Results and Prospects for $K \rightarrow \pi \nu \bar{\nu}$

David E. Jaffe, BNL

- Introduction
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$: E949 experimental method and results
- $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$: KOPIO experimental method and prospects
- Summary and outlook
$K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model and beyond

\[
\begin{array}{lcc}
\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) & \mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) \\
\text{top dep.} & |V_{ts}^* V_{td}| & Im(V_{ts}^* V_{td}) \\
\text{Msmt}^{a,b,c} & (1.57^{+1.75}_{-0.82}) \times 10^{-10} & < 5.9 \times 10^{-7} \\
& & < 4.4 \times \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) \\
\text{SM}^d & (0.77 \pm 0.11) \times 10^{-10} & (0.26 \pm 0.05) \times 10^{-10} \\
\text{SM Uncert.}^f & 7\% & 2\% \\
\text{MFV}^g & 1.91 \times 10^{-10} & 0.99 \times 10^{-10} \\
\text{EZP}^h & (0.75 \pm 0.21) \times 10^{-10} & (3.1 \pm 1.0) \times 10^{-10} \\
\end{array}
\]

Limits are at 90\% CL.

References
(a) PRL 88 (2002) 041803  (b) PR D61 (2000) 072006
(c) PL B398 (1997) 163   (d) hep-ph/0307014
(e) hep-ph/0212321       (f) hep-ph/0101336
(g) Minimal Flavor Violation, Buras, hep-ph/0310208
(h) Enhanced $Z^0$ Penquins, Buras et al., hep-ph/040211
“Golden” modes and the CKM unitarity triangle

\[ \left( \rho, \eta \right) \]

Process | Expts
--- | ---
\[ \mathcal{B}(K^0_L \to \pi^0 \nu \bar{\nu}) \] | KOPIO, E391a
\[ \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \] | E787/E949
\[ \mathcal{A}(B \to J/\psi K^0_S; t) \] | BaBar, Belle
\[ \Delta m_s / \Delta m_d \] | CDF, D0

Comparison of \( |V_{td}| \) from \( \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \) and \( \Delta m_s / \Delta m_d \) is an important test of the SM.

Comparison of \( \sin 2\beta \) from \( \mathcal{B}(K^0_L \to \pi^0 \nu \bar{\nu}) / \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \) and \( \mathcal{A}(B \to J/\psi K^0_S; t) \) is perhaps the definitive test CP violation in the SM.
<table>
<thead>
<tr>
<th>Name</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>Years</td>
<td>1996-97</td>
<td>1995-98</td>
</tr>
<tr>
<td>Stopped $K^+$</td>
<td>$1.7 \times 10^{12}$</td>
<td>$5.9 \times 10^{12}$</td>
</tr>
<tr>
<td>Candidates</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Background</td>
<td>$1.22 \pm 0.24$</td>
<td>$0.15 \pm 0.05$</td>
</tr>
<tr>
<td>$\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$</td>
<td>$&lt; 22 \times 10^{-10}$</td>
<td>$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$</td>
</tr>
</tbody>
</table>

**PNN1**: PRL 88, 041803 (2002).

**PNN2**: Limit at 90%CL is combined result from 1996 (PL B537, 211 (2002)) and 1997 (hep-ex/0403034) data.

![Graph showing K+ → π+ν̅ results](image-url)
$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \text{ and background rates}$$

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ \rightarrow \pi^+ \nu \bar{\nu}$</td>
<td>$0.77 \times 10^{-10}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+ \pi^0$</td>
<td>$2113000000.00 \times 10^{-10}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu$</td>
<td>$6343000000.00 \times 10^{-10}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+ \nu \gamma$</td>
<td>$55000000.00 \times 10^{-10}$</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^0 \mu^+ \nu$</td>
<td>$327000000.00 \times 10^{-10}$</td>
</tr>
<tr>
<td>CEX</td>
<td>$\sim 46000.00 \times 10^{-10}$</td>
</tr>
<tr>
<td>Scattered $\pi^+$ beam</td>
<td>$\sim 25000000.00 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

$$\text{CEX} \equiv (K^+ n \rightarrow K^0 X) \times (K^0 \rightarrow K_L^0) \times (K_L^0 \rightarrow \pi^+ \ell^- \nu)$$

$\ell^-$ is $\mu^-$ or $e^-$

$K^+ n \rightarrow K^0 X$ rate is empirically determined.
Measure everything possible.

