E787/E949: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

(“golden needle in micro-cosmic haystack” – BNL press release)

G. Redlinger, BNL

KAON 2005 Northwestern University 13–17 June, 2005
Outline

- Experimental overview
  - Stopped K technique
  - E787 → E949
- Background analysis
- Result from 2002 data
- Current efforts
  - “Region 2” (p < 195 MeV/c)
E949 Collaboration

UNIVERSITY OF ALBERTA

INR, RAS

National Defense Academy, Japan

UBC

BROOKHAVEN NATIONAL LABORATORY

KEK

Osaka University

Fermilab

Fukui University

Kyoto University

IHEP, Protvino

STONY BROOK

State University of New York

TRIUMF

The University of New Mexico
E787 Collaboration
Introduction

- Highly suppressed in the SM. Sensitive to new physics in the loops.
- Very clean theoretically
  - BR calculable in SM with precision of ~7%. Could be brought down to ~2% with NNLO QCD calculation (Buras et al, hep-ph/0405132)
- SM expectation: \( \text{BR} = (0.78 \pm 0.12) \times 10^{-10} \)
- If there is new physics in quark mixing, the effects could be different in the \( s \to d \) sector compared to \( b \to d \)
**K^+ \rightarrow \pi^+\nu\bar{\nu} measurement**

- Experimentally challenging, but do-able as shown by BNL E787.
- E787 (1995–98) observed two K^+ \rightarrow \pi^+\nu\bar{\nu} candidates with a background of 0.15 ± 0.05 events
- Likelihood analysis based on additional signal/bkg discrimination yielded
  - Probability of bkg alone giving rise to these 2 (or “cleaner”) events = 0.0013
  - BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 1.57 (+ 1.75, -0.82) \times 10^{-10} from E787
- E787 was primarily limited by proton flux from AGS on K production target
- E949 is based on “modest” upgrades to the E787 program
  - Use “entire” proton flux. 15 \times 10^{12} protons/spill \rightarrow 65 \times 10^{12}
  - Longer AGS running during RHIC operation (≥ 25 weeks/yr)
  - Detector upgrades: photon veto, π^+ tracking and kinematic resolution, trigger/DAQ, K^+ tracking system
- Aimed at SES ≤ 10^{-11} or 5–10 SM events
Tools

Grant Wood
American Gothic, 1930
Art Institute of Chicago
AGS in the RHIC era

RHIC

12:00 o'clock

PHOBOS
10:00 o'clock

BRAHMS & PP2PP (\(\bar{p}\))
2:00 o'clock

PHENIX (\(\bar{p}\))
8:00 o'clock

STAR (\(\bar{p}\))
6:00 o'clock

4:00 o'clock

AGS:
- Intensity: \(7 \times 10^{13}\) protons/pulse
- Injector to RHIC: < 1 hour about every 4 hours

Fast extraction

Slow extraction

High Intensity Source
Linac
NSRL (NASA)
Mu g-2
RSVP (NSF)
Tandems

G. Redlinger
G. Redlinger
**E949 detector**

- Incoming beam (~700 MeV/c) tagged by Cerenkov, dE/dx counters
- **Stopped** kaon beam. Wait ~2ns for K decay (reject beam π). High geometrical acceptance.
- **Stopped** decay pion. Redundant measurements of kinematics (R,E,P). Observation of $\pi \to \mu \to e$ decay sequence for μ rejection.
- Photon veto counters surround everything (E949 PV upgrades shown in blue).
- Minimize inactive material.
E949: Beam

E949 (2002) protons on target (typical day)

Proton intensity:
- $76 \times 10^{12}$/spill (peak)
- $65 \times 10^{12}$/spill (typical)

Kaons:
- Incoming: 6–7 MHz
- “Stopping”: ~2 MHz

Not optimal in 2002:
- Short run
- AGS main power supply problem. 20% worse duty factor cf. E787. Lower proton momentum $\Rightarrow$ ~10% in K flux.
- K/π separator problems
**E949: Detector upgrades**

Kinematic resolution (dots: E787, solid: E949)

- Comparable kinematic resolution at x2 instantaneous rate.
  - $\sigma(P) \sim 2.3$ MeV/c
  - $\sigma(R) \sim 0.9$ cm
  - $\sigma(E) \sim 3.0$ MeV

