CPT symmetry, entanglement, and neutral kaons

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Outline

- Introduction

- “Standard” test of CPT symmetry in the neutral kaon system

- Test of QM: test of quantum coherence of the entangled state

- Search for decoherence and CPT violation effects

- Test of Lorentz invariance and CPT symmetry

- Future plans
CPT: introduction

The three discrete symmetries of QM, C (charge conjugation: $q \rightarrow -q$), P (parity: $x \rightarrow -x$), and T (time reversal: $t \rightarrow -t$) are known to be violated in nature both singly and in pairs. Only CPT appears to be an exact symmetry of nature.

CPT theorem:

J. Schwinger (1951)  
G. Lüders (1954)  
R. Jost (1957)
W. Pauli (1952)  

J. Bell (1955)

Exact CPT invariance holds for any quantum field theory (like the Standard Model) formulated on flat space-time which assumes:

1. Lorentz invariance  
2. Locality  
3. Unitarity (i.e. conservation of probability).

Testing the validity of the CPT symmetry probes the most fundamental assumptions of our present understanding of particles and their interactions.
The three discrete symmetries of QM, C (charge conjugation: q → -q), P (parity: x → -x), and T (time reversal: t → -t) are known to be violated in nature both singly and in pairs. Only CPT appears to be an exact symmetry of nature.

Intuitive justification of CPT symmetry [1]:
For an even-dimensional space => reflection of all axes is equivalent to a rotation e.g. in 2-dim. space: reflection of 2 axes = rotation of \( \pi \) around the origin

In 4-dimensional pseudo-euclidean space-time PT reflection is NOT equivalent to a rotation. Time coordinate is not exactly equivalent to space coordinate. Charge conjugation is also needed to change sign to e.g. 4-vector current \( j_\mu \) (or axial 4-v).

CPT (and not PT) is equivalent to a rotation in the 4-dimensional space-time

CPT: introduction

Extension of CPT theorem to a theory of quantum gravity far from obvious.
(e.g. CPT violation appears in several QG models)
No predictive theory incorporating CPT violation => only phenomenological models to be constrained by experiments.

Consequences of CPT symmetry: equality of masses, lifetimes, $|q|$ and $|\mu|$ of a particle and its anti-particle.

Neutral meson systems offer unique possibilities to test CPT invariance;
e.g. taking as figure of merit the fractional difference between the masses of a particle and its anti-particle:

neutral K system $\frac{|m_{K^0} - m_{\bar{K}^0}|}{m_K} < 10^{-18}$

neutral B system $\frac{|m_{B^0} - m_{\bar{B}^0}|}{m_B} < 10^{-14}$

proton- anti-proton $\frac{|m_p - m_{\bar{p}}|}{m_p} < 10^{-8}$

Other interesting CPT tests: e.g. the study of anti-hydrogen atoms, etc..
K mesons – a 70 years history

1944: first indication of a new charged particle with mass ~0.5 GeV/c² in cosmic rays (Leprince-Ringuet, Lheritier)

1947: first K⁰ observation in cloud chamber - V particle (Rochester, Butler)

1955: introduction of Strangeness (Gell-Mann, Nishijima)

K⁰, K₀ are two distinct particles (Gell-Mann, Pais)

1955 prediction of regeneration of short-lived particle (Pais, Piccioni)

1956 Observation of long lived K₁ (BNL Cosmotron)

1957 τ-θ puzzle on spin-parity assignment, P violation in weak interactions

1960: Δm = m₁ - m₅ measured from regeneration

1964: discovery of CP violation (Cronin, Fitch, …)

1970: suppression of FCNC, K₁ → μμ - GIM mechanism/charm hypothesis

1972: Kobayashi Maskawa six quark model: CP violation explained in SM


2000-2006: KLOE at DaΦne: first Φ factory enters in operation, V₁₃ and precision tests of the SM, entangled neutral K pairs and CPT and QM tests.
The neutral kaon: a two-level quantum system

Neutral K mesons are a unique physical system which appears to be created by nature to demonstrate, in the most impressive manner, a number of spectacular phenomena.

If the K mesons did not exist, they should have been invented “on purpose” in order to teach students the principles of quantum mechanics.

T. D. Lee

One of the most intriguing physical systems in Nature

Lev B. Okun
The neutral kaon: a two-level quantum system

$K^0$ and $\bar{K}^0$ can decay to common final states due to weak interactions: strangeness oscillations

$P\left( K^0(0) \rightarrow K^0(t) \right) = \frac{1}{4} \left\{ e^{-\Gamma_L t} + e^{-\Gamma_S t} + 2 e^{-\left(\Gamma_S + \Gamma_L\right)t/2} \cos[\Delta m t] \right\}$

$P\left( K^0(0) \rightarrow \bar{K}^0(t) \right) = \frac{1}{4} \left\{ e^{-\Gamma_L t} + e^{-\Gamma_S t} - 2 e^{-\left(\Gamma_S + \Gamma_L\right)t/2} \cos[\Delta m t] \right\}$
The neutral kaon: a two-level quantum system

$K^0$ and $\bar{K}^0$ can decay to common final states due to weak interactions: strangeness oscillations

$K^0$ and $K^0$ can decay to common final states due to weak interactions:

strangeness oscillations

$P[K^0(t=0) \rightarrow K^0]$  

$P[K^0(t=0) \rightarrow \bar{K}^0]$
The neutral kaon: a two-level quantum system

\[ |\psi(0)\rangle = a(0)|K^0\rangle + b(0)|\bar{K}^0\rangle \quad \Rightarrow \quad |\psi(t)\rangle = a(t)|K^0\rangle + b(t)|\bar{K}^0\rangle + \sum_k c_k(t)|f_k\rangle \]

initial state
decay final states

The time evolution of a two-component state vector \( \Phi \) in the \( \{K^0, \bar{K}^0\} \) subspace (for times \( \gg \) the strong interaction formation time) is given by (Wigner-Weisskopf approximation):

\[
i \frac{\partial}{\partial t} \Phi(t) = H\Phi(t)
\]

\( H \) is the effective hamiltonian (non-hermitian), decomposed into a Hermitian part (mass matrix \( M \)) and an anti-Hermitian part (\( i/2 \) decay matrix \( \Gamma \)):

\[
H = M - \frac{i}{2} \Gamma = \left( \begin{array}{cc} M_{11} & M_{12} \\ M_{21} & M_{22} \end{array} \right) - \frac{i}{2} \left( \begin{array}{cc} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{array} \right)
\]