- Independent measurements of range(R), energy(E) and momentum(P) of π⁺
- Positive identification of incoming K⁺ and outgoing π⁺
- Veto extra photons and charged particles

Background must be suppressed by $10^{11}$: Bkgd/S(SM) < 0.1
Measure background with data — set cuts based on 1/3 of data and evaluate bkgd with remaining 2/3.
E949 experimental method

- \( \sim 700 \) MeV/c \( K^+ \) beam
- Stop \( K^+ \) in scint. fiber target
- Wait at least 2 ns for \( K^+ \) decay
- Measure \( P \) in drift chamber
- Measure range \( R \) and energy \( E \) in target and range stack (RS)
- Stop \( \pi^+ \) in range stack
- Observe \( \pi^+ \to \mu^+ \to e^+ \) in RS
- Veto photons, charged tracks
- New/upgraded detector elements
E949 status for 2002 data taking

Upgrades to E787:
• More protons/sec from AGS
• Improved photon veto hermeticity
• Improved tracking and energy resolution
• Higher rate capability due to DAQ and trigger improvements

Not optimal in 2002:
1. Spill duty factor.
2. Proton beam momentum.
Improved photon veto hermeticity.

Figure: background **Rejection** as a function of $K^+ \rightarrow \pi^+\nu\bar{\nu}$ signal **Acceptance** for the photon veto cut for E787 and E949.

$\sim 2 \times$ better rejection at nominal **PNN1** acceptance of 80% or $\sim 5\%$ more acceptance in E949 with same rejection as E787.
E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations 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.
- Use MC to measure geometrical acceptance for \(K^+ \rightarrow \pi^+ \nu \bar{\nu}\). Verify by measuring \(\mathcal{B}(K^+ \rightarrow \pi^+ \pi^0)\).
- “Blind” analysis. Don’t examine signal region until all backgrounds verified.
### Background suppression

<table>
<thead>
<tr>
<th>Source</th>
<th>Suppression method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kinematics</td>
</tr>
<tr>
<td>$K^+ \rightarrow \mu^+\nu(\gamma)$</td>
<td>√</td>
</tr>
<tr>
<td>$K^+ \rightarrow \pi^+\pi^0$</td>
<td>√</td>
</tr>
<tr>
<td>Scattered beam</td>
<td>√</td>
</tr>
<tr>
<td>CEX</td>
<td></td>
</tr>
</tbody>
</table>

$CEX \equiv K^+n \rightarrow K^0p, K_L^0 \rightarrow \pi^+\ell^-\nu$

Particle ID includes beam Cherenkov, $dE/dx$ and $\pi \rightarrow \mu \rightarrow e$ detection

Veto includes both photon and charged particle vetoing
E787 and E949 analysis strategy

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- Use MC to measure geometrical acceptance for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \rightarrow \pi^+ \pi^0)$.
- “Blind” analysis. Don’t examine signal region until all backgrounds verified.
**Example:** $K^+ \rightarrow \pi^+\pi^0$ background rejection

**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.
**E787 and E949 analysis strategy**

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- 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.
- Use MC to measure geometrical acceptance for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \rightarrow \pi^+ \pi^0)$.
- “Blind” analysis. Don’t examine signal region until all backgrounds verified.
Verify background by loosening cuts

Define rejection power $\equiv 1$ when cuts are set to produce pre-determined signal region ("signal box")

Relax cut to reduce rejection by $\times 10$. New, larger region should have $10\times$ background of signal box.

