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

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Abstract – The $K^+ \to \pi^0\mu^+\nu\gamma$ ($K_{\mu3\gamma}$) and $K^+ \to \pi^0 e^+\nu\gamma$ ($K_{e3\gamma}$) decays are measured with OKA detector at the RF-separated 17.7 GeV/c momentum kaon beam from the U-70 synchrotron. The data obtained corresponds to the value of 2.62×10^{10} «live» kaons passing to the decay volume. The ratios of Br($K_{\mu3\gamma}$)/Br($K_{\mu3}$) and Br($K_{e3\gamma}$)/Br(K_{e3}) are measured. The T-odd correlation $\xi_{\pi\mu\gamma}$ ($\xi_{\pi e\gamma}$), which is the mixed product of the momenta of $\mu^+(e^+)$, π^0, and γ in the kaon rest frame, is measured. The asymmetry of the distribution in ξ is characterized by the ratio $A_\xi = (N_+ - N_-)/(N_+ + N_-)$, where $N_{+(-)}$ is the number of events with positive (negative) ξ. The values of A_ξ for $K_{\mu3\gamma}$ and for $K_{e3\gamma}$ is obtained.

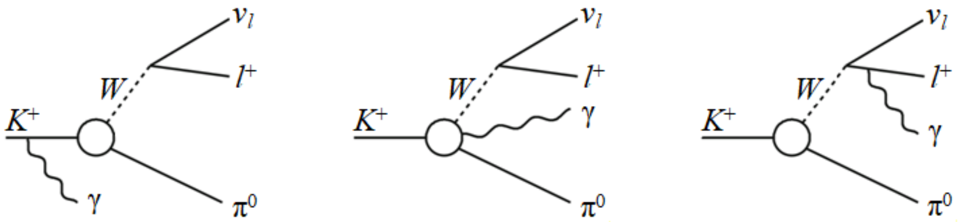
INTRODUCTION

The $K^+ \to \pi^0 l\nu\gamma$ (where $l = \mu^+$ or e^+) decays are among those K-mesons decays where New Physics (NP) can be probed. These decays are especially interesting as they are sensitive to T-odd contributions [1]. According to CPT theorem, observation of T-violation is equivalent to observation of CP-violating effects. These decays also enable us to perform quantitative tests of the Chiral Perturbation Theory (ChPT) and provide the opportunity to test lepton universality by measuring the ratio Br($K^+ \to \pi^0\mu^+\nu\gamma$)/Br($K^+ \to \pi^0 e^+\nu\gamma$).

The matrix element for $K^+ \to \pi^0 l\nu\gamma$ decays has general structure:

$$\begin{aligned} T = \frac{G_f}{\sqrt{2}} eV_{us}\epsilon^{\alpha}(q)\{(V_{\alpha\beta} - A_{\alpha\beta})\overline{u}(p_\nu)\gamma^\beta(1-\gamma^5)v(p_l) \\ + \frac{F_\beta}{2p_l q}\overline{u}(p_\nu)\gamma^\beta(1-\gamma^5)(m_l - \not{p}_l - \not{q})\gamma_\alpha v(p_l)\}. \end{aligned} \tag{1}$$

First term of (1) describes the bremsstrahlung of kaon and the direct emission (Fig. 1a and Fig. 1b). The lepton bremsstrahlung is presented by the second part of (1) and Fig. 1c.



(a) (b) (c)

Fig. 1. Three main diagrams describing $K^+ \to \pi^0 l\nu\gamma$ decay.

To study the triple T-odd correlations we use the variable ξ:

$$\xi_{\pi l\gamma} = \frac{1}{M_K^3} \vec{p}_\gamma \cdot [\vec{p}_\pi \times \vec{p}_l]. \tag{2}$$

To estimate the asymmetry of the distribution over ξ variable we use the value:

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-}, \tag{3}$$

where $N_{+(-)}$ is the number of events with ξ greater (less) than zero. This asymmetry is sensitive to NP as this shown in [2]: for $E^* > 30$ MeV, $\theta_{l\gamma} > 20°$ (E^* is the photon energy and $\theta_{l\gamma}$ is the emition angle in kaon rest frame) $A_\xi = -(3.6 \times 10^{-3} Im(g_s) + 1.2 \times 10^{-2} Im(g_p) + 1.0 \times 10^{-2} Im(g_v + g_a))$ for $K_{\mu 3\gamma}$ and $A_\xi = -(2.9 \times 10^{-6} Im(g_s) + 3.7 \times 10^{-5} Im(g_p) + 3.0 \times 10^{-3} Im(g_v + g_a))$ for $K_{e3\gamma}$, where g_s, g_p, g_v and g_a are the complex scalar, pseudoscalar, vector and pseudovector constants from model independent NP-Lagrangian of 4-fermion interaction, and they are equal to zero for Standard Model.

