$K_S$ lifetime and QM test with interferometry @ KLOE

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for the KLOE collaboration
The Daφne e+e− collider

- Collisions at c.m. energy around the φ mass: \( \sqrt{s} \sim 1019.4 \) MeV
- Beam crossing angle
  \( \alpha_{CRS} \sim \pi-0.025 \) rad
- \( \phi \) momentum in lab. syst.
  \( p_\phi \sim 13 \) MeV/c
- Cross section for \( \phi \) production @ peak:
  \( \sigma_\phi \sim 3 \) μb
- End of Kloe data taking (2006) luminosity:
  \( L_{PEAK} \sim 1.4 \times 10^{32} \) cm\(^{-2}\) s\(^{-1}\)

<table>
<thead>
<tr>
<th>Main ( \phi ) decay mode</th>
<th>BR, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^+K^- )</td>
<td>49.1</td>
</tr>
<tr>
<td>( K_S K_L )</td>
<td>34.0</td>
</tr>
<tr>
<td>( \rho \pi, \pi^+\pi^-\pi^0 )</td>
<td>15.4</td>
</tr>
<tr>
<td>( \eta \gamma )</td>
<td>1.3</td>
</tr>
</tbody>
</table>
The KLOE detector

**Beam pipe** (spherical, 10 cm Ø, 0.5 mm thick)

**Drift chamber** (Ø=4 m, L=3.3 m)

90% He + 10% IsoB, $X_0=900$ m, ~2600 s.w.

$\sigma(p_t)/p_t \sim 0.4\%$; $\sigma_{\text{hit}} \sim 150$ μm (xy),

~ 2 mm (z); $\sigma_{\text{vertex}} \sim 1$ mm

**Electromagnetic calorimeter**

Lead/scintillating fibers 4880 PMT's

$\sigma_E = 5.7\% /\sqrt{E(\text{GeV})}$

$\sigma_t = 54$ ps $/\sqrt{E(\text{GeV})} \oplus 100$ ps

$\sigma_L(\gamma\gamma) \sim 1.5$ cm ($\pi^0$ from $K_L \rightarrow \pi^+\pi^-\pi^0$)

**Superconducting coil** $B = 0.52$ T
KLOE data taking ended on March 2006

\[ \int L \, dt \sim 2.5 \, \text{fb}^{-1} \sim 2.5 \times 10^9 \text{ } K_S K_L \text{ pairs} \]
KLOE provides monochromatic (p=110 MeV/c) and pure beam of kaons from $\phi$ decay ($J^{PC} = 1^{--}$)

$K_S \leftrightarrow \phi \rightarrow K_L \sim 10^6$ events / pb$^{-1}$

where observation of $K_S$ ($K_L$) tags presence of $K_L$ ($K_S$)

This allows:

- precise measurements (absolute BR’s, lifetimes)
- interference measurements with $K_S K_L$ system
Tagging

\[ K_S \rightarrow \pi^+ \pi^- \]

\[ K_L \rightarrow 2\pi^0 \]

\[ K_L \text{ tagged by } K_S \rightarrow \pi^+ \pi^- \]
Efficiency ~ 70% (geometrical)
\[ K_L \text{ momentum resolution } \sim 1 \text{ MeV} \]
\[ K_L \text{ angular resolution } \sim 1^\circ \]

\[ K_S \rightarrow \pi \text{ ev} \]

\[ K_S \text{ tagged by } K_L \text{ interaction in EmC} \]
Efficiency ~ 30%
\[ K_S \text{ momentum resolution } \sim 1 \text{ MeV} \]
\[ K_S \text{ angular resolution } \sim 1^\circ \]
Neutral kaon

Interferometry
Quantum Mechanics coherence test

The $K^0\bar{K}^0$ state from $\phi$ ($J^{PC}=1^{-}$) decay is required to be:

$$|i\rangle = \frac{N}{\sqrt{2}} |K_S(\hspace{1mm}+\hspace{1mm}\bar{p})\rangle |K_L(\hspace{1mm}-\hspace{1mm}\bar{p})\rangle - |K_L(\hspace{1mm}+\hspace{1mm}\bar{p})\rangle |K_S(\hspace{1mm}-\hspace{1mm}\bar{p})\rangle$$

Time evolution obeys a Shrodinger-like eq. with $H=M-i/2\Gamma$. In QM we have

$$I(f_1, t_1; f_2, t_2) \sim |a_{1S}a_{2L}|^2 + |a_{1L}a_{2S}|^2 - 2(1-\zeta_{SL}) \Re \{ (a_{1S}a_{2L})^*(a_{1L}a_{2S}) \}$$

where

$$a_{1S(L)} = \langle f_1 | T | K_{S(L)}(t_1) \rangle$$

$$a_{2S(L)} = \langle f_2 | T | K_{S(L)}(t_2) \rangle$$

Value $\zeta \neq 0$ indicates deviation from QM.

