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The $K_L \to \pi^0 \nu\bar{\nu}$ Decay Beyond the Standard Model*

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Abstract

The $K_L \to \pi^0 \nu\bar{\nu}$ decay is analyzed in a model independent way. When lepton flavor is conserved, this decay mode is a manifestation of CP violating interference between mixing and decay. Consequently, a theoretically clean relation between the measured rate and electroweak parameters holds in any given model.

*Presented at the first symposium of FCNC,
Santa Monica, CA, February 19–21, 1997*

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Abstract

The $K_L \to \pi^0 \nu\bar{\nu}$ decay is analyzed in a model independent way. When lepton flavor is conserved, this decay mode is a manifestation of CP violating interference between mixing and decay. Consequently, a theoretically clean relation between the measured rate and electroweak parameters holds in any given model.

$K_L \to \pi^0 \nu\bar{\nu}$ is unique among K decays in several aspects: (a) It is theoretically very clean; (b) it is purely CP violating [1,2]; and (c) it can be measured in the near future [3] even if the rate is as small as the Standard Model prediction. In the Standard Model a measurement of $\Gamma(K_L \to \pi^0 \nu\bar{\nu})$ provides a clean determination of the Wolfenstein CP violating parameter η or, equivalently, of the Jarlskog measure of CP violation J and, together with a measurement of $\Gamma(K^+ \to \pi^+ \nu\bar{\nu})$, of the angle β of the unitarity triangle [2].

Here we explain what can be learned from the $K \to \pi\nu\bar{\nu}$ decay in a model independent way [4]. We define

$$\lambda \equiv \frac{q}{p}\frac{\bar{A}}{A}, \tag{1}$$

where p and q are the components of interaction eigenstates in mass eigenstates, $|K_{L,S}\rangle = p|K^0\rangle \mp q|\bar{K}^0\rangle$, and $A(\bar{A})$ is the $K^0(\bar{K}^0) \to \pi^0\nu\bar{\nu}$ decay amplitude. Then, the ratio between the K_L and K_S decay rates is [4]

$$\frac{\Gamma(K_L \to \pi^0\nu\bar{\nu})}{\Gamma(K_S \to \pi^0\nu\bar{\nu})} = \frac{1+|\lambda|^2 - 2\mathrm{Re}\lambda}{1+|\lambda|^2 + 2\mathrm{Re}\lambda}. \tag{2}$$

In general, a three body final state does not have a definite CP parity. However, if the light neutrinos are purely left-handed, and if lepton flavor is conserved, the final state is CP even (to an excellent approximation) [4]. If lepton flavor is violated, the final state in $K_L \to \pi^0\nu\bar{\nu}$ is not necessarily a CP eigenstate; specifically, $K_L \to \pi^0\nu_i\bar{\nu}_j$ with $i \neq j$ is allowed. Here, we concentrate on the

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case where the above two conditions are satisfied, so that the final state is purely CP even.

The contributions to the $K_L \to \pi^0 \nu\bar{\nu}$ decay from CP violation in mixing ($|q/p| \neq 1$) and from CP violation in decay ($|\bar{A}/A| \neq 1$) are negligibly small. The deviation of $|q/p|$ from unity is experimentally measured (by the CP asymmetry in $K_L \to \pi \ell \nu$) and is $\mathcal{O}(10^{-3})$. The deviation of $|\bar{A}/A|$ from unity is expected to be even smaller [4]. Therefore, $|\lambda| = 1 + \mathcal{O}(10^{-3})$, and the leading CP violating effect is $\text{Im}\lambda \neq 0$, namely interference between mixing and decay. This puts the ratio of decay rates (2) in the same class as CP asymmetries in various B decays to final CP eigenstates, e.g. $B \to \psi K_S$, where a very clean theoretical analysis is possible [5].

