Measurement of T-odd asymmetry in radiative $K^+ \to \pi^0 e^+ \nu_e \gamma$ decay using OKA detector

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Abstract

The paper presents a measurement of the T-odd correlation in radiation decay $K^+ \to \pi^0 e^+ \nu_e \gamma$ performed on the installation of 101200 candidate events of the investigated decay were identified. Measured correlation $\xi_{\pi e \gamma}$ -is a mixed product of moments $e^+$, $\pi^0$, $\gamma$ in the kaon rest system, normalized by $M_K^3$. To assess the asymmetry of the distribution by $\xi_{\pi e \gamma}$ the value used is $A_\xi = \frac{N_+ - N_-}{N_+ + N_-}$, where $N_+$ is the number of events with $\xi$ greater than (less than) zero. For the $A_\xi$ asymmetry, the value is obtained $A_\xi = (+0.1 \pm 3.9 \text{(stat.)} \pm 1.7 \text{(syst.)}) \times 10^{-3}$ or $|A_\xi| < 5.4 \times 10^{-3} (90\% \text{ CL})$.

1 Introduction

In this article we continue the experimental study of the decay $K^+ \to \pi^0 e^+ \nu_e \gamma$ ($K_{\ell 3\gamma}$) started in [1], performed on triple statistics. This decay is of great interest because it allows a search for the $T$-odd triple correlations, by the $CPT$ theorem equivalent to detection of $CP$-invariance violation, which in kaon physics has been observed so far only in decays of neutral kaons. Therefore, radiation decays of charged K-mesons are of great interest to both theorists and experimenters as a possible alternative source of information about $CP$-invariance violation.
The experimental data currently available on the violation of CP-invariance are explained by the complex phase of the Kabibbo-Kobayashi-Maskawa quark mixing matrix\cite{2,3,4}. However, it has been proven that this mechanism is insufficient for explanations of the observed baryon asymmetry of the universe\cite{5,6,7}. This forces us to look for new sources of violation of CP-invariance. In general, a search for new processes with violation of CP-invariance makes it possible to look for a new physics beyond the Standard Model (SM).

Although CP-violation is extremely small in SM in leptonical and semileptonic decays of kaons, relatively large CP-violating effects are predicted in various models beyond the SM. So, in the decay $K^+ \rightarrow \mu^+\nu\gamma$ various models\cite{8,9,10,11,12,13} predict the $T$-odd transverse polarization of the muon at the level from $5\times 10^{-3}$\cite{11,12} to $5\times 10^{-2}$\cite{13}, and in the decay $K^+ \rightarrow \mu^+\nu\pi^0$ from $5\times 10^{-5}$\cite{14} to $5\times 10^{-3}$\cite{15}. The experimental restrictions (90% CL) for the transverse polarisation are: $P_T < 3.1 \times 10^{-2}$ and $P_T < 5.0 \times 10^{-3}$\cite{16,17}. These experiments provide the best opportunities for detecting the scalar (pseudoscalar) version of the New Physics (NP), while as it was noted in \cite{18}, the decay of $K_{e3\gamma}$ allows to search for the vector (axial) variant of the NP for which the matrix element of the decay $K^+ \rightarrow \pi^0 e^+\nu\gamma$ has a form:

$$ T = \frac{G_F}{\sqrt{2}} e V_{us} e^\mu(q) \left\{ (V_{\mu\nu} - A_{\mu\nu}) \bar{u}(p_{\nu}) \gamma^\nu (1 - \gamma_5)v(p_{\mu}) + \frac{F_\nu}{2p_{\mu}q} \bar{u}(p_{\nu}) \gamma^\nu (1 - \gamma_5)(m_{\nu} - \hat{p}_\nu - \hat{q})\gamma_\mu v(p_{\mu}) \right\}, \quad (1) $$

where hadron tensors $V_{\mu\nu}^{had}$ and $A_{\mu\nu}^{had}$ are defined as

$$ I_{\mu\nu} = i \int d^4x e^{i qx} \langle \pi^0(p')|T V_{\mu\nu}(x) I_{\nu}^{had}(0)|K^+(p)\rangle, \quad I = V, A, $$

with $V_{\nu}^{had} = (1 + g_V)\bar{s}\gamma_\nu u$, $A_{\nu}^{had} = (1 - g_A)\bar{s}\gamma_\nu\gamma_5 u$, $V_{\mu}^{em} = (2\bar{d}\gamma_\mu u - \bar{d}\gamma_\mu\gamma_5 u - \bar{s}\gamma_\mu d)/3$ and $F_\nu$ is the $K_{e3}$ matrix element $F_\nu = (1 + g_V)\langle \pi^0(p')|V_{\nu}^{had}(0)|K^+(p)\rangle$ here $g_V, g_A$ are the vector and pseudovector constants, which can be complex. The first term of equation (1) describes the kaon bramsstrahlung and the structural radiation diagram Fig.1a. The lepton bramsstrahlung radiation is represented by the second part of equation (1) and the diagram Fig.1b.