Example: For $K^+ \rightarrow \pi^+\pi^0$ background, simultaneously loosen photon veto (PV) and kinematic (KIN) cuts each by $\times 10$. Expect $10 \times 10 = 100$ times more background than that of the signal box.
**Compare background prediction with observation near signal region**

<table>
<thead>
<tr>
<th></th>
<th>PV×KIN</th>
<th>10 × 10</th>
<th>20 × 20</th>
<th>20 × 50</th>
<th>50 × 50</th>
<th>50 × 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K_{\pi 2} )</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</td>
<td>4.9</td>
<td>12.4</td>
<td>31.1</td>
<td>62.4</td>
</tr>
<tr>
<td>( K_{\mu 2} )</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</td>
<td>1.4</td>
<td>9.1</td>
<td>14.5</td>
<td>21.8</td>
</tr>
<tr>
<td>( K_{\mu m} )</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</td>
<td>1.3</td>
<td>3.2</td>
<td>5.2</td>
<td>10.4</td>
</tr>
</tbody>
</table>

\[ K_{\pi 2} \equiv K^+ \rightarrow \pi^+\pi^0; \quad K_{\mu 2} \equiv K^+ \rightarrow \mu^+\nu; \]

\[ K_{\mu m} \equiv K^+ \rightarrow \mu^+\nu\gamma, \quad K^+ \rightarrow \pi^0\mu^+\nu \quad \text{and} \quad K^+ \rightarrow \pi^+\pi^0 \quad \text{with} \quad \pi^+ \rightarrow \mu^+\nu \quad \text{decay in flight} \]

TD\(\equiv\pi \rightarrow \mu \rightarrow e\) identification, PV\(\equiv\)Photon Veto rej., KIN\(\equiv\)kinematic rej.

\(M \times N \equiv\) reduction in rejection with respect to signal region
Compare background prediction with observation near signal region

Quantify consistency: Fit $N_{\text{obs}} = cN_{\text{pred}}$ and expect $c = 1$. 

<table>
<thead>
<tr>
<th>Background</th>
<th>$c$</th>
<th>$\chi^2$ Probability</th>
<th>Total background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{\pi 2}$</td>
<td>$0.85^{+0.12}_{-0.11}$</td>
<td>0.17</td>
<td>$0.216 \pm 0.023$</td>
</tr>
<tr>
<td>$K_{\mu 2}$</td>
<td>$1.15^{+0.25}_{-0.21}$</td>
<td>0.67</td>
<td>$0.044 \pm 0.005$</td>
</tr>
<tr>
<td>$K_{\mu m}$</td>
<td>$1.06^{+0.35}_{-0.29}$</td>
<td>0.40</td>
<td>$0.024 \pm 0.010$</td>
</tr>
</tbody>
</table>

Deviation of $c$ from unity is taken into account in evaluation of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$.

Beam and CEX background is $0.014 \pm 0.003$.

The calculated number of background events in the signal region is $0.30 \pm 0.03$ from all background sources.
E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations 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.
- Use MC to measure geometrical acceptance for $K^+ \rightarrow \pi^+\nu\bar{\nu}$. Verify by measuring $\mathcal{B}(K^+ \rightarrow \pi^+\pi^0) = 0.215 \pm 0.005$. World average value is $0.2113 \pm 0.0014$.
- “Blind” analysis. Don’t examine signal region until all backgrounds verified.
E949 improved analysis strategy†

1. E787 background estimation methods are reliable

2. Divide signal region into cells and calculate background ($b_i$) and signal acceptance ($s_i$) for each cell. Example: Tighten PV cut to select subregion with 1/10 of the total predicted $K^+ \rightarrow \pi^+\pi^0$ background within “signal box”

3. Can calculate $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$ using $s_i/b_i$ of any cells containing candidates using likelihood ratio method.

4. Increase total size of signal region to increase acceptance at cost of more total background

† With age comes wisdom.
Opening the box

Range (cm) vs Energy (MeV) for E949 data after all other cuts applied.

Solid line shows signal region.

Single candidate found.

Cluster near 110 MeV is unvetoed $K^+ \rightarrow \pi^+\pi^0$. 
How likely is it that the candidate is due to known background?

Question: Suppose we do 100 experiments, how many will have a candidate from a known background source that is as signal-like or more signal-like than the observed candidate?

Answer: $\sim 7$

The sum of background in all cells with $s_i/b_i$ greater or equal to the cell containing the observed candidate is 0.077. The probability that 0.077 could produce one or more events is 0.074 ($\sim 7/100$).