Photon Veto: x2 more rejection at nominal acceptance
Offline analysis

Jackson Pollock, Greyed Rainbow, 1953. Art Institute of Chicago
Backgrounds to $K^+ \rightarrow \pi^+\nu\bar{\nu}$

- $K^+ \rightarrow \mu^+\nu(\gamma), (\mu^+\pi^0\nu)$
  - Wrong kinematics
  - Mis-ID of $\mu$ as $\pi$
  - (Photon(s) undetected)

- $K^+ \rightarrow \pi^+\pi^0$
  - Wrong kinematics
  - $\pi^0$ undetected

**Scattered beam $\pi$**

- Incoming $\pi$ mis-id as $K$
- $\pi$ fakes $K$–decay at rest (timing)
- $K$ decay-in-flight mismeasured (timing)
- Two beam particles (segmentation)

- $K^+n \rightarrow K^0p$, $KL \rightarrow \pi^+l^-\nu$
  - $KL$ decays in $K$–stopping target
  - Lepton missed
  - No gap between $K^+$ and $KL$

**Key:** Reliable estimate of backgrounds suppressed to the 0.1 evt level
Background estimation: $K\pi\pi$2

Full data set

Remove non-$K\pi\pi$2 backgrounds

Photon tag

Kinematic tag (R,P,E)

Signal region blinded

All other cuts (except PV!)

All other cuts except PV and R,P,E

Photon veto cuts

\[ N(K\pi\pi2) = \frac{N_0}{R-1} \]

\[ R(PV) = \frac{N_1}{N_2} \]

Cuts tuned on $1/3$ of the data.

Cut performance measured (unbiased) on $2/3$ of data. Cut positions are not changed.
**Kμ2 background**

Waveform digitizer analysis (π → μ → e) in pion stopping counter:

**Neural net function**

**Kinematics**

- PMT output
- Time (ns)
- Layer 12
- Upstream
- Output of Neural Net Function
- π⁺
- μ⁺
- Momentum (MeV/c)
- Range (cm)
- Range deviation $\chi_{np}$
- $K^+ → π^+ ν ν$
**Background summary & verification**

<table>
<thead>
<tr>
<th>Background</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K\pi2$</td>
<td>$0.216 \pm 0.023$</td>
</tr>
<tr>
<td>$K\mu2$</td>
<td>$0.044 \pm 0.005$</td>
</tr>
<tr>
<td>$K\mu2\gamma, K\mu3$</td>
<td>$0.024 \pm 0.010$</td>
</tr>
<tr>
<td>1-Beam</td>
<td>$0.0060 \pm 0.0022$</td>
</tr>
<tr>
<td>2-Beam</td>
<td>$0.0028 \pm 0.0021$</td>
</tr>
<tr>
<td>Chg. Exch</td>
<td>$0.0045 \pm 0.0005$</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$0.30 \pm 0.03$</strong></td>
</tr>
</tbody>
</table>

- Signal region expanded to let in more background cf. E787
- Rely on likelihood analysis for further discrimination inside the signal region
- 30% gain in acceptance

Serves as ultimate check of lack of correlations between dual cuts.
Also checks for unknown backgrounds near signal region.
Likelihood functions

The same dual cut technique is used. Background level and signal acceptance are measured for an ensemble of cut positions.

Quantities used for discrimination:
- Muon background
- Momentum ($K_\mu^2$)
- Range vs momentum correlation ($K_\mu^2\gamma + K_\mu^3$)
- Neural net for $\pi \to \mu \to e$
- $K\pi^2$ background
  - Range, Energy, Momentum
  - Photon veto
- Beam background
  - $t(\pi) - t(K)$ for 1–beam bkg and chg exch
  - Veto extra tracks in beamline for 2–beam bkg
**Likelihood functions (2)**

- **Kπ2 kinematics**
- **Kπ2 photon veto**
- **Kμ2γ, Kμ3 kinematics**
- **Kμ2 kinematics**

- **1-beam**
- **2-beam**

**π → μ → e**
Result

Pierre-Auguste Renoir
Young Woman Sewing, 1879
Art Institute of Chicago
**K^+ \rightarrow \pi^+\nu\bar{\nu}. First result from E949**

Single event seen. Not as clean as the previous two events from E787. Effectively contributes half an event to the total sample.