Diagonalizing the effective Hamiltonian:

eigenvalues
\[
\lambda_S = m_S - \frac{i}{2} \Gamma_S, \quad \lambda_L = m_L - \frac{i}{2} \Gamma_L
\]

eigenstates
\[
|K_{S,L}(t)\rangle = e^{-i\lambda_{S,L}t}|K_{S,L}(0)\rangle
\]
The neutral kaon: a two-level quantum system

\[
\left| \psi(0) \right\rangle = a(0) \left| K^0 \right\rangle + b(0) \left| \bar{K}^0 \right\rangle \quad \Rightarrow \quad \left| \psi(t) \right\rangle = \frac{a(t) \left| K^0 \right\rangle + b(t) \left| \bar{K}^0 \right\rangle}{\Phi(t)} + \sum_k c_k(t) \left| f_k \right\rangle
\]

The time evolution of a two-component state vector \( \Phi \) in the \( \left\{ K^0, \bar{K}^0 \right\} \) subspace (for times \( \gg \) the strong interaction formation time) is given by (Wigner-Weisskopf approximation):

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\[
H_{ij} = M_{ij} - \frac{i}{2} \Gamma_{ij}
\]

\[
M_{ij} = M_0 \delta_{ij} + \langle i | H_{wk} | j \rangle + \mathcal{P} \sum_f \left( \frac{\langle i | H_{wk} | f \rangle \langle f | H_{wk} | j \rangle}{M_0 - E_f} \right)
\]

\[
\Gamma_{ij} = 2\pi \sum_f \langle i | H_{wk} | f \rangle \langle f | H_{wk} | j \rangle \delta(M_0 - E_f)
\]

Diagonalizing the effective Hamiltonian:

**eigenvalues**

\[
\lambda_s = m_s - \frac{i}{2} \Gamma_s , \quad \lambda_L = m_L - \frac{i}{2} \Gamma_L
\]

**eigenstates**

\[
\left| K_{S,L}(t) \right\rangle = e^{-i\lambda_{S,L} t} \left| K_{S,L}(0) \right\rangle
\]

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The neutral kaon: a two-level quantum system

Strangeness (flavor) eigenstates:

\[ |K^0\rangle, \quad |\bar{K}^0\rangle \]

\[ |K_1\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle + |\bar{K}^0\rangle \right], \quad |K_2\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle - |\bar{K}^0\rangle \right] \]

\( S = +1 \quad S = -1 \)

CP eigenstates:

\( CP = +1 \quad CP = -1 \)

The physical states (eigenstates of \( H \)):

\[ |K_S\rangle = \frac{1}{\sqrt{2 \left(1 + |\epsilon_S|^2\right)}} \left[ (1 + \epsilon_S) |K^0\rangle + (1 - \epsilon_S) |\bar{K}^0\rangle \right] = \frac{1}{\sqrt{1 + |\epsilon_S|^2}} \left[ |K_1\rangle + \epsilon_S |K_2\rangle \right] \]

\[ |K_L\rangle = \frac{1}{\sqrt{2 \left(1 + |\epsilon_L|^2\right)}} \left[ (1 + \epsilon_L) |K^0\rangle - (1 - \epsilon_L) |\bar{K}^0\rangle \right] = \frac{1}{\sqrt{1 + |\epsilon_L|^2}} \left[ |K_2\rangle + \epsilon_L |K_1\rangle \right] \]

Short lifetime \( \tau_S \sim 90 \text{ ps} \)

Long lifetime \( \tau_L \sim 51140 \text{ ps} \)

CP violation:

\[ \epsilon_S = \epsilon + \delta \]

\[ \epsilon_L = \epsilon - \delta \]

\[ |\epsilon| \equiv 2.232 \times 10^{-3} \quad \text{CPT violation: } |\delta| \ll 10^{-4} \]
"K-spin"

\[ |Z \uparrow\rangle \Rightarrow |K^0\rangle \]
\[ |Z \downarrow\rangle \Rightarrow |\bar{K}^0\rangle \]

How to detect a K-spin?

Active measurement

Strong interactions with a thin absorber

\[ K^0 \rightarrow \text{K}^+ \text{(or } \Lambda) \]
\[ (\bar{K}^0) \rightarrow \text{K}^0 \]

Passive measurement

Semileptonic decay (\(\Delta S = \Delta Q\) rule)

\[ K^0 \rightarrow \text{e}^+ \pi^- \]
\[ \bar{K}^0 \rightarrow \pi^+ \text{e}^- \]

Passive measurement

\(K_1\) or \(K_2\) can be identified via \(2\pi\) or \(3\pi\) decay (\(\epsilon'\) neglected)

\[ X \uparrow\rangle \Rightarrow |K_1\rangle = \frac{1}{\sqrt{2}} \left(|K^0\rangle + |\bar{K}^0\rangle\right) \]
\[ X \downarrow\rangle \Rightarrow |K_2\rangle = \frac{1}{\sqrt{2}} \left(|K^0\rangle - |\bar{K}^0\rangle\right) \]

\[ K^0 + p \rightarrow K^+ + n \]
\[ \bar{K}^0 + n \rightarrow K^- + p \]
\[ \bar{K}^0 + p \rightarrow \Lambda \rightarrow p + \pi^- + \pi^+ \]
CPT violation: standard picture

CP violation: \[ \varepsilon_{S,L} = \varepsilon \pm \delta \]

T violation:

\[ \varepsilon = \frac{H_{12} - H_{21}}{2(\lambda_S - \lambda_L)} - \frac{i\Im M_{12} - \Im \Gamma_{12}/2}{\Delta m + i\Delta \Gamma/2} \]

CPT violation:

\[ \delta = \frac{H_{11} - H_{22}}{2(\lambda_S - \lambda_L)} = \frac{1}{2} \left( m_{K^0} - m_{\bar{K}^0} \right) - \left( i/2 \right) \left( \Gamma_{K^0} - \Gamma_{\bar{K}^0} \right) \frac{\Delta m + i\Delta \Gamma/2}{\Delta m + i\Delta \Gamma/2} \]

- \( \delta \neq 0 \) implies CPT violation
- \( \varepsilon \neq 0 \) implies T violation
- \( \varepsilon \neq 0 \) or \( \delta \neq 0 \) implies CP violation

\( \Delta m = m_L - m_S \), \( \Delta \Gamma = \Gamma_S - \Gamma_L \)

\( \Delta m = 3.5 \times 10^{-15} \) GeV

\( \Delta \Gamma \approx \Gamma_S \approx 2\Delta m = 7 \times 10^{-15} \) GeV

(with a phase convention \( \Im \Gamma_{12} = 0 \))
# neutral kaons vs other oscillating meson systems

