T. K. Komatsubara

KEK-IPNS

Kaon Decay Workshop @KEK February’01

From E787 to E949 and the future: stopped-kaon experiment for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

Outline:

• Introduction
• BNL-E787 experiment: detector
• Why the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment is so “difficult”? (from my personal viewpoint)
• BNL-E949 experiment [2001~]
• The future
$K^+ \to \pi^+ \nu \bar{\nu}$ decay

No FCNC at tree level: induced by loop effects as

**top-quark ($170\text{GeV}/c^2$) dominant**

The best place to determine $|V_{td}|$

\[
\begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\cong
\begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

- Long-distance contributions: negligible
- $\langle K|H|\pi \rangle$ from $K^+ \to \pi^0 e^+ \nu$.
- The theoretical uncertainty $\sim 7\%$
  (m_{charm} contribution in the NLO QCD analysis)
  - a small "overlooked" term from the box diagram (1999)
  - effect of the subleading dimension-8 operators (2000)
$\text{B.R.}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

$4.11 \times 10^{-11} \times A^4 \times X(x_t)^2 \times [(\rho_0 - \rho)^2 + \eta^2]$

$K^+ \rightarrow \pi^+ \nu \bar{\nu} \ \& \ \mathcal{V}_{td}$

\[ r_0 \sim B(K^+ \rightarrow \pi^+ \nu \bar{\nu})^{1/2} \]

\[ r_0 \sim \frac{|V_{td}|}{|V_{bd}|} \]

from $|V_{ub}|/|V_{cb}|$

$(\rho, \eta)$ from $\epsilon_K$, $|V_{ub}/V_{cb}|$, $\Delta M_{B_d}$, $\Delta M_{B_s}$

$\downarrow$

a Standard Model prediction: $(0.75 \pm 0.29) \times 10^{-10}$

a recent review by Buras: \textit{hep-ph/0101336}

* $|\Delta M_{B_d}/\Delta M_{B_s}| \Rightarrow < 1.15 \times 10^{-10}$

a measurement at $1.5 \times 10^{-10}$ would be beyond the SN
stopped $K^+$ decay to $\pi^+$ plus "nothing"

the $\pi^+ (< 227 \text{MeV}/c)$ from 3-body decay

Background rejection is essential in this experiment.

- Kinematics: Momentum/Energy/Range
- $\mu^+$ rejection $\iff K^+ \rightarrow \mu^+\nu$
- Extra particles ($\gamma$) Veto $\iff K^+ \rightarrow \pi^+\pi^0$

each weapon should have rejection of $10^5 \sim 10^6$
← reliable estimation using real data
E787

A Search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and Related Decays


Brookhaven National Laboratory


Fukui University


High Energy Accelerator Research Organization (KEK)

T. Fujiwara and T. Nomura

Kyoto University

Y. Kishi, T. Nakano, and T. Sasaki

Osaka University


Princeton University


TRIUMF

P. Kitching and H-S. Ng

University of Alberta
History of E787 @BNL-AGS

- E787 [BNL-Princeton-TRIUMF] proposed in '83
  - LESB1 beamline ($K/\pi \sim 0.5$)
  - '89-'91 [28 weeks]: $\leq 2.4 \times 10^{-9}$ (90% C.L.)

- upgraded-E787
  [BNL-KEK-Osaka-Princeton-TRIUMF-Alberta + Fukui, Kyoto]
  - LESB3 beamline ($K/\pi > 3$, $\times 5$ $K^+/spill$)
  - major upgrade of detector/trigger/DAQ

'95 (first physics run): 18 weeks,

'96 and '97: 13 + 8 weeks and RESULT $1.5 \times 10^{-10}$

'98: 20 weeks $\iff$ analysis ongoing

**E787 data collection was completed.**

expected sensitivity: $\sim 0.7 \times 10^{-10}$

byproduct modes: analysis under way
new result from '95-'97  Phy.Rev.Lett. 84, 3768 (2000)

- branching ratio $(1.5^{+3.4}_{-1.2}) \times 10^{-10}$
- background level $[0.08\pm0.02$ events]: $1.2 \times 10^{-11}$
- $0.002 < |V_{td}| < 0.04$ ,
  $1.07 \times 10^{-4} < |V^*_{ts}V_{td}| < 1.39 \times 10^{-3}$
- consistent with the SM prediction
LESB3: a two-stage separated 800-MeV/c kaon beamline

J. Doornbos et al., NIM A 444 (2000) 546

- $\sim 5 \times 10^5$ K$^+/10^{12}$ protons on target
- K/π ratio > 3
$K^+ \rightarrow \pi^+$ Decay

- 5 mm $\times$ 5 mm scintillating fibers
- 500 MHz GaAs CCD digitizers

vs. pions or kaon decay-in-flight into the detector ($\pi_{\text{scat}}$)
(Target, Beam counters/chambers)

