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A direct test of $\mathcal{T}$ symmetry in the neutral K meson system at KLOE-2

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Abstract. This work presents prospects for conducting a novel direct test of time-reversal symmetry at the KLOE-2 experiment. Quantum entanglement of neutral K meson pairs uniquely available at KLOE-2 allows to probe the T symmetry directly and independently of CP violation. This is achieved by a comparison of probabilities for a transition and its inverse obtained through an exchange of initial and final states. Such transitions between flavor and CP-definite states of the neutral kaons are only connected by the T conjugation which ensures the CP-independence of the test. While a similar measurement was performed by the BaBar experiment with neutral B mesons, the KLOE-2 detector can test T-violation in the neutral kaons system. Such a test requires i.a. reconstruction of the $\mathrm{K_L} \to 3\pi^0$ decay accompanied by $\mathrm{K_S} \to \pi^{\pm}\ell^{\mp}\nu$ with good timing information. Therefore a new reconstruction method for the $\mathrm{K_L} \to 3\pi^0$ decay is also presented which is capable of reconstructing this process with decay time resolution of $\mathcal{O}(1\tau_S)$.

1. Introduction

The fact that $\mathcal{CP}$ symmetry is not conserved in the neutral meson system has been well known for almost fifty years. Conversely, the time-reversal symmetry in this system, although its violation should follow from the well confirmed $\mathcal{CPT}$ invariance, lacked a direct experimental evidence for decades after $\mathcal{CP}$ violation discovery with neutral kaons in 1964 [1]. The reason for this is that a direct measurement of $\mathcal{T}$ non-invariance would require observation of a probability asymmetry between a process and the same process inverted in time and such an experiment is difficult to realize for any unstable system.

Since for neutral mesons, as zero-spin particles, the transitions to compare are conjugated by an exchange of initial and final states, the oscillation phenomenon is one of the few processes that can be used to obtain both transitions. It was first used to test the time-reversal symmetry by the CPLEAR experiment in 1998, yielding a non-zero probability asymmetry in $\mathrm{K}^0 \to \bar{\mathrm{K}}^0$ and $\bar{\mathrm{K}}^0 \to \mathrm{K}^0$ oscillations [2]. However, the fact that the initial and final states in this case are conjugated both by the $\mathcal{T}$ and $\mathcal{CP}$ operations has lead to a controversy as to whether this result can be attributed solely to $\mathcal{T}$ violation independently of $\mathcal{CP}$ violation. While some authors pointed out the role of decay as initial state interaction in this process [3, 4] and others argued that is not relevant in this case [5, 6], it remained clear that another way to directly test the time reversal symmetry violation independently of $\mathcal{CP}$ would be highly desirable [4].

A suitable measurement comparing selected transitions between $\mathcal{CP}$-definite and flavour-definite states with their time-reversal conjugates was proposed for the neutral B meson system

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by Bernabeu *et al.* in 2012 [7] and soon followed by a similar proposition realizable with neutral kaons [8]. For the transitions' reversibility, quantum entanglement in the system must be used which is available at B-factories and at the DAΦNE ϕ-factory. Among the former, the BaBar experiment has already measured a $\mathcal{T}$-violating asymmetry at 14σ level [9] constituting the first direct observation of $\mathcal{T}$-violation in transitions that are only connected by the time-reversal transformation. In case of K mesons, since entangled $\mathrm{K_S K_L}$ pairs are uniquely available at the DAΦNE collider, KLOE-2 is the only experiment presently able to provide the first time-reversal violation evidence in the neutral kaon system. Prospects for such a measurement at KLOE-2 and first analysis steps are presented in the remainder of this work.

