Study of $K^+ \to \pi^0 e^+ \nu_e \gamma$ decay with OKA setup

*A.Yu.*Polyarush[1,*]

[1]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

Abstract. Results of study of the $K^+ \to \pi^0 e^+ \nu\gamma$ decay at OKA setup are presented. 16889 events of this decay have been observed. The branching ratio with cuts $E^*_\gamma > 10$ MeV, $0.6 < cos\Theta^*_{e\gamma} < 0.9$ is calculated $R = \frac{Br(K^+ \to \pi^0 e^+ \nu_e \gamma)}{Br(K^+ \to \pi^0 e^+ \nu_e)} = (0.574 \pm 0.010(stat.) \pm 0.021(syst.)) \times 10^{-2}$. For the asymmetry A_ξ we get $A_\xi = -0.009 \pm 0.012(stat.)$

1 Introduction

The decay $K^+ \to \pi^0 e^+ \nu\gamma$ provides fertile testing ground for the Chiral Perturbation Theory (ChPT) [1, 2]. $K^+ \to \pi^0 e^+ \nu\gamma$ decay amplitudes are calculated at order ChPT $O(p^4)$ in [1], and branching ratios are evaluated in [3]. Recently, the CHPT analysis has been revised and expanded up to $O(p^6)$ [4]. The matrix element for $K^+ \to \pi^0 e^+ \nu\gamma$ has general structure

$$T = \frac{G_F}{\sqrt{2}} eV_{us}\varepsilon^\mu(q)\Bigg\{(V_{\mu\nu} - A_{\mu\nu})\overline{u}(p_\nu)\gamma^\nu(1-\gamma_5)v(p_l)$$

$$+\frac{F_\nu}{2p_l q}\overline{u}(p_\nu)\gamma^\nu(1-\gamma_5)(m_l - \hat{p}_l - \hat{q})\gamma_\mu v(p_l)\Bigg\} \equiv \epsilon^\mu A_\mu. \quad (1)$$

First term of the matrix element describes Bremsstrahlung of kaon and direct emission. The lepton Bremsstrahlung is presented by the second part of Eq.(1).

This decay is especially interesting as it is sensitive to *T*–odd contributions. According to CPT theorem, observation of *T* violation is equivalent to observation of *CP*–violating effects. An important experimental observable in a *CP* violation search is T–odd correlation. The *T*–odd correlation, for $K^- \to \pi^0 e^- \overline{\nu}\gamma$ decay it is defined as

$$\xi = \frac{1}{M_K^3} p_\gamma \cdot [p_\pi \times p_e]. \quad (2)$$

First suggestion to investigate *T*–odd triple-product correlations was done in [5]

To establish the presence of a nonzero triple-product correlations, one constructs a *T*–odd asymmetry of the form

$$A_\xi = \frac{N_+ - N_-}{N_+ + N_-}, \quad (3)$$

where N_+ and N_- are numbers of events with $\xi > 0$ and $\xi < 0$.

---

[*] e-mail: polyarush@inr.ac

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

2 OKA setup

OKA collaboration operate at IHEP Protvino U-70 Proton Synchrotron of NRC "Kurchatov Institute"-IHEP, Protvino. OKA detector (see Fig. 1) is located in positive RF-separated beam with 12.5% of K-meson. The detailed description of the OKA detector is given in our previous publications [6, 7].

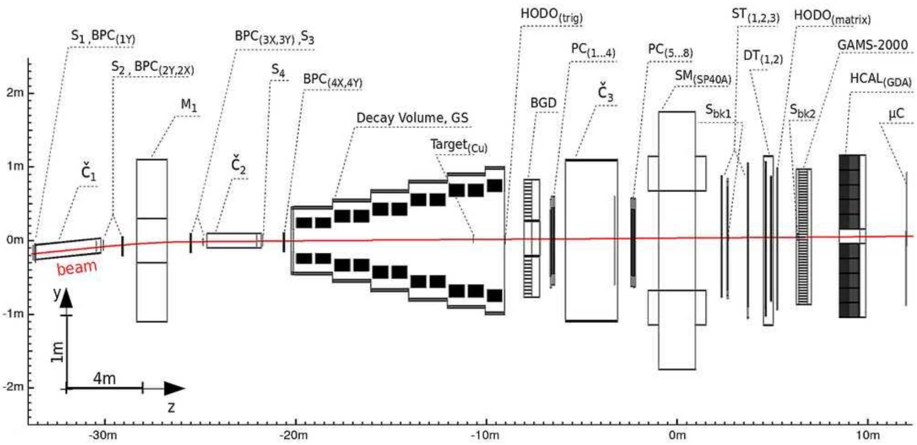

Figure 1. Layout of the OKA detector

3 $K^+ \to \pi^0 e^+ \nu\gamma$ events selection

A study of the $K^+ \to \pi^0 e^+ \nu\gamma$ decay is done with the data set accumulated in the 2012 and 2013 runs with a 17.7 GeV/c beam momentum. The Monte-Carlo simulation based on Geant3 package [8] includes a realistic description of the experimental setup.

