KAON INTEROFEROMETRY AT CPLEAR

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Abstract

The CPLEAR result of the possible loss of quantum coherence and the non-separability of the neutral kaon pair wave function are discussed. In addition, a new idea of testing Bell's Inequality with two regenerators at KLOE2 is proposed.

1 Introduction

Neutral kaon has several remarkable properties (strangeness oscillation, small mass difference between K_L and K_S, CP non-conservation etc) that provides a unique opportunity for testing fundamental physical laws. In this paper, we will summarise two important contribution of CPLEAR to these fundamental measurements: possible loss of quantum coherence and the non-separability of the neutral kaon pair's wave function.

2 CPLEAR experiment

The CPLEAR detector [1] (fig.1) is located at the Low Energy Antiproton Ring (LEAR) at CERN. The continue and intense ($10^6 \bar{p}/s$) 200MeV antiproton beam is extracted from LEAR and stopped inside a 27-bar hydrogen gas target. A cylindrical tracking detector was located inside a solenoid (1m radius, 3.6m long) providing a 0.44T magnetic field parallel to the beam. It consisted of two layers of MWPCs (PC1, PC2), six layers of drift chambers and two layers of streamer tubes. A hodoscope of 32 threshold Cherenkov counters sandwiched between two swcintillator hodoscopes (S1, S2) provided charged particle identification (Cherenkov light, time of flight and energy loss). The cylindrical target (11mm radius) was surrounded by a small cylindrical proportional chamber PC0 (15mm radius, 1mm pitch, $> 99.5\%$ efficiency). A thin
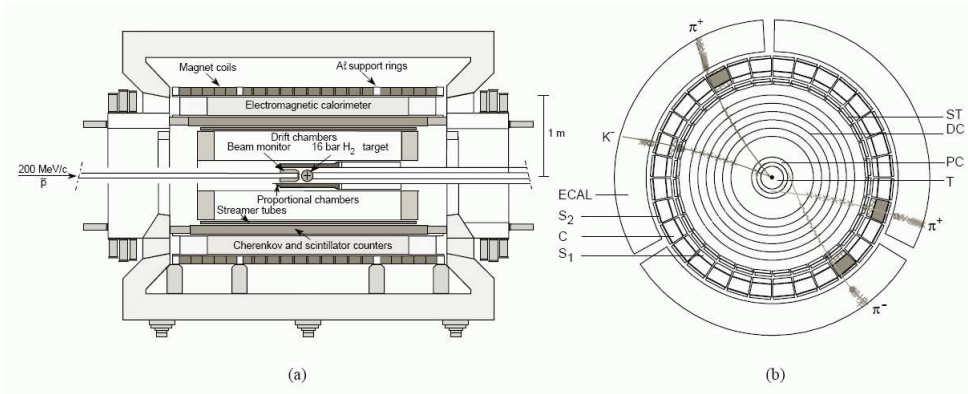
Figure 1: *CPLEAR detector: (a) longitudinal view, and (b) transverse view and display on an event $\bar{p}p \to K^-\pi^+K^0$ with the neutral kaon decaying into $\pi^+\pi^-$.*

silicon detector in front of the target entrance window ensured the presence of an incoming antiproton, thus rejecting background events resulting from interactions in the target support structure. A multi-level trigger optimized to select the initial K^0 or $\bar{K}^0$ via reactions

$$\bar{p}p \to K^-\pi^+K^0$$

$$\bar{p}p \to K^+\pi^-\bar{K}^0$$

(each having a branching ratio of $\approx 2 \times 10^{-3}$). By reconstructing the charged kaon and the opposite charged pion, the production point, the momentum and the initial strangeness of the neutral kaon can be measured. This detector was originally design to measure CP and T violation parameters in the neutral kaon system but it is capable of doing many other physics. The summary of the all physics output of CPLEAR experiment can be found elsewhere [2].