<table>
<thead>
<tr>
<th></th>
<th>$&lt;m&gt;$ (GeV)</th>
<th>$\Delta m$ (GeV)</th>
<th>$&lt;\Gamma&gt;$ (GeV)</th>
<th>$\Delta \Gamma/2$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0$</td>
<td>0.5</td>
<td>$3 \times 10^{-15}$</td>
<td>$3 \times 10^{-15}$</td>
<td>$3 \times 10^{-15}$</td>
</tr>
<tr>
<td>$D^0$</td>
<td>1.9</td>
<td>$6 \times 10^{-15}$</td>
<td>$2 \times 10^{-12}$</td>
<td>$1 \times 10^{-14}$</td>
</tr>
<tr>
<td>$B^0_d$</td>
<td>5.3</td>
<td>$3 \times 10^{-13}$</td>
<td>$4 \times 10^{-13}$</td>
<td>$O(10^{-15})$ (SM prediction)</td>
</tr>
<tr>
<td>$B^0_s$</td>
<td>5.4</td>
<td>$1 \times 10^{-11}$</td>
<td>$4 \times 10^{-13}$</td>
<td>$3 \times 10^{-14}$</td>
</tr>
</tbody>
</table>
“Standard” CPT tests
The Bell-Steinberger relationship

\[ |K\rangle = a_S |K_S\rangle + a_L |K_L\rangle \]

Unitarity constraint:
\[
\left( -\frac{d}{dt} \| K(t) \|^2 \right)_{t=0} = \sum_f a_S \langle f | T | K_S \rangle + a_L \langle f | T | K_L \rangle^2
\]

yields two trivial relations:

\[ \Gamma_{S,L} = \sum_f \left| \langle f | T | K_{S,L} \rangle \right|^2 \]

and a not trivial one, i.e. the B-S relationship:

\[ \langle K_L | K_S \rangle = 2 (\Re \epsilon + i \Im \delta) = \sum_f \langle f | T | K_S \rangle \langle f | T | K_L \rangle^* \]

\[ \frac{i(\lambda_S - \lambda_L^*)}{i(\lambda_S - \lambda_L^*)} \]
Neutral kaons at CPLEAR (CERN)

Pure initial $K^0, \bar{K}^0$ are produced from antiproton annihilation at rest with a hydrogen target

\[
\begin{align*}
(p + \bar{p})_{\text{REST}} & \rightarrow K^0 + K^- + \pi^+ \\
(p + \bar{p})_{\text{REST}} & \rightarrow \bar{K}^0 + K^+ + \pi^- \\
(p + \bar{p})_{\text{REST}} & \rightarrow K^0 + \bar{K}^0
\end{align*}
\]

$P_K \sim 500$ MeV

The detection of a charged kaon tags the strangeness of the accompanying neutral kaon
CPT test at CPLEAR

Test of CPT in the time evolution of neutral kaons using the semileptonic asymmetry

\[ A_\delta (\tau) = \frac{\bar{R}_+ (\tau) - \alpha R_- (\tau)}{\bar{R}_+ (\tau) + \alpha R_- (\tau)} + \frac{\bar{R}_- (\tau) - \alpha R_+ (\tau)}{\bar{R}_- (\tau) + \alpha R_+ (\tau)} \]

\[ R_{\pm} (\tau) = R \left( K^0_{t=0} \rightarrow (e^{\mp} \pi^{\pm} \nu)_{t=\tau} \right) \]

\[ \alpha = 1 + 4 \Re \varepsilon_L \]

\[ A_\delta (\tau >> \tau_S) = 8 \Re \delta \]

\[ \Re \delta = (0.30 \pm 0.33 \pm 0.06) \times 10^{-3} \]

CPLEAR PLB444 (1998) 52
"Standard" CPT test

measuring the time evolution of a neutral kaon beam into semileptonic decays:

\[
\Re \delta = (0.30 \pm 0.33 \pm 0.06) \times 10^{-3}
\]

CPLEAR
PLB444 (1998) 52

using the unitarity constraint (Bell-Steinberger relation)

\[
\Im \delta = (-0.7 \pm 1.4) \times 10^{-5}
\]

PDG fit (2014)

\[
\delta = \frac{1}{2} \left( \frac{m_{\bar{K}^0} - m_{K^0}}{\Delta m + i\Delta \Gamma/2} \right) = \frac{1}{2} \left( \frac{\Gamma_{\bar{K}^0} - \Gamma_{K^0}}{\left(10^{-18}\text{GeV}\right)^2} \right)
\]

Combining \Re \delta and \Im \delta results

Assuming \( \left( \frac{\Gamma_{\bar{K}^0} - \Gamma_{K^0}}{\left(10^{-18}\text{GeV}\right)^2} \right) = 0 \), i.e. no CPT viol. in decay:

\[
\left| m_{\bar{K}^0} - m_{K^0} \right| < 4.0 \times 10^{-19} \text{ GeV}
\]

at 95% c.l.
Entangled neutral kaon pairs
Neutral kaons at a φ-factory

Production of the vector meson φ in $e^+e^-$ annihilations:

$e^+e^- \rightarrow \phi, \quad \sigma_\phi \sim 3 \mu b$

$W = m_\phi = 1019.4 \text{ MeV}$

$\text{BR}(\phi \rightarrow K^0\bar{K}^0) \sim 34\%$

$\sim 10^6$ neutral kaon pairs per pb$^{-1}$ produced in an antisymmetric quantum state with $J^{PC} = 1^{--}$:

$p_K = 110 \text{ MeV/c}$

$\lambda_S = 6 \text{ mm} \quad \lambda_L = 3.5 \text{ m}$

\[
|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0(\bar{p})\rangle |\bar{K}^0(-\bar{p})\rangle - |\bar{K}^0(\bar{p})\rangle |K^0(-\bar{p})\rangle \right]
\]

\[
= \frac{N}{\sqrt{2}} \left[ |K_S(\bar{p})\rangle |K_L(-\bar{p})\rangle - |K_L(\bar{p})\rangle |K_S(-\bar{p})\rangle \right]
\]

$N = \sqrt{\frac{(1 + |\epsilon_S|^2)(1 + |\epsilon_L|^2)}{1 - \epsilon_S \epsilon_L}} \equiv 1$
**Analogy with spin \( \frac{1}{2} \) particles**

\[
|1^{--}\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle \right]
\]

\[
P(K^0, t_1; K^0, t_2) = \frac{1}{4} \left[ 1 - \cos(\Delta m(t_1 - t_2)) \right]
\]

ideal case with \( \Gamma_S = \Gamma_L = 0 \) (no decay!)

with the actual \( \Gamma_S \) and \( \Gamma_L \) (kaons decay!):

\[
P(K^0, t_1; K^0, t_2) = \frac{1}{8} \left\{ e^{-\Gamma_L t_1} - e^{-\Gamma_S t_1} + e^{-\Gamma_S t_2} - e^{-\Gamma_L t_2} \right\}
\]

\[
-2e^{-(\Gamma_S + \Gamma_L)(t_1 + t_2)/2} \cos[\Delta m(t_2 - t_1)]
\]

\[
|S = 0\rangle = \frac{1}{\sqrt{2}} \left[ |A\uparrow\rangle|A\downarrow\rangle - |A\downarrow\rangle|A\uparrow\rangle \right]
\]

\[
P(A \uparrow; B \uparrow) = \frac{1}{4} \left[ 1 - \cos(\theta_{ab}) \right]
\]