2. A $\mathcal{T}$-symmetry test independent of $\mathcal{CP}$

The principle of the time-reversal symmetry test at KLOE-2 is based on defining transitions between states of neutral kaons being either states with definite strangeness $\{\mathrm{K}^0\ (S=+1), \bar{\mathrm{K}^0}\ (S=+1)\}$ or eigenstates of the $\mathcal{CP}$ operator which can be expressed using the former as:

$$|\mathrm{K}_+\rangle = \frac{1}{\sqrt{2}}\left[|\mathrm{K}^0\rangle + |\bar{\mathrm{K}^0}\rangle\right] \qquad (\mathcal{CP}=+1), \tag{1}$$

$$|\mathrm{K}_-\rangle = \frac{1}{\sqrt{2}}\left[|\mathrm{K}^0\rangle - |\bar{\mathrm{K}^0}\rangle\right] \qquad (\mathcal{CP}=-1). \tag{2}$$

State of a neutral kaon can be identified in one of these two bases at the moment of its decay by observation of the decay final state. With an assumption of the $\Delta Q = \Delta S$ rule (well tested in semileptonic kaon decays [10]), each charge of secondary lepton can only be created from a strangeness-definite state of the decaying kaon, as shown in the diagrams in Figure 1. In the following, final states with a positively and negatively charged leptons will be indicated as ℓ^+ and ℓ^-, respectively.

Figure 1. Diagrams of semileptonic decays of neutral kaons. The $\Delta S = \Delta Q$ rule guarantees that the state with a positively-charged lepton comes from K^0 decay whereas $\bar{\mathrm{K}^0}$ always decays into a final state with a lepton of negative charge.

On the other hand, hadronic final states which are $\mathcal{CP}$-even (e.g. two pions, hereafter named the $\pi\pi$ final state) can only be produced from the K_+ kaon state and $\mathcal{CP}$-odd states like $3\pi^0$ come from decays of K_-. It can be shown that $\mathcal{CP}$ violation may be safely neglected in these considerations [8].

Although the above facts allow for identification of the decaying kaon, observing a transition between two kaon states also requires tagging of the kaon state also a certain time before its decay. This can be achieved using neutral kaon pairs available at KLOE-2 which exhibit quantum entanglement of their states. Once the state of the first decaying kaon is identified by observation of its decay, its entangled and still-living partner is known to be in an orthogonal state at the same time. Consequently, observation of its decay after a time interval Δt can lead to the observation of a kaon transition where both initial and final state are tagged in the strangeness or $\mathcal{CP}$-basis.

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3. Time-reversal symmetry violation observables at KLOE-2

There are four possible transitions between flavour and $\mathcal{CP}$-definite states of neutral K mesons, as listed in Table 1. As these transitions are not irreversible, there can be a $\mathcal{T}$-conjugated process defined for each of them. Comparison of rates between each transition and its time-reversal conjugate would constitute a direct $\mathcal{T}$ symmetry test and its independence of $\mathcal{CP}$ violation follows from a comparison of the $\mathcal{T}$-and $\mathcal{CP}$-conjugated processes shown in Table 1, which are not identical.

Table 1. Four possible transitions between flavour and $\mathcal{CP}$-definite states of neutral kaons and their time-reversal conjugates obtained by exchange of initial and final states. The $\mathcal{T}$-conjugated transitions are not identical with the $\mathcal{CP}$ conjugates given in the last column. Each of the transitions is experimentally identified by a time-ordered pair of decays given in parentheses.

	Transition	$\mathcal{T}$-conjugate	$\mathcal{CP}$-conjugate
1	$\mathrm{K}^0 \to \mathrm{K}_+$ $(\ell^-, \pi\pi)$	$\mathrm{K}_+ \to \mathrm{K}^0$ $(3\pi^0, \ell^+)$	$\bar{\mathrm{K}^0} \to \mathrm{K}_+$
2	$\mathrm{K}^0 \to \mathrm{K}_-$ $(\ell^-, 3\pi^0)$	$\mathrm{K}_- \to \mathrm{K}^0$ $(\pi\pi, \ell^+)$	$\bar{\mathrm{K}^0} \to \mathrm{K}_-$
3	$\bar{\mathrm{K}^0} \to \mathrm{K}_+$ $(\ell^+, \pi\pi)$	$\mathrm{K}_+ \to \bar{\mathrm{K}^0}$ $(3\pi^0, \ell^-)$	$\mathrm{K}^0 \to \mathrm{K}_+$
4	$\bar{\mathrm{K}^0} \to \mathrm{K}_-$ $(\ell^+, 3\pi^0)$	$\mathrm{K}_- \to \bar{\mathrm{K}^0}$ $(\pi\pi, \ell^-)$	$\mathrm{K}^0 \to \mathrm{K}_-$