For the first time, a search for the triple $T$-odd correlations in the radiative decays of K-mesons

Figure 1: Diagram of $K^+ \rightarrow \pi^0 e^+\nu\gamma$ decay
was proposed in [19]. To study the triple $T$-odd correlations, a variable is used

$$\xi_{\pi e\gamma} = \frac{1}{M_K} \vec{p}_\pi \cdot [\vec{p}_\pi \times \vec{p}_\gamma]$$

(2)

To estimate the asymmetry of the distribution over the $\xi$ variable, we use the value

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

(3)

where $N_+(-)$ is the number of events with $\xi$ greater than (less than) zero. In paper [18] the following theoretical constraint for the vector and axial versions of the New physics in the framework of a model based on a gauge group $SU(2)_L \times SU(2)_R \times U(1)$, was obtained:

$$|A_\xi(K^+ \rightarrow \pi^0 e^- \nu_e\gamma)| < 0.8 \cdot 10^{-4}$$

(4)

In SM in the tree level, the asymmetry is zero, but a comparable value of $A_\xi$ appears as a result of electromagnetic interaction in the final state. This effect in one-loop approximation was calculated in [20, 21], the result is: $A_\xi = -0.59 \cdot 10^{-4}$, and $A_\xi = -0.93 \cdot 10^{-4}$ respectively.

2 Experiment

The OKA experiment has been carried out on the IHEP U-70 proton synchrotron on a secondary separated beam of K mesons with a momentum of 17.7GeV/c, enriched with K mesons up to 20%. The OKA setup is described in detail in our recent publications [1, 22, 23]. It consists (see figure 2) of a beam spectrometer, a decay volume with a veto system, a charged particle spectrometer, an electromagnetic calorimeter, a hadron calorimeter and a muon detector. The trigger used is described in [1].

Figure 2: Scheme of the OKA setup.
Monte Carlo (MC) calculations for the background and signal processes was carried out using the GEANT3\cite{24} package. Events are weighted according to theoretical matrix elements. The signal MC uses the $O(p^4)$ approximation of the Chiral perturbation theory(ChPT)\cite{20}.

3 Event selection

The events with one positively charged track registered by the detector’s track system and four showers in the GAMS-2000 electromagnetic calorimeter are selected as the candidates for the $K^+ \rightarrow \pi^0 e^+ \nu_e \gamma$ decay.

One of the showers should be associated with the charged track. The positron identification is done using the ratio of the shower energy and the momentum of the positron measured by the tracking system. In addition, a restriction on the distance between the charged track extrapolation to the front plane of the electromagnetic detector and the nearest shower is used: $d<3$ cm.

To reconstruct $\pi^0$, a pair from the three remaining showers (photons) not associated with the track with an invariant mass closest to the table value of the mass of $\pi^0$ is used (Fig. 3). To suppress the background, a selection $|m_{\gamma\gamma} - m_{\pi^0}| <30$ MeV is used. The energy of the photons included in $\pi^0$ should be greater than 0.5 GeV. The energy of the remaining photon should exceed 0.7 GeV.

![Figure 3: The invariant mass off $\gamma\gamma$-pairs closest to the table value of $\pi^0$ mass](image)

4 Background suppression

The main background decay channels for the investigated decay are:
1) $K^+ \rightarrow \pi^+\pi^0\pi^0$ with 1 lost $\gamma$ and $\pi^+$ falsely identified as a positron.
2) $K^+ \rightarrow \pi^+\pi^0$ with a random additional $\gamma$ and $\pi^+$ falsely identified as a positron.
3) $K^+ \rightarrow \pi^0e^+\nu_e$ with additional $\gamma$ due to the interaction of $e^+$ with the set-up substance.
4) $K^+ \rightarrow \pi^+\pi^0\gamma$ with $\pi^+$ falsely identified as a positron.
5) $K^+ \rightarrow \pi^0\pi^0e^+\nu_e$ with 1 $\gamma$ lost. All these background processes are included in the Monte Carlo calculations.