Singlet (S=0)

The time difference plays the same role as the angle between the spin analyzers

kaons change their identity with time, but remain correlated
The KLOE detector at the Frascati $\phi$-factory DAFNE

Integrated luminosity (KLOE)

Total KLOE $\int L \, dt \sim 2.5 \, \text{fb}^{-1}$
(2001 - 05) $\rightarrow \sim 2.5 \times 10^9$ $K_S K_L$ pairs
The KLOE detector at the Frascati $\phi$-factory DAFNE

**Integrated luminosity (KLOE)**

- Total KLOE $\int L \, dt \sim 2.5$ fb$^{-1}$
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**KLOE detector**

- DAFNE collider
- Lead/scintillating fiber calorimeter
- Drift chamber
- 4 m diameter $\times$ 3.3 m length
- Helium based gas mixture
**Neutral kaon interferometry**

\[ |i\rangle = \frac{N}{\sqrt{2}} \left[ |K_S(\bar{p})\rangle|K_L(-\bar{p})\rangle - |K_L(\bar{p})\rangle|K_S(-\bar{p})\rangle \right] \]

Double differential time distribution:

\[ I(f_1,t_1;f_2,t_2) = C_{12} \left\{ |\eta_1|^2 e^{-\Gamma_L t_1 - \Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1 - \Gamma_L t_2} \right\} \]

\[ -2|\eta_1||\eta_2| e^{-\left(\Gamma_S + \Gamma_L\right)(t_1 + t_2)/2} \cos\left[ \Delta m (t_2 - t_1) + \phi_1 - \phi_2 \right] \]

where \( t_1(t_2) \) is the proper time of one (the other) kaon decay into \( f_1(f_2) \) final state and:

\[ \eta_i = |\eta_i|e^{i\phi_i} = \left< f_i | T | K_L \right> / \left< f_i | T | K_S \right> \]

\[ C_{12} = \frac{|N|^2}{2} \left| \left< f_1 | T | K_S \right> \left< f_2 | T | K_S \right> \right|^2 \]

From these distributions for various final states \( f_i \) one can measure the following quantities: \( \Gamma_S \), \( \Gamma_L \), \( \Delta m \), \( |\eta_i| \), \( \phi_i \equiv \text{arg}(\eta_i) \)

characteristic interference term at a \( \phi \)-factory => interferometry
Neutral kaon interferometry: main observables

\[ I(\Delta t) \text{ (a.u)} \]

\[ \mathcal{R} \delta + \mathcal{R} x_- \]

\[ \mathcal{S} \delta + \mathcal{S} x_+ \]

\[ \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^0 \pi^0 \]

\[ A_L = 2\mathcal{R} \epsilon - \mathcal{R} \delta - \mathcal{R} y - \mathcal{R} x_- \]
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal "CP states" $K_+$ and $K_-

$$|K_+\rangle = |K_1\rangle \quad (CP = +1)$$

$$|K_-\rangle = |K_2\rangle \quad (CP = -1)$$

$$|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0(\bar{p})\rangle|\bar{K}^0(-\bar{p})\rangle - |K^0(\bar{p})\rangle|K^0(-\bar{p})\rangle \right]$$

$$= \frac{1}{\sqrt{2}} \left[ |K_+(\bar{p})\rangle|K_-(\bar{p})\rangle - |K_-(\bar{p})\rangle|K_+(\bar{p})\rangle \right]$$

- decay as filtering measurement
- entanglement -> preparation of state
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$

\[
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\]

\[
|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0(\bar{p})\rangle |\bar{K}^0(-\bar{p})\rangle - |\bar{K}^0(\bar{p})\rangle |K^0(-\bar{p})\rangle \right]
\]

- decay as filtering measurement
- entanglement -> preparation of state

![Diagram](image_url)
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$.

$$|K_+\rangle = |K_1\rangle \quad (CP = +1)$$
$$|K_-\rangle = |K_2\rangle \quad (CP = -1)$$

$$|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0(\bar{p})\rangle |\bar{K}^0(-\bar{p})\rangle - |\bar{K}^0(\bar{p})\rangle |K^0(\bar{p})\rangle \right]$$

- decay as filtering measurement
- entanglement -> preparation of state

$$K^0 \rightarrow K_-$$ reference process

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$|K_+\rangle = |K_1\rangle$ (CP = +1)
$|K_-\rangle = |K_2\rangle$ (CP = -1)

$|i\rangle = \frac{1}{\sqrt{2}} 
\begin{bmatrix}
|K^0(\bar{p})\rangle|\bar{K}^0(-\bar{p})\rangle - |\bar{K}^0(\bar{p})\rangle|K^0(-\bar{p})\rangle
\end{bmatrix}$

- decay as filtering measurement
- entanglement -> preparation of state

The diagram illustrates the process where

$K^0 \rightarrow K_-$

is the reference process

$K_- \rightarrow \bar{K}^0$

is the CPT-conjugated process

$\bar{K}^0 \rightarrow K^0$

$\pi^+ \bar{\nu}$
Direct test of CPT symmetry in neutral kaon transitions

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$

$$|K_+\rangle = |K_1\rangle \quad (CP = +1)$$
$$|K_-\rangle = |K_2\rangle \quad (CP = -1)$$

Note: CP and T conjugated process

$$\overline{K^0} \rightarrow K_- \quad K_- \rightarrow K^0$$

$$K^0 \rightarrow K_- \quad \text{reference process}$$

$$K_- \rightarrow \overline{K} \quad \text{CPT-conjugated process}$$

\[ |i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0(\bar{p})\rangle |\overline{K^0}(\bar{p})\rangle - |\overline{K^0}(\bar{p})\rangle |K^0(\bar{p})\rangle \right] \]

$$= \frac{1}{\sqrt{2}} \left[ |K_+(\bar{p})\rangle |K_-(\bar{p})\rangle - |K_-(\bar{p})\rangle |K_+(\bar{p})\rangle \right]$$

- decay as filtering measurement
- entanglement -> preparation of state

\[ \varepsilon_{i} = \left| \langle i | K_+ \rangle \right|^2 = \frac{1}{2} \]
**Direct test of CPT symmetry in neutral kaon transitions**

- EPR correlations at a $\phi$-factory (or B-factory) can be exploited to study other transitions involving also orthogonal “CP states” $K_+$ and $K_-$.