Simple QM $\rightarrow f_1=f_2=\pi^+\pi^-$ the event distribution as function of $\Delta t=|t_2-t_1|$ gives:

$$I(\Delta t) \sim e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1-\zeta_{SL}) e^{-(\Gamma_L+\Gamma_S)\Delta t/2} \cos(\Delta m \Delta t)$$

Initial symmetry requires $\rightarrow$ no events at the same time ($\Delta t=0$).
Fit function: \[ I(\Delta t) \approx e^{-\Gamma_L \Delta t} + e^{-\Gamma_S \Delta t} - 2(1 - \zeta_{SL}) e^{-(\Gamma_L + \Gamma_S) \Delta t/2} \cos(\Delta m \Delta t) \]

\( \Gamma_S, \Gamma_L, \Delta m \) fixed from PDG;

After including resolution, efficiency, BKG from coherent and incoherent regeneration on beam pipe, non-resonant \( e^+e^- \rightarrow \pi^+ \pi^- \pi^+ \pi^- \) process, 380 pb\(^{-1}\) analyzed data gives:

\[ \zeta_{SL} = (1.8 \pm 4.0_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-2} \]

\[ \zeta_{0\bar{0}} = (1.0 \pm 2.1_{\text{stat}} \pm 0.4_{\text{syst}}) \times 10^{-6} \]

KLOE \[ \text{PLB 642(2006) 315} \]
Analyzed data: \( L = 1.5 \text{ fb}^{-1} \) (2004-05 data) gives:

\[ \rightarrow \text{high sensitivity to } \zeta_{00} \]

Improvement \( \times 2 \) wrt published result

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

\[ \zeta_{00} = (1.4 \pm 9.5_{\text{stat}} \pm 3.8_{\text{syst}}) \times 10^{-7} \]

\[ \text{KLOE final} \]

\[ \text{BELLE} \]

**CPLEAR**

\[ p \bar{p} \rightarrow K^0 K^0, \bar{K}^0 \bar{K}^0, \]

S-like

\[ K^0 \bar{K}^0 \]

S-unlike

KK produced in a \( J^{PC} = 1^{-} \) state (BR=0.7%) From measured asymmetry

\[ A = (P_{\text{unlike}} - P_{\text{like}}) / ( + ) \]


\[ \zeta_{SL} = 0.13 \pm 0.16 \quad \zeta_{00} = 0.4 \pm 0.7 \]

**Belle**

\[ \Upsilon(4S) \rightarrow B^0 \bar{B}^0, \bar{B}^0 B^0, \quad B^0 \bar{B}^0 \]

SF \quad OF

From \( A = (P_{\text{OF}} - P_{\text{SF}}) / ( + ) \)

Belle obtains [PRL99(2007)131802]:

\[ \zeta_{00}^B = 0.029 \pm 0.057 \]
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 [Bernabeu, et al. PRL 92 (2004) 131601, NPB744 (2006) 180].

at most one expects: \[ |\omega|^2 = O\left(\frac{E^2/M_{PLANCK}}{\Delta \Gamma}\right) \sim 10^{-5} \rightarrow |\omega| \sim 10^{-3} \]

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

The maximum sensitivity to $\omega$ is expected for $f_1=f_2=\pi^+\pi^-$
• Analysed data: 1 fb^{-1} (2005 data)

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

KLOE final:

$\Re \omega = (-1.6^{+3.0}_{-2.1} \text{ stat} \pm 0.4 \text{ syst}) \times 10^{-4}$

$\Im \omega = (-1.7^{+3.3}_{-3.0} \text{ stat} \pm 1.2 \text{ syst}) \times 10^{-4}$

