Quantum mechanics and CPT symmetry tests in the system of two neutral kaons

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29.03.2011
Experimental setup

A system of two neutral kaons

CPT and QM tests
  Same final states
  Double semileptonic decay

Playing with data
  Cuts
  Function
  Regeneration problem
  Effect on shape
  Results

KLOE-2 upgrades
Laboratori Nazionali di Frascati
DAΦNE facility layout:
Selected DAΦNE parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy of particles</td>
<td>510 MeV</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>up to 120 per ring</td>
</tr>
<tr>
<td>Number of particles in a bunch</td>
<td>$\sim 10^{10}$</td>
</tr>
<tr>
<td>Frequency of collisions</td>
<td>$\sim 370$ MHz</td>
</tr>
</tbody>
</table>
KLOE cross-section:
Requirements for the DC:

- observing kaons’ decay products
- high and uniform reconstruction efficiency over a large volume
- good momentum resolution
- transparency to particles in order to minimize $K_L$ into $K_S$ regeneration
Drift chamber:
Requirements for the EC:

- determination of neutral vertices
- good time resolution
- distinction of $K_L \to 2\pi^0$ from $K_L \to 3\pi^0$ decays
- minimisation of splitting and merging effects
Electromagnetic calorimeter:
DAΦNE is a $\phi$-factory, with $E_{\text{CM}} \approx m_\phi$.

Main $\phi$ decay modes:

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+ K^-$</td>
<td>49.1</td>
</tr>
<tr>
<td>$K^0 \bar{K}^0$</td>
<td>33.8</td>
</tr>
<tr>
<td>$\rho \pi + \pi^+ \pi^- \pi^0$</td>
<td>15.6</td>
</tr>
<tr>
<td>$\eta \gamma$</td>
<td>1.26</td>
</tr>
</tbody>
</table>
Neutral kaons can be described in different bases depending on the features one wants to describe:

- the basis of strangeness eigenstates: \( K^0, \bar{K}^0 \);
- the basis of Hamiltonian eigenstates: \( K_S, K_L \) - well defined lifetimes:
  \[
  |K_S\rangle = \frac{1}{\sqrt{2 \left( 1 + |\epsilon_S|^2 \right)}} \left[ (1 + \epsilon_S) |K^0\rangle + (1 - \epsilon_S) |\bar{K}^0\rangle \right],
  \]
  \[
  |K_L\rangle = \frac{1}{\sqrt{2 \left( 1 + |\epsilon_L|^2 \right)}} \left[ (1 + \epsilon_L) |K^0\rangle - (1 - \epsilon_L) |\bar{K}^0\rangle \right];
  \]
- the basis of \( CP \) operator eigenstates: \( K_1, K_2 \)
\( \phi \rightarrow K^0 \bar{K}^0 \) is a strong process \( \Rightarrow \) strangeness, \( P \) and \( C \) eigenvalues conserved:

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

with \( N \approx 1 \).

- possibility of testing EPR-like phenomena
Calculations within QM lead to double decay rate of the two kaons:

\[
I(f_1, f_2, \Delta t \geq 0) = \frac{C_{12}}{\Gamma_S + \Gamma_L} \left\{ |\eta_1|^2 e^{-\Gamma_L \Delta t} + |\eta_2|^2 e^{-\Gamma_S \Delta t} + 
- 2 |\eta_1| |\eta_2| e^{-\frac{\Gamma_S + \Gamma_L}{2} \Delta t} \cos [\Delta m \Delta t + \phi_2 - \phi_1] \right\},
\]

with \( C_{12} = C_{12}(f_1, f_2) \) and \( \eta_i = |\eta_i| e^{i\phi_i} \equiv \frac{\langle f_i | T | K_L \rangle}{\langle f_i | T | K_S \rangle} \) (for \( \Delta t \leq 0 \) one substitutes \( \Delta t \rightarrow -\Delta t \) and interchanges indices 1 and 2).
For the case of identical final states $I(f_1, f_2; \Delta t)$ simplifies:

$$I(f_1, f_2; \Delta t) = \frac{C_{12} |\eta|^2}{\Gamma_S + \Gamma_L} \left\{ e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2e^{-\frac{\Gamma_S + \Gamma_L}{2} \Delta t} \cos(\Delta m \Delta t) \right\}$$
we do not expect any events in $\Delta t = 0$ according to QM

correlation of EPR type

to account for decoherence one can modify the equation for double decay rate:

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

$$- 2 (1 - \zeta) |\eta_1| |\eta_2| e^{-\frac{\Gamma_S + \Gamma_L}{2} (t_1 - t_2)} \cos [\Delta m (t_1 - t_2) + \phi_2 - \phi_1] \}.$$
Current measurements give:

\[
\zeta_{SL} = \left(0.3 \pm 1.8_{\text{stat}} \pm 0.6_{\text{syst}}\right) \cdot 10^{-2},
\]

\[
\zeta_{00} = \left(1.4 \pm 9.5_{\text{stat}} \pm 3.8_{\text{syst}}\right) \cdot 10^{-7}.
\]
CPT theorem assumptions:

- Lorentz invariance
- Unitarity
- Locality
Possibility of \( CPT \) nonconservation connected with unitarity criterion:

- black holes can emit particles (Hawking)
- possibility of evolution of pure states into mixed states close to black holes (part of the system falls behind the event horizon)
- description of the state in the future - sum over all possible black hole states
- such evolution from pure to mixed state is incompatible with \( CPT \) invariance (Wald)
- similar transitions may also be possible on a microscopic (elementary particle) level
these theoretical considerations led Ellis et al. to develop a phenomenological framework for discussing QM violation due to decoherence.

suitable modification of the double decay rate:

\[
I \left( \pi^+\pi^-, t_1 ; \pi^+\pi^-, t_2 \right) = \\
= 2 |A_0|^4 \left\{ R_L \left( e^{-\Gamma_{S t_1} - \Gamma_{L t_2}} + e^{-\Gamma_{L t_1} - \Gamma_{S t_2}} \right) - 2 |\tilde{\eta}_{+-}|^2 \cos [\Delta m (t_1 - t_2)] e^{-(\bar{\Gamma} + \alpha - \gamma)(t_1 + t_2)} \right.
\]

\[
+ 4 \frac{\beta}{|d|} |\tilde{\eta}_{+-}| \sin (\Delta m t_1 + \phi_{+-} - \phi_{SW}) e^{-(\bar{\Gamma} + \alpha - \gamma)t_1} e^{-\Gamma_{S t_2}} + \\
+ 4 \frac{\beta}{|d|} |\tilde{\eta}_{+-}| \sin (\Delta m t_2 + \phi_{+-} - \phi_{SW}) e^{-(\bar{\Gamma} + \alpha - \gamma)t_2} e^{-\Gamma_{S t_1}} + \\
- 2 \left( \frac{\gamma}{\Delta \Gamma} + 2 \frac{\beta}{|d|} |\tilde{\eta}_{+-}| \frac{\sin \phi_{+-}}{\cos \phi_{SW}} \right) e^{-\Gamma_{S (t_1 + t_2)}} \right\}
\]
Another way to look for CPT violation: double semileptonic decay $(\pi^+ l^- \bar{\nu}, \pi^- l^+ \nu)$

- kaons obey the $\Delta S = \Delta Q$ rule
The $\eta$ parameters are: $\eta_{l+} = 1 - 2\delta$, $\eta_{l-} = -1 - 2\delta$. 

![Graph showing decay rate vs. $\Delta t_t\tau_s$ with two curves for $\delta = 0$ and $\delta = 0.0005 + 0.05i$.](image-url)
Events selection:

- identification of two neutral kaons from $\phi$ meson decay, in turn decaying into $\pi^+\pi^-$ pairs
- cut on $K_L$ invariant mass:

$$\sqrt{2 \left( m_{\pi}^2 + \sqrt{(m_{\pi}^2 + \vec{p}_{\pi_1}^2)(m_{\pi}^2 + \vec{p}_{\pi_2}^2)} - \sum_{i=x,y,z} p_{\pi_1}^i p_{\pi_2}^i \right)} - m_{K^0} < 5 \text{ MeV}$$