The time-reversal asymmetry can be defined using ratios of probabilities of transitions at time Δt to probabilities of their $\mathcal{T}$-inverses at the same time. Four theoretical ratios may be defined this way:

$$R_1(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_+(\Delta t)]}{P[\mathrm{K}_+(0) \to \mathrm{K}^0(\Delta t)]}, \qquad R_2(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]},$$
$$R_3(\Delta t) = \frac{P[\bar{\mathrm{K}^0}(0) \to \mathrm{K}_+(\Delta t)]}{P[\mathrm{K}_+(0) \to \bar{\mathrm{K}^0}(\Delta t)]}, \qquad R_4(\Delta t) = \frac{P[\bar{\mathrm{K}^0}(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \bar{\mathrm{K}^0}(\Delta t)]}. \tag{3}$$

Each of the transitions used in the above ratios is experimentally identified by a time-ordered pair of kaon decays given in brackets in Table 1. For transitions 1 and 3, the conjugated process would involve the first kaon to decay into $3\pi^0$, for which little statistics is expected as the search for $\mathcal{CP}$-violating decay $\mathrm{K_S} \to 3\pi^0$ at KLOE yielded no candidates [11]. For the remaining transitions 2 and 4, however, large statistics is available at KLOE-2 and their probabilities can be measured through numbers of double kaon decays to states f_1, f_2 separated by time Δt, denoted as $I(f_1, f_2; \Delta t)$. Experimental equivalents of ratios R_2 and R_4 are thus defined as follows:

$$R_2^{exp}(\Delta t) = \frac{\mathrm{I}(l^-, 3\pi^0; \Delta t)}{\mathrm{I}(\pi\pi, l^+; \Delta t)} = R_2(\Delta t) \times \frac{C(l^-, 3\pi^0)}{C(\pi\pi, l^+)}, \tag{4}$$

$$R_4^{exp}(\Delta t) = \frac{\mathrm{I}(l^+, 3\pi^0; \Delta t)}{\mathrm{I}(\pi\pi, l^-; \Delta t)} = R_4(\Delta t) \times \frac{C(l^+, 3\pi^0)}{C(\pi\pi, l^-)}. \tag{5}$$

The theoretical ratios ($R_i(\Delta t)$) are easily extracted from R_2^{exp} and R_4^{exp} as shown in Eq. 4, 5 by using coefficients dependent on neutral kaon branching fractions and widths [8]:

$$\frac{C(l^-, 3\pi^0)}{C(\pi\pi, l^+)} \simeq \frac{C(l^+, 3\pi^0)}{C(\pi\pi, l^-)} \simeq \frac{\mathrm{BR}(\mathrm{K_L} \to 3\pi^0)}{\mathrm{BR}(\mathrm{K_S} \to \pi\pi)} \frac{\Gamma_L}{\Gamma_S}, \tag{6}$$

all of which have been measured by KLOE [12] and whose precision should be further improved by KLOE-2 [13].

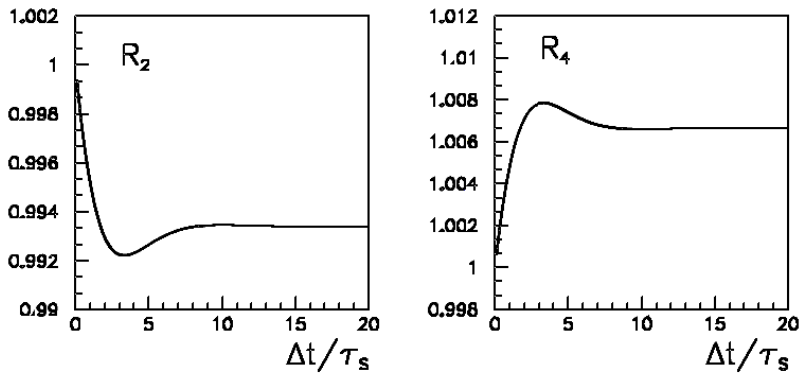

Figure 2. Expected behaviour of the R_i ratios as a function of decay time difference. The figure was adapted from [8].