The status of theoretical calculations for $K^+ \to \pi^0 l \nu \gamma$ decay is presented in Table 1.

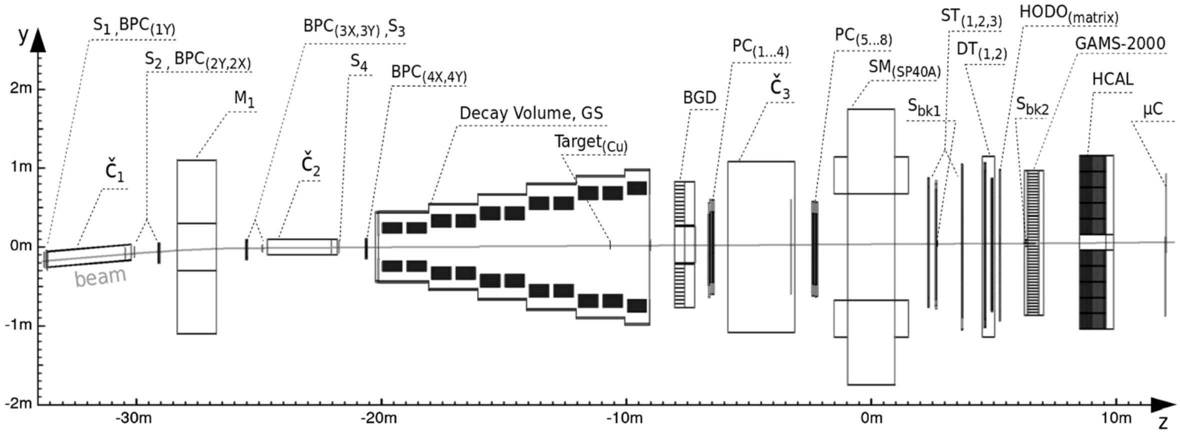
	Br ($K_{\mu 3\gamma}$)	A_ξ ($K_{\mu 3\gamma}$)	Br ($K_{e3\gamma}$)	A_ξ ($K_{e3\gamma}$)
Bijnens et al. [3]	1.9×10^{-5}	—	2.8×10^{-4}	—
Braguta et al. [1]	2.15×10^{-5}	1.14×10^{-4}	3.18×10^{-4}	-0.59×10^{-4}
Khriplovich et al. [4]	1.81×10^{-5}	2.38×10^{-4}	2.72×10^{-4}	-0.93×10^{-4}

Table 1. Theoretical calculations of $K^+ \to \pi^0 l \nu \gamma$ branching, the following cuts in the kaon rest frame are used: $E^* \geq 30$ MeV, $\theta_{l\gamma} \geq 20°$, theoretical errors are not specified by authors. Values of A_ξ are calculated in Standard Model.

THE OKA DETECTOR

The OKA (from abbreviation for "Experiments On KAons" or "Опыты с КАонами") is the experiment with fixed target aiming to study the kaon decays and taking data since 2010. It is located at NRC "Kurchatov Institute" – IHEP in Protvino (Russia) and uses U-70 Proton Synchrotron. Secondary kaon-enriched hadron beam is obtained by RF-separation witn Panofsky scheme [5–7]. The beam has the momentum of 17.7 *GeV/c* with kaons content up to 12.5% and an intensity of 5×10^5 kaons per 2 second U-70 spill.