The E949 candidate is more likely to be due to background than the two E787 candidates.

<table>
<thead>
<tr>
<th>Candidate</th>
<th>E787A</th>
<th>E787C</th>
<th>E949A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>0.006</td>
<td>0.02</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>E787</td>
<td>E949</td>
<td></td>
</tr>
<tr>
<td>-------------------------------</td>
<td>-------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>Stopped $K^+ ,(N_K)$</td>
<td>$5.9 \times 10^{12}$</td>
<td>$1.8 \times 10^{12}$</td>
<td></td>
</tr>
<tr>
<td>Total Acceptance</td>
<td>$0.0020 \pm 0.0002$</td>
<td>$0.0022 \pm 0.0002$</td>
<td></td>
</tr>
<tr>
<td>Total Background</td>
<td>$0.14 \pm 0.05$</td>
<td>$0.30 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>Candidate</td>
<td>E787A</td>
<td>E787C</td>
<td>E949A</td>
</tr>
<tr>
<td>$S_i/b_i$</td>
<td>50</td>
<td>7</td>
<td>0.9</td>
</tr>
<tr>
<td>$W_i$</td>
<td>0.98</td>
<td>0.88</td>
<td>0.48</td>
</tr>
</tbody>
</table>

$b_i = \text{background of cell containing candidate}$

$S_i \equiv \mathcal{B}A_i N_K = \text{signal for cell containing candidate}$

$A_i \equiv \text{acceptance}$

$\mathcal{B} = \text{measured central value of } K^+ \to \pi^+ \nu \bar{\nu} \text{ branching fraction}$

$W_i \equiv S_i/(S_i + b_i) = \text{event weight}$

Event weight $W_i$ and $S_i/b_i$ assumes SM signal hypothesis as well as calculated background.
Range (cm) vs Energy (MeV) for combined E787 and E949 data after all other cuts applied.
Dashed line is E787 signal region.
Solid line is E949 signal region.
Combined E787 and E949 results for \( \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) \)

\[
\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \quad (68\% \text{CL interval})
\]

\[
\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) > 0.42 \times 10^{-10} \text{ at } 90\% \text{CL}.
\]

SM prediction\(^\dagger\): \( \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10} \)

The probability that background alone gave rise to the three observed events or to any more signal-like configuration is 0.001.

E787 result: \( \mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10} \)

Impact of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ on Unitarity Triangle

Green lines show $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ impact on Unitarity Triangle: central value (dashed), 68\% interval (dot-dash), 90\% interval (solid). Theoretical uncertainty is included.

Red ovals show 68\%, 90\% and 95\% areas from other measurements ($|V_{ub}|$, $\epsilon_K$, $\sin 2\beta$, $\Delta m_d$, $\Delta m_s/\Delta m_d$)

Provided by Gino Isidori.
Progress in $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

E949(02) = combined E787 & E949.
E949 projection with full running period.

Narrowing of “SM prediction” assumes measurement of $B_s$ mixing consistent with prediction.
CP-violating decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

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(Received 6 January 1989)

The process $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ offers perhaps the clearest window yet proposed into the origin of CP violation. The largest expected contribution to this decay is a direct CP-violating term at $\approx$few $\times 10^{-12}$. The indirect CP-violating contribution is some 3 orders of magnitude smaller, and CP-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of $\approx 1\%$ can be extracted from previous data on $K_L^0 \rightarrow 2\pi^0$. This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product $\sin \theta_2 \sin \theta_3 \sin \delta$ can be made.

“Experimentally, the problems are perhaps best represented by the statement that nobody has yet shown that a measurement of this decay is absolutely impossible.” F.J. Gilman, “CP Violation in Rare K Decays”, Blois CP Violations 1989:481-496
\[ K_{L}^{0} \rightarrow \pi^{0} \nu \bar{\nu} \text{ Progress} \]

KTeV result with “pencil” \( K_{L}^{0} \) beam (PLB447 (1999) 240). E391a, JHF expts use a similar technique.
The KOPIO Technique: Work in $K_L^0$ CMS

Measure everything possible.