Finally, determination of an asymptotic behaviour of theoretical ratios $R_2(\Delta t)$ and $R_4(\Delta t)$ would measure violation of time-reversal symmetry in the neutral kaon system. Figure 2 shows the expected dependence of these ratios with assumed time-reversal violation. If $\mathcal{T}$ was conserved, the ratios should tend to unity for large time intervals Δt. Indeed, it can be shown [8] that asymptotic discrepancy of $R_2(\Delta t)$ and $R_4(\Delta t)$ from 1 is related to the $\mathcal{T}$-violating parameter ϵ as:

$$R_2(\Delta t \gg \tau_S) \simeq 1 - 4\Re\epsilon, \quad (7)$$

$$R_4(\Delta t \gg \tau_S) \simeq 1 + 4\Re\epsilon. \quad (8)$$

Therefore, a measurement of R_2^{exp} and R_4^{exp} as functions of Δt for large time differences at KLOE-2 will provide measurement of degree of $\mathcal{T}$ symmetry violation in the neutral K meson system.

4. KLOE-2 and DAΦNE

4.1. The DAΦNE ϕ-factory

DAΦNE is an electron-positron collider located at the accelerator complex of INFN National Laboratory of Frascati (LNF). It is composed of two separate storage rings, each storing a beam of 0.51GeV. The rings intersect at two regions, one of which provides events to the KLOE detector (Figure 3). The center-of-mass energy of the colliding beams ($\sqrt{s}$ ≈1020MeV) is the mass of the phi-meson resonance, which is produced with a cross-section of about 3μb.

The ϕ-mesons are produced almost at rest ($\beta_\phi \approx 0.015$), with only a small momentum component in the direction perpendicular to the beam axis. Their almost immediate decays ($\tau_\phi = 1.55 \pm 0.01 \times 10^{-22}$s) provide pairs of K mesons, either charged (with a branching fraction of 48.9%) or neutral (34.2%). The K^+K^- and K_LK_S pairs are widely used to study kaon properties as the possibility of tagging kaons by their partner's decay allows absolute branching ratios to be measured. Furthermore, the neutral kaon pairs provided by DAΦNE have an additional unique feature. Due to quantum numbers conservation in a strong ϕ meson decay, the K_SK_L pairs are produced in an anti-symmetric zero-strangeness state:

$$|i\rangle = \frac{1}{\sqrt{2}} \left(\left|K^0(+\vec{p})\right\rangle \left|\bar{K^0}(-\vec{p})\right\rangle - \left|\bar{K^0}(+\vec{p})\right\rangle \left|K^0(-\vec{p})\right\rangle \right), \quad (9)$$

or as expressed in the basis of $\mathcal{CP}$ eigenstates:

$$|i\rangle = \frac{1}{\sqrt{2}} \left(|\mathrm{K}_+(+\vec{p})\rangle \, |\mathrm{K}_-(-\vec{p})\rangle - |\mathrm{K}_-(+\vec{p})\rangle \, |\mathrm{K}_+(-\vec{p})\rangle \right). \quad (10)$$

This initial state of the neutral kaon system produced by DAΦNE exhibits quantum entanglement of the two kaon states in the genuine EPR sense [14]. What follows is that whereas state of each kaon is undefined until the observation of the first decay, measurement of one of the states (by observation of its decay) guarantees the partner particle to be in the orthogonal state at the same time.

This feature allows for a broad range of kaon interferometry based tests of fundamental symmetries [15] such as CPT and Lorentz Symmetry tests [16]. Moreover, it is the property which opens a possibility of a time-reversal symmetry at KLOE-2.

