$K^+ \to \pi^0 \mu^+\nu\gamma$ and $K^+ \to \pi^0 e^+\nu\gamma$ decays: recent results from the «OKA» experiment

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The matrix element for this decay has general structure:

\[
T = \frac{G_f}{\sqrt{2}} e V_{us} \epsilon^{\alpha}(q) \left\{ (V_{\alpha \beta} - A_{\alpha \beta}) \bar{u}(p_\nu) \gamma^\beta (1 - \gamma^5) v(p_l) + \frac{F_\beta}{2p_l q} \bar{u}(p_\nu) \gamma^\beta (1 - \gamma^5) (m_l - \hat{p}_l - \hat{q}) \gamma^\alpha v(p_l) \right\}.
\]

First term of the \( T \) describes the bremsstrahlung of kaon and the direct emission, (a, b). The lepton bremsstrahlung presented by the second part of \( T \) and (c).

Diagrams describing \( K^+ \to \pi^0 l^+ \nu \gamma \).
$K^+ \rightarrow \pi^0 l^+ \nu \gamma$ decays are among those kaon decays where new physics beyond Standard Model can be probed. These decays are especially interesting as they are sensitive to T-odd contributions. According to CPT theorem, observation of T-violation is equivalent to observation of CP-violating effects.

Second, precise tests of ChPT.

Third, it is interesting to test lepton universality:

$$\frac{Br(K_{\mu 3\gamma})}{Br(K_{e 3\gamma})}.$$
Important experimental observable used in CP-violation searches is the T-odd correlation for $K^+ \to \pi^0\mu^+\nu\gamma$ decay defined as:

$$\xi_{\pi l\gamma} = \frac{1}{M_K^3} \vec{p}_\gamma \cdot \left[ \vec{p}_\pi \times \vec{p}_l \right].$$

To establish the presence of nonzero triple-product correlations, one construct a T-odd asymmetry of the form:

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-},$$

$N_+(\cdot)$ – number of events with $\xi >(<) 0$. 
The OKA collaboration operates at the IHEP Protvino U-70 Proton Synchrotron. Detector is located in positive RF-separated beam with 12.5% of $K$-meson 17.7 GeV/c $3 \cdot 10^5$ kaons per 2 sec U-70 spill. Separation is provided by two SC deflectors cooled by superfluid He.
$Trg = S_1 \cdot S_2 \cdot S_3 \cdot S_4 \cdot \tilde{C}_1 \cdot \tilde{C}_2 \cdot \tilde{S}_{bk} \cdot (E_{GAMS} > 2.5 GeV)$

$S_1 - S_4$ are scintillating counters; $\tilde{C}_1$, $\tilde{C}_2$ – Cherenkov counters ($\tilde{C}_1$ sees pions, $\tilde{C}_2$ pions and kaons); $S_{bk}$ – two scintillation counters on the beam axis after the magnet to suppress undecayed particles.

1. Beam spectrometer: PC’s;
2. Decay volume with Veto system;
3. PC’s and DT’s for magnetic spectrometer;
4. Magnet;
5. Matrix hodoscope: SiPM;
7. Muon identification: HCAL + $\mu$C;
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**Decay Volume with Veto system**

DV: 11m;
Veto: 670 Lead-Scintillator sandwiches $20 \times (5\text{mm Sc} + 1.5\text{mm Pb})$, WLS readout.

**Inside**

**Veto system**
Contrary to the $K_{e3\gamma}$ decay, where high statistics (OKA, NA62) measurements are available, $K_{\mu3\gamma}$ decay is poorly known.

### $K^+ \rightarrow \pi^0\mu^+\nu\gamma$ experimental status

<table>
<thead>
<tr>
<th>VALUE ($10^{-5}$)</th>
<th>CL%</th>
<th>EVTS</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>CHG</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25 ± 0.25</td>
<td>OUR AVERAGE</td>
<td>1.10 ± 0.32 ± 0.05</td>
<td>23</td>
<td>1 ADLER</td>
<td>2010</td>
<td>B787</td>
</tr>
<tr>
<td>1.46 ± 0.22 ± 0.32</td>
<td>153</td>
<td>TCHIKILEV</td>
<td>2007</td>
<td>ISTR</td>
<td>-</td>
<td>$30 &lt; E_\gamma &lt; 60$ MeV</td>
</tr>
<tr>
<td>2.4 ± 0.5 ± 0.6</td>
<td>125</td>
<td>SHIMIZU</td>
<td>2006</td>
<td>K470</td>
<td>+</td>
<td>$E_\gamma &gt; 30$ MeV, $\Theta_{\mu\gamma} &gt; 20^\circ$</td>
</tr>
<tr>
<td>&lt;6.1</td>
<td>90</td>
<td>LIUNG</td>
<td>1973</td>
<td>HLBC</td>
<td>+</td>
<td>$E(\gamma) &gt; 30$ MeV</td>
</tr>
</tbody>
</table>

1. Value obtained from $B(K^+ \rightarrow \pi^0\mu^+\nu\gamma) = (2.51 \pm 0.74 \pm 0.12) \times 10^{-5}$ obtained in the kinematic region $E_\gamma > 20$ MeV, and then theoretical $K_{\mu3\gamma}$ spectrum has been used. Also $B(K^+ \rightarrow \pi^0\mu^+\nu\gamma) = (1.58 \pm 0.46 \pm 0.08) \times 10^{-5}$, for $E_\gamma > 30$ MeV and $\Theta_{\mu\gamma} > 20^\circ$, was determined.