To suppress the backgrounds (1) - (5), we use selections:

Cut 1: $E_{\text{miss}} = E_{\text{beam}} - E_{\text{detected}} > 0.5\text{GeV}$.

The requirement on the missing energy mainly reduces the background (4).

Cut 2: $\Delta y = |y_\gamma - y_e|$ $> 3\text{ cm}$, where $y$ is the vertical coordinate of the point where the positron and photon hit the electromagnetic calorimeter. The magnetic field rotates the track of the charged particle in the $xz$ plane. This selection suppresses, first of all, the background (3) from the decay of $K^+ \rightarrow \pi^0 e^+\nu_e$.

Cut 3: $|x_\nu, y_\nu| < 100\text{ cm}$. A straight line along the direction of the missing momentum must cross the aperture of the electromagnetic calorimeter. This selection helps to suppress the backgrounds (1,5) where there are lost photons.

Cut 4: $0.004 < \Theta_{e\gamma} < 0.080\text{ rad}$. The left part of this selection is introduced precisely to suppress the background (3). The right part of the selection is applied against the background (2) of $K_{e3}$ decays.

Cut 5: $M_{K^+\rightarrow\pi^0e^+\nu_e\gamma} > 0.45\text{GeV}$. $M_{K^+\rightarrow\pi^0e^+\nu_e\gamma}$ - the reconstructed mass of the $(\pi^0e^+\nu_e\gamma)$ systems, assuming that the mass of an unregistered particle is zero ($m_\nu = 0$). The distribution of $M_K$ at this stage of the selections is shown in Fig. 4.

Cut 6: $-0.006 < M_\nu^2 < 0.006\text{GeV}^2$. To strengthen the selection 5, we use the requirement for the missing mass squared $M_\nu^2 = (P_K - P_{\pi^0} - P_e - P_\gamma)^2$. For signal events, this variable corresponds to the square of the neutrino mass and must be zero within the measurement accuracy, and for background events, the distribution for this variable is much wider.

The dominant background for the $K_{e3\gamma}$ decay is that from $K_{e3}$ decay with an additional photon - background (3). This background is suppressed by selection 2, as well as by the cut on the angle between the positron and the photon in the laboratory system $\Theta_{e\gamma}$. The distribution of $K_{e3}$-background events has a very narrow peak at zero $\Theta_{e\gamma}$. This peak is much narrower than in signal events. This is because the emission of photons by the positron in the background process occurs as a result of $e^+$ interactions in the detector material after the decay vertex, and the angle in the reconstruction program is still calculated, as if the radiation was emitted from the primary vertex.

The background decay channel (4) has a branching at the level of the studied one and is suppressed by the correct identification of the positron, as well as the missing energy selection(1).

The background channel (5) is suppressed by the selection of the missing mass (Cut 6).

As a result, after all the selections, we are left with 101200 candidate events for the decay of $K^+ \rightarrow \pi^0e^+\nu_e\gamma$. The background is 17700 events. The normalization of backgrounds was carried out by comparing the number of registered $K^+ \rightarrow \pi^0e^+\nu_e$ decays in the data and MC.
Figure 4: Distribution over the reconstructed kaon mass. The dotted curve is the total background. A solid histogram is the sum of the MC signal and background.

5 Results

Violation of T-invariance leads to asymmetry in the distribution over the variable $\xi$ (2), shown in Fig. 5.

The measured value of $A_\xi$ (3), characterizing the asymmetry, is calculated for $E^*_\gamma > 10$ MeV and $\Theta^*_e > 10^\circ$, where $E^*_\gamma$, $\Theta^*_e$ - the photon energy and emission angle in the kaon rest frame

$A_\xi = (+0.1 \pm 3.9\text{ (stat.)} \pm 1.7\text{ (system.)}) \times 10^{-3}$,

The statistical error is calculated taking into account the background. The corresponding constraint is $|A_\xi| < 5.44 \times 10^{-3}$ (90% CL).