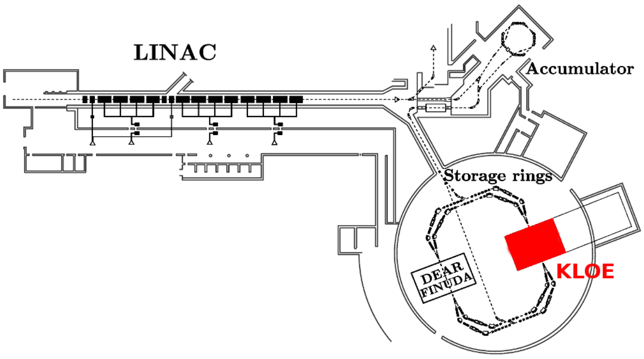

Figure 3. The accelerator complex at LNF. The DAΦNE collider is composed of two storage rings intersecting at two points, at one of which the KLOE detector is located. The figure was adapted from [12].

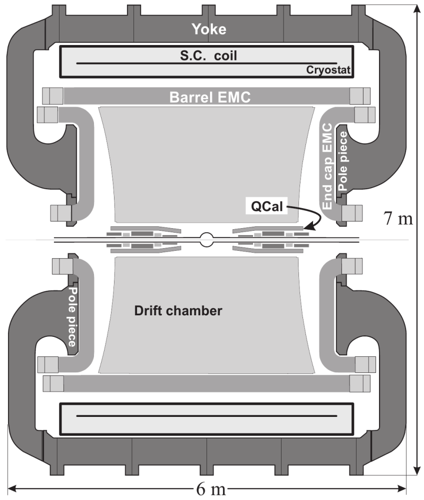

Figure 4. Longitudinal section of the KLOE detector. The figure was adapted from [12].

4.2. The KLOE detector

Tho KLOE (K LOng Experiment) detector is shaped as a barrel surrounding one of the DAΦNE interaction points, with a radius of 2 m and length of almost 3.5 m. Its large size is dictated by the mean path travelled by the long-lived neutral kaons produced there, which is about 3.4 m. The detector is constituted by a cylindrical drift chamber surrounded by an electromagnetic calorimeter (see the longitudinal detector section in Figure 4) which provides good coverage around the interaction point (98% of solid angle).

The drift chamber [17] uses a gas mixture based on helium (90%) and isobutane (10%) which ensures small material budget in order to prevent K_L regeneration and photon conversion in the gas. The resolution of the KLOE Drift Chamber (DC) is 150 μm in the transverse plane and 2 mm in the z direction. Momentum of charged particles can be reconstructed with the relative resolution of 0.4% whereas vertexing resolution is of the order of 1 mm [17]. The whole detector is immersed in a magnetic field of 0.52 T provided by a superconducting coil.

The calorimeter [18] is a sampling electromagnetic detector with scintillating fibers as active material and passive lead layers to enhance electromagnetic shower production. It provides an excellent timing resolution and high detection efficiency for photons in the 20–500 MeV energy range [18], which is crucial for the reconstruction presented in section 5.2. Spatial and time resolution of the KLOE calorimeter is given below:

$$\sigma_t = \frac{54\,ps}{\sqrt{E[GeV]}} \oplus 140ps, \quad \sigma_E = \frac{5.7\%E}{\sqrt{E[GeV]}}, \quad \sigma_x = \sigma_y = 1\,cm, \quad \sigma_z = \frac{1.2\,cm}{\sqrt{E[GeV]}} \tag{11}$$

4.3. Upgrade of KLOE to KLOE-2

KLOE started its operation at the DAΦNE collider in 1999 and was taking data collecting a total integrated luminosity of 2.5 fb^{-1} which corresponds to about 10^{10} of produced ϕ mesons. During KLOE runs DAΦNE reached a peak value of instantaneous luminosity of $1.4 \cdot 10^{32}\ cm^{-2}s^{-1}$.