- Microbunched $K_L^0$ beam
- Measure $\gamma$ directions in PR
- Measure $\gamma$ energy in CAL
- Reconstruct $\pi^0$ from $\gamma\gamma$
- Measure $K_L^0$ velocity from TOF
- Photon veto
- Charged track veto
- Kinematic veto
### Some KOPIO performance requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimal Requirement</th>
<th>Expected Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_\gamma) resolution</td>
<td>(3.5% / \sqrt{E})</td>
<td>(2.7% / \sqrt{E})</td>
</tr>
<tr>
<td>(\theta_\gamma) resolution (250 MeV)</td>
<td>25 to 30 mrad</td>
<td>23 mrad</td>
</tr>
<tr>
<td>(t_\gamma) resolution</td>
<td>100 ps / \sqrt{E}</td>
<td>50 ps / \sqrt{E}</td>
</tr>
<tr>
<td>(x_\gamma, y_\gamma) resolution (250 MeV)</td>
<td>10 mm</td>
<td>&lt; 1 mm</td>
</tr>
<tr>
<td>microbunch width</td>
<td>300 ps</td>
<td>200 ps</td>
</tr>
<tr>
<td>microbunch extinction</td>
<td>(10^{-3})</td>
<td>(&lt; 10^{-3})</td>
</tr>
<tr>
<td>photon veto inefficiency</td>
<td>(\bar{E}_{787})</td>
<td>(0.3\bar{E}_{787})</td>
</tr>
<tr>
<td>charged veto inefficiency</td>
<td>(10^{-5}(\pi^+), 10^{-4}(\pi^-))</td>
<td>(&lt; 10^{-5}(\pi^+), &lt; 10^{-4}(\pi^-))</td>
</tr>
</tbody>
</table>
Micro-bunched slow extraction

Empty buckets generate energy modulation of debunched beam.
Higher cavity voltage and/or smaller $\Delta P/P \rightarrow$ shorter bunches.
Need ~200 ps bunches every 40 ns with ~95% extraction efficiency.
Microbunch width $\sigma$ and interbunch extinction $E$.

93 MHz RF

measured $\sigma = 240$ ps

predicted $\sigma = 215$ ps

Predicted $E \sim 0.0003$

measured $E \sim 0.015$

25/100 MHz RF

Predicted $\sigma = 185$ ps

Predicted $E \sim 0.002$
The central production angle of the KOPIO neutral beam is 42.5°. The aspect ratio is 100 × 5 mrad² (horiz × vert) after passing thru 5 cm of Pb, sweeping magnets and a collimation system. Expect ∼ 3.5 K_L and ∼ 600(300) n with E(n) > 10(262) MeV per microbunch. Figure shows the calculated normalized neutron profiles for 2 aspect ratios at the front of the pre-radiator (1400 cm from target) Aspect ratio # 1 is 100 × 5 mrad².
Preradiator

- Measures the direction of rays with 25mr by tracking an e⁻-e⁺ pair in the early shower.
- Total radiation length 2 (70% of converts).
- Consists of 4 2.5x2.5m² (2x2m² active region) quadrants.
- Each quadrant has 8 modules (construction unit).
- A module has 8 alternating X, Y readout chambers, 9 scintillator, and thin radiator (Cu and Al) planes.
- Each combination (scintillator+chamber+radiator) is 0.03 r.l. thick.
- A photon veto system that is mounted in the same support structure surrounds the active region of the preradiator.
- Chamber electronics will be mounted outside the photon veto system.
- All photo-tubes can easily be accessed for maintenance.
**Preradiator**

Preradiator angular resolution: 25 mrad at 250 MeV
Scintillator production

- Six hole scintillator has been produced successfully.
- Surface quality and dimension stability will be improved in the near future tests.
- Attenuation length is still shorter than expected, but for the application of fast timing measurement the impact is small.
- No hole diameter dependence.
Shashlyk calorimeter energy resolution *(physics/0310047)*

- BNL E865
- BNL E923 prototype
- KOPIO prototype
- another KOPIO prototype
Charged Particle Vetoing