3 Loss of quantum coherence

The formalism of time evolution of the kaon normally used is according to a QM closed system description. Some approaches to quantum gravity [3] suggest that topologically non-trivial space-time fluctuations (space-time foam) entail an intrinsic, fundamental information loss, and therefore transitions from pure to mixed state [4]. The $K^0 - \bar{K}^0$ system is then described by a 2x2 density matrix ρ, which obeys

$$\dot{\rho} = -\mathrm{i}[\Lambda\rho - \rho\Lambda^\dagger] + \delta\!\!\!/\Lambda\rho, \tag{1}$$

where Λ is the time-dependent 2x2 matrix ($\Lambda = M - \frac{i}{2}\Gamma$, the mass and decay matrices) and the term $\not{\partial}\Lambda\rho$ induces a loss of quantum coherence in the observed system. In this context, the time evolution of the $K^0 - \bar{K}^0$ system allows for another 9 parameters, in addition to the usual seven. The CPLEAR experiment has measured 3 (α, β and γ) of the 9 parameters (the rest 6 are assumed to be zero). If different from zero, α, β and γ would point to a loss of coherence of the wave function (and also to CPT violation). The decay-rate asymmetries from the $\pi^+\pi^-$ decay channel,

$$A_{2\pi}(\tau) = \frac{N_{\bar{K}^0 \to \pi^+\pi^-}(\tau) - N_{K^0 \to \pi^+\pi^-}(\tau)}{N_{\bar{K}^0 \to \pi^+\pi^-}(\tau) + N_{K^0 \to \pi^+\pi^-}(\tau)}, \tag{2}$$

and for $e\pi\nu$ decay channel,

$$A_{\Delta m}(\tau) = \frac{[N_{\bar{K}^0 \to e^-\pi^+\bar{\nu}}(\tau) + N_{K^0 \to e^+\pi^-\nu}(\tau)] - [N_{\bar{K}^0 \to e^+\pi^-\nu}(\tau) + N_{K^0 \to e^-\pi^+\bar{\nu}}(\tau)]}{[N_{\bar{K}^0 \to e^-\pi^+\bar{\nu}}(\tau) + N_{K^0 \to e^+\pi^-\nu}(\tau)] + [N_{\bar{K}^0 \to e^+\pi^-\nu}(\tau) + N_{K^0 \to e^-\pi^+\bar{\nu}}(\tau)]}, \tag{3}$$

were fitted to data with the constraint of $|\eta_{+-}|$ and δ_l measured at long lifetimes (fig.2). It was obtained from the fit, as 90% CL limit [5]:

$$\alpha < 4.0 \times 10^{-17} \text{GeV},$$

$$\beta < 2.3 \times 10^{-19} \text{GeV},$$

$$\alpha < 3.7 \times 10^{-21} \text{GeV},$$

to be compared with a possible order of magnitude of

$$O(m_K^2/m_{\text{Planck}}) = 2 \times 10^{-20} \text{GeV}$$

for such effects. The result was consistent with no loss of quantum coherence.

4   Non-separability of the $K^0\bar{K}^0$ wave function

The strangeness of the pair of $K^0\bar{K}^0$ produced in the $\bar{p}p$ annihilation, $\bar{p}p \to K^0\bar{K}^0$ in $J^{PC} = 1^{--}$ state (92.6% of the case in CPLEAR [6]) is entangled:

$$|\psi\rangle = \frac{1}{\sqrt{2}}[|K^0\rangle_a \otimes |\bar{K}^0\rangle_b - |\bar{K}^0\rangle_a \otimes |K^0\rangle_b], \tag{4}$$

