CP-violating decay $K_L^0 \to \pi^0 \nu\bar{\nu}$

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The process $K_L^0 \to \pi^0 \nu\bar{\nu}$ offers perhaps the clearest window yet proposed into the origin of *CP* violation. The largest expected contribution to this decay is a direct *CP*-violating term at $\approx$few$\times 10^{-12}$. The indirect *CP*-violating contribution is some *3 orders of magnitude* smaller, and *CP*-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of $\sim 1\%$ can be extracted from previous data on $K_L^0 \to 2\pi^0$. This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product $\sin\theta_2 \sin\theta_3 \sin\delta$ can be made.

The Glashow-Iliopoulos-Maiani- (GIM-) mechanism[1]-suppressed processes $K^+ \to \pi^+ \nu\bar{\nu}$ (Refs. 2–5) and $K_L^0 \to \pi^0 e^+ e^-$ (Ref. 6) have been much discussed recently as tests of the standard model (SM). In each case the current experimental limit[7,8] lies more than 2 orders of magnitude above the SM prediction, affording a large window for new physics. If the predicted levels can be reached, these decays put interesting constraints on the Kobayashi-Maskawa[9] (KM) matrix parameters and on the top-quark mass. The latter process is particularly interesting from the point of view of *CP* since the predicted direct *CP* violation is of the same order of magnitude as the indirect (state-mixing) contribution. By contrast, relatively little attention has been paid to the closely related and no less interesting process $K_L^0 \to \pi^0 \nu\bar{\nu}$ (Ref. 10). As I will discuss below, this decay is expected to have a branching ratio of $\sim 10^{-11}$. Since there is no published upper limit on this decay, it offers a potentially enormous range in which to search for new effects. As in the case of $K_L^0 \to \pi^0 e^+ e^-$, $K_L^0 \to \pi^0 \nu\bar{\nu}$ is *CP* violating in leading order. However, unlike the former process, there is no potentially large, 2γ-mediated *CP*-conserving contribution.[11] In fact the potential long-distance contributions in general are suppressed by *CP* violation and/or the GIM mechanism to extremely small levels.

In the excellent approximation that $K^+ \to \pi^+ \nu\bar{\nu}$ and $K^0 \to \pi^0 \nu\bar{\nu}$ are short-distance dominated,[12] their amplitudes are related by isospin: $A(K^0 \to \pi^0 \nu\bar{\nu}) = (1/\sqrt{2}) A(K^+ \to \pi^+ \nu\bar{\nu})$. It then follows that the amplitudes for decays of the *CP* eigenstates K_1^0 and K_2^0 into $\pi^0 \nu\bar{\nu}$ are equal to the real and imaginary parts, respectively, of the amplitude for $K^+ \to \pi^+ \nu\bar{\nu}$ (Ref. 10). Ignoring higher-order *CP*-violating effects,

$$A(K_L^0 \to \pi^0 \nu\bar{\nu}) = \epsilon A(K_1^0 \to \pi^0 \nu\bar{\nu}) + A(K_2^0 \to \pi^0 \nu\bar{\nu}) \ .$$

In principle this leads to interference effects, but as will be shown, the first term is so much smaller than the second that these can be ignored. Note that modulo very small QCD corrections and assuming massless leptons,[2,3]

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = B(K^+ \to \pi^0 e^+ \nu) \frac{2\alpha^2}{16\pi^2 \sin^4\theta_W} \times \left| \sum_{j=c,t} V_{js}^* V_{jd} D(x_j) \right|^2 \Big/ V_{us}^2$$

for each neutrino flavor, where V_{ij} are the KM matrix elements, $x_j = (m_j^2/m_W^2)$, and $D(x)$ is a kinematic function which is ~ 0.004 for m_c, and of order 1 for reasonable values of m_t. Substituting for the constants and the K_{e3} branching ratio, assuming small mixing angles, and ignoring QCD corrections,[13]

$$B(K^+ \to \pi^+ \nu\bar{\nu}) = 0.70 \times 10^{-6} |D(x_c) + s_2(s_2 + s_3 e^{i\delta}) \times D(x_t)|^2$$

for each neutrino flavor, where s_2, s_3, and δ are the usual KM parameters. Currently favored values of the KM parameters and m_t give $0.5\text{–}8.0 \times 10^{-10}$ for the branching ratio summed over three neutrino flavors.[5,12]