The scheme of OKA setup is presented in Fig. 2. It consists of: beam magnetic spectrometer (*y*-deflecting magnet M1 and set of "beam" proportional chambers $\mathrm{BPC}_{(1Y,2Y,2X,\ldots,4X,4Y)}$, 1500 channels); 11 *m* long helium-filled Decay Volume DV with photon veto guard system GS (670 Lead-Scintillator sandwiches) and the electromagnetic calorimeter BGD (with wide central opening); magnetic spectrometer for decay products (2.0 × 1.4 m^2 *x*-deflecting magnet $\mathrm{SM}_{(\mathrm{SP40A})}$, proportional chambers $\mathrm{PC}_{(1,\ldots,8)}$, straw tubes $\mathrm{ST}_{(1,2,3)}$ and drift tubes $DT_{(1,2)}$, matrix hodoscope $HODO_{(matrix)}$ for better time resolution and *x*-*y* tracking, total 6800 channels); calorimetry (e/m calorimeter GAMS-2000, hadron calorimeter HCAL); four muon counters μC after HCAL. Trigger system consists of four scintillation counters $S_{(1-4)}$, two threshold Cherenkov counters $\check{C}_{1,2}$ to detect kaons, two scintillation counters $S_{bk1,2}$ to suppress undecayed beam particles. There is also auxiliary Cherenkov counter $\check{C}_3$. More about OKA detector can be found in [8, 9].



$$\text{Trigger}: S_1 \times S_2 \times S_3 \times S_4 \times \bar{\check{C}}_1 \times \check{C}_2 \times \bar{S}_{bk} \times (E_{GAMS2000} > \text{threshold, 50\% efficiency at 2.5 GeV})$$

Fig. 2. Scheme of OKA detector. For more detailed information see text.

BACKGROUND AND EVENT SELECTION

The main background decay channels for the investigated decays are: $K^+ \to l\nu\pi^0$ with an extra photon, $K^+ \to \pi^+\pi^0\pi^0$ where one of the π^0 photon is not detected and π^+ is misidentified as a l, $K^+ \to \pi^+\pi^0$ with a "fake photon" and π^+ misidentified as a l, $K^+ \to \pi^+\pi^0\gamma$ when π^+ is misidentified as a l, $K^+ \to \pi^0\pi^0 l\nu$ when one γ is lost. All these background sources are included in MC calculations. For $K_{\mu3\gamma}$ decay backgrounds 1, 2 and 4 are dominated, for the $K_{e3\gamma}$ decay – is 1st.

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 ν and $M_\nu = 0$ is assumed and a similar observable $M(K_{l3}) = M(l, \pi^0, \nu)$.

For $K_{\mu3\gamma}$ and $K_{e3\gamma}$ signal events we use sets of selection criteria. General criteria: good quality vertex within DV, 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, absence of additional track segments after spectrometer magnet, missing energy > 0.5 *GeV*, $|M_{\gamma\gamma} - M_{\pi0}| < 20$ *MeV*.

Special $K_{\mu 3\gamma}$ criteria: muon compatible signal in GAMS + HCal + μC and three e/m showers in GAMS with $E_\gamma > 0.6$ *GeV*, missing mass $MM(\pi^+\pi^0) < 0.12$ *GeV* (effective against $K^+ \to \pi^+\pi^0\pi^0$ bkg).

Special $K_{e3\gamma}$ criteria: 4 e/m showers in GAMS with $E_\gamma > 0.7$ *GeV* and one charged track is identified as e^+ with $0.8 < E/p < 1.2$, the effective mass for γ-pair $0.12 < M_{\gamma\gamma} < 0.15$ *GeV*, $\Delta y = |y_\gamma - y_e| > 3$ *cm* (y is the vertical coordinate of a particle in GAMS, the magnetic field turns charged particles in the xz-plane), $|x_\nu, y_\nu| < 100$ *cm* (the reconstructed missing momentum direction must cross the active area of GAMS), the reconstructed mass of the system $M(K^+ \to \pi^0 e^+ \nu\gamma) > 0.45$ *GeV*, missing $\mathrm{M}^2(\pi^0 e^+\gamma) = (\mathrm{P_K} - \mathrm{P}_\pi - \mathrm{P}_e - \mathrm{P}_\gamma)^2 < 0.003$ GeV^2, 4 *mrad* $< \theta_{e\gamma} < 80$ *mrad* (effective against $K^+ \to \pi^+\pi^0$ and $K^+ \to e^+\nu\pi^0$ bkg).

RESULTS AND CONCLUSION

Violation of *T*-invariance leads to asymmetry in the distribution over the variable ξ (2), shown in Fig. 3.

As a result for $30 < E^* < 60$ *MeV* we have ratio of $\mathrm{R}_\mu = \mathrm{Br}(K_{\mu 3\gamma})/\mathrm{Br}(K_{\mu 3}) = (4.45 \pm 0.25(\text{stat.})) \times 10^{-4}$ and value of $A_\xi = -0.006 \pm 0.069(\text{stat.})$ for 960 ± 55 $K_{\mu 3\gamma}$ events.

