Final results on $K^+ \to \pi^+ \nu \bar{\nu}$ from BNL E949

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Sensitivity to New Physics

The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio can be precisely predicted in the SM (and most models) owing to knowledge of the transition matrix element from similar processes and minimal long-distance effects.

In the SM, $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.85 \pm 0.07) \times 10^{-10}$ (arXiv:0805.4119).

Ref: G.Isidori, arXiv:0801.3039, attributed to Frederico Mescia
**Experimental method**

### Previous $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ results

<table>
<thead>
<tr>
<th>Region</th>
<th>“PNN2”</th>
<th>“PNN1”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P(\pi^+)$ MeV/c</td>
<td>[140,195]</td>
<td>[211,229]</td>
</tr>
<tr>
<td>Stopped $K^+$</td>
<td>$1.7 \times 10^{12}$</td>
<td>$7.7 \times 10^{12}$</td>
</tr>
<tr>
<td>Background events</td>
<td>$1.22 \pm 0.24$</td>
<td>$0.45 \pm 0.06$</td>
</tr>
<tr>
<td>Candidate events</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>$B(K^+ \rightarrow \pi^+ \nu \bar{\nu})$</td>
<td>$&lt; 22 \times 10^{-10}$ (90% CL)</td>
<td>$(1.47^{+1.30}_{-0.89}) \times 10^{-10}$</td>
</tr>
</tbody>
</table>

**Rate vs.**

$\pi^+$ momentum in $K^+$ rest frame

![Graph showing rate vs. momentum](image)
**E949 experimental method**

- **Measure everything possible**
- \( \sim 700 \text{ MeV}/c \) \( K^+ \) beam
- Stop \( K^+ \) in scint. fiber target
- Wait at least 2 ns for \( K^+ \) decay (delayed coincidence)
- Measure \( \pi^+ \) momentum \( P \) in drift chamber
- Measure \( \pi^+ \) range \( R \) and energy \( E \) in target and range stack (RS)
- Stop \( \pi^+ \) in range stack
- Observe \( \pi^+ \rightarrow \mu^+ \rightarrow e^+ \) in RS
- Veto photons, charged tracks
- **New/upgraded detector elements compared to E787**
A BEAUTIFUL LIKENESS OF PETER.
HOW DO YOU DO IT?

SIMPLE! YOU TAKE A BIG ROCK,
THEN YOU CHIP AWAY EVERYTHING
THAT DOESN'T LOOK LIKE PETER,
E787 and E949 analysis strategy

- 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.
- 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.
- “Blind analysis”. Don’t examine signal region until all backgrounds verified.
Backgrounds in the pnn2 region

**Process** | **Rate**
---|---
\( K^+ \to \pi^+ \nu \bar{\nu} \) | \( 0.8 \times 10^{-10} \)
\( K^+ \to \pi^+ \pi^0 \) | \( 2092000000.0 \times 10^{-10} \)
\( K^+ \to \pi^+ \pi^0 \gamma \) | \( 2750000.0 \times 10^{-10} \)
\( K^+ \to \pi^+ \pi^- e^+ \nu \) | \( 409000.0 \times 10^{-10} \)
\( K^+ \to \mu^+ \nu \) | \( 6344000000.0 \times 10^{-10} \)
\( K^+ \to \mu^+ \nu \gamma \) | \( 62000000.0 \times 10^{-10} \)
\( K^+ \to \mu^+ \pi^0 \nu \) | \( 332000000.0 \times 10^{-10} \)
CEX | \( \sim 46000.0 \times 10^{-10} \)
Scattered \( \pi^+ \) beam | \( \sim 250000000.0 \times 10^{-10} \)

CEX \( \equiv (K^+ n \to K^0 X) \times (K^0 \to K_L^0) \times (K_L^0 \to \pi^+ \mu^- \nu) \)

\( K^+ n \to K^0 X \) rate is empirically determined.
Main pnn2 background: $K^+ \rightarrow \pi^+\pi^0$ -scatters

The main background below the $K^+ \rightarrow \pi^+\pi^0$ peak is due to $K\pi_2$ decays where the $\pi^+$ scatters in the target losing energy simultaneously obscuring the correlation with the $\pi^0$ direction.
Suppression of $K\pi_2$-scatter background