$$|K_+\rangle = |K_1\rangle \ (CP = +1)$$

$$|K_-\rangle = |K_2\rangle \ (CP = -1)$$

$$|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0(\bar{p})\rangle|\bar{K}^0(-\bar{p})\rangle - |\bar{K}^0(\bar{p})\rangle|K^0(-\bar{p})\rangle\right]$$

$$= \frac{1}{\sqrt{2}} \left[ |K_+(\bar{p})\rangle|\bar{K}_-(-\bar{p})\rangle - |\bar{K}_-(\bar{p})\rangle|K_+(-\bar{p})\rangle\right]$$

- decay as filtering measurement
- entanglement -> preparation of state

In general with $f_X$ decayng before $f_Y$, i.e. $\Delta t>0$ \ (K$_{X,Y}$ = $K^0$, $\bar{K}^0$, $K_+$, $K_-$) :

$$I(f_X, f_Y; \Delta t) = C(f_X, f_Y) \times P[K_X(0) \rightarrow K_Y(\Delta t)]$$

with

$$C(f_X, f_Y) = \frac{1}{2(\Gamma_S + \Gamma_L)} |\langle f_X|T|\bar{K}_X\rangle\langle f_Y|T|K_Y\rangle|^2$$
Direct test of CPT symmetry in neutral kaon transitions

CPT symmetry test

<table>
<thead>
<tr>
<th>Reference</th>
<th>$CPT$-conjugate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transition</td>
<td>Decay products</td>
</tr>
<tr>
<td>$K^0 \to K_+$</td>
<td>$(\ell^-, \pi \pi)$</td>
</tr>
<tr>
<td>$K^0 \to K_-$</td>
<td>$(\ell^-, 3\pi^0)$</td>
</tr>
<tr>
<td>$\bar{K}^0 \to K_+$</td>
<td>$(\ell^+, \pi \pi)$</td>
</tr>
<tr>
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<td>$(\ell^+, 3\pi^0)$</td>
</tr>
</tbody>
</table>

One can define the following ratios of probabilities:

$$R_{1,CPT}(\Delta t) = \frac{P[K^0(0) \to K_+(\Delta t)]}{P[K^0(0) \to \bar{K}^0(\Delta t)]}$$
$$R_{2,CPT}(\Delta t) = \frac{P[K^0(0) \to K_-(\Delta t)]}{P[K^0(0) \to \bar{K}^0(\Delta t)]}$$
$$R_{3,CPT}(\Delta t) = \frac{P[\bar{K}^0(0) \to K_+(\Delta t)]}{P[K^0(0) \to K^0(\Delta t)]}$$
$$R_{4,CPT}(\Delta t) = \frac{P[\bar{K}^0(0) \to K_-(\Delta t)]}{P[K^0(0) \to K^0(\Delta t)]}$$

Any deviation from $R_{i,CPT}=1$ constitutes a violation of CPT-symmetry.

J. Bernabeu, A.D.D. in preparation
Direct test of CPT symmetry in neutral kaon transitions

for visualization purposes, plots with
Re(δ)=3.3 × 10^{-4}  Im(δ)=1.6 × 10^{-5}

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

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

\[ R_{2,CPT}^{exp}(\Delta t) = R_{2,CPT}(\Delta t) \times D_{CPT} \]

\[ R_{4,CPT}^{exp}(\Delta t) = R_{4,CPT}(\Delta t) \times D_{CPT} \]

\[ R_{2,CPT}^{exp}(\Delta t) = R_{1,CPT}(|\Delta t|) \times D_{CPT} \]

\[ R_{4,CPT}^{exp}(\Delta t) = R_{3,CPT}(|\Delta t|) \times D_{CPT} \]

Test feasible at KLOE-2, studies in progress !!
Test of Quantum Coherence
EPR correlations in entangled neutral kaon pairs from $\phi$

$$ \left| i \right> = \frac{1}{\sqrt{2}} \left[ \left| K^0 \right> \left| \bar{K}^0 \right> - \left| \bar{K}^0 \right> \left| K^0 \right> \right] $$

Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

EPR correlation:
no simultaneous decays ($\Delta t=0$) in the same final state due to the fully destructive quantum interference
EPR correlations in entangled neutral kaon pairs from $\phi$

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Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

EPR correlation:
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$$\Delta t = |t_1 - t_2|$$
EPR correlations in entangled neutral kaon pairs from $\phi$

$$|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle \right]$$

Same final state for both kaons: $f_1 = f_2 = \pi^+\pi^-$

Interference effects are a key feature of QM, "the only mystery" according to Feynman

=>$\Delta t/\tau_S$ Experimental test
\[ \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{test of quantum coherence} \]

\[ |i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right] \]

\[ I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t) = \frac{N}{2} \left[ \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right. \]

\[ \left. -2 \Re \left( \langle \pi^+ \pi^-, \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^-, \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right) \right] \]
$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{test of quantum coherence}$

$$|i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right]$$

$$I\left(\pi^+ \pi^- , \pi^+ \pi^- ; \Delta t \right) = \frac{N}{2} \left[ \left| \langle \pi^+ \pi^- , \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \right|^2 + \left| \langle \pi^+ \pi^- , \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle \right|^2 \right.$$  

$$\left. - \left(1 - \xi_{00} \right) \cdot 2 \Re \left( \langle \pi^+ \pi^- , \pi^+ \pi^- | K^0 \bar{K}^0(\Delta t) \rangle \langle \pi^+ \pi^- , \pi^+ \pi^- | \bar{K}^0 K^0(\Delta t) \rangle^* \right) \right]$$
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Decoherence parameter:
\[ \xi_{00}^{-} = 0 \quad \rightarrow \quad \text{QM} \]
\[ \xi_{00}^{-} = 1 \quad \rightarrow \quad \text{total decoherence} \]

(also known as Furry's hypothesis or spontaneous factorization)

[W. Furry, PR 49 (1936) 393]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032

Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)
\[
\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^- \pi^+\pi^- : \text{test of quantum coherence}
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I(\Delta t) \text{ (a.u.)}

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Decoherence parameter:

- \( \xi_{00} = 0 \rightarrow \text{QM} \)
- \( \xi_{00} = 1 \rightarrow \text{total decoherence} \)
  (also known as Furry's hypothesis or spontaneous factorization)

\[ \xi_{00} = 4 \times 10^{-6} \]

\[ \xi_{00} = 0 \]

\[ \Delta t/\tau_S \]

Bertlmann, Grimus, Hiesmayr PR D60 (1999) 114032
Bertlmann, Durstberger, Hiesmayr PRA 68 012111 (2003)
\[ \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{test of quantum coherence} \]

- Analysed data: \( L = 1.5 \text{ fb}^{-1} \)
- Fit including \( \Delta t \) resolution and efficiency effects + regeneration

**KLOE result:**

\[ \xi_{00}^- = \left( 1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{Syst}} \right) \times 10^{-7} \]

Observable suppressed by CP violation: \( |\eta^-|^2 \sim |\varepsilon|^2 \sim 10^{-6} \rightarrow \text{terms } \xi_{00}/|\eta^-|^2 \rightarrow \text{high sensitivity to } \xi_{00} \)

