First Observation of the Decay
\[ K^+ \rightarrow \pi^+ \gamma \gamma \]

AGS Experiment 787
Brookhaven National Laboratory

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E787

A Search for \( K^+ \rightarrow \pi^+ \nu\bar{\nu} \) and Related Decays

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TRIUMF
\( \chiPT \)

- Chiral expansion of the Lagrangian in terms of the pseudo-scalar meson fields.
- \( \chiPT \) works at the light meson mass scale assuming 
  \( \Lambda \to 0 \)
- Kaon decays are used to test the accuracy of \( \chiPT \)
- \( \chiPT \) has been applied to
  - \( K \to l\nu\gamma \)
  - \( K \to l\nu\pi \)
  - \( K \to \pi l\nu \)
  - \( K \to \pi l\nu\gamma \)
  - \( K \to \pi\pi l\nu \)
  - \( K \to \pi\pi\pi \)
  - \( K \to \pi\pi\gamma \)
  - \( K \to \pi\pi\pi\gamma \)
  - \( K \to \gamma\gamma \)
  - \( K \to \gamma\gamma \)
  - \( K \to \pi\pi\gamma \)
  - \( K \to \pi l l^+ \)
  - \( K \to \pi l l^+\gamma \)
$K^+ \rightarrow \gamma \pi^+ \gamma \gamma$

Feynman Diagrams
\[
\frac{d\Gamma(z)}{dz}_{\kappa^+\pi^-\gamma\gamma} = \frac{M_{K^+}^2}{2(8\pi)^3}\sqrt{\lambda(1, z, r_\pi^2)z^2(|\Lambda(z)|^2 + |C(z)|^2)}
\]

\[\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ca)\]

\[A(z) = \frac{G_{8\alpha}}{2\pi z} \left[ (r_\pi^2 - 1 - z) F\left(\frac{z}{r_\pi^2}\right) + (1 - z - r_\pi^2) F(z) + \hat{z} \right] \]

\[F(z) = \begin{cases} 
1 - \frac{4}{z} \sin^{-1} \left( \frac{\sqrt{\phi}}{2} \right)^2 & \text{if } z \leq 4 \\
1 + \frac{1}{z} \left[ \ln(\phi) + i\pi \right]^2 & \text{if } z \geq 4
\end{cases} \quad \phi = \frac{1 - \sqrt{1 - \frac{1}{z}}}{1 + \sqrt{1 - \frac{1}{z}}}
\]

\[\hat{z} = 32\pi^2 \left[ 4(L_9 + L_{10}) - \frac{1}{3}(w_1 + 2w_2 + 2w_1) \right]
\]

\[C'(z) = \frac{G_{8\alpha}}{\pi} \left[ \frac{z - r_\pi^2}{z - r_\pi^2 + i r_\pi \Gamma_{\pi^0}/M_K} - \frac{z - \frac{1}{3}(2 + r_\pi^2)}{z - r_\eta^2} \right]
\]

\[z - \left( \frac{M_{\gamma\gamma}}{M_K} \right)^2 \quad r_\pi^2 = \frac{M_\pi}{M_K} \quad r_\eta = \frac{M_\eta}{M_K} \quad 0 \leq z \leq (1 - r_\pi)^2.
\]

C. Eckert, A. D. D. Pich and E. de Rafael

$\chi$PT($\hat{c}$) and Phase Space $(\frac{M_{\pi\pi}}{M_K})^2$ Spectrum
\( \chi^P T \) Prediction For \( K^+ \to \pi^+ \gamma\gamma \) Decay Rate

\[
\Gamma(K^+ \to \pi^+ \gamma\gamma) = \Gamma_{\text{inap}} + \Gamma_{\text{wz}}
\]

\[
\Gamma_{\text{inap}} = (2.80 + 0.87\bar{c} + 0.17\bar{c}^2) \times 10^{-23}\text{GeV}
\]

\[
\Gamma_{\text{wz}} = 0.26 \times 10^{-23}\text{GeV}
\]

\[
\text{Br}(K^+ \to \pi^+ \gamma\gamma) \geq 4 \times 10^{-7}
\]
Summary

- A search for the decay mode $K^+ \rightarrow \pi^+ \gamma\gamma$ was conducted using the AGS E787 detector.