$|\omega| < 1.0 \times 10^{-3}$ @ 95\% CL


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

$-0.0084 \leq \Re \omega \leq 0.0100$ at 95\% C.L.
$K_s$ lifetime
Introduction
- 730 pb⁻¹ (2004 Data);
- Lifetime from fit to proper time \( t_0 \);
- Distribution of \( K^0 \rightarrow \pi^+ \pi^- \) decay;
- \( \phi \) position event by event

Selection
- Require good tracking fit for \( \pi \)'s;
- \( |M_{\pi^+ \pi^-} - M_K| < 2 \text{ MeV} \ (\sim 2\sigma) \);
- Acceptance cuts to improve vtx resolution;
- After all cuts \( \rightarrow \sim 25 \) million decay events

Redundant determination of \( k_S \) momentum:
1) From pion tracks: \( p_S(\pi\pi) \);
2) By using informations from line of flight and \( \sqrt{s} \): \( p_S(\text{boost}) \)
$z_{IP}$ resolution
(typical collision region \(\sim 3\) cm)

\[ \chi^2/\text{ndf} = 19.75 / 7 \]
Constant = 20217.
Mean = -0.79852E-02
Sigma = 0.20044

$K_S$ momentum

\[ p_S(\pi\pi) - p_S(\text{boost}) \]
VTX position calibration

- VTX position calibration correlated with momentum calibration

\[ dl = a \, dp \]

- Bias \( dl \) depends on \( \phi \);
- Calibrated using

\[ dp = p_S^{2\pi} - p_S^{\text{boost}} \]

from Monte Carlo

Data after vtx calibration

\[ \frac{\tau_s}{\tau_s^0} \]
Improve time resolution with a geometrical fit: $K_S$ direction fixed, free parameters are IP position and decay distance, $d$.

Proper time resolution on MC

<table>
<thead>
<tr>
<th>$\chi^2$/ndf</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>P1</td>
<td>3062.9 ±</td>
<td>62.47</td>
</tr>
<tr>
<td>P2</td>
<td>0.72698 ±</td>
<td>0.1060E-01</td>
</tr>
<tr>
<td>P3</td>
<td>2632.6 ±</td>
<td>63.93</td>
</tr>
<tr>
<td>P4</td>
<td>0.23898 ±</td>
<td>0.5344E-02</td>
</tr>
<tr>
<td>P5</td>
<td>-1.4620E-01 ±</td>
<td>0.2001E-02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\chi^2$/ndf</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>18036.</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>0.20634</td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>6721.4</td>
<td></td>
</tr>
<tr>
<td>P4</td>
<td>0.37485</td>
<td></td>
</tr>
<tr>
<td>P5</td>
<td>-0.35195E-03</td>
<td></td>
</tr>
</tbody>
</table>
Proper time Fit

- Results as function of $K_S$ direction (different resolutions);
- Fit range: 18 bins from $-2$ to $+7 \tau_0^S$;
- Resolution described by two gaussians;
- 5 parameter fit: $\tau_S + 4$ parameters describing resolution.

Lifetime obtained from a weighted average on 270 independent fits.
The distribution of $\chi^2$ from each fit to data is compared with the expected distribution.

- Few bins at the border of the FV have bad probability $\rightarrow$ variation of the result by $6 \times 10^{-4}$ (included in the systematic error).
Systematic errors

<table>
<thead>
<tr>
<th>Source</th>
<th>fractional value $\times 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>- selection cuts</td>
<td>3.3</td>
</tr>
<tr>
<td>- $\cos \theta_K$ FV cut</td>
<td>5.7</td>
</tr>
<tr>
<td>- Kaon mass</td>
<td>0.4</td>
</tr>
<tr>
<td>- fit range</td>
<td>5.0</td>
</tr>
</tbody>
</table>

$$\tau_{K_S} = (89.56 \pm 0.03_{\text{stat}} \pm 0.07_{\text{syst}}) \text{ ps}$$

preliminary
Updated results on $K_S$ lifetime

New world average $\tau_S = 89.59 \pm 0.04$ (ps) ($4.6 \times 10^{-4}$)

(PDG08 = 5.6 x 10^{-4})
Conclusion

- Many KLOE measurements have been refined and finalized with full statistics;

- KLOE performed the best QM test with interferometry;

