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Precision tests of Quantum Mechanics and CPT symmetry with entangled neutral kaons at KLOE

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The quantum interference between the decays of entangled neutral kaons is a very powerful tool for testing the quantum coherence of the entangled kaon pair state. The studied process $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\pi^+\pi^-$ exhibits the characteristic Einstein-Podolsky-Rosen correlations [1] that prevent both kaons to decay into $\pi^+\pi^-$ at the same time. The newly published result is based on data sample collected with the KLOE detector at DAΦNE and corresponds to an integrated luminosity of about 1.7 fb^{-1} , i.e. to $\sim 1.7 \times 10^9$ $\phi \to \mathrm{K_S K_L}$ decays. From the fit to the observed time difference distribution of the two kaon decays, the decoherence and CPT violation parameters of various phenomenological models are measured. A stringent upper limit on the branching ratio of the $\phi \to \mathrm{K_S K_S}, \mathrm{K_L K_L}$ decay is also derived. Independently, the comparison of neutral meson transition rates between flavour and CP eigenstates allows direct and model independent tests of time-reversal T and CPT symmetries to be conducted, through ratios of rates of two classes of processes: $\mathrm{K_S K_L} \to (\pi^\pm e^\mp \nu)(3\pi^0)$ and $\mathrm{K_S K_L} \to (\pi^+\pi^-)(\pi^\pm e^\mp \nu)$. In addition to this a straightforward extension to the case of CPT symmetry is performed providing the first model independent test of CPT symmetry violation in transitions of neutral kaons.

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1. Decoherence and CPT test

Neutral kaons are one of the most puzzling physical systems. Their properties like decay, mixing and CP violation provide an unique environment to test principles of quantum mechanics and discrete symmetries. Here, entanglement as one of the most bizarre feature of quantum mechanics and the oscillation (transition) between the particle and its own anti-particle are used to perform such tests.

The intensity of the CP–violating decay $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ in the $\{K_S, K_L\}$ basis as a function of the kaon decay proper times t_1 and t_2 and parameter ζ_{SL} describing deviations from quantum mechanics is:

$$
\begin{aligned}
I(t_1, t_2; \zeta_{SL}) \quad \propto \quad & e^{-\Gamma_L t_1 - \Gamma_S t_2} + e^{-\Gamma_S t_1 - \Gamma_L t_2} \\
& -2(1-\zeta_{SL}) e^{-\frac{(\Gamma_S+\Gamma_L)}{2}(t_1+t_2)} \cos[\Delta m (t_1 - t_2)] \,, \qquad (1)
\end{aligned}
$$

where the second line corresponds to fully destructive quantum interference between physical states ($K_{S,L}$) having masses ($m_{S,L}$) and widths ($\Gamma_{S,L}$) as a function of difference of masses $\Delta m = m_L - m_S$ and proper decay times. A spontaneous factorization of the state is obtained for $\zeta_{SL} = 1$, while quantum mechanics holds in the case of $\zeta_{SL} = 0$. An analogous mechanism can be presented for the $\{K^0, \bar{K}^0\}$ basis [2] with $\zeta_{0\bar{0}}$ being the corresponding decoherence parameter

A possible decoherence in quantum gravity framework can be expressed as a complex parameter describing CPT violation induced at the initial state [3–5]:

$$
|i\rangle \quad = \quad \frac{1}{\sqrt{2}} \left[|K^0\rangle|\bar{K}^0\rangle - |\bar{K}^0\rangle|K^0\rangle + \omega \left(|K^0\rangle|\bar{K}^0\rangle + |\bar{K}^0\rangle|K^0\rangle \right) \right] \,, \qquad (2)
$$

where $\omega = |\omega| e^{i\phi_\omega}$.

The models briefly mentioned above are fit to the data distribution of the difference of the kaon decay times measured with the KLOE detector to obtain values of the defined parameters. The analysis is based on a data sample [6] four times larger and statistically independent with respect to the previous KLOE measurement [7]. An improved background and signal selection are performed.

The obtained results [6] are more than twice improved with respect to previous KLOE results [7] and are consistent with no decoherence and no CPT violation.

2. T and CPT symmetry test in transition

A direct test of CPT and T symmetry is also possible with entangled neutral kaons [8]. The states with definite flavour or CP:

$$
\mathcal{S}\,|K^0\rangle = +1\,|K^0\rangle\,, \mathcal{S}\,|\bar{K}^0\rangle = -1\,|\bar{K}^0\rangle\,, \qquad (3)
$$

$$
\begin{aligned}
|K_+\rangle &= \frac{1}{\sqrt{2}} \left[|K^0\rangle + |\bar{K}^0\rangle \right] \text{ with CP} = +1, \\
|K_-\rangle &= \frac{1}{\sqrt{2}} \left[|K^0\rangle - |\bar{K}^0\rangle \right] \text{ with CP} = -1,
\end{aligned} \qquad (4)
$$

can be identified through observation of their decay products. The state of one kaon is identified at the moment of decay of the other kaon. Therefore an identification of its state at the decay, after time Δt after the decay of the first kaon, allows to infer about a transition between the strangeness and CP-definite states. It can be shown that for each of such transitions a time-dependent ratio of probabilities can be defined to test the T symmetry.

At KLOE two of those ratios are accessible:

$$R_{2,T}(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]}$$
$$R_{4,T}(\Delta t) = \frac{P[\bar{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \bar{\mathrm{K}}^0(\Delta t)]}. \tag{5}$$

as well as two ratios sensitive to CPT violation [9]:

$$R_{2,CPT}(\Delta t) = \frac{P[\mathrm{K}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \mathrm{K}^0(\Delta t)]},$$
$$R_{4,CPT}(\Delta t) = \frac{P[\bar{\mathrm{K}}^0(0) \to \mathrm{K}_-(\Delta t)]}{P[\mathrm{K}_-(0) \to \bar{\mathrm{K}}^0(\Delta t)]}. \tag{6}$$

Each of these ratios is proportional to intensity $I(f_1, f_2; \Delta t)$ as the double decay rate into final states f_1 and f_2 as a function of the difference of kaon decay times Δt [10]. Additionally, a test with double ratio for T and CPT is also possible. Such double ratio constitutes a CPT violation observable which was never measure before.

Based on the 1.7 fb^{-1} of data collected by the KLOE experiment at DAΦNE the model independent test with the entangled $\mathrm{K}^0\bar{\mathrm{K}}^0$ pairs is recently performed for the first time showing no evidence for T and CPT symmetry violation [11].

3. Summary

The entangled neutral kaons are used again for precise measurements at KLOE. The improved accuracy on decoherence parameters and first, model-independent test of T and CPT symmetries with K meson pairs confirms not only the unique properties of such system, but capabilities of the detection system as well. A data sample corresponding to 5.5 fb^{-1} of integrated luminosity is collected with the upgraded detector KLOE–2. The new detector is equipped with the Inner Tracker [12] for improvement of resolution on the vertex position and acceptance for tracks with low transverse momentum, two pairs of small angle tagging devices to detect low (Low Energy Tagger - LET [13]) and high (High Energy Tagger - HET [14]) energy e^+e^- originated from $e^+e^- \to e^+e^-X$ reactions; crystal calorimeters (CCALT) to cover the low polar angle region to increase acceptance for very forward electrons and photons down to 8° [15]; and a tile calorimeter (QCALT) used for the detection of photons coming from K_L decays in the drift chamber [16]. This new data and the improved performance of the upgraded detector will allow for even more precise results in the field of kaon physics, and also in hadronic physics in general to be achieved [17].

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