Journal of Physics: Conference Series **2446** (2023) 012027 doi:10.1088/1742-6596/2446/1/012027

Can future observation of the living partner post-tag the past decayed state in entangled neutral K-mesons?

Antonio Di Domenico

Department of Physics, Sapienza University of Rome, and INFN Sezione di Roma, P.le A. Moro, 2, I-00185 Rome, Italy

E-mail: `antonio.didomenico@roma1.infn.it`

on behalf of KLOE-2 Collaboration

Abstract. Novel quantum phenomena have been recently discussed [1] in association to a peculiar time correlation between entangled neutral kaons produced at a ϕ-factory: the past state of the first decayed kaon, when it was still entangled before its decay, is post-tagged by the result and the time of the future observation on the other kan decay. This surprising "from future to past" effect is fully observable and leads to the unique experimental tag of the $\mathrm{K_S}$ state, an unsolved problem since the discovery of $\mathcal{CP}$ violation. The first preliminary results obtained on the analysis of data collected by the KLOE experiment at the DAΦNE collider, and showing experimental evidence of this new effect are presented.

1. Introduction

Neutral kaons in $\phi \to \mathrm{K^0\bar{K}^0}$ decays are produced in a fully antisymmetric entangled state:

$$|i\rangle = \frac{\mathcal{N}}{\sqrt{2}}\{|\mathrm{K_S}\rangle|\mathrm{K_L}\rangle - |\mathrm{K_L}\rangle|\mathrm{K_S}\rangle\} \tag{1}$$

with $|\mathcal{N}|^2 = \left(1 - |\langle \mathrm{K_S}|\mathrm{K_L}\rangle|^2\right)^{-1} \simeq 1$. The entangled state $|i\rangle$ at any time t after its production remains unaltered, even in presence of $\mathrm{K^0} - \mathrm{\bar{K}^0}$ mixing:

$$|i(t)\rangle \;\; = \;\; \frac{\mathcal{N}}{\sqrt{2}}\{|\mathrm{K_S}\rangle e^{-i\lambda_S t}|\mathrm{K_L}\rangle e^{-i\lambda_L t} - |\mathrm{K_L}\rangle e^{-i\lambda_L t}|\mathrm{K_S}\rangle e^{-i\lambda_S t}\} = e^{-i(\lambda_S+\lambda_L)t}|i\rangle . \tag{2}$$

Under particle exchange we call particle-1 the first one to decay at time t_1, particle-2 the last to decay at time t_2. If nothing is registered after the observation of the first decay at time t_1 (i.e. integrating over all subsequent decays at times t_2 of particle-2), the *survival probability* of the entangled state is necessarily characterised by the total width $\Gamma = \Gamma_S + \Gamma_L$ of the system:

$$P\left(t_1\right) = \| \; |i(t = t_1)\rangle \; \|^2 = e^{-\Gamma t_1} \; . \tag{3}$$

This also holds for any decay channel t_1-distribution with no other subsequent observation.

2. The future post-tags the past effect

The decay amplitude of state $|i\rangle$ to channel f_1 at time t_1 for particle-1 and channel f_2 at time t_2 for particle-2, and the corresponding observable double differential decay rate $I(f_1, t_1; f_2, t_2)$ can be readily calculated using the formalism first introduced by Lee and Yang (see Refs.[2, 3, 1, 4]):

$$\begin{aligned} I(f_1,t_1;f_2,t_2) &= |\langle f_1(t_1)f_2(t_2)|T|i(t)\rangle|^2 \\ &= C_{12}\{|\eta_1|^2 e^{-\Gamma_L t_1-\Gamma_S t_2} + |\eta_2|^2 e^{-\Gamma_S t_1-\Gamma_L t_2} \\ &\quad -2|\eta_1||\eta_2| e^{-\frac{(\Gamma_S+\Gamma_L)}{2}(t_1+t_2)} \cos[\Delta m \Delta t + \phi_1 - \phi_2]\}, \end{aligned} \tag{4}$$

with $\langle f_i|T|\mathrm{K_S}\rangle$ and $\langle f_i|T|\mathrm{K_L}\rangle$ the decay amplitudes to the f_i channel of $\mathrm{K_S}$ and $\mathrm{K_L}$, $\eta_i \equiv |\eta_i|e^{i\phi_i} = \frac{\langle f_i|T|\mathrm{K_L}\rangle}{\langle f_i|T|\mathrm{K_S}\rangle}$, and $C_{12} = \frac{|\mathcal{N}|^2}{2}|\langle f_1|T|\mathrm{K_S}\rangle\langle f_2|T|\mathrm{K_S}\rangle|^2$.