- Photon veto of $\pi^0 \rightarrow \gamma\gamma$
  Photon detection in beam region is important
- Identification of $\pi^+$ scattering in the target
  - 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 $K^+$
E949 scintillating fiber target

‘Typical’ pattern in target fibers for $K^+ \to \pi^+\pi^0$ decay.
Identification of $\pi^+$ scattering

Kink in pattern of target fibers

Excess energy in kaon fibers ("CCDPUL")

David E. Jaffe (BNL)
Suppression of $K_{\pi^2}$ scatter background

Black: Photon-tagged sample
Blue: After target cuts (except CCDPUL)
Red: After all target cuts

Black: $\pi^+$-scatter-tagged sample
Red: After photon veto cuts
Experimental method

Estimation of $K_{\pi^2}$ scattering background

- $K_{\pi^2}$ scattering background is suppressed by PV and target cuts.
- To estimate PV rejection, multiple $\pi^+$-scattering samples are prepared by inverting different combinations of target cuts.
- The “normalization” sample is estimated by inverting the PV cut, but the sample is contaminated with $K_{\pi^2}$ scatters in the range stack (RS) and by $K^+ \rightarrow \pi^+\pi^0\gamma$.

After disentangling the processes:

<table>
<thead>
<tr>
<th>Process</th>
<th>Background events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\pi^2}$ TG-scatter</td>
<td>$0.619 \pm 0.150^{+0.067}_{-0.100}$</td>
</tr>
<tr>
<td>$K_{\pi^2}$ RS-scatter</td>
<td>$0.030 \pm 0.005 \pm 0.004$</td>
</tr>
<tr>
<td>$K_{\pi^2\gamma}$</td>
<td>$0.076 \pm 0.007 \pm 0.006$</td>
</tr>
</tbody>
</table>
**Experimental method**

\[ K^+ \rightarrow \pi^+\pi^-e^+\nu \ (K_{e4}) \] background

\[ \begin{align*}
&K^+ \rightarrow \pi^+\pi^-e^+\nu \text{ can be a background if the } \pi^- \text{ and } e^+ \\
&\text{have very little kinetic energy and evade detection.}
\end{align*} \]

Figure: \( \pi^+ \) momentum \( (P_\pi) \) vs. total kinetic energy of \( \pi^- \) and \( e^+ \) from simulated \( K^+ \rightarrow \pi^+\pi^-e^+\nu \) decays.

Signal region is

\[ 140 < P_\pi < 199 \text{ MeV}/c \]

Cannot make a purely data-based background estimate due to inability to isolate \( K_{e4} \) from the larger \( K_{\pi2} \)-scatter background.
**Experimental method**

\[ K^+ \rightarrow \pi^+\pi^- e^+\nu \] background

Isolate \( K_{e4} \) sample using target pattern recognition, similar to \( K_{\pi2} \) scatter.

Estimate rejection power of target pattern recognition with simulated data supplemented by measured \( \pi^- \) energy deposition spectrum in scintillator.

![Graph showing energy deposition spectrum and pattern recognition](image)

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David E. Jaffe (BNL)  
Final E949 results  
Sept 9-13, 2008
The branching ratio that corresponds to one event in the absence of background is the Single-Event Sensitivity (SES).

For the E787+E949 pnn1 analysis, SES = 0.63 × 10^{-10}.
Verification of background estimates

Relax PV and CCDPUL cuts to define 2 distinct regions $PV_1$ and $CCD_1$ immediately adjacent to the signal region. Define a third region $PV_2$ by further loosening of the PV cut. Compare the observed ($N_{obs}$) with the expected number ($N_{exp}$) of events in each region.

<table>
<thead>
<tr>
<th>Region</th>
<th>$N_{exp}$</th>
<th>$N_{obs}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CCD_1$</td>
<td>0.79$^{+0.46}_{-0.51}$</td>
<td>0</td>
</tr>
<tr>
<td>$PV_1$</td>
<td>9.09$^{+1.53}_{-1.32}$</td>
<td>3</td>
</tr>
<tr>
<td>$PV_2$</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 $N_{exp}$ is taken into account.
Division of the signal region

- 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 $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ using $S_i/B_i$ of any cells containing events using the likelihood ratio method.
Examining the signal region

