First results from BNL E949 on the rare decay $K^+ \rightarrow \pi^+ \nu \nu$

Tadashi Nomura (Kyoto Univ.)
for BNL E949 collaboration

BNL/FNAL/New Mexico/Stony Brook (USA)
Alberta/British Columbia/TRIUMF (Canada)
IHEP/INR (Russia)
Fukui/KEK/Kyoto/NDA/Osaka/RCNP (Japan)
Outline

- Introduction
- The E949 experiment
- Analysis
- Results
- Conclusions


**Introduction**

- **K^+ \rightarrow \pi^+ \nu\nu** in the Standard Model
  - Z penguin and Box diagram
  - Top in the loop, Sensitive to $|V_{td}|$
    - Charm contrib. well calculated
  - Small theoretical uncertainty \( \sim 7\% \)
  - One of golden modes to explore CKM matrix
  - \( \text{Br (SM)} \approx 0.8 \times 10^{-10} \)

- **Experimental status**
  - 2 events observed by BNL E787 (1995-98)
    - \( \text{BR}=1.57(\pm 1.75/-0.82) \times 10^{-10} \)
  - Now, E949, as the successor of E787, aimed at 5-10 SM events
E949 Experiment

- Event signature = $K^+$ comes in, only $\pi^+$ comes out
- Basic concepts (common to E787)
  - Stopped $K^+$ experiment
  - Measure full kinematics of decay particle ($\pi^+$)
    - Energy (E) / Momentum (P) / Range (R)
  - PID by recording $\pi^-\mu^-e$ decay chain
  - Hermetic veto detectors ($\gamma$)
  - Reduce two major backgrounds
    - $K^+\to\mu^+\nu$ (Br=63%)
      - Kinematics (monochromatic)
      - PID ($\pi/\mu$ separation)
    - $K^+\to\pi^+\pi^0$ (Br=21%)
      - Kinematics (monochromatic)
      - Photon veto
E949 Detector

Side view (cutaway)

- Active target (scintillation fibers) to stop $K^+$
- Drift chamber and the magnetic field to measure $\pi^+$ momentum
- 19 layers of scintillators (“Range Stack”) to measure E and R
- Waveform digitizer to record $\pi$-$\mu$-e decay chain in the $\pi^+$ stopping RS counter
- Photon vetoes surrounding $4\pi$ solid angle (BV / BVL / Endcap /…)

End view (top half)

- New!
- Renew inner 5 layers!
- Equip gain monitor!

August 5 - 11, 2004 5th Recontres du Vietnam - Particle physics and astrophysics - Hanoi, Vietnam
Highlight of Upgrade - from E787 to E949 -

- To having higher sensitivity…
  - 2 times higher beam intensity
  - Better photon vetoes
  - Better kinematics measurement

Kπ2 Rejection
E949 (red) vs. E787 (blue)

2 times better rejection at 80% acceptance

Same or even better resolution in 2x higher rate environment
Physics Run in 2002

• 12 weeks in 2002
  (1/5 of approved 60 weeks)
  – Detector worked well
  – Data taken smoothly
• Accumulated $K^+ = 1.8 \times 10^{12}$

<table>
<thead>
<tr>
<th></th>
<th>E787</th>
<th>E949</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS energy</td>
<td>GeV</td>
<td>24</td>
</tr>
<tr>
<td>Beam intensity</td>
<td>Tp</td>
<td>25 – 40</td>
</tr>
<tr>
<td>Duty factor</td>
<td>%</td>
<td>52</td>
</tr>
<tr>
<td>$K/\pi$ ratio</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>Accumulated $K^+$</td>
<td>$10^{12}$</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Conditions not optimized due to ...
AGS power supply failure (energy, duty factor)
DC separator trouble ($K/\pi$ ratio)

August 5 - 11, 2004  
5th Recontres du Vietnam - Particle physics and astrophysics  
Hanoi, Vietnam
Analysis Overview

- Signal
  - \( P > P(K\pi^2) \) region ("PNN1")
- Background sources
  - \( K^+ \rightarrow \pi^+\pi^0 \)
  - \( K^+ \rightarrow \mu^+\nu, \mu^+\nu\gamma \)
  - Beam backgrounds
- Strategy
  - Blind analysis
  - Evaluate background level with real data
    - characterized by functions
  - Likelihood ratio technique