As a result of this cleanliness, the CP violating phase can be extracted almost without any hadronic uncertainty, even if this phase comes from New Physics. Defining θ to be the relative phase between the $K - \bar{K}$ mixing amplitude and the $s \to d\nu\bar{\nu}$ decay amplitude, namely $\lambda = e^{2i\theta}$, we get from eq. (2)

$$\frac{\Gamma(K_L \to \pi^0 \nu\bar{\nu})}{\Gamma(K_S \to \pi^0 \nu\bar{\nu})} = \frac{1 - \cos 2\theta}{1 + \cos 2\theta} = \tan^2 \theta. \tag{3}$$

In reality, however, it will be impossible to measure $\Gamma(K_S \to \pi^0 \nu\bar{\nu})$. We can use the isospin relation, $A(K^0 \to \pi^0 \nu\bar{\nu})/A(K^+ \to \pi^+ \nu\bar{\nu}) = 1/\sqrt{2}$, to replace the denominator by the charged kaon decay mode:

$$a_{CP} \equiv r_{\text{is}} \frac{\Gamma(K_L \to \pi^0 \nu\bar{\nu})}{\Gamma(K^+ \to \pi^+ \nu\bar{\nu})} = \frac{1 - \cos 2\theta}{2} = \sin^2 \theta, \tag{4}$$

where $r_{\text{is}} = 0.954$ is the isospin breaking factor [6]. The ratio (4) may be experimentally measurable as the relevant branching ratios are $\mathcal{O}(10^{-10})$ in the Standard Model [2] and even larger in some of its extensions.

Eq. (4) implies that a measurement of a_{CP} will allow us to determine the CP violating phase θ without any information about the magnitude of the decay amplitudes. Also, using $\sin^2 \theta \leq 1$ and $\tau_{K_L}/\tau_{K^+} = 4.17$, we get the model independent bound

$$\text{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 1.1 \times 10^{-8} \left(\frac{\text{BR}(K^+ \to \pi^+ \nu\bar{\nu})}{2.4 \times 10^{-9}} \right). \tag{5}$$

This bound is much stronger than the direct experimental upper bound [7] $\text{BR}(K_L \to \pi^0 \nu\bar{\nu}) < 5.8 \times 10^{-5}$.

New Physics can modify both the mixing and the decay amplitudes. $\varepsilon = \mathcal{O}(10^{-3})$ implies that any new contribution to the mixing amplitude carries almost the same phase as the Standard Model one. On the other hand, the upper bound[8] $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) < 2.4 \times 10^{-9}$, which is much larger than the Standard Model prediction [2], allows New Physics to dominate the decay amplitude (with an arbitrary phase). We conclude that a significant modification of a_{CP} can only come from New Physics in the decay amplitude. For example, in models with extra quarks, the decay amplitudes can be dominated by tree level Z-mediated diagrams[4].

In superweak models, all CP violating effects appear in the mixing amplitudes. Then, CP violation in $K_L \to \pi^0\nu\bar{\nu}$ should be similar in magnitude to that in $K_L \to \pi\pi$. In models of approximate CP symmetry, all CP violating effects are small. Both scenarios predict then $a_{CP} = \mathcal{O}(10^{-3})$, in contrast to the Standard Model prediction, $a_{CP} = \mathcal{O}(1)$. In other words, a measurement of $a_{CP} \gg 10^{-3}$ (and, in particular, $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) \gtrsim \mathcal{O}(10^{-11})$) will exclude these two scenarios of New Physics in CP violation.

In the Standard Model there are two clean ways to determine the unitarity triangle: (1) CP asymmetries in B^0 decays [5]; and (2) the combination of $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})$ and $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$ [2]. In general, New Physics will affect both determinations. Moreover, it is very unlikely that the modification of the two methods will be the same. Consequently, a comparison between these two clean determinations will be a very powerful tool to probe CP violation beyond the Standard Model. Because of the very small theoretical uncertainties in both methods even a small new physics effect can be detected. In practice, we will be limited only by the experimental sensitivity.

In conclusion: a measurement of $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})$ is guaranteed to provide us with valuable information. It will either give a new clean measurement of CP violation or indicate lepton flavor violation.

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