This is analogous [7] to the polarization in a two-photon system, more commonly used in EPR-type experiments [8]. Even though due to $K^0 - \bar{K}^0$ oscillations the individual kaon's strangeness varies with time, the measurement of the
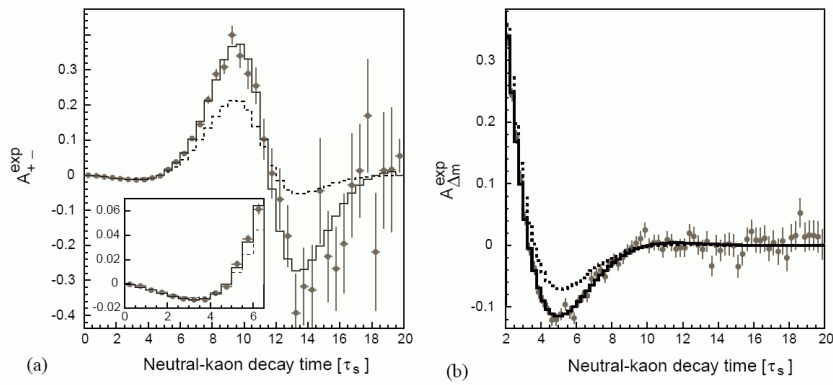
Figure 2: *The measured decay-rate asymmetries (a) $A_{2\pi}$ and (b) $A_{\Delta m}$ analysed for a possible loss of coherence. The solid lines are the result of the fit. The dashed lines represent the expected asymmetries with positive values of α, β, γ, which are 10 times larger than the limits obtained.*

strangeness of one kaon at a given time predicts with certainty the strangeness state of the other unmeasured kaon at equal proper time. There is a perfect strangeness anti-correlation at a distance. The expected QM intensities for the like-strangeness ($K^0 K^0$ or $\bar{K}^0 \bar{K}^0$) and unlike-strangeness ($K^0 \bar{K}^0$ or $\bar{K}^0 K^0$) final states a and b, observed at times t_a and t_b respectively are:

$$I_{like}(t_a, t_b) = \frac{1}{8}[e^{-i\gamma_L t_a - i\gamma_S t_b} + e^{-i\gamma_S t_a - i\gamma_L t_b} - 2e^{-\frac{\gamma_S + \gamma_L}{2}(t_a + t_b)} \cos(\Delta m \Delta t)],$$
(5)

$$I_{unlike}(t_a, t_b) = \frac{1}{8}[e^{-i\gamma_L t_a - i\gamma_S t_b} + e^{-i\gamma_S t_a - i\gamma_L t_b} + 2e^{-\frac{\gamma_S + \gamma_L}{2}(t_a + t_b)} \cos(\Delta m \Delta t)]$$
(6)

where $\Delta m = m_L - m_S$ and $\Delta t = t_a - t_b$. They are shown in fig. 3a. For an experiment, it is easier to measure the asymmetry:

$$A_{(t_a, t_b)} = \frac{I_{unlike}(t_a, t_b) - I_{like}(t_a, t_b)}{I_{unlike}(t_a, t_b) + I_{like}(t_a, t_b)} = \frac{2e^{-\frac{\gamma_S + \gamma_L}{2}(t_a + t_b)} \cos(\Delta m \Delta t)}{e^{-i\gamma_L t_a - i\gamma_S t_b} + e^{-i\gamma_S t_a - i\gamma_L t_b}}.$$
(7)

as shown in fig. 3b.

The strangeness was identified by product of the strong interaction in two absorbers near the target, fig. 4a, via the observation in the same event, at two different times, of a Λ and a K^+ (unlike strangeness) or a Λ and a K^- (like strangeness) [9]. The asymmetries for unlike- and like-strangeness
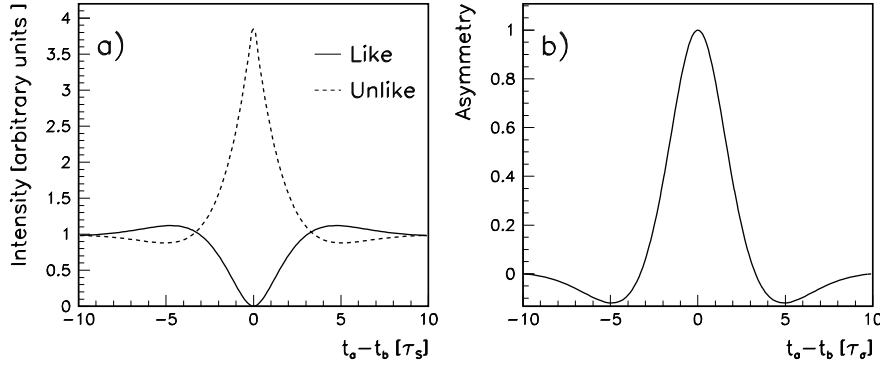
Figure 3: QM prediction for (a) intensity of the like- and unlike-strangeness as a function of Δt and (b) the asymmetry