- New preliminary result on $K_s$ lifetime: good agreement with recent measurements;

- Neutral kaon interferometry, CPT symmetry and QM tests are one of the main issues of the KLOE-2 physics program (see Gauzzi talk). Limits on the parameters for these specific issues can be improved by a factor of ten.
SPARES
Test from KL-crash (Data)

By using KL-crash position and time we perform a test for $K_\pi$ direction as derived from pions ($\alpha = \text{angular deviation}$)
Vertex calibration

\[ \phi^{2d} \]

\[ \text{dp}_{\text{MC}} \text{(MeV)} \]

\[ \chi^2/\text{ndf} \]

\[ P1 \]

\[ P2 \]

\[ P3 \]

\[ 6062. / 15 \]

\[ -0.41164E-02 \]

\[ 0.74377E-01 \]

\[ -0.39385E-01 \]
## KLOE-2

<table>
<thead>
<tr>
<th>Mode</th>
<th>Test of</th>
<th>Param.</th>
<th>Present best published measurement</th>
<th>KLOE-2 L=50 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^+\pi^- \pi^+\pi^-)</td>
<td>QM</td>
<td>(\zeta_{00})</td>
<td>((1.0 \pm 2.1) \times 10^{-6})</td>
<td>(\pm 0.1 \times 10^{-6})</td>
</tr>
<tr>
<td>(\pi^+\pi^- \pi^+\pi^-)</td>
<td>QM</td>
<td>(\zeta_{SL})</td>
<td>((1.8 \pm 4.1) \times 10^{-2})</td>
<td>(\pm 0.2 \times 10^{-2})</td>
</tr>
<tr>
<td>(\pi^+\pi^- \pi^+\pi^-)</td>
<td>CPT &amp; QM</td>
<td>(\alpha)</td>
<td>((-0.5 \pm 2.8) \times 10^{-17}) GeV</td>
<td>(\pm 2 \times 10^{-17}) GeV</td>
</tr>
<tr>
<td>(\pi^+\pi^- \pi^+\pi^-)</td>
<td>CPT &amp; QM</td>
<td>(\beta)</td>
<td>((2.5 \pm 2.3) \times 10^{-19}) GeV</td>
<td>(\pm 0.1 \times 10^{-19}) GeV</td>
</tr>
<tr>
<td>(\pi^+\pi^- \pi^+\pi^-)</td>
<td>CPT &amp; QM</td>
<td>(\gamma)</td>
<td>((1.1 \pm 2.5) \times 10^{-21}) GeV</td>
<td>(\pm 0.2 \times 10^{-21}) GeV</td>
</tr>
<tr>
<td>(\pi^+\pi^- \pi^+\pi^-)</td>
<td>CPT &amp; EPR corr.</td>
<td>Re((\omega))</td>
<td>((1.1 \pm 7.0) \times 10^{-4})</td>
<td>(\pm 2 \times 10^{-5})</td>
</tr>
<tr>
<td>(\pi^+\pi^- \pi^+\pi^-)</td>
<td>CPT &amp; EPR corr.</td>
<td>Im((\omega))</td>
<td>((3.4 \pm 4.9) \times 10^{-4})</td>
<td>(\pm 2 \times 10^{-5})</td>
</tr>
<tr>
<td>(K_{S,L} \rightarrow \pi\nu)</td>
<td>CPT &amp; Lorentz</td>
<td>(\Delta a_0)</td>
<td>([0.4 \pm 1.8] \times 10^{-17}) GeV</td>
<td>(\pm 2 \times 10^{-18}) GeV</td>
</tr>
<tr>
<td>(\pi^+\pi^- \pi^+\pi^-)</td>
<td>CPT &amp; Lorentz</td>
<td>(\Delta a_Z)</td>
<td>([2.4 \pm 9.7] \times 10^{-18}) GeV</td>
<td>(\pm 7 \times 10^{-19}) GeV</td>
</tr>
<tr>
<td>(\pi^+\pi^- \pi\nu)</td>
<td>CPT &amp; Lorentz</td>
<td>(\Delta a_{X,Y})</td>
<td>([&lt;10^{-21}) GeV]</td>
<td>(\pm 4 \times 10^{-19}) GeV</td>
</tr>
</tbody>
</table>

[...] = preliminary