For $K_{e3\gamma}$ we have three ratios of $\mathrm{R} = \mathrm{Br}(K_{e3\gamma})/\mathrm{Br}(K_{e3})$ [10] and values of A_ξ [11] in three slightly different ranges of E^* and $\theta_{e\gamma}$.

$\mathrm{R}_1 = \mathrm{Br}(K_{e3\gamma})/\mathrm{Br}(K_{e3}) = (1.990 \pm 0.017(\text{stat.}) \pm 0.021(\text{syst.})) \times 10^{-2}$ and $A_\xi = (+0.1 \pm 3.9(\text{stat.}) \pm 1.7(\text{syst.})) \times 10^{-3}$ for $E^* > 10$ *MeV*, $\theta_{e\gamma} > 10°$ for more than 65000 $K_{e3\gamma}$ events.

For the cuts $E^* > 30$ *MeV* and $\theta_{e\gamma} > 20°$, used in theoretical papers [1, 3] $\mathrm{R}_2 = (0.587 \pm 0.010(\text{stat.}) \pm 0.015(\text{syst.})) \times 10^{-2}$ and $A_\xi = (+4.4 \pm 7.9(\text{stat.}) \pm 1.9(\text{syst.})) \times 10^{-3}$ for more than 17000 $K_{e3\gamma}$ events.

For $E^* > 10$ MeV and $0.6 < \cos(\theta_{e\gamma}) < 0.9$ $\mathrm{R}_3 = (0.532 \pm 0.010(\text{stat.}) \pm 0.012(\text{syst.})) \times 10^{-2}$, and $A_\xi = (-7.0 \pm 8.1(\text{stat.}) \pm 1.5(\text{syst.})) \times 10^{-3}$ for more than 19000 $K_{e3\gamma}$ events.

These results are in good agreement with results of our previous ISTRA+ experiment for both $K_{\mu 3\gamma}$ [12] and $K_{e3\gamma}$ [13] decays, but total errors are two-three times smaller.

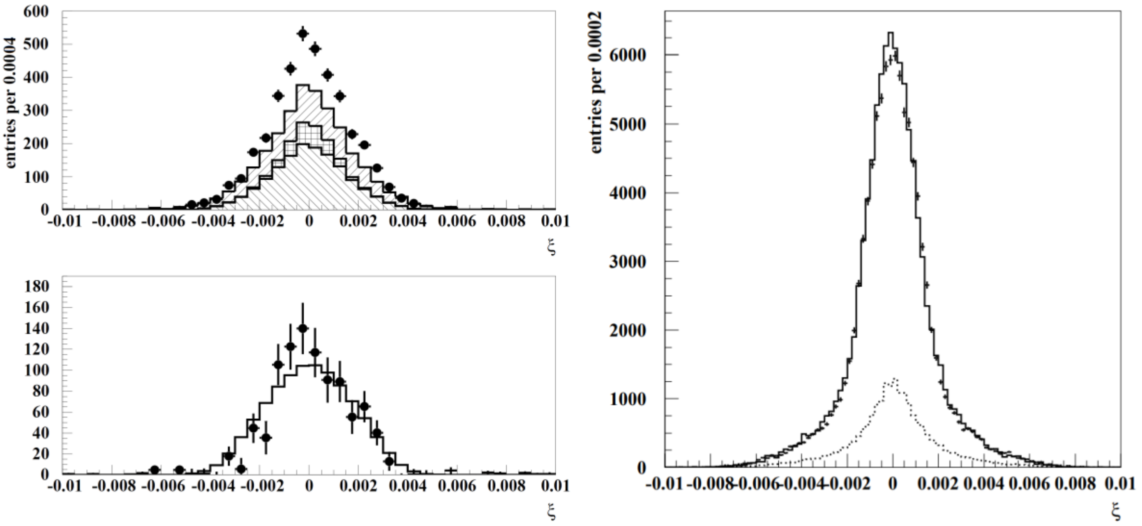


Fig. 3. Distribution over ξ variable. Points with errors are real data. Left – for $K_{\mu 3\gamma}$: top – with MC $K_{\mu 3}$(diagonal right shading) bkg, MC $K_{2\pi\gamma}$ (checker shading) bkg, MC $K_{3\pi}$ (diagonal left shading) bkg, bottom – bkg substracted, histogram is MC $K_{\mu 3\gamma}$ signal. Right – for $K_{e3\gamma}$: dotted curve is the total bkg, histogram is the MC signal plus bkg.

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