To select $K^+ \to \pi^0 e^+ \nu\gamma$ decay channel a set of requirements is applied:

1) One positive charged track detected in tracking system and 4 showers detected in electromagnetic calorimeters GAMS- 2000 and EGS.

2) One shower must be associated with charged track.

3) Charged track identified as positron. The electron identification is done using the ratio of the energy of the shower to the momentum of the associated charged track. The particles with 0.8< E/p < 1.2 are accepted as electrons. The distance between the charged track extrapolation to the front plane of the electoromagnetic detector and the nearest shower must be less than 3 cm.

4) Vertex situated within the decay volume.

5) The effective mass $M_{\gamma\gamma}$ for one $\gamma\gamma$ – pair is $0.12 < M_{\gamma\gamma} < 0.15$ GeV.

Absence of signals in veto system above noise threshold is required.

4 Background suppression

The main background decay channels for the decay $K^+ \to \pi^0 e^+ \nu_e \gamma$ are:

(1) $K^+ \to \pi^0 e^+ \nu$ with extra photon. The main source of additional photons is an positron interactions in the substance of the detector.

(2) $K^+ \to \pi^+ \pi^0 \pi^0$ where one of the π^0 photons is not detected and π^+ decays to $e\nu$ or mistakenly identified as an positron.

(3) $K^+ \to \pi^+ \pi^0$ with "fake photon" and π^+ decayed or mistakenly identified as positron. Fake photon clusters can come from the interactions π^+ in the material of the detector, external bremsstrahlung upstream of the magnet, accidentals. All these sources are included in our MC calculations.

(4) $K^+ \to \pi^+ \pi^0 \gamma$ when π^+ decays or is mistakenly identified as positron.

(5) $K^+ \to \pi^0 \pi^0 e^+ \nu$ when one γ is lost.

To suppress the background channels, we used a set of kinematic cuts:

Cut 1: $E_{miss} > 0.5$ GeV

Requirement on the missing energy in the decay reduces mainly background (4).

Cut 2: $|\Delta y| = |y_\gamma - y_{e+}| > 5$ cm, where y_γ, y_{e+} are the y-coordinates of the γ and e^+ intersection of the front plane of the calorimeter GAMS.

Cut 3: $| \ x, y \ | < 100$cm, where x, y are the coordinates of the reconstructed neutrino intersection of the front plane of the calorimeter GAMS.

Cut 4: $M_K > 0.045$GeV, where M_K - K meson mass restored from the kinematics of the event.

In order to suppress all the main backgrounds, we use a cut on the missing mass squared

$$M^2(\pi^0 e \gamma) = (P_K - P_{\pi^0} - P_e - P_\gamma)^2.$$

For the signal events this variable corresponds to the square of the neutrino mass and must be zero within measurement accuracy.

Cut 5: $-0.003 < M^2(\pi^0 e^+ \gamma) < 0.003$.

The dominant background to $K_{e3\gamma}$ arises from K_{e3} with extra photon. The background (1) is suppressed by cut 2 and requirement on the angle between electron and photon in the laboratory frame $\Theta_{e\gamma}$. The distribution of the K_{e3}-background events has very sharp peak at zero angle. This peak is significantly narrower than that for signal events. This happens, in particular, because the emission of the photons by the electron from K_{e3} decay occurs in the setup material downstream the decay vertex, but angle is still calculated as if emission comes from the vertex.

Table 1. Event reduction statistics for the real data and the background MC.

Cut	Data	K^+_{e3}	$K^+_{3\pi}$	$K^+_{2\pi}$	$K^+ \to \pi^0 \pi^0 e^+ \nu$
1	705505	418301	19869	12299	1647
2	89044	14788	13401	2167	1076
3	60276	7817	8388	1629	942
4	31508	4014	2796	522	135
5	27860	3108	419	421	104
6	19490	2048	262	230	60

Cut 6: $0.004 < \Theta_{e\gamma} < 0.040$.

Right part of this cut is introduced for suppression of backgrounds (2,3,4,5).

After applying all the cuts, 19490 events are selected, with a background of 2601 events. Background normalization was done by comparison numbers of events for K_{e3} decay in MC and real data samples. Event reduction statistics is summarized in Table 1.