2. Obtained from measuring $B(K_{\mu3\gamma}) / B(K_{\mu3})$ and using PDG 2002 value $B(K_{\mu3}) = 3.27\%$. $B(K_{\mu3}) = (8.82 \pm 0.94 \pm 0.86) \times 10^{-5}$ is obtained for $5$ MeV $< E_\gamma < 30$ MeV.
### $K^+ \rightarrow \pi^0 l^+ \nu\gamma$ theoretical status

<table>
<thead>
<tr>
<th></th>
<th>$\text{Br} (K\mu_3\gamma)$</th>
<th>$A_\xi (K\mu_3\gamma)$</th>
<th>$\text{Br} (K\epsilon_3\gamma)$</th>
<th>$A_\xi (K\epsilon_3\gamma)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bijnens et al.</td>
<td>$1.9 \times 10^{-5}$</td>
<td>—</td>
<td>$2.8 \times 10^{-4}$</td>
<td>—</td>
</tr>
<tr>
<td>Braguta et al.</td>
<td>$2.15 \times 10^{-5}$</td>
<td>$1.14 \times 10^{-4}$</td>
<td>$3.18 \times 10^{-4}$</td>
<td>$-0.59 \times 10^{-4}$</td>
</tr>
<tr>
<td>Khriplovich et al.</td>
<td>$1.81 \times 10^{-5}$</td>
<td>$2.38 \times 10^{-4}$</td>
<td>$2.72 \times 10^{-4}$</td>
<td>$-0.93 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Theoretical calculations for $K\epsilon_3\gamma$ branching. The following cuts in the kaon rest frame are used: $E^* \geq 30$ MeV, $\theta_{l\gamma} \geq 20^\circ$, where $E^*$ is the photon energy. Theoretical errors were not specified by authors.
$K_{l3}$ is used as normalization channel. Two main observables for signal and normalization events are used: reconstructed mass $M(K_{l3\gamma}) = M(l^+, \pi^0, \nu, \gamma)$, where all missing momentum is attributed to $\nu$ and $M_\nu = 0$ is assumed and a similar observable $M(K_{l3}) = M(l^+, \pi^0, \nu)$.

1) $K^+ \rightarrow l^+\nu\pi^0$ with an extra photon. The main source of extra photons is lepton interaction in the detector;
2) $K^+ \rightarrow \pi^+\pi^0\pi^0$ where one of the $\pi^0$ photon is not detected and $\pi^+$ is misidentified as a $l^+$;
3) $K^+ \rightarrow \pi^+\pi^0$ with a “fake photon” and $\pi^+$ misidentified as a $l^+$. The fake photons can come from $\pi^+n$ interactions in the gamma detector and from accidentals;
4) $K^+ \rightarrow \pi^+\pi^0\gamma$ when $\pi^+$ is misidentified as a $l^+$;
5) $K^+ \rightarrow \pi^0\pi^0l^+\nu$ when one $\gamma$ is lost.

All these background sources are included in MC calculations.

In $K_{\mu3\gamma}$ decays backgrounds 1, 2 and 4 are dominated.
**$K_{\mu3\gamma}$ event selection**

General criteria (all one track events): good quality beam with proper momentum, vertex within decay volume, good quality secondary track with reasonable $\chi^2$ etc.

**Cut**

<table>
<thead>
<tr>
<th>$K_{\mu3}$</th>
<th>$K_{\mu3\gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon compatible signal in GAMS, HCal and $\mu C$</td>
<td>++</td>
</tr>
<tr>
<td>2 e/m showers in GAMS with $E_\gamma &gt; 0.6$ GeV</td>
<td>-+</td>
</tr>
<tr>
<td>3 e/m showers in GAMS with $E_\gamma &gt; 0.6$ GeV</td>
<td>--</td>
</tr>
<tr>
<td>$</td>
<td>M_{\gamma\gamma} - M_{\pi0}</td>
</tr>
<tr>
<td>Missing energy $&gt; 0.5$ GeV</td>
<td>++</td>
</tr>
<tr>
<td>No amplitude overflow in GAMS counters</td>
<td>++</td>
</tr>
<tr>
<td>The position of radiative photon at GAMS surface is not near beam hole nor at the boundary</td>
<td>--</td>
</tr>
<tr>
<td>Total energy in Veto and BGD is below threshold</td>
<td>++</td>
</tr>
<tr>
<td>Number of additional track segments after spectrometer magnet is zero</td>
<td>++</td>
</tr>
</tbody>
</table>
| $K_{\mu3}$ special: $\cos(\mu^+\pi^0)$ in rest frame $> -0.95$.
   Effective against $K^+ \rightarrow \pi^+\pi^0$ bkg | +- |
| $K_{\mu3\gamma}$ special: missing mass $MM(\pi^+\pi^0) < 0.12$ GeV.
   Effective against $K^+ \rightarrow \pi^+\pi^0\pi^0$ bkg | -- |
In kaon rest frame. Left: distribution of $\cos(\mu_3 \gamma)$, right: energy of odd gamma distribution. Magenta – MC $K_{\mu3\gamma}$ signal, red – MC bkg from $K_{\pi^+\pi^0\pi^0}$, green – MC bkg from $K_{\pi^+\pi^0\gamma}$, blue – MC bkg from $K_{\mu3}$. 
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*K_{μ3γ} event selection*