Example Background: $K_L^0 \rightarrow \pi^- e^+ \nu \gamma$

Plastic Scintillator

KEK: 1 GeV/c

\[ \bar{\varepsilon} \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\bar{\varepsilon}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+$</td>
<td>$(3.2 \pm 0.9) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\pi^+$</td>
<td>$&lt;1.6 \times 10^{-5}$</td>
</tr>
<tr>
<td>$e^-$</td>
<td>$&lt;1.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>$(6.0 \pm 0.6) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

NIM A359, 478 (1995)
Fig. 1: Base design of catcher

- 5 inch PMT
- Winston cone funnel
- Lead plate (2 mm)
- Aerogel (50 mm)
- Flat mirror

One module distribution

20 x 20 cm modules

30 x 30 cm modules
Expected performance with current design

**Photon efficiency / Neutron sensitivity**

» Average over +/- 10cm(y), normal incident to Catcher

**Photon efficiency**

>99% @ 300MeV

**Neutron sensitivity**

0.3% @ 0.8GeV
### Background suppression tools

<table>
<thead>
<tr>
<th>(K_L^0) Decay</th>
<th>(B/3 \times 10^{-11})</th>
<th>Kinematic</th>
<th>Photon veto</th>
<th>Charged veto</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^0\pi^0) even</td>
<td>3.1 (\times 10^7)</td>
<td>(E^*)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
</tr>
<tr>
<td>(\pi^0\pi^0) odd</td>
<td>3.1 (\times 10^7)</td>
<td></td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
</tr>
<tr>
<td>(\pi^\pm e^\mp\nu\gamma)</td>
<td>1.2 (\times 10^8)</td>
<td>(M_{\gamma\gamma}, \chi^2)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
</tr>
<tr>
<td>(\pi^+\pi^-\pi^0)</td>
<td>4.2 (\times 10^9)</td>
<td>(E^*<em>\pi, E</em>{\text{MISS}})</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
</tr>
<tr>
<td>(\pi^0\pi^\pm e^\mp\nu)</td>
<td>1.7 (\times 10^6)</td>
<td>(E^*_\pi)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
</tr>
<tr>
<td>(\pi^0\pi^0\pi^0)</td>
<td>7.0 (\times 10^9)</td>
<td>(E^*_\pi)</td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
</tr>
<tr>
<td>(\pi^0\gamma\gamma)</td>
<td>5.6 (\times 10^4)</td>
<td></td>
<td>(\checkmark)</td>
<td>(\checkmark)</td>
</tr>
<tr>
<td>(\gamma\gamma)</td>
<td>2.7 (\times 10^7)</td>
<td>(M_{\gamma\gamma}, E^*_\pi)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- even \(\equiv\) both \(\gamma\) from same \(\pi^0\)
- odd \(\equiv\) \(\gamma\) from different \(\pi^0\)
- \(\chi^2\) \(\equiv\) \(\chi^2\) of fit of \(\gamma\) 3-momenta to a common vertex
- \(M_{\gamma\gamma}\) \(\equiv\) 2 photon invariant mass
- \(E^*_i\) \(\equiv\) energy in \(K_L^0\) rest frame, \(i = \pi^0, \gamma_1, \gamma_2\)
- \(E_{\text{MISS}}\) \(\equiv\) \(E(K_L^0) - E(\gamma_1) - E(\gamma_2)\)
Kinematic rejection of $K_L^0 \to \pi^0\pi^0$ background

![Graph showing resolution effects included]
Background from $K_L^0 \rightarrow \pi^\pm e^\mp \nu \gamma$ occurs when the $e^+$ converts at the vacuum vessel. $\pi^0$ candidates are formed from $\gamma_1 \gamma_2$. For $e^+ e^- \rightarrow \gamma_0 \gamma_1$, $p(\gamma_1) \approx p(e^+)$ and $p(\gamma_0) \approx p(e^-)$. Modest rejection possible from lower energy $\gamma_0$ and increased $\chi^2$ from slight change of $\gamma_1$ from the original $e^+$ direction.
Kinematic rejection of $K_L^0 \rightarrow \pi\pi\pi$ backgrounds