events (ΛK^+ and ΛK^-) were measured for two experimental configurations C(0) and C(5) (fig.4b) corresponding to $\Delta t \approx 0$ and $\Delta t \approx 1.2\tau_S$ proper time differences between the two strangeness measurements, or path difference Δl of ≈ 0 and 5cm. As shown in fig. 5, these asymmetries are consistent with the values predicted from QM, and therefore consistent with the non-separability hypothesis of the $K^0\bar{K}^0$ wave funtion. The non-separability hypothesis is also strongly favoured by the yield of $\Lambda\Lambda$ events. The probability of satisfying the separability hypothesis of Furry is $< 10^{-4}$.

If after the production of the $K^0\bar{K}^0$ pair, a spontaneous decoherence takes place, i.e. a fraction of the two neutral kaon are separated and evolve independently, then the asymmetry above would be different. This can be parametrized by a factor $(1 - \xi)$, which multiphy the QM interference term in equations (5) and (6). This decoherence could happen either in the $K_L - K_S$ basis or in the $K^0 - \bar{K}^0$ basis. Bertlmann, Grimus and Hiesmayr [10] has measured this decoherence based on the CPLEAR result (fig. 5) and the result is $0.13^{+0.16}_{-0.15}$ and 0.4 ± 0.7 respectively. An improved measurement was done at KLOE [11].

5   Testing Bell Inequality at KLOE2

Having shown that the neutral kaon pair wave function is entangled, a more interesting measurement would be to test the Bell Inequality [12]. However,
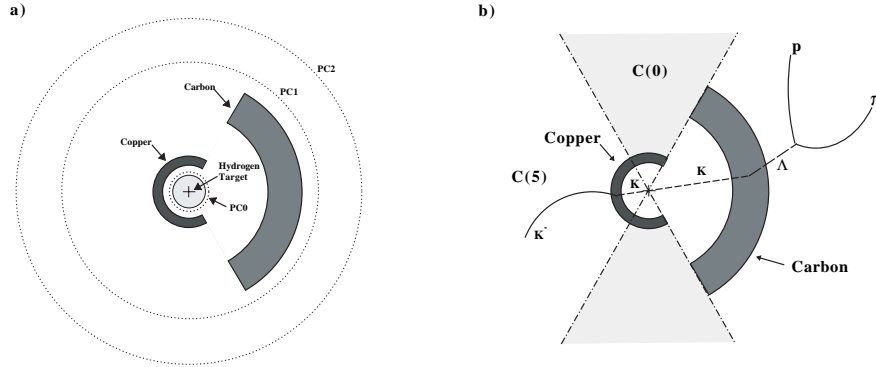
Figure 4: (a) Central region of the CPLEAR detector with the two absorbers and (b) conceptual sketch of the experiment with a ΛK event.
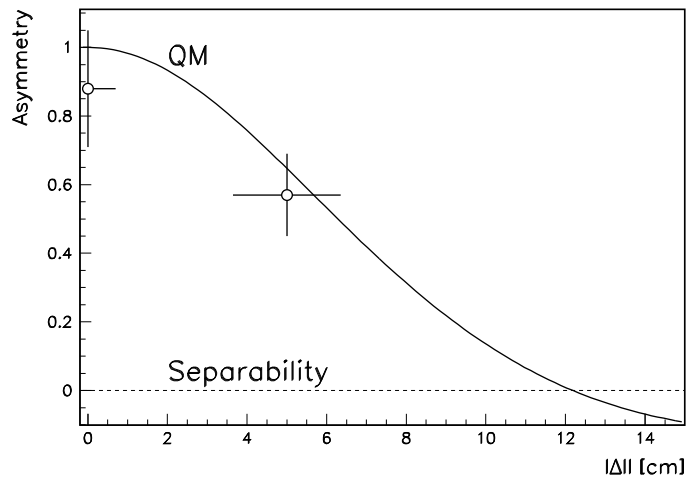