In the recent years, the KLOE detector has undergone a thorough upgrade to start new measurements as KLOE-2. The upgrades involved the addition of new calorimeters at small angles around the beam axis to increase acceptance for photons and instrument the final focusing region [19, 20]. Moreover, new sets of detectors have been installed close to the beam line for tagging $\gamma\gamma$ events through detection of scattered high and low energy e^+e^- [21, 22]. Finally, a novel tracking device was constructed and installed in the region between the interaction point and drift chamber inner wall. This KLOE-2 Inner Tracker is a pioneer construction of a cylindrical Gas Electron Multiplier (GEM) tracker [23] composed of 4 layers of a triple-GEM detector barrel-shaped around the KLOE-2 interaction point. Its addition to KLOE-2 improves vertexing capabilities and increases acceptance for tracks with low transverse momentum.

The KLOE-2 detector restarted operation in 2014 in view of collecting a sample of the order of 10 fb^{-1} in the next years. The physics programme of KLOE-2 is rich [13] and includes the possibility to conduct the first direct $\mathcal{T}$ symmetry test with neutral kaons described in this work.

5. Prospects for experimental realization of the $\mathcal{T}$ test at KLOE-2

5.1. Required reconstruction of events

In order to measure the double decay rates used in R_2^{exp} and R_4^{exp} (Eq. 4–5) reconstruction must be performed for the following two classes of events, each composed of a pair of kaon decays separated by a time interval of Δt:

$$\phi \to \mathrm{K_S K_L} \quad \to 2\pi\ \pi^{\mp}\ell^{\pm}\nu, \tag{12}$$

$$\phi \to \mathrm{K_S K_L} \quad \to \pi^{\pm}\ell^{\mp}\nu\ 3\pi^0. \tag{13}$$

As the time-reversal symmetry test observables (Eq. 4–5) are time-dependent, it is important to reconstruct the time interval between decays with good accuracy. In turn, the resolution of kaon decay times in the asymptotic plateau region of $\Delta t \gg \tau_S$ should be $\mathcal{O}(1\tau_S)$ which to translates to decay point spatial resolution $\mathcal{O}(1\ cm)$.

Figure 5 schematically shows the reconstruction of these two classes of events. In case of a two-pion final state, charged pions ($\pi^+\pi^-$) may be chosen rather than $\pi^0\pi^0$ to profit from pion tracks reconstructed by the KLOE drift chamber. Both kaon decay vertices can then be easily reconstructed using charged particle tracks (Figure 5, left). The other class of processes, shown in Figure 5, right, is significantly more challenging to reconstruct as one of the decays, $\mathrm{K_L} \to 3\pi^0$, only involves neutral particles. Moreover, as the kinematics of the accompanying $\mathrm{K_S}$ decay is not closed due to a missing neutrino, reconstruction of $\mathrm{K_L} \to 3\pi^0$ must rely solely on information on clusters created in the EMC by photons originating in π^0 decays. Therefore a special vertex reconstruction method was devised for this decay.

5.2. New $\mathrm{K_L} \to 3\pi^0$ reconstruction method for $\mathrm{K_S K_L} \to \pi^{\pm}e^{\mp}\nu_e\ 3\pi^0$

The new reconstruction method presented in this work aims at providing spatial coordinates of the $\mathrm{K_L}$ decay point and $\mathrm{K_L}$ decay time by using only the photons from $\mathrm{K_L} \to 3\pi^0 \to 6\gamma$ recorded by the electromagnetic calorimeter (Figure 6).