How do signal/backgrounds look like in the R-P plane?
Evaluation of Backgrounds

- Invert one of the cuts and then measure BG rejection

\[ \chi_{rm} = \frac{R_{\text{meas}} - R_{\text{expect}}}{\sigma_R} \]

\[ K^+ \rightarrow \mu^+ \gamma \rightarrow \mu^+ \nu \gamma, \ldots \]

\[ K^+ \rightarrow \mu^+ \nu, \text{ but short range} \]

\[ P \text{ and NN function} \]

\[ \chi_{rm} \text{ and NN function} \]

\[ \pi^- - \mu^- - e \text{ decay chain in the } \pi \text{ stopping RS} \]

\[ K^+ \rightarrow \pi^+ \pi^0 \]

\[ P(E,R) \text{ and Photon veto} \]

BG level evaluated as functions of cut positions

Neural net function for \( \pi \) and \( \mu \)
Sensitivity and Background

**Sensitivity**

<table>
<thead>
<tr>
<th></th>
<th>E787</th>
<th>E949</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_K (10^{12}) )</td>
<td>5.9</td>
<td>1.8 x 0.305</td>
</tr>
<tr>
<td>Acceptance (%)</td>
<td>0.20 ± 0.02</td>
<td>0.22 ± 0.02 x 1.1</td>
</tr>
<tr>
<td>Sensitivity ((10^{-10}))</td>
<td>0.83</td>
<td>2.6 x 0.336</td>
</tr>
</tbody>
</table>

**Background**

- 10% larger acceptance, by enlarging the signal box to lower edge of E/P/R space, resulting in larger \( K\pi 2 \) backgrounds

**Analysis**

<table>
<thead>
<tr>
<th>Source</th>
<th>E787</th>
<th>E949</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K\pi 2 )</td>
<td>0.032</td>
<td>0.216 ± 0.023</td>
</tr>
<tr>
<td>( K\mu 2 )</td>
<td>0.064</td>
<td>0.044 ± 0.005</td>
</tr>
<tr>
<td>( K\mu\nu\gamma, \ldots )</td>
<td>0.024 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>Beam</td>
<td>0.050</td>
<td>0.014 ± 0.003</td>
</tr>
<tr>
<td>Total</td>
<td><strong>0.14 ± 0.05</strong></td>
<td><strong>0.298 ± 0.026</strong></td>
</tr>
</tbody>
</table>

• All the cuts fixed and BG level estimated.

Now, how to calculate the branching ratio?

August 5 - 11, 2004  5th Rencontres du Vietnam - Particle physics and astrophysics - Hanoi, Vietnam
Likelihood method

- The signal region is divided into cells by binning parameter space (E, P, R, NN func, photon veto…)
  - Once cuts are fixed, calculate BG level in each cell $b_i$
  - Expected signal $S_i$ from $\text{BR}$ and calculated acceptance $A_i$
    \[ S_i = \text{BR} \text{ (as a free parameter)} \times N_k \times A_i \]
- Likelihood technique in small $S_i$, $b_i$ (T. Junk, NIM A434, 435 (99))
  - Ratio of two Poisson probabilities ($S+B$ or $B$ only)
  - Estimator defined as
    \[ X(BR) = \prod_{i=1}^{n} \frac{\exp^{-(S_i+b_i)}(S_i+b_i)^{d_i}}{d_i!} \frac{\exp^{-(b_i)}(b_i)^{d_i}}{d_i!} = \prod_{i=1}^{n} \exp^{-s_i}(1 + \frac{S_i}{b_i})^{d_i} \]
    \[ (d_i = \# \text{ of observed candidate in the cell}) \]

➢ When maximum $X(BR)$, the central value of the $\text{BR}$
Open the Box

- Range vs Energy after all the cuts
- Single candidate in the box !!

<table>
<thead>
<tr>
<th>Details</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum (MeV/c)</td>
<td>227.3</td>
</tr>
<tr>
<td>Range (cm)</td>
<td>39.2</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>128.9</td>
</tr>
<tr>
<td>$K^+ \to \pi^+$ decay time (ns)</td>
<td>4.3</td>
</tr>
<tr>
<td>$\pi^+ \to \mu^+$ decay time (ns)</td>
<td>6.2</td>
</tr>
<tr>
<td>$\mu^+ \to e^+$ decay time (ns)</td>
<td>1370</td>
</tr>
</tbody>
</table>

August 5 - 11, 2004  5th Rencontres du Vietnam - Particle physics and astrophysics - Hanoi, Vietnam
Event Display

$\pi \rightarrow \mu$ decay in the stopping RS (identified as 2 pulses)

Target fibers around $K^+$ stopping
Branching Ratio

- E949 alone

\[ Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 0.96^{+0.49}_{-0.50} \times 10^{-10} \]

- Combine E949 & E787

\[ Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10} \]

» errors for 68% C.L.