$t_{\pi} - t_k \geq 2^{n \text{sec}}$

[Delayed Coincidence]
stopping counter
vs. muons from $K^+ \rightarrow \mu^+ \nu$, $K^+ \rightarrow \mu^+ \nu \gamma$

- Energy/Range - Momentum relation

- $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ chain (Transient Digitizer)
Typical Event

$K^+ \rightarrow \pi^+ \pi^0 \gamma \gamma$

$\pi^+ (t=10 \text{ ns})$

$K^+ (t=0 \text{ ns})$

Veto $\sim 1 \text{ MeV}$

$\pm$ a few ns
Evidence for the Decay $K^+ \to \pi^+ \nu \bar{\nu}$

S. Adler et al., (E787 collaboration)


'95 data [18 weeks]
Why the $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ experiment is so "difficult"?

(from my personal viewpoint)

or

Things that are NOT secret, but you cannot easily learn by reading the papers
Acceptance $= 0.21^{+0.01}_{-0.01} (\text{stat})^{+0.02}_{-0.02} (\text{sys}) \%$

<table>
<thead>
<tr>
<th>Acceptance factors</th>
<th>method</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ phase space</td>
<td>M.C.</td>
<td>0.155</td>
</tr>
<tr>
<td>Solid angle acceptance</td>
<td>M.C.</td>
<td>0.407</td>
</tr>
<tr>
<td>$\pi^+$ nucl. int., decay-in-flight</td>
<td>M.C.</td>
<td>0.513</td>
</tr>
<tr>
<td>$K^+$ stop efficiency</td>
<td>BR($K_{\mu2}$)</td>
<td>0.704</td>
</tr>
<tr>
<td>$K^+$ decay after 2 ns</td>
<td>$K_{\mu2}$</td>
<td>0.850</td>
</tr>
<tr>
<td>Reconstruction efficiency</td>
<td>$K_{\mu2}$</td>
<td>0.959</td>
</tr>
<tr>
<td>Other kinematic constraints</td>
<td>$\pi_{\text{scat}}, \pi_{\pi2}$</td>
<td>0.665</td>
</tr>
<tr>
<td>$\pi - \mu - e$ decay acceptance</td>
<td>$\pi_{\text{scat}}$</td>
<td>0.306</td>
</tr>
<tr>
<td>Beam and target analysis</td>
<td>$K_{\mu2}$</td>
<td>0.699</td>
</tr>
<tr>
<td>Accidental loss</td>
<td>$K_{\mu2}$</td>
<td>0.785</td>
</tr>
<tr>
<td>Total acceptance</td>
<td></td>
<td>0.21%</td>
</tr>
</tbody>
</table>

**Diagram**

- $\pi^+ \pi^+ \pi^-$
- $\pi^+ \pi^0$ (0.056)
- $\mu^+ \pi^0$ (0.032)
- $e^- \pi^0$ (0.048)
- Momentum (MeV/c) from 0 to 300

**Search Region**

[Graph showing various decay modes and their corresponding momentum distributions]
Figure 4.1: Range in scintillator ($R$) vs. momentum ($P$), and kinematic categorization of events passing the $K_{\pi 2}(1)$ trigger. The $\pi^+\nu\bar{\nu}(1)$ signal region is shown as a box. The $K_{\mu 2}$ peak momentum is reconstructed higher than the accepted value of 236 MeV/c [10] because a “pion hypothesis” has been used to calculate the momentum loss in the target (see section B.1).
$K^+ \rightarrow \mu^+ \nu \ [K\mu2] \ 63$

$\mu^+ \text{ rejection} \ {\text{online}} \ {\text{offline}}$
\[ \mu^+ \text{ Rejection} \]

[500MHz Transient Digitizers for RS]

tag \( \pi^+ \rightarrow \mu^+ \rightarrow e^+ \) decay chain by recording RS pulses

online trigger (tag \( \pi^+ \rightarrow \mu^+ \))
\( \rightarrow \) Level 1.1 [hardware]

Control Board with ASIC's
(Application Specific Integrated Circuits)
\( \Rightarrow \) decision time: \((150 \sim 250 \mu s)_{L1.6} \rightarrow 15-20 \mu s\)
Level 1.1 Trigger Results

Without L1.1 cut  With L1.1 cut

$K_{\pi^2(1)}$ triggers

$p\nu\nu\nu$ triggers

Kinetic energy charged track spectra with and without the l1.1 trigger cut for $K_{\pi^2(1)}$ and $p\nu\nu\nu$ triggers

$\pi^+$ tagging efficiency $\sim 60\%$

$\mu^+$ rejection factor $\sim 15 - 25$

Trigger Decision Time $\sim 10 - 20$ $\mu$s

$S. \ Adler$
\[ K^+ \rightarrow \pi^+ \pi^0 \quad [K\pi\pi] \]