From CPLEAR data, Bertlmann et al. (PR D60 (1999) 114032) obtain:

\[ \xi_{00}^- = 0.4 \pm 0.7 \]

In the B-meson system, BELLE coll. (PRL 99 (2007) 131802) obtains:

\[ \xi_{00}^B = 0.029 \pm 0.057 \]
φ → K_S K_L → π^+ π^- π^+ π^- : test of quantum coherence

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- Fit including Δt resolution and efficiency effects + regeneration

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\[ \xi_{00} = \left( 1.4 \pm 9.5^{\text{STAT}} \pm 3.8^{\text{SYST}} \right) \times 10^{-7} \]

Observable suppressed by CP violation: \[ |\eta_{+-}|^2 \sim |\varepsilon|^2 \sim 10^{-6} \]

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Best precision achievable in an entangled system
\( \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{test of quantum coherence} \)

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\xi_{00} = (1.4 \pm 9.5_{\text{STAT}} \pm 3.8_{\text{SYST}}) \times 10^{-7}
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Observable suppressed by CP violation: \( |\eta_+|^2 \sim |\xi|^2 \sim 10^{-6} \)

=> terms \( \xi_{00}/|\eta_+|^2 \) => high sensitivity to \( \xi \)

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**Best precision achievable in an entangled system**
Search for decoherence and CPT violation effects
Decoherence and CPT violation

Possible decoherence due quantum gravity effects (BH evaporation) (apparent loss of unitarity):

Black hole information loss paradox => Possible decoherence near a black hole.

Hawking [1] suggested that at a microscopic level, in a quantum gravity picture, non-trivial space-time fluctuations (generically space-time foam) could give rise to decoherence effects, which would necessarily entail a violation of CPT [2].

Modified Liouville – von Neumann equation for the density matrix of the kaon system with 3 new CPTV parameters $\alpha, \beta, \gamma$ [3]:

\[
\dot{\rho}(t) = -iH\rho + i\rho H^+ + QM + L(\rho; \alpha, \beta, \gamma)
\]

extra term inducing decoherence: pure state => mixed state

Decoherence and CPT violation

Possible decoherence effects due to quantum gravity effects (BH evaporation) (apparent loss of unitarity):

**Black hole information loss paradox**

Possible decoherence near a black hole. (like candy rolling on the tongue by J. Wheeler)

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extra term inducing decoherence: pure state $\Rightarrow$ mixed state

---

Decoherence and CPT violation

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Modified Liouville – von Neumann equation for the density matrix of the kaon system with 3 new CPTV parameters $\alpha, \beta, \gamma$ [3]:

$$\dot{\rho}(t) = -iH\rho + i\rho H^+ + L(\rho; \alpha, \beta, \gamma)$$

$$\alpha, \beta, \gamma = O\left(\frac{M_K^2}{M_{PLANK}}\right) \approx 2 \times 10^{-20} \text{ GeV}$$

\[ \phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : \text{decoherence and CPT violation} \]

Study of time evolution of **single kaons** decaying in \( \pi^+ \pi^- \) and semileptonic final state

**CPLEAR PLB 364, 239 (1999)**

\[ \alpha = (-0.5 \pm 2.8) \times 10^{-17} \text{ GeV} \]
\[ \beta = (2.5 \pm 2.3) \times 10^{-19} \text{ GeV} \]
\[ \gamma = (1.1 \pm 2.5) \times 10^{-21} \text{ GeV} \]

In the complete positivity hypothesis
\[ \alpha = \gamma \quad , \quad \beta = 0 \]

=> only one independent parameter: \( \gamma \)

The fit with \( I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t, \gamma) \) gives:

**KLOE result** \( L=1.5 \text{ fb}^{-1} \)

\[ \gamma = \left( 0.7 \pm 1.2_{\text{STAT}} \pm 0.3_{\text{Syst}} \right) \times 10^{-21} \text{ GeV} \]

**PLB 642(2006) 315**

**Found. Phys. 40 (2010) 852**
$\phi \rightarrow K_S K_L \rightarrow \pi^+ \pi^- \pi^+ \pi^- : $ CPT violation in entangled K states

In presence of decoherence and CPT violation induced by quantum gravity (CPT operator “ill-defined”) the definition of the particle-antiparticle states could be modified. This in turn could induce a breakdown of the correlations imposed by Bose statistics (EPR correlations) to the kaon state:


\[ |i\rangle \propto \left( |K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle \right) + \omega \left( |K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle|K^0\rangle \right) \]
\[ \propto \left( |K_S\rangle|K_L\rangle - |K_L\rangle|K_S\rangle \right) + \omega \left( |K_S\rangle|K_S\rangle - |K_L\rangle|K_L\rangle \right) \]

at most one expects:

\[ |\omega|^2 = O \left( \frac{E^2/M_{\text{PLANCK}}}{\Delta \Gamma} \right) \approx 10^{-5} \Rightarrow |\omega| \sim 10^{-3} \]

In some microscopic models of space-time foam arising from non-critical string theory:

[Bernabeu, Mavromatos, Sarkar PRD 74 (2006) 045014]

\[ |\omega| \sim 10^{-4} \div 10^{-5} \]

The maximum sensitivity to $\omega$ is expected for $f_1=f_2=\pi^+\pi^-$

All CPTV effects induced by QG ($\alpha, \beta, \gamma, \omega$) could be simultaneously disentangled.
\[ \phi \to K_S K_L \to \pi^+ \pi^- \pi^+ \pi^- : \text{CPT violation in entangled K states} \]

Fit of \( I(\pi^+ \pi^-, \pi^+ \pi^-; \Delta t, \omega) \):

- Analysed data: 1.5 fb\(^{-1}\)

**KLOE result:**

\[ \Re \omega = \left( -1.6^{+3.0}_{-2.1}^{\text{STAT}} \pm 0.4^{\text{Syst}} \right) \times 10^{-4} \]

\[ \Im \omega = \left( -1.7^{+3.3}_{-3.0}^{\text{STAT}} \pm 1.2^{\text{Syst}} \right) \times 10^{-4} \]

\[ |\omega| < 1.0 \times 10^{-3} \text{ at 95% C.L.} \]

In the B system [Alvarez, Bernabeu, Nebot JHEP 0611, 087]:

\[ -0.0084 \leq \Re \omega \leq 0.0100 \text{ at 95% C.L.} \]
CPT symmetry and Lorentz invariance test
CPT and Lorentz invariance violation (SME)

- CPT theorem:
  Exact CPT invariance holds for any quantum field theory which assumes:
  (1) Lorentz invariance  (2) Locality  (3) Unitarity (i.e. conservation of probability).
- “Anti-CPT theorem” (Greenberger 2002):
  Any unitary, local, point-particle quantum field theory that violates CPT invariance necessarily violates Lorentz invariance.

