Measurement of $K^+ \to \pi^+ \nu\bar{\nu}$
Final Results from E949

Steve Kettell, BNL
September 18th, 2009
22\textsuperscript{nd} International Workshop on Weak Interactions and Neutrinos
K$^+ \rightarrow \pi^+ \nu\nu$ Motivation

One of the Golden Modes for study of the CKM matrix and CP violation. The rate can be calculated precisely from fundamental parameters and any deviation in the measured rate will be a clear signal for new physics.

1. FCNC, hard GIM suppression
2. No long distance contribution
3. Hadronic Matrix element from Ke3 & isospin
4. NNLO QCD calculation of c-quark contribution
**K^+ → π^+νν Motivation**

**Standard Model** *(Buras et al., Mescia and Smith, Brod and Gorbahn):*

\[ B(K^0_L → π^0ν\bar{ν}) = 1.8 \times 10^{-10} \left( \frac{\text{Im} \lambda_t}{λ^5} X(x_t) \right)^2 = 2.76 ± 0.40 \times 10^{-11} \]

\[ B(K^+ → π^+ν\bar{ν}) = 1.0 \times 10^{-10} A^4 \left[ \eta^2 + (ρ_0 - ρ)^2 \right] = 8.5 ± 0.7 \times 10^{-11} \]

\[ \text{Im} \lambda_t = \text{Im} V_{ub}^* V_{ub} = η A^2 λ^5 \]

Golden Relation: \[ \sin (2β)_{πK_S} = \sin (2β)_{K → πν\bar{ν}} \]
K$^+ \to \pi^+ \nu\bar{\nu}$ Motivation

**SUSY: Rare meson decays into light neutralinos**

\[ K^+ \to \pi^+ \nu\bar{\nu} \to N \times SM \]

Minimal Flavor Violation e.g. Littlest Higgs Model with T-parity

\[ B(K^0_L \to \pi^0 \nu\bar{\nu}) \text{ vs. } B(K^+ \to \pi^+ \nu\bar{\nu}) \]

H. K. Dreiner *et al.* Bonn-TH-2009-04

Outline of \( K^{+} \rightarrow \pi^{+}\nu\nu \) Experimental Method

- **Problem:** 3-body decay (2 missing \( \nu \)'s); \( \text{BR}<10^{-10} \)
- **Event signature** = single \( K^+ \) in, single \( \pi^+ \) out
- **Basic concepts**
  - Precise and redundant measurement of kinematics
    - e.g. Energy (E) / Momentum (P) / Range (R)
    - or Velocity (V) / Momentum (P) / Range (R)
  - PID: \( \pi^-\mu^-e \) decay chain and/or P/R, P/V, dE/dx…
  - Hermetic veto detectors (\( \gamma \))
- **Major backgrounds**
  - \( K^+ \rightarrow \mu^+\nu \) (Br=63%)
    - Kinematics (monochromatic)
    - PID: \( \pi^+/\mu^+ \)
  - \( K^+ \rightarrow \pi^+\pi^0 \) (Br=21%)
    - Kinematics (monochromatic)
    - Photon veto
  - Scattered beam particles
    - Timing
    - PID: \( K^+ / \pi^+ \)

Exploit with E949 upgrades
Outline of $K^+ \rightarrow \pi^+ \nu\nu$ Experimental Method

- **Measure background from data**
  - A priori identification of background sources.
  - Suppress each background with at least two independent cuts.
  - Measure background with data, if possible, by inverting cuts and measuring rejection taking any correlation into account.
  - Automatically accounts for electronics glitches and variations in veto performance

- **Blind Analysis**
  - Don’t examine signal region until all backgrounds verified.
  - To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
  - Verify background estimates by loosening cuts and comparing observed and predicted rates.
Measurement of backgrounds with data

Illustration of Bifurcation Method

- **looser**
  - `B` 
  - `D` 
  - `A` 
  - `C`

Signal region:
- `B` 
- `D` 
- `A` 
- `C`

- **cut1**
  - `B` 
  - `D` 
  - `if cut1, cut2 uncorrelated,`
  - `A/B = C/D`
  - `A = BC/D`

- **cut2**

- **Photon veto**

- **invert cut1**
  - `B` 
  - `D` 
- `A` 
- `C`

- **apply cut2**
  - `B` 
  - `D` 
- `A` 
- `C`

- **Tag kinematics outside πνν box – in K_{π2} peak**

- **online PV**

- **bg = B/(R-1)**
  - `B` 
  - `D` 
- `A` 
- `C`

- **apply cut1**
  - `B` 
  - `D` 
- `A` 
- `C`

- **Ranges (cm)**
  - `20` 
  - `30` 
  - `40`
  - `0` 
  - `20` 
  - `40` 
  - `60`
  - `80` 
  - `100` 
  - `120` 
  - `140` 