- Two triggers were designed to probe the high and low momentum regions of the $\pi^+$ emanating from the $\pi\gamma\gamma$ decay.

- The detector was exposed to approximately $10^{11} K^+$ mesons.

- Each trigger sample underwent a separate analysis of which the final results of one and the partial results of the other will be presented here.
E787 Detector Geometry
Range Stack and Barrel Veto View

Kπ2 Event Topology

The Range Stack
21 layers/24 sectors of plastic scintillator
Layers 2 - 10 multiplexed by 3 into layers A, B and C

The Barrel Veto
4 layers/48 sectors of lead/plastic scintillator sandwich
E787 Detector
Drift Chamber and Range Stack Kinematic Performance
Pions

1991 Detector (Pre-Upgrade) 

1995 Detector (Post-Upgrade)

Top Row Energy vs Momentum
Bottom Row Range vs Momentum
Triggers π scats

π⁺ scattering triggers
Level 1 Trigger
\( \pi^+ \rightarrow \mu^+ \nu_\mu \) tagging trigger

- Search for double pulse.
- Pulse height vs pulse area algorithm.
- Excess area indicates \( \pi \rightarrow \mu \) candidate.

500 MHz TD pulses from RS SC

\( K_{\pi^2} \) triggers

\( \pi \nu \bar{\nu}(1) \) triggers
Level 1.1 Trigger Results

Without L1.1 cut | With L1.1 cut

\( K_{\pi 2}(1) \) triggers

\( \pi\nu\nu\bar{\nu} \) triggers

Kinetic energy charged track spectra with and without the L1.1 trigger cut for \( K_{\pi 2}(1) \) and \( \pi\nu\nu\bar{\nu} \) triggers

\( \pi^+ \) tagging efficiency \( \approx 60\% \)

\( \mu^+ \) rejection factor \( \approx 15 - 25 \)

Trigger Decision Time \( \approx 10 - 20 \mu s \)

S. Adler
The $\pi\gamma\gamma$ triggers

$\pi\gamma\gamma$ trigger 1
- Delayed coincidence.
- Long range track.
- $\gamma$ veto in EC and RS.
- Pion tagging trigger.
- Large energy deposit in barrel veto.
- Two photon cluster tags.
- No opening angle cut.
- Crude low $\text{di-}\gamma$ invariant mass cut.

$\pi\gamma\gamma$ trigger 2
- Delayed coincidence.
- Short ranged track.
- $\gamma$ veto in EC and RS.
- No Pion tagging trigger.
- Large energy deposit in barrel veto.
- Two photon cluster tags.
- Large opening angle cut.
- Crude high $\text{di-}\gamma$ invariant mass cut.
\( \pi^+ \gamma \gamma \) 1 Offline Analysis

<table>
<thead>
<tr>
<th>Analysis</th>
<th>No. of Surviving Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>After online cuts</td>
<td>730693</td>
</tr>
<tr>
<td>After pass 1</td>
<td>69095</td>
</tr>
<tr>
<td>After pass 2</td>
<td>21198</td>
</tr>
<tr>
<td>After pass 3</td>
<td>0</td>
</tr>
<tr>
<td>Integrated ( K^+ ) flux</td>
<td>5.2880 ( \times 10^{10} )</td>
</tr>
</tbody>
</table>

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**Pass 1 Event reconstruction**

- Target, DC, RS track recon.
- Photon Clustering

**Pass 2 Refined Event Reconstruction and preliminary kinematics analysis**

- Refined target analysis.
- Refined RS tracking analysis.
- Kinematic track fitting

**Pass 3 Full kinematic Analysis**

- 3 body final state constraint fitting.
- Final kinematic "Box" cut.