Resolution effects included
KOPIO signal and background estimates

<table>
<thead>
<tr>
<th>Process</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L^0 \rightarrow \pi^0 \nu \overline{\nu}$ at SM rate</td>
<td>40</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^0 \pi^0$</td>
<td>12.4</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^\pm e^\mp \nu \gamma$</td>
<td>4.5</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^\mp \pi^+ \pi^0$</td>
<td>1.7</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \pi^\pm e^\mp \nu$</td>
<td>0.02</td>
</tr>
<tr>
<td>$K_L^0 \rightarrow \gamma \gamma$</td>
<td>0.02</td>
</tr>
<tr>
<td>$\Lambda \rightarrow \pi^0 n$</td>
<td>0.01</td>
</tr>
<tr>
<td>Interactions ($nN \rightarrow \pi^0 X$)</td>
<td>0.2</td>
</tr>
<tr>
<td>Accidentals</td>
<td>0.6</td>
</tr>
<tr>
<td>Total Background</td>
<td>19.5</td>
</tr>
</tbody>
</table>

$\Delta B/B \approx 20\%$ or

$\Delta \eta/\eta \approx 10\%$ at $S/B=2$
Possible impact of E949, KOPIO $K \rightarrow \pi \nu \bar{\nu}$ measurements

Assumptions:
E949 & KOPIO run for approved running period.
$K \rightarrow \pi \nu \bar{\nu}$ rates at twice SM expectation
$\Delta m_s = 17.0 \pm 1.7 \text{ ps}^{-1}$
$\sin 2\beta = 0.70 \pm 0.02$
**Summary and outlook for $K \to \pi \nu \bar{\nu}$**

**E949** has observed an additional $K^+ \to \pi^+ \nu \bar{\nu}$ candidate and measures $\mathcal{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ for the combined data of E787 and **E949**. The result is consistent with the current Standard Model prediction.

**E949** analysis of $K^+ \to \pi^+ \nu \bar{\nu}$ for momenta $P(\pi^+) < 195$ MeV/c in progress.

**E949**: Approved (1999), HEP at AGS halted (2002), other funding sources sought...

Another stopped-$K^+$ experiment to measure $K^+ \to \pi^+ \nu \nu$ under consideration at KEK in Japan. $K^+$ decay-in-flight experiments under consideration at FNAL and CERN.

**E391a**: $(K^0_L \to \pi^0 \nu \bar{\nu}$ at KEK) Began stable data-taking in March 2004

**KOPIO**: Approved by NSF (2003), construction start in 2005, in need of zealous collaborators.

These experiments would be able to test the precise predictions for $K \to \pi \nu \bar{\nu}$ branching fractions.

Thanks to G.Isidori, E949 & KOPIO collaborations.
Extras
\[ \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = K_+ \left( \left[ \text{Im} \lambda_t \frac{X}{\lambda^5} \right]^2 + \left[ \text{Re} \lambda_c \frac{P_0}{\lambda} + \text{Re} \lambda_t \frac{X}{\lambda^5} \right]^2 \right) \]

\[ \mathcal{B}(K^0_L \rightarrow \pi^0 \nu \bar{\nu}) = K_0 \left( \left[ \text{Im} \lambda_t \frac{X}{\lambda^5} \right]^2 \right) \]

\[ \lambda_i \equiv V_{is}^* V_{id} \]

\[ K_+ \equiv r_+ B \]

\[ K_0 \equiv r_0 B \tau(K^0_L) / \tau(K^+) \]

\[ B \equiv 3\alpha^2 \mathcal{B}(K^+ \rightarrow \pi^0 e^+ \nu) / 2\pi^2 \sin^4 \theta_W \]

\[ X \equiv X(x_t) \equiv \frac{x_t}{8(x_t-1)} \left( x + 2 + \frac{3x-6}{x-1} \ln x \right) \]

\[ x_t \equiv (m_t/m_W)^2 \]

\[ r_+ = 0.901 \]

\[ r_0 = 0.944 \]

\[ P_0 = 0.40 \pm 0.06 \text{ (charm)} \]
Pulse fitting in stopping counter

IP1FLG 0 KPIFLG 100 DT 2.13
Tmuav 6.15 Emut 150.68

Prod 3.59 Elast 22.48

Cmupi 2.35, 1.57

Cmuend 39.25, 96.5
US probs 0.210.980
DS probs 0 0.060

Epion 918.19, 677.9
Emuon 105.01, 216.12

Tpio 5.43, 6.97
Tmuon 7.2, 5.09

Ped(single) 4.56, 5.51
Ped(double) 3.93, 4.88
Compare TD properties of candidate with $\pi^+$ and $\mu^+$ samples

