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Charge asymmetry in the $\tau^\pm \rightarrow K_L \pi^\pm \bar{\nu}$ decays. Prospects for a high luminosity τ -charm factory

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Abstract

We propose a measurement of the charge asymmetry in $\tau \rightarrow K_L \pi \nu$ decays. At a $L \sim 10^{33} - 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ τ -charm factory, this can provide an important test of CPT in the $K^0 - \bar{K}^0$ system.

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The observation of CP violation, until now, has been restricted to the decays $K_L \rightarrow \pi^+\pi^-$, $K_L \rightarrow \pi^0\pi^0$ and to the charge asymmetry observed in the semileptonic decays $K_L \rightarrow \pi^\pm \mu^\mp \begin{smallmatrix} (-) \\ \nu \end{smallmatrix}$ and $K_L \rightarrow \pi^\pm e^\mp \begin{smallmatrix} (-) \\ \nu \end{smallmatrix}$ [1], [2]. These decays measure the CP-violating parameter ϵ_L in the expansion of K_L in terms of the states of well defined strangeness K^0 and $\bar{K}^0$:

$$K_L = \frac{1}{\sqrt{2}}[(1 + \epsilon_L)K^0 - (1 - \epsilon_L)\bar{K}^0]$$

The short lived state K_S can be as well written as

$$K_S = \frac{1}{\sqrt{2}}[(1 + \epsilon_S)K^0 + (1 - \epsilon_S)\bar{K}^0]$$

Assuming CPT invariance the observation of CP violation in the $K^0 - \bar{K}^0$ system would imply a T violation of the same amount. On the other hand if the CPT theorem is not valid we can have an interaction with a T-conserving and a T-nonconserving component, the magnitude of the last being different from the CP-violating one. If CPT is conserved we expect $\epsilon_S = \epsilon_L$. If instead T were conserved $\epsilon_S + \epsilon_L = 0$ [3], [4]. This fundamental point at present rests on the experimental result for the phase of ϵ in the decay $K_L \rightarrow \pi\pi$ and on the sign and the magnitude of the observed charge asymmetry in K_L leptonic decays. CP violation has not been observed in K_S decays; in fact the CP violating process $K_S \rightarrow 3\pi$ has an expected branching ratio of order $\sim 10^{-9}$. Moreover at hadron machines the production of pure K_S beams is more difficult than K_L ones. For this reasons no direct measurement of ϵ_S has been performed yet.

It is the purpose of these note to call attention to a novel possibility for a possible measurement of ϵ_S , based on the observation of a charge asymmetry in the $\tau^\pm \rightarrow K_L \pi^\pm \begin{smallmatrix} (-) \\ \nu \end{smallmatrix}$ decays.

Inverting the equations above, we write the K^0 and $\bar{K}^0$ in terms of K_L and K_S states

$$K^0 = \frac{1}{\sqrt{2}}[(1 - \epsilon_L)K_S + (1 - \epsilon_S)K_L]$$

$$\bar{K}^0 = \frac{1}{\sqrt{2}}[(1 + \epsilon_L)K_S - (1 + \epsilon_S)K_L]$$

Due to the $\Delta S = \Delta Q$ rule τ^+ (τ^-) couples with the K^0 ($\bar{K}^0$) state only (see Fig. 1 a) ¹. At $t = 0$ we will start, therefore, with a pure K^0 or $\bar{K}^0$ state.

At $t \gg \tau_s$ only the K_L components of K^0 and $\bar{K}^0$ survive. Thus projecting $\tau^\pm$ onto this components we obtain the relative probabilities

$$\begin{aligned} R(\tau^+ \rightarrow K_L) &= |(1 - \epsilon_S)^*|^2 \\ R(\tau^- \rightarrow K_L) &= |(1 + \epsilon_S)^*|^2 \end{aligned}$$

¹Here and in the following we assume the absolute validity of the $\Delta S = \Delta Q$ rule. For a more general treatment see [3].