A comparison with the result of previous experiment is given in the table 0 for the cuts $E^*_\gamma > 10$ MeV, $0.6 < \cos \Theta^*_e < 0.9$, which were used in [25].

| $A_\xi$ | $N_{ev}$ | experiment |
|---------|---------|------------|
| $-0.007 \pm 0.008 \pm 0.002$ | 19295 | this experiment |
| $-0.015 \pm 0.021$ | 1456 | ISTRA+ [25] |

Table 0: Comparison of experimental results

For the cuts $E^*_\gamma > 30$ MeV and $\Theta^*_e > 20^\circ$, used in theoretical papers [18, 21], the following result is obtained:

$A_\xi = (+4.4 \pm 7.9\text{ (stat.)} \pm 1.9\text{ (syst.)}) \times 10^{-3}$
Figure 5: Distribution over $\xi$ variable. The dotted curve is the total background. The solid histogram is the sum of the MC signal and background.

Let’s take a closer look at the assessment of the systematic errors for the case $E^*_\gamma > 10\text{MeV}$ and $\Theta^*_{e\gamma} > 10^\circ$. The systematic due to selections is determined by varying each of them and is given in the table 1. Additional systematics occurs from the uncertainty of zero of the $\xi_{\pi e\gamma}$ scale due to measurement errors. The evaluation of this contribution gives $\pm 0.00065$.

| $N_{\text{cut}}$ | 1 | 2 | 3 | 4 | 5 | 6 |
|-----------------|---|---|---|---|---|---|
| $\Delta \cdot 10^3$ | 0.03 | 0.04 | 0.04 | 0.03 | 0.96 | 0.70 |

Table 1: The contribution of the variation of each of the cuts to the systematic error for $E^*_\gamma > 10\text{MeV}$ and $\Theta^*_{e\gamma} > 10^\circ$.

The estimate of a false asymmetry in the $\xi_{\pi e\gamma}$ distribution due to the acceptance of the setup, the efficiency of the reconstruction and selections was carried out using the signal MC, in which there is no $CP$ violation. The measured difference between the original (0) and reconstructed value of the $A_\xi$ equals to: $\Delta_A = 0.0012 \pm 0.0011$, that is, there is no significant effect. The error of the estimate is added to the systematics.

The systematics related to the models used in MC is also investigated. In signal MC $O(p^4)$ approximation of ChPT is replaced by $O(p^2)$. This gives a negligible effect.
6 Summary

The paper continues a study of the $K^+ \to \pi^0 e^+ \nu_e \gamma$ decay on statistics of $10^5$ events three times higher than the one used in [1]. A search is performed for $T(CP)$-odd effects in this decay, which could manifest themselves in a non-zero value of the asymmetry $A_\xi$ (2) of the $\xi$ (1) distribution. As a result, the values of $A_\xi$ for three regions in the photon energy and emission angle in the kaon rest frame are obtained:

$$A_\xi = (+0.1 \pm 3.9\text{(stat.)} \pm 1.7\text{(syst.)}) \times 10^{-3}, \quad |A_\xi| < 5.44 \times 10^{-3}(90\%\ CL)$$

for $E_\gamma^* > 10 \text{ MeV}$ and $\Theta_{e\gamma}^* > 10^\circ$.

$$A_\xi = (-7.0 \pm 8.1\text{(stat.)} \pm 1.5\text{(syst.)}) \times 10^{-3}, \quad |A_\xi| < 1.05 \times 10^{-2}(90\%\ CL)$$

for $E_\gamma^* > 10 \text{ MeV}$, $0.6 < \cos\Theta_{e\gamma}^* < 0.9$.

$$A_\xi = (+4.4 \pm 7.9\text{(stat.)} \pm 1.9\text{(syst.)}) \times 10^{-3}, \quad |A_\xi| < 1.04 \times 10^{-2}(90\%\ CL)$$

for $E_\gamma^* > 30 \text{ MeV}$ and $\Theta_{e\gamma}^* > 20^\circ$.

Within extensions of SM the non-zero asymmetry in the decay occur in the vector and axial vector theories, which, in the most general form, can be described by the matrix element (1), in which the constants $g_A$ and $g_V$ are complex. In paper [18] in the framework of ChPT $O(p^4)$ the following estimate is obtained: $A_\xi = \text{Im}(g_A + g_V) \times 3 \cdot 10^{-3}$ for $E_\gamma^* > 30 \text{ MeV}$ and $\Theta_{e\gamma}^* > 20^\circ$. From here and from our result we can get the constraint $\text{Im}(g_A + g_V) < 3.5(90\%\ CL)$. This result may be possibly improved by selecting an optimal region in $(E_\gamma^*, \Theta_{e\gamma}^*)$. For more specific variant of SM-extension, for example, those considered in [26], the estimate $|A_\xi| < 0.8 \times 10^{-4}$ was obtained in [18].

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