Figure 5: Asymmetry of the measured $\Lambda K^{\pm}$ for the two experimental configurations. The solid curve is the QM prediction. The dashed line is the prediction for a separate wave function hypothesis by Furry.
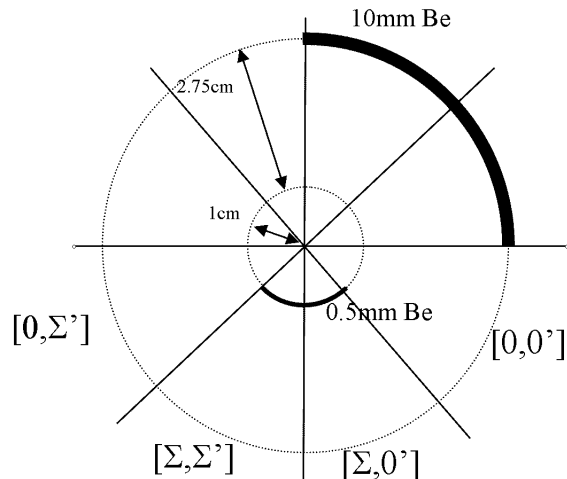
Figure 6: Tranverse view of the proposed two thin regenerator position for the 4 possible configurations to be placed near interation point at KLOE2 detector.

it was proven that due to the rapid decay of the kaon wavefunction, it is not possible to violate Bell Inequality in the $K^0\bar{K}^0$ maximally entangle state [13]. Nevertherless, Bell Inequality can be violated in the non-maximally entangled state [14]. Coherent regeneration in a thin material could be used to create such state from the initial $K^0\bar{K}^0$ pair.

Following the idea by Eberhard [15], originally proposed for asymmetric kaon factory, 4 set-ups with 2 regenerators are used. Translating into a symmetric machine, we proposse to have two partial rings of regenerators which correspond to 4 possible configuration: [0,0'], [Σ,0'], [0,Σ'] and [Σ,Σ'] (fig. 6). Measuring 4 $K_L K_L$ probabilities (by the interation in the calorimeter), the Wigner's form of Bell Inequality can be used:

$$P_{K_L,K_L}(\Sigma, \Sigma') \geq P_{K_L,K_L}(0, 0') + P_{K_L,K_L}(\Sigma, 0') + P_{K_L,K_L}(0, \Sigma'). \qquad (8)$$

Back of envelop calculations using the regeneration parameters from Di Domenico [16] show that for configuraion [Σ,0'] and [0,Σ'], a statistics of 114 events/fb^{-1} and 100 events/fb^{-1} respectively can be achieved at KLOE2. Alternatively, one can also measure $K_S K_S$ decays (into $\pi^+\pi^-$), this gives more statistics of 218 events/fb^{-1} and 346 events/fb^{-1}. Therefore, only around < 5fb^{-1} of data are needed, certainly feasible at the new proposed KLOE2 detector with minor modification of introducing two regenerators.

6 Conclusion

Neutral Kaon is a rich system to testing fundamental QM issues. Here we have presented the test of coherence loss due to quantum gravity and a test of EPR entangled kaon pair. A further test of Bell Inequality should be possible at KLOE2.

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