Quantities related to pion particle identification from TD variables. Events with similar background rejection and fitted muon time $< 10$ ns are selected. The pion signal (blue) and the muon background (red) are shown in the same plots. The arrows indicate the positions of the candidate event.
Remind: E949-2002 beam conditions were not optimized

- a failure of the AGS power supply
- reduced operating voltage of one of the DC separators
- 12 weeks

The conditions will be improved in the next run.

<table>
<thead>
<tr>
<th></th>
<th>E787</th>
<th>E949-’02</th>
<th>E949 optimized</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGS energy (GeV)</td>
<td>24</td>
<td>22</td>
<td>24</td>
</tr>
<tr>
<td>beam spill (sec)</td>
<td>2.2</td>
<td>2.2</td>
<td>4.1</td>
</tr>
<tr>
<td>cycle (sec)</td>
<td>4.2</td>
<td>5.4</td>
<td>6.4</td>
</tr>
<tr>
<td>duty factor (%)</td>
<td>52</td>
<td>41</td>
<td>64</td>
</tr>
<tr>
<td>$K^+ / \pi^+$</td>
<td>4</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$N_K$ in the spill</td>
<td>1.8</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>$N_K$ MHz</td>
<td>0.8</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>rates in the detector (M)</td>
<td>$\times 2$</td>
<td>$\times 2$ or less</td>
<td>$\geq 60$</td>
</tr>
<tr>
<td>beam time (weeks)</td>
<td>12</td>
<td></td>
<td>$\geq 60$</td>
</tr>
</tbody>
</table>
PNN2: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ below $K^+ \rightarrow \pi^+ \pi^0$ peak

- More phase space than PNN1
- Less loss due to $\pi^+ N$ interactions
- $P(\pi^+) = (140,195)$ MeV/c probes more of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ spectrum
- Main background mechanism is $K^+ \rightarrow \pi^+ \pi^0$ followed by $\pi^+$ scatter in target.
E949 PNN2 analysis

- E787: PNN2 acceptance approx. half PNN1 acceptance
- Goal is equal PNN2 and PNN1 sensitivity with $S/B = 1$. This implies $\times 2$ increase in acceptance and $\times 5$ increase in background rejection.
- Upgraded photon veto increased PNN1 background rejection. Quantitative assessment of improvement for PNN2 underway.
- Improved algorithms to identify $K^+ \rightarrow \pi^+\pi^0$ followed by $\pi^+$ scatter in target.
Candidate E787A
E949 Range vs Momentum accepted by trigger
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimal Requirement</th>
<th>Expected Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\gamma}$ resolution</td>
<td>3.5%/\sqrt{E}</td>
<td>2.7%/\sqrt{E}</td>
</tr>
<tr>
<td>$\theta_{\gamma}$ resolution (250MeV)</td>
<td>(25 – 30) mr</td>
<td>23 mr</td>
</tr>
<tr>
<td>$t_{\gamma}$ resolution</td>
<td>100ps/\sqrt{E}</td>
<td>50ps/\sqrt{E}</td>
</tr>
<tr>
<td>$x_{\gamma}, y_{\gamma}$ resolution(250MeV)</td>
<td>10mm</td>
<td>&lt; 1mm</td>
</tr>
<tr>
<td>$\mu$-bunch width</td>
<td>300ps</td>
<td>200ps</td>
</tr>
<tr>
<td>$\gamma$-veto inefficiency</td>
<td>$e_{ET87}$</td>
<td>0.3$e_{ET87}$</td>
</tr>
</tbody>
</table>
**Simulation**: Combined Energy Resolution

\[ \sigma \sim \frac{3\%}{\sqrt{E(\text{GeV})}} \]
E391a at KEK