- cut on $K_S$ and $K_L$ missing masses:

$$10 \text{ MeV}^2 > \sum_{i=x,y,z} \left[ \left( \sqrt{m_{K^0}^2 + (p_{K_{S(L)}^i})^2} - \sqrt{m_{\pi}^2 + (p_{\pi_{1S(L)}}^i)^2} - \sqrt{m_{\pi}^2 + (p_{\pi_{2S(L)}}^i)^2} \right)^2 + \left( p_{K_{S(L)}}^i - p_{\pi_{1S(L)}}^i - p_{\pi_{2S(L)}}^i \right)^2 \right] > -50 \text{ MeV}^2$$
Event selection (continued):

- cut on $K_S$ and $K_L$ missing momenta:

$$\sqrt{\sum_{i=x,y,z} \left( p_{K_S(L)}^i - p_{\pi_{1S(L)}}^i - p_{\pi_{2S(L)}}^i \right)^2} < 10 \text{ MeV}$$

- cut on event global fit:

$$\sum_{K=K^0,\bar{K}^0} \left( \frac{V^K_i - (V^K_i + I^K \hat{n}^K_i)}{\sigma_i} \right)^2 < 15,$$
Fitted function was of the form:

\[ n_i = N \left( \sum_j s_{ij} \epsilon_j I_j (\alpha, \beta, \gamma) \right), \]

where:
- \( n_i \) - expected number of events in the \( i \)th bin,
- \( N \) - normalizing factor,
- \( s_{ij} \) and \( \epsilon_j \) are elements of the smearing matrix and efficiency vector,

\[ I_{t'} (\alpha, \beta, \gamma) = \int_{t'}^{t'+\delta t'} I(\pi^+\pi^-, \pi^+\pi^-; \Delta t) \, d(\Delta t). \]
Regeneration on the beam pipe and DC inner wall difficult to describe

![Graph showing data and various regeneration processes](image-url)
One can check how nonzero values of $\alpha$, $\beta$ and $\gamma$ parameters (separately) affect the shape of the curve:

\[ \alpha = 10^{-16} \text{GeV} \]
\[ \beta = \gamma = 0 \]
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\[ \beta = 2 \times 10^{-18} \text{GeV} \]
\[ \alpha = \gamma = 0 \]

\[ \gamma = 10^{-20} \text{GeV} \]
\[ \alpha = \beta = 0 \]
Earlier results:

<table>
<thead>
<tr>
<th></th>
<th>CPLEAR</th>
<th>KLOE 2007 (2002 data)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>$(-0.5 \pm 2.8) \cdot 10^{-17}$ GeV</td>
<td>$(-10^{+41}_{-31} \pm 9) \cdot 10^{-17}$ GeV</td>
</tr>
<tr>
<td>$\beta$</td>
<td>$(2.5 \pm 2.3) \cdot 10^{-19}$ GeV</td>
<td>$(3.7^{+6.9}_{-9.2} \pm 1.8) \cdot 10^{-19}$ GeV</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$(1.1 \pm 2.5) \cdot 10^{-21}$ GeV</td>
<td>$(-0.5^{+5.8}_{-5.1} \pm 1.2) \cdot 10^{-21}$ GeV</td>
</tr>
</tbody>
</table>
Example of a fit:
fit with $\alpha = \gamma$, $\beta = 0$ assumptions seems to be correct

with freed parameters, obtained values are an order of magnitude bigger than expected

the results should be treated as less significant than those officially obtained by KLOE and CPLEAR collaborations

example of theoretical predictions (based on “solar neutrino problem”):

$$\gamma \geq 7.4 \cdot 10^{-22} \text{ GeV} \quad \text{for } \alpha < 2\gamma,$$

$$\alpha \geq 1.5 \cdot 10^{-21} \text{ GeV} \quad \text{for } \alpha > 2\gamma.$$
Schematic view of KLOE-2 upgrades in the vicinity of the interaction point:
Main additions:

- inner tracker - 4 layers of CGEM detectors to improve decay vertex reconstruction
- calorimeters to increase acceptance
- $\gamma\gamma$ taggers
Thank you for your attention