Each EMC cluster contains information on its location as well as recording time (X_i, Y_i, Z_i, T_i). Thus, one might consider a set of possible points at which the corresponding photon originated. Such a set constitutes a sphere centered at cluster position with a radius equal to path length travelled by the γ. The latter, however, is unknown due to its dependence on the unknown decay time of the kaon t, which is also the γ creation time if the π^0 lifetime

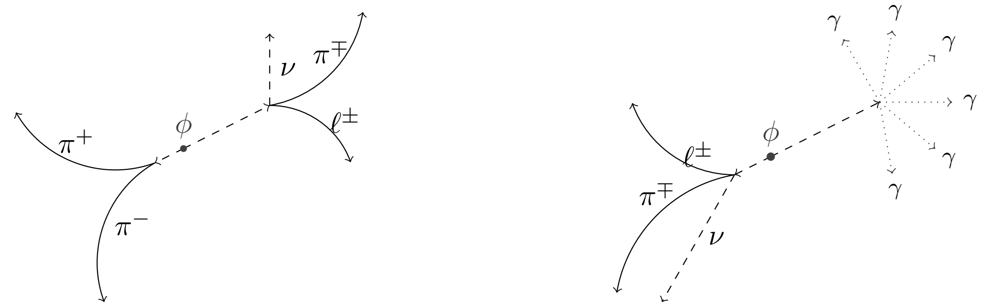

Figure 5. Schematic view of the two classes of processes whose reconstruction is required to measure R_2^{exp} and R_4^{exp} for the $\mathcal{T}$ test. Continuous lines denote DC tracks of charged particles while dashed and dotted lines correspond to neutral particles. Process shown in the right poses a reconstruction challenge due to the $\mathrm{K_L} \to 3\pi^0$ decay involving neutral particles only.

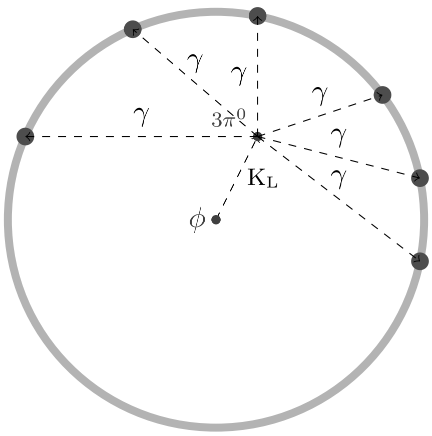

Figure 6. The $\mathrm{K_L} \to 3\pi^0 \to 6\gamma$ process in the cross-section view of the detector. The neutral kaon nor the pions are recorded by the tracking detectors and the only experimental information on this decay are up to six clusters in the KLOE electromagnetic calorimeter (grey band) created by photons to which the neutral pions decay almost immediately.

is neglected (Figure 7). The equation describing the sphere of origin points for i-th calorimeter cluster is:

$$(T_i - t)^2 c^2 = (X_i - x)^2 + (Y_i - y)^2 + (Z_i - z)^2. \tag{14}$$

Such a sphere can be defined for each recorded EMC cluster. The $\mathrm{K_L}$ decay vertex is the common origin of all the photons and therefore can be reconstructed as the intersection of the photon spheres as shown in Figure 6. If at least 4 photons are recorded, their corresponding system of equations (Eq. 14) can be solved analytically. This yields two solutions for the $\mathrm{K_L}$ decay vertex coordinates and decay time, among which the physical solution is identified by a set of criteria and the other one is rejected as a mathematical artifact. Possible presence of up to six recorded photons is used to numerically solve an overdetermined system of equations to obtain improved accuracy.

It should be stressed that this reconstruction method directly yields the kaon decay time in addition to vertex location, which eliminates the need to calculate it with kaon travelled path length and momentum which would introduce additional uncertainty to its evaluation. In conjunction with the excellent timing properties of the KLOE electromagnetic calorimeter, this reconstruction yields a good resolution of long-lived kaon decay time although being based on calorimetric information only.

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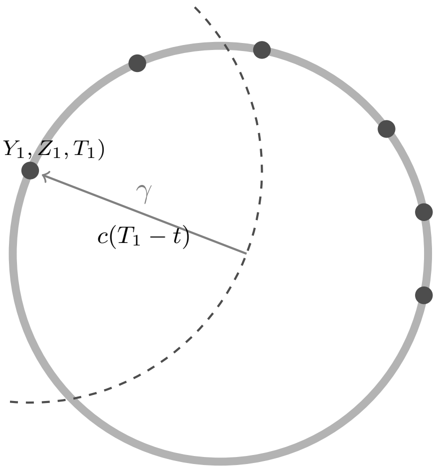

Figure 7. For each of the EMC clusters its position and recording time is reconstructed by the calorimeter with a good resolution (see 11). This allows to define a set of possible origin points of the incident photon as a sphere centered at the cluster whose radius is proportional to the difference of cluster time and $\mathrm{K_L}$ decay time.