Photon Veto

beam cuts

target cuts
Strategy of stopped $K^+$ experiment

- stopped $K^+$ (slowed by BeO degrader)
  \[ \sim 20\% \, @ \, 790\text{MeV/c} \]

rate $\propto$ incident beam (not 'stopped $K^+$ '):
  
  the beam momentum $\downarrow$ (less degrader)
  $\implies$ $K^+$ stopping fraction $\uparrow$

- duty factor
• \( K^+ \rightarrow \pi^+ \nu \bar{\nu} \)

below the \( K_{\pi2} \) peak
(lower \( \pi^+ \) momentum)

Figure 2: a) A typical \( K_{\pi2} \) event: \( \pi^+ \) enters into the range stack and two photons from \( \pi^0 \) enters the photon detector. b) A \( K_{\pi2} \) background event in the region below \( K_{\pi2} \): that is produced to the beam direction enters the range stack after large angle scatter and the higher energy photon goes to the beam hole.

**target analysis**

**PV systems**
Interaction of $\pi^+$/\(\mu^+$/\(\gamma\) in the Target, Range Stack

In addition to

- Multiple Coulomb scattering (with non-Gaussian tail) of $\pi^+$/\(\mu^+\) and
- Electromagnetic shower of $\gamma$,

- $\pi^+$ hadronic interactions in plastic scintillator:

<table>
<thead>
<tr>
<th>Type</th>
<th>Reaction</th>
<th>$\sigma$(125MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>elastic</td>
<td>$\pi^+^{12}\text{C} \rightarrow \pi^+^{12}\text{C}$</td>
<td>214 mb</td>
</tr>
<tr>
<td>pseudo-elastic</td>
<td>$\pi^+^{12}\text{C} \rightarrow \pi^+^{12}\text{C}^*$</td>
<td>11 mb</td>
</tr>
<tr>
<td>quasi-elastic</td>
<td>$\pi^+^{12}\text{C} \rightarrow \pi^+ p^{11}\text{B}^{(*)}$</td>
<td>52 mb</td>
</tr>
<tr>
<td></td>
<td>$\pi^+^{12}\text{C} \rightarrow \pi^+ n^{11}\text{C}^{(*)}$</td>
<td>31 mb</td>
</tr>
<tr>
<td></td>
<td>$\pi^+^{12}\text{C} \rightarrow \pi^0 N X$</td>
<td>16 mb</td>
</tr>
<tr>
<td>absorption</td>
<td>$\pi^+^{12}\text{C} \rightarrow X$(without$\pi$)</td>
<td>194 mb</td>
</tr>
<tr>
<td>spallation</td>
<td>$\pi^+^{12}\text{C} \rightarrow \pi^+ X$</td>
<td>120 mb</td>
</tr>
</tbody>
</table>

- $\mu^+$ elastic/inelastic scattering:
  - hard scattering
  - $\mu^+^{12}\text{C}$ Giant Dipole Resonance

- Photo-nuclear absorption

Cross section, energy loss, scattering angle, ... are unknown/uncertain to the low-energy particles from stopped-kaon decays.
We cannot rely on Monte Carlo; we need to work on and learn from data.
Figure 4: Schematic cross section through a typical collider detector. Shown, from the beam pipe out, are the locations of vertex detector, tracker, electromagnetic calorimeter, hadronic calorimeter, and muon chambers.
Figure 4: Schematic cross section through a typical collider detector. Shown, from the beam pipe out, are the locations of vertex detector, tracker, electromagnetic calorimeter, hadronic calorimeter, and muon chambers.

1. \( \pi^+ / \mu^+ \) non-destructive measurement in (destructive) TG1, RS

2. three timings (\( t_{\pi} \), \( t_{\mu} \), \( t_e \))
   \(<\text{wait these decays}>\) \( \leftarrow \) accidental loss

3. waveform digitization \( \leftarrow \) huge event size
E949
An experiment to measure the branching ratio
\[ B(K^+ \rightarrow \pi^+ \nu\bar{\nu}) \]

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J. Mikenberger, T. Numao, J.-M. Ponistone and R. Ponistone
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Measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

Alberta/UBC/FNAL/IHEP/INR/Kyoto/UNM/Yeshiva
BNL/Fukui/KEK/Osaka/TRIUMF
Measurement of $B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

Albertya/UBC/FNAL/HEP/INR/Kyoto/UNM/Yeshiva
BNL/Fukui/KEK/Osaka/TRIUMF

**BV Liner**

*RS (Layer T, 2~5)*
*PV*
*RM*
Detector upgrade from **E787**

- **BV** Liner
- **RS**: layer \( T, 2\sim5 \) replaced
- **PV**: new/improved counters
- **BM**: new B4 counter, degrader
- **Trigger**: programable Level0 board, Mean Timers
- **DAQ**
- **RS** Monitor system using LEDs
- **RS** TDC readout: \( e^+ \) identification without TD
- ...