- Kostelecky et al. developed a phenomenological effective model providing a framework for CPT and Lorentz violations, based on spontaneous breaking of CPT and Lorentz symmetry, which might happen in quantum gravity (e.g. in some models of string theory)

**Standard Model Extension (SME)** [Kostelecky PRD61, 016002, PRD64, 076001]

**CPT violation in neutral kaons according to SME:**
- At first order CPTV appears only in mixing parameter $\delta$ (no direct CPTV in decay)
- $\delta$ cannot be a constant (momentum dependence)

\[
\varepsilon_{S,L} = \varepsilon \pm \delta
\]

\[
\delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K \left( \Delta a_0 - \vec{\beta}_K \cdot \Delta a \right) / \Delta m
\]

where $\Delta a_\mu$ are four parameters associated to SME lagrangian terms and related to CPT and Lorentz violation.
The Earth as a moving laboratory

FIG. 1: Standard Sun-centered inertial reference frame [9].
Search for CPT and Lorentz invariance violation (SME)

\[ \delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K \left( \Delta a_0 - \vec{\beta}_K \cdot \Delta \vec{a} \right) / \Delta m \]

\( \delta \) depends on sidereal time \( t \) since laboratory frame rotates with Earth.
For a \( \phi \)-factory there is an additional dependence on the polar and azimuthal angle \( \theta, \phi \) of the kaon momentum in the laboratory frame:

\[
\delta(\vec{p}, t) = \frac{i \sin \phi_{SW} e^{i \phi_{SW}}}{\Delta m} \left\{ \Delta a_0 \\
\quad + \beta_K \Delta a_z (\cos \theta \cos \chi - \sin \theta \sin \phi \sin \chi) \\
\quad + \beta_K \left[ -\Delta a_x \sin \theta \sin \phi + \Delta a_y (\cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi) \right] \sin \Omega t \\
\quad + \beta_K \left[ +\Delta a_y \sin \theta \sin \phi + \Delta a_x (\cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi) \right] \cos \Omega t \right\}
\]

\( \Omega \): Earth’s sidereal frequency  \( \chi \): angle between the z lab. axis and the Earth’s rotation axis
Search for CPT and Lorentz invariance violation (SME)

\[ \delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K \left( \Delta a_0 - \beta_K \cdot \Delta \vec{a} \right) / \Delta m \]

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\[
\delta(\vec{p},t) = \frac{i \sin \phi_{SW} e^{i \phi_{SW}}}{\Delta m} \gamma_K \left\{ \Delta a_0 \right. \\
+ \beta_K \Delta a_Z \left( \cos \theta \cos \chi - \sin \theta \sin \phi \sin \chi \right) \\
+ \beta_K \left[ -\Delta a_x \sin \theta \sin \phi + \Delta a_y \left( \cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi \right) \right] \sin \Omega t \\
+ \beta_K \left[ +\Delta a_y \sin \theta \sin \phi + \Delta a_x \left( \cos \theta \sin \chi + \sin \theta \cos \phi \cos \chi \right) \right] \cos \Omega t \right\}
\]

\( \Omega \): Earth’s sidereal frequency \( \chi \): angle between the z lab. axis and the Earth’s rotation axis

At DAΦNE K mesons are produced with angular distribution \( dN/d\Omega \propto \sin^2 \theta \)
Search for CPTV and LV: exploiting EPR correlations

\[ |i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right] \]

\[ \eta_i = |\eta_i| e^{i\phi_i} = \frac{\langle f_i | T | K_L \rangle}{\langle f_i | T | K_S \rangle} \]

\[ I(f_1, f_2; \Delta t) \propto \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-\left(\Gamma_S + \Gamma_L\right) \Delta t/2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\} \]

\[ \eta_{+1}^{(1)} = \varepsilon \left( 1 - \delta \left[ \mp \vec{p}, t \right] / \varepsilon \right) \]

\[ \eta_{+1}^{(2)} = \varepsilon \left( 1 - \delta \left[ \mp \vec{p}, t \right] / \varepsilon \right) \]

\[ I(\Delta t) \text{ (a.u.)} \]
Search for CPTV and LV: exploiting EPR correlations

\[ |i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right] \]

\[ \eta_i = |\eta_i| e^{i\phi_i} = \frac{\langle f_i | T | K_L \rangle}{\langle f_i | T | K_S \rangle} \]

\[ I(f_1, f_2; \Delta t) \propto \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-\left(\Gamma_S + \Gamma_L\right) \Delta t / 2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\} \]

\[ \eta^{(1)}_{+-} = \varepsilon \left( 1 - \delta \frac{\langle +\mathbf{p}, t \rangle}{\varepsilon} \right) \]

\[ \eta^{(2)}_{+-} = \varepsilon \left( 1 - \delta \frac{\langle -\mathbf{p}, t \rangle}{\varepsilon} \right) \]
Search for CPTV and LV: exploiting EPR correlations

\[ |i\rangle = \frac{1}{\sqrt{2}} \left[ |K^0\rangle |\bar{K}^0\rangle - |\bar{K}^0\rangle |K^0\rangle \right] \]

\[ \eta_i = |\eta_i| e^{i\phi_i} = \frac{\langle f_i | T | K_L \rangle}{\langle f_i | T | K_S \rangle} \]

\[ I(f_1, f_2; \Delta t) \propto \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} - 2|\eta_1||\eta_2| e^{-(\Gamma_S + \Gamma_L)\Delta t/2} \cos(\Delta m \Delta t + \phi_2 - \phi_1) \right\} \]

\[ \eta_{+}^{(1)} = \varepsilon \left( 1 - \delta \frac{p . t}{\varepsilon} \right) \]

\[ \eta_{+}^{(2)} = \varepsilon \left( 1 - \delta \frac{-p . t}{\varepsilon} \right) \]

from the asymmetry at \textbf{small} \( \Delta t \)

\[ \Im \left( \delta/\varepsilon \right) \approx 0 \text{ because } \delta \perp \varepsilon \]

from the asymmetry at \textbf{large} \( \Delta t \)
Search for CPTV and LV: results

\[ \delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K \left( \Delta a_0 - \beta_K \cdot \Delta \bar{a} \right) / \Delta m \]

Data divided in
4 sidereal time bins x 2 angular bins
Simultaneous fit of the \( \Delta t \) distributions
to extract \( \Delta a_\mu \) parameters
Search for CPTV and LV: results

\[ \delta = i \sin \phi_{SW} e^{i \phi_{SW}} \gamma_K \left( \Delta a_0 - \beta_K \cdot \Delta \tilde{a} \right) / \Delta m \]