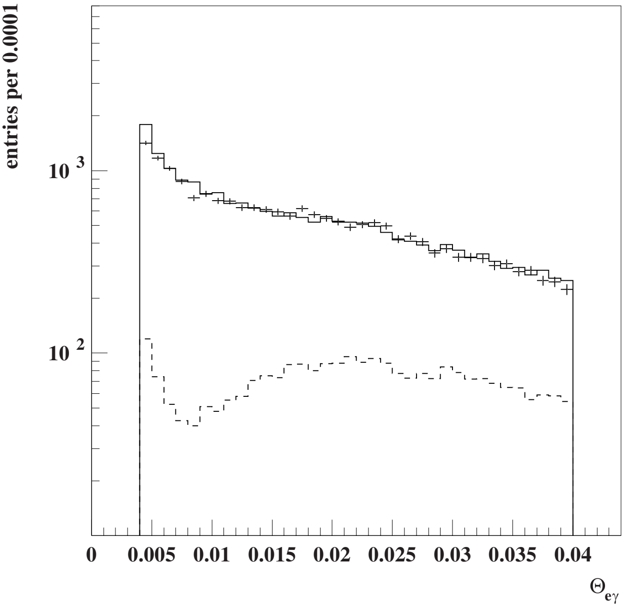

Figure 2. Distribution over $\Theta_{e\gamma}$ - the angle between electron and photon in lab. system. Real data (points with errors), MC background (solid line histogram) and signal plus MC background (dashed line histogram)

5 Results

Distribution over $\Theta_{e\gamma}$ - the angle between electron and photon in laboratory system (see Fig. 2). Reasonable agreement of the data with MC is seen. When generating the signal MC, a generator based on $O(p^2)$ [9] is used.

To obtain the branching ratio of the $K_{\pi^0 e^+ \nu_e \gamma}$ relative to the K_{e3} (R), the background and efficiency corrected number of $K_{e3\gamma}$ events is compared to that of 9055376 K_{e3} events found with the similar selection criteria. Further, the branching ratio with cuts $E^*_\gamma > 10$ MeV, $0.6 < cos\Theta^*_{e\gamma} < 0.9$, chosen for comparability with the previous experiments is calculated.

$$R = \frac{Br(K^+ \to \pi^0 e^+ \nu_e \gamma)}{Br(K^+ \to \pi^0 e^+ \nu_e)} = (0.574 \pm 0.010(stat.) \pm 0.021(syst.)) \times 10^{-2} \tag{4}$$

Systematic errors are estimated by variation of the cuts of Table 1 and using two different ways of backgrounds normalization.

A comparison with the results of previous experiments is shown in Table 2. Statistics more than four times compared to the previous measurement.

For the asymmetry A_ξ(for the same cuts as in Table 2) we preliminary get

$$A_\xi = -0.009 \pm 0.012(stat.) \tag{5}$$

Table 2. $\mathrm{Br}(K^+ \to \pi^0 e^+ \nu_e \gamma)/\mathrm{Br}(K^+ \to \pi^0 e^+ \nu_e)$ for $E^*_\gamma > 10$ MeV,$0.6 < cos\Theta^*_{e\gamma} < 0.9$ in comparison with previous data.

$R_{exp} \times 10^2$	N_{ev}	experiment
0.574 ± 0.01	6687	this experiment
0.48 ± 0.02	1423	ISTRA+ [10]
0.46 ± 0.08	82	XEBC [11]
0.56 ± 0.04	192	ISTRA [12]
0.76 ± 0.28	13	HLBC [13]

Systematic errors require further study.

References

[1] Bijnens J, Echer G and Gasser J Nucl.Phys. B **396**, 81 (1993)
[2] Pitch A Rep. Prog. Phys. **58**, 563 (1995)
[3] Maiani L, Pancheri G and Paver N, 1988 The Second DAFNE Physics Handbook (INFN-LNF-Divisione Ricerca, SIS-Ufficio Pubblicazioni, Frascati (Roma) Italy, ISBN 88-86409-02-8)
[4] B.Kubis *et al* Eur Phys. J. **C50** 557 (2007).
[5] Gevas J, Iliopolus J and Kaplan J Phys. Lett. **20** 432 (1966)
[6] Sadovsky AS *et al.* arXiv:1709.01473 [hep-ex] (2017)
[7] Yushchenko O P *et al.* arXiv:1708.09587 [hep-ex] (2017)
[8] Brun R *et al* Preprint CERN-DD/EE/84-1 (1984)
[9] Braguta V.V., Likhoded A A and Chalov A.E Phys. Rev. D **65** , 054038 (2002)[hep-ph/0106147]
[10] Ajinenko I V*et al* Yad. Fiz **70** 2125 (2007)
[11] Barmin V V*et al* SJNP **53**, 606 (1991)
[12] Bolotov V N *et al* JETP Lett. **42** 68, (1986) Yad. Fiz. **44** 108 (1986)
[13] Romano F *et al* Phys Lett. **36B** 525 (1971)