Test of discrete symmetries in transitions with entangled neutral kaons at KLOE-2

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on behalf of
KLOE-2 Collaboration
DAΦNE: The Frascati $\phi$-factory
KLOE-2: main detectors

**Drift Chamber**
\[ \sigma_p / p \approx 0.4\% \]
(tracks with \( \theta > 45^\circ \))
\[ \sigma_{\text{hit}} \approx 150\,\mu\text{m (xy), 2 mm (z)} \]
\[ \sigma_{\text{vertex}} \approx 1\,\text{mm} \]

**Calorimeter e.m.**
Both side read-out (PM)
\[ \sim 4\pi \text{ solid angle coverage} \]
\[ \sigma_{E/E} \approx 5.7\% / \sqrt{E(\text{GeV})} \]
\[ \sigma_t \approx 54\,\text{ps} / \sqrt{E(\text{GeV})} \oplus 100\,\text{ps} \]

**Interaction point (IP)**
Sphere Al-Be (Ø 20 cm)

**General purpose detector**

**SC Magnet**
\[ B = 0.52\,\text{T} \]
KLOE-2: interaction region detectors

CCALT - LYSO Crystal w SiPM - Low polar angle

QCALT - Tungsten / Scintillating Tiles w SiPM - $K_L$ decays Quadrupole Instrumentation

LET: 2 calorimeters LYSO + SiPMs @ ~ 1 m from IP $e^+e^-$ taggers for gg physics (HET)

HET: Scintillator hodoscope + PMTs pitch:5 mm; placed at 11 m from IP

Inner Tracker – 4 layers of Cylindrical GEM detectors To improve the track and vertex reconstruction First time CGEM in high energy experiment
Integrated luminosity (KLOE)

KLOE-2 dataset:

5.5 fb\(^{-1}\) (2014/18)

\[ L_{\text{peak}} = 2.38 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]

(Crab-Waist)

KLOE dataset:

2.5 fb\(^{-1}\)

\[ L_{\text{peak}} = 1.52 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} \]

KLOE+KLOE-2 data sample:

8 fb\(^{-1}\) → 2.4 x 10\(^{10}\) \(\phi(1020)\) mesons decay recorded
Neutral kaons at KLOE-2

**KAON MASS Eigenstates**

**TAGGING** ($t_1 \ll t_2$)

**SINGLE KAON PROPERTY:**
- Branching fractions
- Form factors
- Lifetimes

**INTERFERENCE** ($t_1 \sim t_2$)

**KAON SYSTEM TIME EVOLUTION:**
Tests of:
- T/CPT in transitions
- CPT & Lorentz Invariance
- QM coherence
Correlation in two kaon state

The \( \phi \) meson decay in entangled pair of neutral kaons with \( J^{PC}=1^- \) quantum numbers:

\[
|i\rangle = \frac{1}{\sqrt{2}}(|K_0\rangle|\bar{K}_0\rangle - |\bar{K}_0\rangle|K_0\rangle) = \mathcal{N}(|K_S(\bar{p})\rangle|K_L(-\bar{p})\rangle - |K_S(-\bar{p})\rangle|K_L(\bar{p})\rangle),
\]

The antisymmetry of the state is preserved in its time evolution; the decay amplitude for the state into final states \( f_1, f_2 \) at time \( t_1, t_2 \) is:

\[
\langle f_1(t_1), f_2(t_2)|i\rangle^2 = \frac{N}{\sqrt{2}} \left\{ |\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} - 2|\eta_1||\eta_2|e^{-(\Gamma_S+\Gamma_L)(t_1+t_2)/2} \cos \left[ \Delta m(t_2 - t_1) + \phi_1 - \phi_2 \right] \right\}
\]

Interference term
Time dependent Kaon tagging

Entanglement allows to “prepare” the initial state desired by “tagging” the other kaon decay.

\[ |K?\rangle \quad |K?\rangle \]

\[ \phi \]
Entanglement allows to “prepare” the initial state desired by “tagging” the other kaon decay.

The “first kaon” \( (K_\alpha) \) decays \( (f_1^\alpha) \) is observed at \( t_1 \). This decay reveal the state of the kaon system at the time \( t_1 \).
Time dependent Kaon tagging

Entanglement allows to “prepare” the initial state desired by “tagging” the other kaon decay.

\[ t = t_1 + \Delta t \]

The “second kaon” evolve from the tagged initial state
Time dependent Kaon tagging

Entanglement allows to “prepare” the initial state desired by “tagging” the other kaon decay.

The $f_2^\beta$ decay is observed at $t_2$. In this way we have to possibility to observe the $|\bar{K}_\alpha\rangle \rightarrow |K_\beta\rangle$ transition probability as a function of the time difference $\Delta t$.
Transformations under discrete symmetry connect different transitions between CP and Flavor eigenstates.

<table>
<thead>
<tr>
<th>Reference</th>
<th>T-conjug.</th>
<th>CP-conjug.</th>
<th>CPT-conjug.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0 \rightarrow K_+$</td>
<td>$K_+ \rightarrow K^0$</td>
<td>$\bar{K}^0 \rightarrow K_+$</td>
<td>$K_+ \rightarrow \bar{K}^0$</td>
</tr>
<tr>
<td>$K^0 \rightarrow K_-$</td>
<td>$K_- \rightarrow K^0$</td>
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$K^0/\bar{K}^0$ Flavor eigenstate  $K_+/K_-$ CP eigenstate

Direct and model independent tests of time-reversal (T) and CPT symmetry → comparison of transition rates between flavor and CP eigenstates

Bernabeu et al. JHEP 10 (2015) 139
Direct T and CPT tests in transitions of neutral kaons

Eigenstate

|    | $K^0$ $\rightarrow$ $\pi^-/\nu$ | S  = +1  \\
|----|----------------------|---------|  \\
|    | $\bar{K}^0$ $\rightarrow$ $\pi^+/\bar{\nu}$ | S  = -1  \\
|    | $K_+$ $\rightarrow$ $\pi^+\pi^-$ | CP  = +1  \\
|    | $K_-$ $\rightarrow$ $3\pi^0$ | CP  = -1  \\

A decay in the semileptonic channel select the opposite flavor state.