- **Energy (MeV)**
  - `0` 
  - `20` 
  - `40` 
  - `60` 
  - `80` 
  - `100` 
  - `120` 
  - `140` 

- **In online PV**

WIN09  September 18, 2009
E787

BROOKHAVEN NATIONAL LABORATORY
MEMORANDUM

DATE: October 17, 1983
TO: T. Kycia, S. Smith
FROM: R.B. Palmer
SUBJECT: E787

I have good news. Proposal 787, "Study of the Decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$", has been approved for the full requested time of 2500 hours. The High Energy Advisory Committee strongly endorsed this proposal, characterizing it as dealing with one of the two most important areas in particle physics today:

E787 was initiated by Ted Kycia and Stew Smith and was led by Laurie Littenberg, Stew Smith and Doug Bryman:
- Engineering run in 1988
- Data runs in 1989–1991
- Upgrade 1991–1994
- Data runs in 1994–1999 ← Discovery of $K^+ \rightarrow \pi^+\nu\bar{\nu}$
Below $K_{\pi 2}$ (pnn2) limit:

$140 < p_\pi < 195$ MeV/c
1 candidate event with an expected background of 1.22 +/- 0.24 events.

Background limited, with S/N<0.2
Set an upper limit of $B(K^+ \rightarrow \pi^+ \nu \nu) < 22 \times 10^{-10}$
E949 was proposed in 1998 and approved in 1999 (D. Bryman, S, Kettell, S. Sugimoto):
- Use entire AGS flux (65 Tp)
  - high duty factor
  - low K momentum
- various detector improvements
- Photon Veto (esp. for pnn2)
- Ran for 12 weeks in 2002
E949 Overview (1)

- ~700 MeV/c $K^+$ beam (75%)
- Active target (scintillation fibers) to stop $K^+$
- Wait at least 2ns for $K^+$ decay (delayed coincidence)
- Drift chamber to measure $\pi^+$ momentum
- 19 layers of scintillator, Range Stack (RS) to measure E and R
- Stop $\pi^+$ in RS, waveform digitizer to record $\pi^+ - \mu^+ - e^+$ decay chain
- Veto photons, charged tracks over $4\pi$ (BV/BVL/Endcap/…)

Steve Kettell, BNL
E949 Overview (2): Data Taking Conditions

- E787 collected $N_K = 5.9 \times 10^{12}$ in 81 weeks over 5 years.
- E949 proposed $N_K = 18 \times 10^{12}$ in 60 weeks over 3 years.
- E949 collected $N_K = 1.7 \times 10^{12}$ in 12 weeks in 2002.
- Beam conditions were less than optimal
  - broken separator: more $\pi^+$ less $K^+$
  - spare M.G.: lower $p^+$ mom., poor duty factor
- Detector worked very well
- Smooth data taking

<table>
<thead>
<tr>
<th></th>
<th>E787</th>
<th>E949 Prop.</th>
<th>E949</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS mom. GeV/c</td>
<td>25.5</td>
<td>25.5</td>
<td>21.9</td>
</tr>
<tr>
<td>Beam intensity Tp</td>
<td>15-35</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Duty factor %</td>
<td>41-55</td>
<td>63</td>
<td>41</td>
</tr>
<tr>
<td>$K^+/p^+$</td>
<td>3.7-4.2</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>$N_K$</td>
<td>$10^{12}$</td>
<td>5.9</td>
<td>18</td>
</tr>
</tbody>
</table>

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E949 Overview (3): Performance

• **Goal:** double sensitivity while increasing $s/b = 1^2$ 
  
  2 $\times$ acceptance and 5 $\times$ rejection

• Improved PV: new detectors at small angles

• Improved algorithms to identify $\pi^+$ scatters in target

Improved PV key to pnn2 exploitation

**Photon Veto**

**Kinematics**

$K\pi_2$ momentum, energy and range

E949 (yellow histogram) vs. E787 (circle)

- Same or even better resolution
- in 2 $\times$ higher rate environment
E949 pnn1 analysis

E949 observed one new event in the primary pnn1 region

PRL 93, 031801 (2004)

\[ Br(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10} \]
### Advantages
- More phase space than pnn1
- Fewer $\pi^+N$ interactions
- Probe $K^+\rightarrow\pi^+\nu\nu$ spectrum

### Disadvantages
- Need photon detection near beam
- Must identify $\pi^+$ target scattering
  - kink in the pattern of target fibers
  - $\pi^+$ track that does not point back to the $K^+$ decay point
  - energy deposits inconsistent with an outgoing $\pi^+$
  - unexpected energy deposit in the fibers traversed by the $K^+$
\[ K^+ \rightarrow \pi^+ \pi^0 \] target scattering background

Typical target pattern:

Target kink: transverse scatter
Longitudinal scattering
CCD pulse cut

Run 48133  Event 1001  eh 28.783  tr 0.234  tpi 8.924

<table>
<thead>
<tr>
<th>Single</th>
<th>Kaon</th>
<th>Pion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob</td>
<td>0</td>
<td>0.98</td>
</tr>
<tr>
<td>Time</td>
<td>-0.216</td>
<td>-0.855</td>
</tr>
<tr>
<td>Energy</td>
<td>25.812</td>
<td>22.295</td>
</tr>
<tr>
<td>Amplt</td>
<td>1825.45</td>
<td>1384.74</td>
</tr>
<tr>
<td>Cut</td>
<td>Failed</td>
<td>Passed</td>
</tr>
</tbody>
</table>

Decay Vertex 420 Raw High

Decay Vertex 420 Raw Low
$K^+ \rightarrow \pi^+ \pi^0$ background

Photon tagged

Target cut

CCD pulse

$\pi_{\text{scat}}$ tagged

C+D

Photon cut

Photon Cuts

B

D

bg

C

TG-scat Cuts
Beam background

- **Single beam:** particle ID, timing

  ![Graph showing particle ID and timing](image)

- **Double beam:** redundant particle ID along beam line

  ![Diagram showing redundant particle ID](image)

  - Cerenkov
  - Wire chamber
  - Target
  - B4
  - AD
Muon background

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

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

- Range momentum
- dE/dx range stack
- \( \pi \rightarrow \mu \rightarrow e \) chain

\[ KK^+ \rightarrow \mu\mu^+ \nu \gamma \]

\[ KK^+ \rightarrow \mu\mu^+ \nu \pi \]

![Diagram showing range momentum and dE/dx range stack with specific events marked.](image-url)
Ke4 ($K^+ \rightarrow \pi^+ \pi^- e^+ \nu$) background

$\pi^- e^+$ energy can be very low

Ke4 MC event

$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$ can be a background if the $\pi^-$ and $e^+$ have very little kinetic energy and evade detection.

A Ke4 candidate from data

$T2 = T_{\pi^-} + T_{e^+}$ (MeV)

Signal region
Ke4 \((K^+ \rightarrow \pi^+\pi^-e^+\nu)\) background

- A Ke4-rich sample is tagged in data by selecting events with extra target energy.
- Use MC to evaluate the rejection of cuts.
- The \(\pi^-\) annihilation energy spectrum is from our experimental measurement.
Charge exchange \((K^+n \rightarrow K^0p)\) background

\[ K^+ n \rightarrow K^0 p, \quad K^0_L \rightarrow \pi^+ l^- \nu \]

**Characteristics:**

- a gap between \(K^+\) and \(\pi^+\)
- z info of \(\pi^+\) is not consistent with \(K^+\) track

- A CEX rich data sample is tagged by a gap between \(K^+\) and \(\pi^+\)
- Model \(K_L\) momentum from \(K_S\) monitors
- Use MC to evaluate the rejection
# Total background and sensitivity

<table>
<thead>
<tr>
<th>Process</th>
<th>Bkgd events (E949)</th>
<th>Bkgd events (E787)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\pi 2}$-scatter</td>
<td>$0.649 \pm 0.150^{+0.067}_{-0.100}$</td>
<td>$1.030 \pm 0.230$</td>
</tr>
<tr>
<td>$K_{\pi 2\gamma}$</td>
<td>$0.076 \pm 0.007 \pm 0.006$</td>
<td>$0.033 \pm 0.004$</td>
</tr>
<tr>
<td>$Ke4$</td>
<td>$0.176 \pm 0.072^{+0.233}_{-0.124}$</td>
<td>$0.052 \pm 0.041$</td>
</tr>
<tr>
<td>CEX</td>
<td>$0.013 \pm 0.013^{+0.010}_{-0.003}$</td>
<td>$0.024 \pm 0.017$</td>
</tr>
<tr>
<td>Muon</td>
<td>$0.011 \pm 0.011$</td>
<td>$0.016 \pm 0.011$</td>
</tr>
<tr>
<td>Beam</td>
<td>$0.001 \pm 0.001$</td>
<td>$0.066 \pm 0.045$</td>
</tr>
<tr>
<td>Total bkgd</td>
<td>$0.93 \pm 0.17^{+0.32}_{-0.24}$</td>
<td>$1.22 \pm 0.24$</td>
</tr>
<tr>
<td>E949 pnn2</td>
<td></td>
<td>E787 pnn2</td>
</tr>
<tr>
<td>Total Kaons</td>
<td>$1.70 \times 10^{12}$</td>
<td>$1.73 \times 10^{12}$</td>
</tr>
<tr>
<td>Total Acceptance</td>
<td>$1.37 \times 10^{-3}$</td>
<td>$0.84 \times 10^{-3}$</td>
</tr>
<tr>
<td>SES</td>
<td>$4.3 \times 10^{-10}$</td>
<td>$6.9 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

For E787+E949 pnn1 SES=$0.63 \times 10^{-10}$

SES is the branching ratio for a single event observed w/o background
Outside box study (verify bkg. est.)