<table>
<thead>
<tr>
<th></th>
<th>E787</th>
<th>E949</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_K (10^{12}))</td>
<td>5.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Candidate</td>
<td>E787A</td>
<td>E787C</td>
</tr>
<tr>
<td>(S_i / b_i)</td>
<td>50</td>
<td>7</td>
</tr>
<tr>
<td>(W_i = S_i / (S_i + b_i))</td>
<td>0.98</td>
<td>0.88</td>
</tr>
<tr>
<td>BG Prob.</td>
<td>0.006</td>
<td>0.02</td>
</tr>
</tbody>
</table>

\(E949(02) = \text{combined E787&E949}\)
E949 projection with 60 weeks run
(assuming current BR value)
Impact on Unitary Triangle

- Contour in $\rho - \eta$ plane

Green arcs indicate this $K^+ \rightarrow \pi^+ \nu \nu$ result (including theoretical uncertainties)

Central value
- 68% interval
- 90% interval

by the courtesy of G. Ishidori

Central value
off the “SM”

$\Rightarrow$ **Need more data!!**
Conclusions

• E949 successfully ran as a first step
  – Upgrade to E787 successfully
  – 12 weeks, \( N_K = 1.8 \times 10^{12} \)
• Likelihood applied to evaluate branching ratio
• E949 (02) has observed an additional candidate
• Combining the E787 and E949 results,
  \[
  Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \ (68\% \ C.L.)
  \]
• Prospects
  – E949 PNN2 analysis (\( P_{\pi^+} < 195 \) MeV/c region) in progress
  – Further E949 run?
    • We are ready to complete the experiment and waiting for funding!!
Extras
Verify background prediction

- Loosen cuts and look in M x N times larger box
  - Two independent cuts for one background
- For ex., Photon Veto, TD(NN function), and KINematics
- Compare prediction and observed # of events

<table>
<thead>
<tr>
<th></th>
<th>PV x KIN</th>
<th>10 x 10</th>
<th>20 x 20</th>
<th>20 x 50</th>
<th>50 x 50</th>
<th>50 x 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kπ2</td>
<td>Observed</td>
<td>3</td>
<td>4</td>
<td>9</td>
<td>22</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>1.1 ± 0.18</td>
<td>4.9 ± 0.6</td>
<td>12.4 ± 1.3</td>
<td>31.1 ± 3.1</td>
<td>62.4 ± 5.6</td>
</tr>
<tr>
<td>Kμ2</td>
<td>Observed</td>
<td>0</td>
<td>1</td>
<td>12</td>
<td>16</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>0.35 ± 0.03</td>
<td>1.4 ± 0.1</td>
<td>9.1 ± 0.6</td>
<td>14.5 ± 1.0</td>
<td>21.8 ± 1.5</td>
</tr>
<tr>
<td>Kμνγ</td>
<td>Observed</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Predicted</td>
<td>0.31 ± 0.09</td>
<td>1.3 ± 0.4</td>
<td>3.2 ± 1.0</td>
<td>5.2 ± 2.2</td>
<td>10.4 ± 2.8</td>
</tr>
</tbody>
</table>
Second pulse time for $\pi$ and $\mu$

- Case $\pi^+ : \mu^+$ from $\pi \rightarrow \mu\nu$ decay
- Case $\mu^+ :$ accidental or pulse fluctuation
Pulse fitting in the $\pi^+$ stopping counter

Introduction

Experiment

Analysis

Results

Conclusions

---

August 5 - 11, 2004  5th Rencontres du Vietnam - Particle physics and astrophysics -  Hanoi, Vietnam

---
TD properties of the candidate

- Plots with $\pi^+$ and $\mu^+$ samples

  Arrows show the candidate event

Blue: $\pi^+$ (fitted $\pi \rightarrow \mu$ time$<10$ns)
Red: $\mu^+$
$S_i$ and $b_i$ for the candidate cell

- Signal $S_i = 5.3 \times 10^{-5}$, with $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu) = 1.47 \times 10^{-10}$
- Background $b_i = 5.7 \times 10^{-5}$

$W_i = S_i / b_i = 0.9$