Data divided in
4 sidereal time bins x 2 angular bins
Simultaneous fit of the \( \Delta t \) distributions to extract \( \Delta a_\mu \) parameters

with \( L = 1.7 \text{ fb}^{-1} \) KLOE final result

**PLB 730 (2014) 89–94**

\[ \Delta a_0 = \left( -6.0 \pm 7.7_{\text{STAT}} \pm 3.1_{\text{SYST}} \right) \times 10^{-18} \text{ GeV} \]

\[ \Delta a_X = \left( 0.9 \pm 1.5_{\text{STAT}} \pm 0.6_{\text{SYST}} \right) \times 10^{-18} \text{ GeV} \]

\[ \Delta a_Y = \left( -2.0 \pm 1.5_{\text{STAT}} \pm 0.5_{\text{SYST}} \right) \times 10^{-18} \text{ GeV} \]

\[ \Delta a_Z = \left( -3.1 \pm 1.7_{\text{STAT}} \pm 0.6_{\text{SYST}} \right) \times 10^{-18} \text{ GeV} \]

presently the most precise measurements in the quark sector of the SME

B meson system:
\[ \Delta a_{B_{x,y}}^{B}, (\Delta a_0^{B} - 0.30 \Delta a_Z^{B}) \sim O(10^{-13} \text{ GeV}) \]
[Babar PRL 100 (2008) 131802]

D meson system:
\[ \Delta a_{D_{x,y}}^{D}, (\Delta a_0^{D} - 0.6 \Delta a_Z^{D}) \sim O(10^{-13} \text{ GeV}) \]
[Focus PLB 556 (2003) 7]
Future perspectives
KLOE-2 at upgraded DAΦNE

DAΦNE upgraded in luminosity:
- a new scheme of the interaction region has been implemented (crabbed waist scheme)
- increase of L by a factor ~ 3 demonstrated by an experimental test (without KLOE solenoid), PRL104, 174801, 2010.

KLOE-2 experiment:
- extend the KLOE physics program at DAΦNE upgraded in luminosity
- collect O(10) fb\(^{-1}\) of integrated luminosity in the next 2-3 years

Physics program (see EPJC 68 (2010) 619-681)
- Neutral kaon interferometry, CPT symmetry & QM tests
- Kaon physics, CKM, LFV, rare K\(_S\) decays
- \(\eta, \eta'\) physics
- Light scalars, \(\gamma\gamma\) physics
- Hadron cross section at low energy, \(a_\mu\)
- Dark forces: search for light U boson

Detector upgrade:
- \(\gamma\gamma\) tagging system
- inner tracker
- small angle and quad calorimeters
- FEE maintenance and upgrade
- Computing and networking update
- etc.. (Trigger, software, …)
Inner tracker at KLOE

- Construction and installation inside KLOE completed (July 2013)
- Data taking (started on Nov. 2014) and commissioning in progress
## Prospects for KLOE-2

<table>
<thead>
<tr>
<th>Param.</th>
<th>Present best published measurement</th>
<th>KLOE-2 (IT) L=5 fb(^{-1})</th>
<th>KLOE-2 (IT) L=10 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\zeta_{00})</td>
<td>((0.1 \pm 1.0) \times 10^{-6})</td>
<td>(\pm 0.26 \times 10^{-6})</td>
<td>(\pm 0.18 \times 10^{-6})</td>
</tr>
<tr>
<td>(\zeta_{SL})</td>
<td>((0.3 \pm 1.9) \times 10^{-2})</td>
<td>(\pm 0.49 \times 10^{-2})</td>
<td>(\pm 0.35 \times 10^{-2})</td>
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<tr>
<td>(\alpha)</td>
<td>((-0.5 \pm 2.8) \times 10^{-17}) GeV</td>
<td>(\pm 5.0 \times 10^{-17}) GeV</td>
<td>(\pm 3.5 \times 10^{-17}) GeV</td>
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<tr>
<td>(\beta)</td>
<td>((2.5 \pm 2.3) \times 10^{-19}) GeV</td>
<td>(\pm 0.50 \times 10^{-19}) GeV</td>
<td>(\pm 0.35 \times 10^{-19}) GeV</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>((1.1 \pm 2.5) \times 10^{-21}) GeV compl. pos. hyp. ((0.7 \pm 1.2) \times 10^{-21}) GeV</td>
<td>(\pm 0.75 \times 10^{-21}) GeV compl. pos. hyp. (\pm 0.33 \times 10^{-21}) GeV</td>
<td>(\pm 0.53 \times 10^{-21}) GeV compl. pos. hyp. (\pm 0.23 \times 10^{-21}) GeV</td>
</tr>
<tr>
<td>(\text{Re}(\omega))</td>
<td>((-1.6 \pm 2.6) \times 10^{-4})</td>
<td>(\pm 0.70 \times 10^{-4})</td>
<td>(\pm 0.49 \times 10^{-4})</td>
</tr>
<tr>
<td>(\text{Im}(\omega))</td>
<td>((-1.7 \pm 3.4) \times 10^{-4})</td>
<td>(\pm 0.86 \times 10^{-4})</td>
<td>(\pm 0.61 \times 10^{-4})</td>
</tr>
<tr>
<td>(\Delta a_0)</td>
<td>((-6.2 \pm 8.8) \times 10^{-18}) GeV</td>
<td>(\pm 4.8 \times 10^{-18}) GeV</td>
<td>(\pm 3.4 \times 10^{-18}) GeV</td>
</tr>
<tr>
<td>(\Delta a_Z)</td>
<td>((-0.7 \pm 1.0) \times 10^{-18}) GeV</td>
<td>(\pm 0.6 \times 10^{-18}) GeV</td>
<td>(\pm 0.4 \times 10^{-18}) GeV</td>
</tr>
<tr>
<td>(\Delta a_X)</td>
<td>((3.3 \pm 2.2) \times 10^{-18}) GeV</td>
<td>(\pm 0.76 \times 10^{-18}) GeV</td>
<td>(\pm 0.54 \times 10^{-18}) GeV</td>
</tr>
<tr>
<td>(\Delta a_Y)</td>
<td>((-0.7 \pm 2.0) \times 10^{-18}) GeV</td>
<td>(\pm 0.76 \times 10^{-18}) GeV</td>
<td>(\pm 0.54 \times 10^{-18}) GeV</td>
</tr>
</tbody>
</table>
Conclusions

• The entangled neutral kaon system at a $\phi$-factory is an excellent laboratory for the study of CPT symmetry, discrete symmetries in general, and the basic principles of Quantum Mechanics;
• Several parameters related to possible
  • CPT violation
  • Decoherence
  • Decoherence and CPT violation
  • CPT violation and Lorentz symmetry breaking
have been measured at KLOE, in some cases with a precision reaching the interesting Planck’s scale region;
• All results are consistent with no CPT symmetry violation and no decoherence

• Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program. (G. Amelino-Camelia et al. EPJC 68 (2010) 619-681)
• The precision of several tests could be improved by about one order of magnitude