**Backgrounds**

- \( K^+ \rightarrow \pi^+ \pi^0 = .58 \pm .11 \) events
- \( K^{*+} \rightarrow \pi^0 \mu^+ \nu_\mu \lesssim .05 \) events
$K^+ \rightarrow \pi^+ \gamma \gamma$ Final Event Sample
Including systematic errors in the 90% c.l. upper limit

\[ U.L. = \frac{2.3 \times (1 + 2.3 \cdot \tau^2)}{\text{Sensitivity}} \]

- Systematic errors \( \approx 15\% 
- Statistical error \( \approx 5\% 
- 2.3 \rightarrow 2.37

Upper limit = \[ \frac{2.37}{N_{K^0}\text{Lice} J_s A_{\pi\gamma\gamma}(1)} \]

\[ = \frac{2.37}{(5.2880 \times 10^{10}) (0.591 \pm 0.012) (1.50 \pm 0.24) \times 10^{-4}} \]

\[ \text{Br}(K^+ \rightarrow \pi^+\gamma\gamma) < 5.02 \times 10^{-7} \]

Phase Space Matrix Element
$\chi^2_{PT}$ Upper limit as a function of $\delta$: 

![Graph showing $\chi^2_{PT}$ upper limit as a function of $\delta$]
The \( \pi \gamma \gamma(1) \) trigger is also sensitive to the decay
\[
K^+ \rightarrow \pi^+ X^0, \quad X^0 \rightarrow \gamma \gamma
\]

Where \( X^0 \) is a massive, short lived particle.
### $\pi\gamma\gamma$ 2 Offline Analysis

<table>
<thead>
<tr>
<th>Analysis</th>
<th>No. of Surviving Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass</td>
<td></td>
</tr>
<tr>
<td>After online cuts</td>
<td>2,726,738</td>
</tr>
<tr>
<td>After pass 1</td>
<td>334,289</td>
</tr>
<tr>
<td>After pass 2</td>
<td>130,991</td>
</tr>
<tr>
<td>After pass 3</td>
<td>31</td>
</tr>
</tbody>
</table>

Integrated $K^+$ flux $\approx 10^{11}$

---

**Pass 1 Event reconstruction**
- Target, DC, RS track recon.
- Photon veto in RS and EC.
- Charged track mass.

**Pass 2 $K^+ \rightarrow \pi^+\pi^0$ background cuts**
- Momentum cut
- di-$\gamma$ mass cut

**Pass 3 Full kinematic Analysis**
- Tightening of selected pass1 and pass2 cuts.
- 3 body final state constraint fitting.

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**Backgrounds**
- $K^+ \Rightarrow \pi^+\pi^0\pi^0 = 1.92 \pm 1.80$
- $K^+ \Rightarrow \pi^+\pi^0\gamma = 2.64 \pm 2.74$

**Signal**
- $K^+\gamma \Rightarrow \pi^+\gamma\gamma = 25.9 \pm 6.5$
AGS E787 Collaboration

Signal and Montecarlo $M_{\gamma\gamma}$ Spectral Plots

$K^+ \rightarrow \pi^+ \gamma \gamma$

Preliminary Results

MC cpt $c = -4$

MC cpt $c = 0$

MC cpt $c = +4$

MC Phase Space
Conclusion

\( \pi\gamma\gamma \) 2 analysis, (High end of the \( M_{\gamma\gamma} \) spectrum)

\( K^+ \rightarrow \pi^+\gamma\gamma \)

has been seen for the first time!

\( M_{\gamma\gamma} \) Spectrum differs from Phase Space Prediction

\( M_{\gamma\gamma} \) Spectrum is consistent with \( \chi^P_T \) Prediction

Partial Branching Ratio Measurement for \( 100 \text{MeV} < P_{\pi^+} < 180 \text{MeV} \)

\( \pi\gamma\gamma \) 1 analysis, (Low end of the \( M_{\gamma\gamma} \) spectrum)

<table>
<thead>
<tr>
<th>Matrix Element</th>
<th>90% C.L. Upper Limit</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^+ \rightarrow \pi^+\gamma\gamma ) Phase Space</td>
<td>(&lt; 5.02 \times 10^{-7} )</td>
<td>Factor of 2 improvement</td>
</tr>
<tr>
<td>( K^+ \rightarrow \pi^+\gamma\gamma ) ( \chi^P_T )</td>
<td>(&lt; 1 \times 10^{-4} - 1 \times 10^{-3} )</td>
<td>Strong dependence on ( \hat{c} )</td>
</tr>
</tbody>
</table>
| \( K^+ \rightarrow \pi^+\chi^0, \chi^0 \rightarrow \gamma\gamma \) | \(< 3.8 \times 10^{-8} \) | \( M_{\chi^0} = 60 \text{ MeV} \)
| | | \( \tau_{\chi^0} < 10^{-11} \text{ sec} \) |