In this formalism, the state of the surviving kaon (particle-2) immediately before its decay at time t_2 – after the first decay at time t_1 – is expressed as:

$$|K^{(2)}(t=t_2)\rangle = \frac{\mathcal{N}}{\sqrt{2}}\langle f_1|T|\mathrm{K_S}\rangle e^{-i(\lambda_S+\lambda_L)t_1}\left[e^{-i\lambda_L\Delta t}|\mathrm{K_L}\rangle - \eta_1 e^{-i\lambda_S\Delta t}|\mathrm{K_S}\rangle\right] . \tag{5}$$

Similarly, exploiting the t_1, t_2 symmetry of the Lee-Yang approach, the past state of particle-1 immediately before its decay at time t_1 is [1]:

$$|K^{(1)}(t=t_1)\rangle = \frac{\mathcal{N}}{\sqrt{2}}\langle f_2|T|\mathrm{K_S}\rangle\{e^{-i\lambda_S t_1}\left[\eta_2\, e^{-i\lambda_L t_2}|\mathrm{K_S}\rangle\right] - e^{-i\lambda_L t_1}\left[e^{-i\lambda_S t_2}|\mathrm{K_L}\rangle\right]\} . \tag{6}$$

This is a striking result which clearly involves a correlation-in-time from the future observation at time t_2 to the past, inferring the initial kaon state *before* its first decay at t_1. It becomes well defined during the time evolution of the entangled state $|i\rangle$ when the state of particle-1 (and particle-2) should have been undefined in the absence of any observation. The *post-tagging* implied by Eq.(6) is not an artefact of the formalism but a factual observable accessible to experimental studies and thus it is fully physical. As function of t_1, two different regimes can be identified: the generic interference region, in which the t_2 dependence of Eq. (6) is apparent, and the decoherence region, in which the relative weight of the $\mathrm{K_L}$ component is negligible. Decoherence is reached for large time differences $\Delta t = t_2 - t_1$ satisfying the condition:

$$e^{-\Delta\Gamma\Delta t/2}/|\eta_2| \ll 1 \qquad [\mathrm{K_S}\text{-tag}] , \tag{7}$$

leading to a pure $\mathrm{K_S}$ beam before the first decay. This consequence of the surviving correlation-in-time is most rewarding. Due to $\mathcal{CP}$ violation and the non-orthogonality of the stationary states $\langle \mathrm{K_L}|\mathrm{K_S}\rangle \neq 0$, there is no decay channel able to tag either $\mathrm{K_S}$ or $\mathrm{K_L}$ on an event-by-event basis. Fulfilment of condition (7) constitutes the only known practical method to *prepare* (post-tag) a $\mathrm{K_S}$ beam (i.e. the short-lived stationary state) with arbitrary high purity (depending on Δt and η_2), preparation otherwise impossible with other methods.

As illustration of the observables in the two different regimes, Figure 1 shows the decay rate distribution into a generic channel f_1 of state (6) as a function of t_1 in two cases: either observed at $t_2 = 3\ \tau_S$ (interference region) or when condition (7) is satisfied (decoherence region), with $f_2 = f_1$ to maximize the interference effects and make visible the difference between the two cases. This choice $f_2 = f_1$ also emphasizes the differing results as due to the dependence on the time alone of the future observation. Whereas the decoherence case shows a definite width Γ_S, the future observation in the interference region leads to a t_1-distribution with no definite lifetime. In the latter case the t_1 distribution does depend on the decay channel.

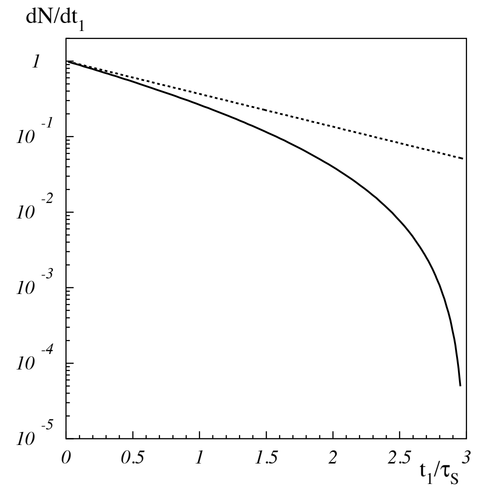

Figure 1. The decay rate distribution into a generic channel f_1 of state (6) as a function of t_1 for the future observation at $t_2 = 3\ \tau_S$ (solid line), and when condition (7) for decoherence is satisfied (dashed line), with $f_2 = f_1$. The last shows a definite lifetime τ_S and does not depend on the decay channel f_1. All distributions are normalised to unity at $t_1 = 0$.

