as LESB3 and the same good 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.

Table 3 shows a comparison of the PS operation between the AGS to E949 and the 50-GeV PS, with the one-third proton beam and the optimizations above, to a new stopped kaon experiment. Assuming that there is no loss to the K^+ yields between the 50-GeV protons and 30-GeV protons, the instantaneous proton rate in the spill is 3.5 times higher than E949 (and is more or less consistent with the increase of the average current) and the acceptance is increased by 1.5 due to the stopping fraction.

5.2 Detector and Experiment

The goal of this initial design for a new experiment is to collect about 100 signal events from stopped kaon decays with the S/N ratio of 5. In the same time, to seek the observation of $\pi^+\nu\bar{\nu}$-2 events and the measuement of the π^+ spectrum in the $K^+ \to \pi^+\nu\bar{\nu}$ decay below the $K_{\pi 2}$ is an important motivation [24] .

In the new experment, we expect the following improvements in comparison to the E949 proposal.

- Running mode:
  - stopping fraction ($\times 1.5$ by the K550 beam line),
  - duty factor ($\times 0.83$ by the optimized PS operation), and
  - beam hours ($\times 1.5$ by $\sim$three years of running).

[22] The average current is therefore unchanged.
[23] The K550 was originally designed for E949 as a replacement of the present line LESB3 at AGS.
[24] It would also be emphasized that a lot of medium-rare kaon decay modes can be measured in the same detector and the Chiral Perturbation Theory [53], a model of low-energy QCD, can be studied with good accuracy.

PS operation		AGS to LESB3 for E949	50GeV-PS · 1/3 to K550 for new exp.	
proton energy	GeV	24	30	
protons on Tgt	10^{12}/spill	65	100	$\times$ 1.54
machine cycle	sec	6.4	3.42	$\times$ 1/1.87
average current	μA	1.63	4.68	$\times$ 2.88
slow extraction	sec	4.1	1.8	$\times$ 1/2.3
duty factor		0.64	0.53	$\times$ 0.83
instantaneous rate	10^{12}/sec	16	55.6	$\times$ 3.5
K^+ momentum	MeV/c	730	550	(no lose)
stopping fraction		0.26	0.4	$\times$ 1.5

Table 3: Comparison of the PS operation between the AGS to the BNL-E949 experiment and the 50-GeV PS, with the one-third proton beam and the optimizations in the text, to a new stopped kaon experiment.

- New, rate-capable detector ($\times$2.0).
- re-optimization of the detector and analysis:
  - S/N=5 by relaxing the TD cuts for the $\mu^+ \to e^+$ chain and etc ($\times$1.2),
  - brighter detector and better energy resolution ($\times$1.2), and
  - pipeline trigger, faster DAQ, ... ($\times$1.1).
- increase the phase space by $\pi^+\nu\bar{\nu}$-2 ($\times$2)

Of course some of the factors in the above list are not guaranteed. In particular the $\pi^+\nu\bar{\nu}$-2 analysis is questioned, and the possibility is being studied intensively by the E787 and E949 experiments.

To design and construct a new detector, based on the E787/E949 experience, would be promising. As discussed in early sections, major upgrades of the target and RS to achieve better resolutions and rate capabilities are the key, and ideas are:

- segmentation ("chopping") of the RS scintillators by four and more, and
- readout by scintillating-fibers or brighter scintillators to get more light outputs.

In addition, segmentation of the target and beam counters and installation of faster photon detectors near the beam line would be helpful. The conceptual design of the new detector and intensive Monte Carlo studies to prove the performance are going to start for the Letter of Intent to do the experiment using the 50-GeV PS in the High-Intensity Proton Accelerator Facility.

6 Conclusion

The stopped kaon experiment is currently the best method to observe the $K^+ \to \pi^+\nu\bar{\nu}$ decay, even though it is not an easy job as explained in this paper. The BNL E787 experiment measured the branching ratio $1.5^{+3.4}_{-1.2} \times 10^{-10}$ from the 1995-97 datasets based on one observed event, and the expected sensitivity from the entire data is about 0.8×10^{-10}. The new E949 experiment is rising and start taking data in 2001. R&D issues for the future will be studied in E949, and we are going to start the conceptual design of the detector for a new experiment.

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