<table>
<thead>
<tr>
<th></th>
<th>E787</th>
<th>E949</th>
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<tbody>
<tr>
<td>No. kaons</td>
<td>$5.9 \times 10^{12}$</td>
<td>$1.8 \times 10^{12}$</td>
</tr>
<tr>
<td>Total Acceptance</td>
<td>$0.0020 \pm 0.0002$</td>
<td>$0.0022 \pm 0.0002$</td>
</tr>
<tr>
<td>Total Background</td>
<td>$0.14 \pm 0.05$</td>
<td>$0.30 \pm 0.03$</td>
</tr>
<tr>
<td>S/B</td>
<td>50, 7</td>
<td>0.9</td>
</tr>
<tr>
<td>Weight</td>
<td>0.98, 0.88</td>
<td>0.48</td>
</tr>
<tr>
<td>Background prob.</td>
<td>0.006, 0.02</td>
<td>0.07</td>
</tr>
</tbody>
</table>

$$\text{BR}(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 1.47 (+1.30, -0.89) \times 10^{-10}$$

combined E787,E949

PRL 93 (2004) 031801
Impact on unitarity triangle

CKM fitter: hep-ph/0406184

Still room for new physics to appear in $\Delta F=1$ kaon decays.

Needs more data.
“Region 2” $p(\pi) < 195\text{ MeV}/c$
“Region 2” \( p(\pi) < 195 \text{ MeV/c} \)

Potentially big gains to be had:
- x2 phase space
- x1.5 fewer pions disappearing (via interactions) before stopping
  Gives access to \( \pi \) spectrum shape.

However, very severe background from \( K\pi2 \): pion scattering in target (downshift in R,E,P) correlated with \( \pi^0 \) directed towards area of weak photon coverage.
“Region 2” $p(\pi) < 195$ MeV/c

Region 2 analysis of E787 1997 data
(PRD 70 (2004) 037102)

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<tr>
<td>N(K)</td>
<td>$1.12 \times 10^{-12}$</td>
<td>$0.61 \times 10^{-12}$</td>
</tr>
<tr>
<td>Total acceptance</td>
<td>$7.65 \times 10^{-4}$</td>
<td>$9.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>Total background</td>
<td>$0.73 \pm 0.18$</td>
<td>$0.49 \pm 0.16$</td>
</tr>
<tr>
<td># events seen</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

$\text{BR}(K^+ \to \pi^+ \nu\bar{\nu}) < 2.2 \times 10^{-9}$ @ 90%CL
E787 1996+1997 combined

Need x2 in acceptance and x5 in bkg rejection in E949 to reach S/N=1 with comparable sensitivity to region 1.

Analysis in progress. Focused on photon veto and target scattering.
Future and conclusion

Georgia O'Keefe
Black Cross, New Mexico, 1929
Art Institute of Chicago
Conclusion

- E949 upgrade successful. Detector performed well at higher rates.
- Backgrounds well understood. Likelihood analysis extended to regions of higher background than E787, giving more signal acceptance.
- All E787 and E949 data in region 1 (p(\(\pi\)) > 211 MeV/c) have been analyzed. 
  \[ BR(K^+ \rightarrow \pi^+\nu\bar{\nu}) = 1.47 \times 10^{-12} \]
  based on 3 candidates. There is a tension with the CKM fits from B decays, but more data is needed.
- Highly likely that E949 would have reached its goal if run to completion. But alas, E949 only ran for 20% of the approved running time.
- Analysis of region 2 (p(\(\pi\)) < 195 MeV/c) is in progress. Hoping to achieve S/N ~ 1 in this region.
- More running of E949? NSF proposal...
Conclusion

- E949 upgrade successful. Detector performed well at higher rates.
- Backgrounds well understood. Likelihood analysis extended to regions of higher background than E787, giving more signal acceptance.
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  \[ \text{BR}(K^+ \to \pi^+\nu\bar{\nu}) = 1.47 (+1.30, -0.89) \times 10^{-12} \] 
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- Analysis of region 2 ($p(\pi)<195$ MeV/c) is in progress. Hoping to achieve S/N \(\sim 1\) in this region.
- More running of E949? NSF proposal...

Q: “Are you an optimist?”
A: “I remain a willing prisoner of hope.” – Bishop Desmond Tutu