3. Experimental results

A data sample collected by the KLOE experiment at DAΦNE corresponding to an integrated luminosity of about 1.7 fb^{-1} is analysed to study the t_1 distribution of the first decaying kaon in the $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\,\pi^+\pi^-$ process. Two different cases are considered (similarly to Fig.1 with $f_1 = f_2 = \pi^+\pi^-$): (i) the decoherence regime with $t_2 > 30\ \tau_S$ and the $\mathrm{K_S}$-tag condition (7) satisfied, (ii) the interference regime with $2.5 < t_2 < 3\ \tau_S$. The preliminary results are shown in Fig.2, where the experimental t_1 distributions obtained in the two cases are fitted with the prediction of quantum mechanics based on eq.(6), and taking into account the experimental resolution effects on t_1 and t_2 times with a smearing matrix obtained from a Monte Carlo simulation, as in the decoherence analysis presented in Ref. [5], and with the histogram normalization as a single fit parameter. In both cases the background from the non-resonant $e^+e^- \to 4\pi$ process and from kaon regeneration on the beam pipe is negligible [5]. The t_1 distributions in the two cases are compared in Fig.3, normalizing them to unity at $t_1 = 0$.

From these preliminary results, a first evidence of the dependence of the t_1 distribution from the future t_2 time is obtained, confirming the "future post-tags the past" effect discussed above.

This result seems also to confirm the counterintuitive feature of time in quantum mechanics [1], and goes beyond other phenomena, like delayed choice experiments with entangled photon systems, that are stationary at all times, and have the result independent on whether the choice is made in the past or in the future.

4. Conclusions

A novel quantum time correlation phenomenon in the entangled neutral kaon system at KLOE/KLOE-2 has been briefly illustrated. This surprising "future post-tags the past" effect is fully observable, and naturally leads to the tagging of the $\mathrm{K_S}$ state, and to the definition of new observables.

A preliminary analysis of the KLOE data on $\phi \to \mathrm{K_S K_L} \to \pi^+\pi^-\,\pi^+\pi^-$ events shows a first evidence of this effect.

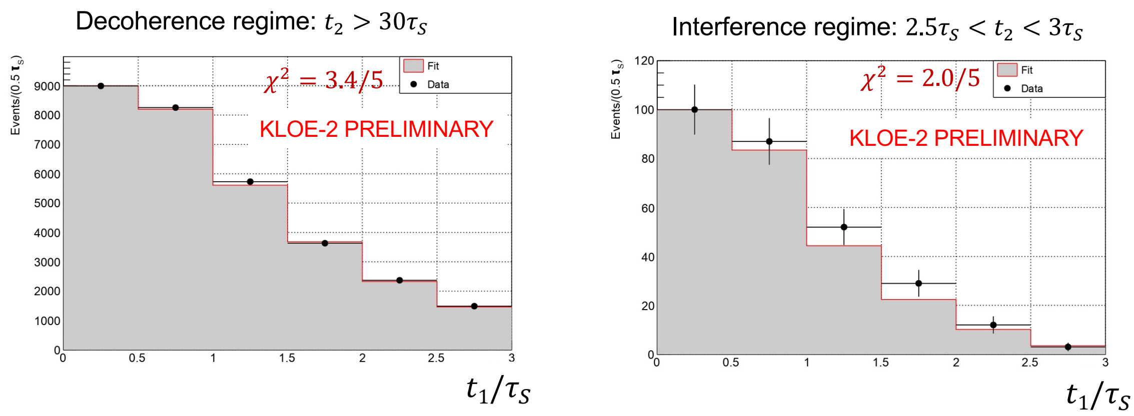

Figure 2. The measured t_1 distribution for $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ events (black dots), in the case of the decoherence regime with $t_2 > 30\ \tau_S$ (left), and the interference regime with $2.5 < t_2 < 3\ \tau_S$ (right). The result of the fit with the prediction of quantum mechanics based on eq.(6) taking into account the experimental resolution effects on t_1 and t_2 times with a smearing matrix obtained from a Monte Carlo simulation (histogram) is superimposed.

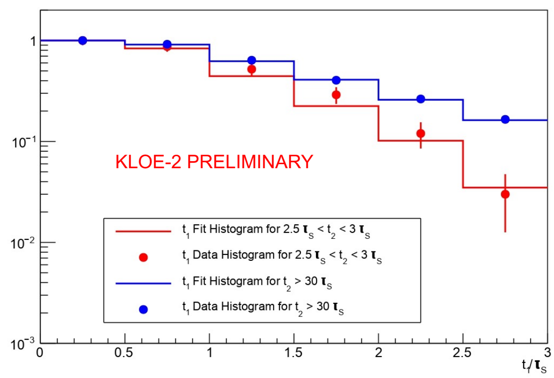

Figure 3. The measured t_1 distribution for $\phi \to K_S K_L \to \pi^+\pi^-\pi^+\pi^-$ events in the case of the decoherence regime with $t_2 > 30\ \tau_S$ (blue points), and the interference regime with $2.5 < t_2 < 3\ \tau_S$ (red points) Both distributions are normalized to unity at $t_1 = 0$. The corresponding predictions of quantum mechanics taking into account the experimental resolution effects are superimposed (blue and red histograms).

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