- Keep signal region hidden
- Relax photon veto or CCD pulse cut
- Check the predicted events and observed events in the extended region $A'$

<table>
<thead>
<tr>
<th>Region</th>
<th>$N_{\text{exp}}$</th>
<th>$N_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CCD_L$</td>
<td>$0.79^{+0.46}_{-0.51}$</td>
<td>0</td>
</tr>
<tr>
<td>$PV_L$</td>
<td>$9.09^{+1.53}_{-1.32}$</td>
<td>3</td>
</tr>
<tr>
<td>$PV_{\text{looser}}$</td>
<td>$32.4^{+12.3}_{-8.1}$</td>
<td>34</td>
</tr>
</tbody>
</table>

The probability to observe $\leq 3$ events when $9.09^{+1.53}_{-1.32}$ are expected is 2%.
The probability of the observation in regions $CCD_1$ and $PV_1$ given the expectation is 5%; the expectation is $[2\%, 14\%]$ when the uncertainty in $N_{\text{exp}}$ is taken into account.
Inside-the-box study

- The background is not uniformly distributed in the signal region.
- Use the remaining rejection power of the photon veto, delayed coincidence, $\pi \rightarrow \mu \rightarrow e$ and kinematic cuts to divide the signal region into 9 cells with differing levels of signal acceptance ($S_i$) and background ($B_i$).
- Calculate $B(K^+ \rightarrow \pi^+ \nu \nu)$ using $S_i/B_i$ of any cells containing events using the likelihood ratio method.

**Momentum (MeV/c) of:**

**Signal**

$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$

- **p box:** $p > 140$
- **Tight p box:** $p > 165$
Measured $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ BR of this analysis

- $BR = (7.89\pm9.26) \times 10^{-10}$

- The probability of all 3 events to be due to background alone is 0.037

- ...due SM signal + background is 0.056

- SM prediction:
  $BR = (0.85\pm0.07) \times 10^{-10}$
Combined with all E787/E949 result

- BR = (1.73 ± 0.15) × 10^{-10}

- The probability of all 7 events to be due to background alone is 0.001

- ...due to SM signal + background is 0.06

- SM prediction:
  BR = (0.85 ± 0.07) × 10^{-10}
Implications for $K_L \to \pi^0 \nu \nu$

Grossman and Nir (PLB 398 (1997) 163):

$$r_{IS} \frac{\Gamma(K_L \to \pi^0 \nu \bar{\nu})}{\Gamma(K^+ \to \pi^+ \nu \bar{\nu})} = \sin^2 \theta$$

where

$r_{IS} = 0.954$, isospin breaking factor

$\theta$ = relative phase between $K - \bar{K}$ mixing amplitude and $s \to d \nu \bar{\nu}$ decay amplitude

$$B(K_L \to \pi^0 \nu \bar{\nu}) < \frac{\tau(K_L)}{\tau(K^+)} B(K^+ \to \pi^+ \nu \bar{\nu}) / r_{IS}$$

$$< 14.6 \times 10^{-10} \ (90\% \text{CL})$$

Current experimental limit: $B(K_L \to \pi^0 \nu \bar{\nu}) < 670 \times 10^{-10}$ (E391a, PRL 100, 201802 (2008)).
BR of **Scalar** and **Tensor** form factors

<table>
<thead>
<tr>
<th></th>
<th>Scalar</th>
<th>Tensor</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR ($\times 10^{-10}$):</td>
<td>$9.94^{+8.48}_{-4.20}$</td>
<td>$4.87^{+3.91}_{-2.43}$</td>
<td>$1.73^{+1.15}_{-1.05}$</td>
</tr>
</tbody>
</table>

**Trigger simulation**

- **Probability (2.5 MeV/c)**
- **Pion momentum (MeV/c)**

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The mass of $X$ is unknown.

$X$ might have limited lifetime

We assume the detection efficiency of decay products of $X$ is 100% if the decay occurs within the detector.
Based on seven E787/E949 $K^+ \to \pi^+ \nu \bar{\nu}$ events the BR is consistent with the SM, but remains higher than expected...more data is needed!

E949 is finished, but NA62 at CERN is moving forward and experiments at J-PARC and FNAL are under consideration.

Plans are underway to move the E949 detector to Japan.

$K \to \pi \nu \nu$ remains an incisive test of the flavor structure of our physical world, whether described by the SM or new physics and some combination of experiments should go forward!

Together $K^+ \to \pi^+ \nu \nu$ and $K_L \to \pi^0 \nu \nu$ provide a unique opportunity for discovery of new physics.