Introducing the charge asymmetry δ_c and neglecting terms of order ϵ^2 we get

$$\delta_c = \frac{R(\tau^-) - R(\tau^+)}{R(\tau^+) + R(\tau^-)} \sim 2Re(\epsilon_S)$$

It is important to stress the fact that the above argument and formulas are valid under the assumption that the decay amplitudes of the processes $\tau^\pm \rightarrow K^0 \pi^\pm \begin{smallmatrix} (-) \\ \nu \end{smallmatrix}$ be equal to each other. This is true only if CPT is conserved in the decay amplitudes themselves; even in this case, however, ϵ_S could be different from ϵ_L because of CPT violation in the mass matrix. More generally we can write the charge asymmetry as

$$\delta_c \sim \frac{(|A|^2 - |\bar{A}|^2) + 2((|A|^2 + |\bar{A}|^2)Re(\epsilon_S))}{(|A|^2 + |\bar{A}|^2) + 2((|A|^2 - |\bar{A}|^2)Re(\epsilon_S))}$$

where A and $\bar{A}$ are the decay amplitudes for the processes $\tau^- \rightarrow \bar{K}^0 \pi^- \nu$, and $\tau^+ \rightarrow K^0 \pi^+ \bar{\nu}$ respectively. Therefore any deviation of δ_c from the expected value $2Re(\epsilon_L)$ would imply a CPT non conservation either in the decay amplitudes or in the mass matrix or both.

It is a noticeable fact that $|A|^2$ and $|\bar{A}|^2$ can be measured in the same experiment by looking at the processes $\tau^\pm \rightarrow \pi^\pm K_S \begin{smallmatrix} (-) \\ \nu \end{smallmatrix}$.

Since we expect δ_c to be of order 3×10^{-3} , at least as many as 10^6 $\tau^\pm \rightarrow K_L$ decays are needed to measure it in a statistically relevant way. This means that $\sim 2 \times 10^8$ $\tau^\pm$ pairs are required, the measured branching ratio being of order 5×10^{-3} [5].

At a $L \sim 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ τ -charm factory, considering an year of 10^7 s, $4(7) \times 10^7$ $\tau^+\tau^-$ pairs per year are produced at $\sqrt{s} = 3.67(4.25) \text{ GeV}$. Therefore our goal will be reached after $\sim 5(3)$ years of running at such a machine. A 10 % statistical accuracy will require luminosities of order $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

Projects for $L \sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ τ -charm factories have been widely studied and proved to be possible [6]. Moreover studies on very high luminosity ($O(10^{34})$) flavour factories have been recently carried out, especially in the Φ -factory case [4].

The K_L can be experimentally tagged looking for neutral hadronic energy deposits in the calorimeters with the best possible spatial and energy resolution.

A number of possible backgrounds to our signal have been considered:

1. Running below the ψ' will reduce any heavy flavour multi-hadronic background to essentially zero. The remaining hadronic background can be cut away requiring, for example, the absence of another strange particle in the event and/or missing energy requirements.
2. Due to the large difference in decay time between K_S and K_L , the K_S background is totally negligible.
3. The processes $\tau \rightarrow K_L \pi \nu + n \pi^0$ are expected to produce the same asymmetry and so do not need to be differentiated (see Fig. 1 a).

4. A potentially very dangerous background could come from the processes $\tau^\pm \rightarrow \pi^\pm \nu + n\pi^0$ where the neutral electromagnetic energy fakes the hadronic one. This imposes stringent requirements on the h/γ separation capability of the detector.
5. The most dangerous background, in our opinion, comes however from the process $\tau^\pm \rightarrow K^\pm K_L^{(-)} \bar{\nu}$. This process has not been observed yet but its rate is expected to be $\sim 10\%$ of the signal [8]. As can be seen from Fig. 1 b, it produces an asymmetry with the opposite sign.
Particle identification is here fundamental. At the energy concerned it is conceivable to completely separate $\pi^\pm$ and $K^\pm$ via dE/dX measurements and/or time of flight techniques.

The above mentioned points fix the requirements on the detector performances for this measurement. Such a detector should provide full hermeticity, good particle identification and excellent calorimetry. This fits completely with the requirements for many of the other possible measurements at a τ -charm factory [9].

Finally we conclude that the measurement of δ_c is feasible at a τ -charm factory and will enrich the already copious program of such a facility.

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Figure Captions

Figure 1 Graphs for the two processes (a) $\tau^- \rightarrow \bar{K}^0 \pi^- \nu$ and (b) $\tau^- \rightarrow K^0 K^- \nu$. In (a) the possible production of one (or more) π^0 s is also sketched.

Fig. 1