The nine cells

<table>
<thead>
<tr>
<th>Bkgd</th>
<th>Events</th>
<th>S/B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.152</td>
<td>0</td>
<td>0.84</td>
</tr>
<tr>
<td>0.038</td>
<td>0</td>
<td>0.78</td>
</tr>
<tr>
<td>0.019</td>
<td>0</td>
<td>0.66</td>
</tr>
<tr>
<td>0.005</td>
<td>0</td>
<td>0.57</td>
</tr>
<tr>
<td>0.243</td>
<td>1</td>
<td>0.47</td>
</tr>
<tr>
<td>0.059</td>
<td>0</td>
<td>0.45</td>
</tr>
<tr>
<td>0.027</td>
<td>1</td>
<td>0.42</td>
</tr>
<tr>
<td>0.007</td>
<td>0</td>
<td>0.35</td>
</tr>
<tr>
<td>0.379</td>
<td>1</td>
<td>0.20</td>
</tr>
</tbody>
</table>

The probability of all 3 events to be due to background only is 0.037.

No momentum cut applied. Solid line represents signal region, dashed line shows tightened kinematic cuts. Gray points are simulated $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.
Measured $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ for E949 & E787

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$

- The probability of all 7 events to be due to background only is 0.001.
- SM expectation: $\mathcal{B} = (0.85 \pm 0.07) \times 10^{-10}$
- The pnn1 analyses are 4.2 times more sensitive than the pnn2 analyses due to a combination of acceptance and kaon exposure.

E787(dashed) and E949(solid) signal regions shown. All cuts applied.
The future

What happens next?

- In an ill-considered decision of the Executive Branch of the US Government, E949 was cancelled in 2002 after receiving only 20% of the approved beam time.

- Experiment NA62 (formerly NA48/3) at CERN was approved in 2007 and is in preparation.

- NA62 proposes to observe $\approx 65 \ K^+ \rightarrow \pi^+ \nu \bar{\nu}$ per year with a background of $\approx 10$ events using a 75 GeV/c beam. The use of kaon decay-in-flight to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ has not been attempted before.

- There is a letter of intent for a stopped kaon decay experiment in Japan.

- “A few % measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ appears feasible at Fermilab Project X or J-PARC.” - D. Bryman & L. Littenberg
In 25 years of research with BNL E787 and E949, the search for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decays went from a limit on the branching ratio of $< 1.4 \times 10^{-7}$ (90%CL) to a measurement of $(1.73^{+1.15}_{-1.05}) \times 10^{-10}$ (arXiv:0808.2459) that is twice as large as, but still consistent with, the Standard Model expectation of $(0.85 \pm 0.07) \times 10^{-10}$.

The techniques, philosophy and results of E949 and E787 have shown the way for experimental searches of rare decays.
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Backgrounds in high momentum (pnn1) region

Mechanisms for the main backgrounds in the high momentum region

1. Mismeasurement of $\pi^+$ kinematics
2. Undetected photons from $\pi^0 \rightarrow \gamma \gamma$

3. $K^+ \rightarrow \mu^+\nu$ ($K_{\mu2}$)
   1. Mismeasurement of $\mu^+$ kinematics
   2. Misidentification of $\mu^+$ as $\pi^+$
Estimation of background rates with data

- **Apply cut2 & invert cut1**: Select B events
- **Invert cut2**: Select C+D events
  - & apply cut1: Select C events
- **Rejection of cut1** is $R = (C+D)/C$
- **Background estimate** = $B/(R-1)$
Example: Estimating $K^+ \rightarrow \pi^+\pi^0$ pnn1 background with data

**Left:** Kinematically selected $K^+ \rightarrow \pi^+\pi^0$ with photon veto applied. Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

**Right:** Select photons. Phase space cuts in P, R, E.
Photon veto in the beam region

Active Degrader (AD)
14cm diameter, 17cm long,
12 azimuthal segments
6.1 radiation lengths
$K^+ \rightarrow \pi^+\gamma\gamma$ is not a background

- Partial branching fraction for $140 < P_{\pi} < 200$ MeV/$c$ is $\approx 1.1 \times 10^{-7}$.
- Photon veto rejection of $\pi^0 \rightarrow \gamma\gamma$ is $> 10^6$.
- Rate of $K^+ \rightarrow \pi^+\gamma\gamma$ background is $< 1.1 \times 10^{-13}$ without considerations of $\pi^+$ acceptance.