![Graphs showing event selection](image)

Left – $K_{μ3γ}$ invariant mass distribution. Right – $ξ$ distribution. Top – with bkg, bottom – bkg subtracted. Magenta – MC $K_{μ3γ}$ signal, red – MC bkg from $K_{π^+π^0π^0}$, green – MC bkg from $K_{π^+π^0γ}$, blue – MC bkg from $K_{μ3}$. 
**Ke3γ event selection**

**Cut**

- 4 e/m showers in GAMS with $E_γ > 0.7$ GeV;
- One charged track is identified as $e^+$ with $0.8 < E/p < 1.2$;
- Missing energy $> 0.5$ GeV;
- No amplitude overflow in GAMS counters;
- The position of radiative photon at GAMS surface is not near beam hole nor at the boundary;
- Total energy in Veto and BGD is below threshold;
- Number of additional track segments after spectrometer magnet is zero;
- The effective mass for γ-pair $0.12 < M_{γγ} < 0.15$ GeV;
- $\Delta y = |y_γ - y_e| > 3$ cm, where $y$ is the vertical coordinate of a particle in the e/m calorimeter (the magnetic field turns charged particles in the xz-plane);
- $|x_ν , y_ν| < 100$ cm. The reconstructed missing momentum direction must cross the active area of the e/m calorimeter.
- The reconstructed mass of the system $M (K^+ → e^+ ν π^0 γ) > 0.45$ GeV
- $|M^2_{miss (π^0 e^+ γ)}| = (P_K - P_{π^0} - P_e - P_γ)^2 < 0.006$ GeV$^2$;
- $4$ mrad $< \theta_{eγ} < 80$ mrad;
In kaon rest frame. Left: distribution of \( \cos(\Theta_{e\gamma}) \), right: energy of odd gamma distribution. Histrogram – MC signal plus total background, MC background – dotted line histogram.
Left – $K_{e3\gamma}$ invariant mass distribution. Right – $\xi$ distribution. Total background – dotted line histogram.
Preliminary results and conclusion

• We have $960 \pm 55$ (stat) $K_{\mu3\gamma}$ and $19295$ (101200 candidates) $K_{e3\gamma}$ signal events;

• $Br(K_{\mu3\gamma})/Br(K_{\mu3}) = (4.45 \pm 0.25$ (stat)) $\times 10^{-4}$, $30 < E^* < 60$ MeV;

• Using PDG value $Br(K_{\mu3}) = 3.352\%$: $Br(K_{\mu3\gamma}) = (1.492 \pm 0.085$ (stat)) $\times 10^{-5}$, which is in agreement with ISTRA+ measurement, but statistical errors is 3 times smaller;

• Theory: $1.9 \times 10^{-5}$ (Bijinens), $2.15 \times 10^{-5}$ (Braguta), $1.81 \times 10^{-5}$ (Khriplovich);

• $A_\xi = -0.006 \pm 0.069$. Theory: $1.14 \times 10^{-4}$ (Braguta), $2.38 \times 10^{-4}$ (Khriplovich);

• $Br(K_{e3\gamma})/Br(K_{e3}) = (58.7 \pm 1.0$ (stat) $\pm 1.5$ (syst)) $\times 10^{-4}$, $30 < E^* < 60$ MeV and $\theta_{e\gamma} > 20^\circ$;

• Using PDG value $Br(K_{e3}) = 5.07\%$: $Br(K_{e3\gamma}) = (2.97 \pm 0.13) \times 10^{-4}$;

• Theory: $2.8 \times 10^{-4}$ (Bijinens), $3.18 \times 10^{-4}$ (Braguta), $2.72 \times 10^{-4}$ (Khriplovich);

• $A_\xi = (+4.4 \pm 7.9$ (stat) $\pm 1.9$ (syst)) $\times 10^{-3}$. Theory: $-0.59 \times 10^{-4}$ (Braguta), $-0.93 \times 10^{-4}$ (Khriplovich);

• Our results are preliminary.
Thank you for your attention!