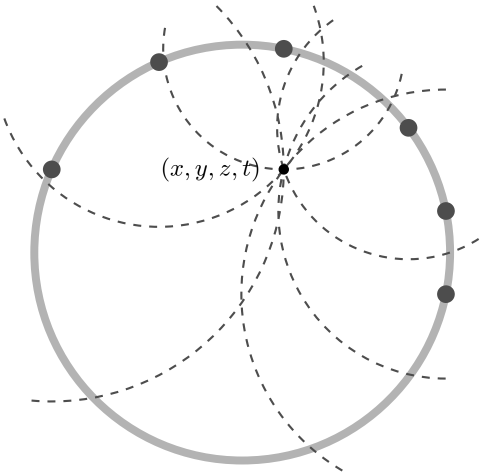

Figure 8. The $\mathrm{K_L}$ decay vertex is also a common origin points of the 6 photons which hit the calorimeter. Therefore, its location can be found analytically as the intersection of at least 4 of the spheres defined for each EMC clusters.

5.3. Resolution of $\mathrm{K_L}$ *decay time reconstruction*

The reconstruction was tested using a MC simulated sample of $\mathrm{K_L} \to 3\pi^0$ events (generated with the official KLOE software [24]) including complete detector response and run-by-run data taking conditions. Time resolution, crucial for the time-reversal symmetry test at KLOE-2, was studied as a function of the decay vertex distance from the ϕ-meson decay vertex, i.e. the path length travelled by the kaon before its decay. The result, shown in Figure 9 proves that this reconstruction algorithm has an almost constant resolution at the level of $2\tau_S$ independently of the decay vertex location. This is a promising result for the future test of time-reversal symmetry at KLOE-2 and studies on the required processes will continue towards this test. This will allow $\mathcal{T}$ to be tested in the asymptotic region of $\Delta t \gg \tau_S$ as stated in Section 5.1. This new reconstruction method for the challenging $\mathrm{K_L} \to 3\pi^0$ decay opens the way for KLOE-2 to provide the first direct evidence for time-reversal symmetry violation in the neutral kaon system.

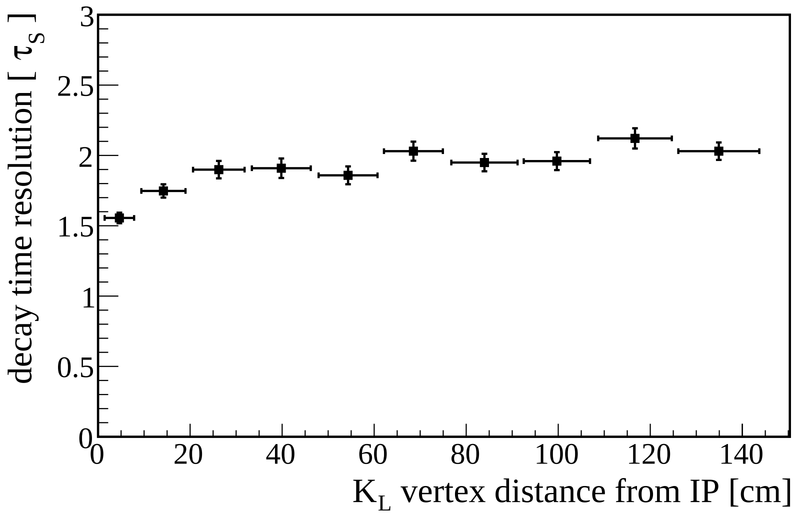

Figure 9. The K_L decay time resolution as a function of the decay distance from ϕ decay point.

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