**Schedule:**

- Engineering run from this spring.
- First Physics run in this summer/autumn/winter (with RHIC).
Sensitivity Improvement (compared to the published '95-97 result of E787)

- Running mode:
  - stopping fraction ($\times 1.1$)
  - high duty factor with 65Tp from AGS ($\times 1.4$)
  - beam hours: $\sim 2$ years of running with RHIC ($\times 1.5$)

- Apparatus (trigger, DAQ, software, ...):
  - efficiency improvements ($\times 2.1$)

- reoptimize analysis or increase the phase space ($\times 2$)
- Total gain of $\times 10$

Goals:
- Sensitivity $(8-14) \times 10^{-12}$ in 6000 hr ($\sim 2$ years of running with RHIC).
- Determine $|V_{td}|$ to 20–5%.
The future

targetting

Sensitivity $1.0 \times 10^{-12}$
or $\sim 100$ signal events
or the BR measurement with 10%

around the year 2010

Two options:

1. In-flight Kaon decay
   CKM Experiment at FNAL
   (talk by B. Tschirhart, in Special Session)
   $\Leftarrow$ The technique is not proved yet.

2. Stopped Kaon decay
   Can we further improve the E949-type detector
   in a JHF experiment
   and compete with CKM ??
Key 1: $K^+$ Beam
The JHF-50GeV Slow-Extraction is not optimized to the stopped $K^+ \to \pi^+ \nu \bar{\nu}$ experiment.

<table>
<thead>
<tr>
<th>PS operation</th>
<th>AGS to LESB3 for E949</th>
<th>JHF-mod to K550 (pnnJHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton energy GeV</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td>protons on Tgt $10^{12}$/spill</td>
<td>65</td>
<td>100 $\times$ 1.54</td>
</tr>
<tr>
<td>machine cycle sec</td>
<td>6.4</td>
<td>3.42 $\times$ 1/1.3</td>
</tr>
<tr>
<td>average current $\mu$A</td>
<td>1.63</td>
<td>4.68 $\times$ 2.88</td>
</tr>
<tr>
<td>slow extraction sec</td>
<td>4.1</td>
<td>1.8 $\times$ 1/2.3</td>
</tr>
<tr>
<td>duty factor</td>
<td>0.64</td>
<td>0.53 $\times$ 0.83</td>
</tr>
<tr>
<td>instant. rate $10^{12}$/sec</td>
<td>16</td>
<td>55.6 $\times$ 3.5</td>
</tr>
<tr>
<td>$K^+$ momentum MeV/c</td>
<td>730</td>
<td>550 (no loss)</td>
</tr>
<tr>
<td>stopping fraction</td>
<td>0.26</td>
<td>0.4 $\times$ 1.5</td>
</tr>
</tbody>
</table>

Key 2: Detector
The upgrade of (destructive) Target and Range Stack (better measurement, rate capability)

- RS segmentation (chopping : < 1/4)
- scintillator/SCF readout with more light outputs

start Conceptual Design, based on the E787/E949 experience.
stopped $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ experiment at JHF

Improvement (compared to the BNL-E949 proposal)

- Running mode:
  - stopping fraction ($\times 1.5$ by K550)
  - duty factor ($\times 0.83$)
  - beam hours: $\sim$3 years of running ($\times 1.5$)

- New Detector [segmented, faster, ...]:
  - rate capability for higher intensity ($\times 2.0$)

- re-optimization ($\times 1.5$)
  - $S/N = 5$ $\Rightarrow$ TD electron cut, ... ($\times 1.2$)
  - brighter detector $\Rightarrow$ better E resolution, ... ($\times 1.2$)
  - pipeline trigger, faster DAQ, ... ($\times 1.1$)

- increase the phase space:
  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ below the $K_{\pi^2}$ peak ($\times 2$)
  and measure the $\pi^+$ spectrum to confirm the SM prediction.

Goals:

- Sensitivity $1 \times 10^{-12}$ (Background $2 \times 10^{-11}$)
- $\sim$ 100 SM signals, $S/N = 5$.
- competition with the "in-flight" experiment
Summary

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ in the stopped-kaon experiment

- Not an easy job, but
  the stopped-kaon experiment is currently the best method to observe the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay.

- BNL-E787 in '95-'97: $(1.5^{+3.4}_{-1.2}) \times 10^{-10}$, and
  the expected sensitivity: $\sim 0.7 \times 10^{-10}$,
  still consistent with the SM and with beyond the SM.

- The new BNL-E949 experiment is rising, and
  starts taking data this year, and
  R&D issues for pnnJHF will be intensively studied.