Amplitude ratio

$$R_2(\Delta t) = \frac{P(K^0(0) \rightarrow K_-(\Delta t))}{P(K_-(0) \rightarrow K^0(\Delta t))}$$

$$R_4(\Delta t) = \frac{P(\bar{K}^0(0) \rightarrow K_-(\Delta t))}{P(K_-(0) \rightarrow \bar{K}^0(\Delta t))}$$

Observable

$$\frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^+\Delta t)} \sim \frac{I(l^+, 3\pi^0; \Delta t)}{I(\pi\pi, l^-\Delta t)}$$

Experimentally accesible

$\mathbf{R_2}$ (a.u.)

$\mathbf{R_4}$ (a.u.)
Direct T and CPT tests in transitions of neutral kaons

Eigenstate

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<th>$K^0$</th>
<th>$\pi^- + \nu$</th>
<th>S</th>
<th>+1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{K}^0$</td>
<td>$\pi^+ - \bar{\nu}$</td>
<td>S</td>
<td>-1</td>
</tr>
<tr>
<td>$K_+$</td>
<td>$\pi^+ \pi^-$</td>
<td>CP</td>
<td>+1</td>
</tr>
<tr>
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<td>$3\pi^0$</td>
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Entanglement allows to “prepare” the initial state desired by “tagging” the other kaon decay.

Amplitude ratio

$$ R^\text{CPT}_2(\Delta t) = \frac{P(K^0(0) \to K_-(\Delta t))}{P(K_-(0) \to \bar{K}^0(\Delta t))} \sim \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^- \Delta t)} $$

$$ R^\text{CPT}_4(\Delta t) = \frac{P(\bar{K}^0(0) \to K_-(\Delta t))}{P(K_-(0) \to K^0(\Delta t))} \sim \frac{I(l^+, 3\pi^0; \Delta t)}{I(\pi\pi, l^+ \Delta t)} $$

Experimentally accessible
All ratios are build with the same pair of decays:

Denominator contains a charged vertex decay without kinematic closure (neutrino escapes) and a decay vertex without tracks. This particular pair of decays has never been used before in KLOE-2 analysis.

\[
I(l^\pm, 3\pi^0; \Delta t) = \frac{I(\pi\pi, l^\pm \Delta t)}{I(\pi\pi, l^\pm \Delta t)}
\]

The numerator is the simplest case because has larger statistics in the $\Delta t$ region of interest and has a very well studied decay, $K \rightarrow \pi\pi$, tipically used for tagging.
One vertex ($K \rightarrow \pi \pi$)
kinematically closed:
+ Invariant mass at the vertex
+ Total momentum

A second vertex is required with tracks associated to EMC clusters in order to perform PID using TOF
+ $\delta t(\pi e)$ hypothesis
+ lepton mass

K_S K_L \rightarrow \pi^+ \pi^- ; \pi e$ event selection
Many selections are required to clean the sample and identify signal. All cuts are based on the neutral vertex reconstructed and imply the kinematic closure of the decay.
The semileptonic decay can’t be selected as for the normalization sample, because the kaon momentum is reconstructed from the 6 photons with larger resolution.

Time information from EMC and tracking from DCH have to be exploited deeply to properly select the semileptonic decay.

Using different mass hypothesis for the two tracks and combining them the selection is performed.
To construct observables we have to correct the number of observed event in each category by the efficiency.

Many different control samples have to be considered in order to properly cross check the Monte-Carlo simulation avoiding systematical correlation and statistical independence between efficiency correction.
Direct $T$ symmetry test in transitions of neutral kaons

$R_2 = \frac{K^0(0) \rightarrow K_-(\Delta t)}{K_-(0) \rightarrow K^0(\Delta t)}$

$R_2(\Delta t >> \tau_S) \sim 1 - 4 \Re(\varepsilon_K)$

$R_4 = \frac{\bar{K}^0(0) \rightarrow K_-(\Delta t)}{K_-(0) \rightarrow \bar{K}^0(\Delta t)}$

$R_4(\Delta t >> \tau_S) \sim 1 + 4 \Re(\varepsilon_K)$

$\sigma(R_2) = 0.017$

$\sigma(R_4) = 0.017$
Direct CPT symmetry test in transitions of neutral kaons

\[ R_{2}^{\text{CPT}} = \frac{I(l^-, 3\pi^0; \Delta t)}{I(\pi\pi, l^-; \Delta t)} \]

\[ R_{4}^{\text{CPT}} = \frac{I(l^+, 3\pi^0; \Delta t)}{I(\pi\pi, l^+; \Delta t)} \]

CPT invariance \[ \Rightarrow \frac{R_{2}^{\text{CPT}}(\Delta t >> \tau_s)}{R_{4}^{\text{CPT}}(\Delta t >> \tau_s)} = 1 \]

Preliminary

\[ \sigma(DR) = 0.028 \]
Conclusions & Outlook

- KLOE-2 data-taking has been completed with 5.5 fb\(^{-1}\) acquired
- A total sample of 8 fb\(^{-1}\) of data at \(\varphi\) peak is now available
- Preliminary results on discrete symmetry tests in transitions are encouraging
- Tests of discrete symmetries with neutral kaons are a key issues at KLOE-2 physics program and data analysis is in progress