The branching ratio for the indirect *CP*-violating contribution is then

$$B(K_L^0 \to \pi^0 \nu\bar{\nu})_\epsilon = |\epsilon|^2 \frac{\tau_{K_L}}{\tau_{K^+}} 3 \times 0.70 \times 10^{-6} \times [D(x_c) + s_2(s_2 + s_3 c_\delta) D(x_t)]^2$$

while that of the direct is

$$B(K_L^0 \to \pi^0 \nu\bar{\nu})_{\text{direct}} = \frac{\tau_{K_L}}{\tau_{K^+}} 3 \times 0.70 \times 10^{-6} \times [s_2 s_3 s_\delta D(x_t)]^2 \ .$$

In the context of the standard model with three generations, bounds have been derived[5,14] on s_2, s_3, and to some extent on δ and m_t, from measurements of or limits on τ_b, $B(b \to c e \nu)$, $\bar{B}$-B mixing, $\Gamma(b \to u e \nu)/\Gamma(b \to c e \nu)$, exclusive B decay branching ratios, ϵ, ϵ', etc. Neither experiment nor theory is sufficiently advanced to allow specific predictions, but sets of parameters which are consistent with all known input can be obtained. For the purpose of estimating the size of the various contributions to $K_L^0 \to \pi^0\nu\bar{\nu}$, I choose one such set: $s_2=0.08$, $s_3=0.03$, $\delta=165°$, $m_t=100$ GeV, $m_c=1.5$ GeV. Then, ignoring QCD corrections, for three generations, this gives

$$B(K^+\to\pi^+\nu\bar{\nu})\approx 2.5\times 10^{-10}$$

and remembering that $|\epsilon|=0.002\,275$,

$$\begin{aligned} B(K_L^0\to\pi^0\nu\bar{\nu})_\epsilon &= 5.18\times10^{-6}\times4.18\times3\\ &\quad\times0.70\times10^{-6}(10.99\times10^{-3})^2\\ &\approx 5.5\times10^{-15}\\ B(K_L^0\to\pi^0\nu\bar{\nu})_{\text{direct}} &= 4.18\times3\\ &\quad\times0.70\times10^{-6}(1.07\times10^{-3})^2\\ &\approx 10^{-11}\ . \end{aligned}$$

Note that although the real part of the K^+ amplitude is 10 times as large as the imaginary for these values of the parameters, this is far outweighed by the small value of ϵ. The ratio of direct to indirect *CP* violation is roughly[15] 1800. This is to be contrasted with the case of $K_L^0\to\pi^0e^+e^-$ where this ratio is $\sim$1:1 and $K^0\to2\pi$ where it is[16] $\sim$1:300. In addition, as in the case of $K_L^0\to\pi^0e^+e^-$, but not of $K^0\to2\pi$, the relevant hadronic matrix element need not be calculated *ab initio*, but as we have seen, may be obtained from the known rate of K_{e3} decay. Thus from the point of view of the standard model, one has the potential for an extremely clean determination of the *CP*-violating product $s_2s_3s_\delta$, if one can measure $K_L^0\to\pi^0\nu\bar{\nu}$ at the requisite level. As will be discussed below, such an experiment is very difficult. However, as will also be discussed, the effective present bound on this process is quite weak, so that a huge window for new physics (nonstandard *CP*-violating currents, $K_L^0\to\pi^0$ + new scalar, etc.) exists.

Although there has been no dedicated search for $K_L^0\to\pi^0\nu\bar{\nu}$ our ignorance of the branching ratio is not quite complete. Following a suggestion by Hoffman,[17] it is possible to extract such a limit from the work of Cronin *et al.*,[18,19] an early measurement of $K_L^0\to2\pi^0$. In that experiment, the signal for $K_L^0\to2\pi^0$ was a single photon whose c.m. energy was greater than that possible from $K_L^0\to3\pi^0$ (maximum 165 MeV) and less than that of $K_L^0\to2\gamma$ (249 MeV). The photon spectrum from $K_L^0\to2\pi^0$ is a flat box extending from 19 to 229 MeV. The interval between 180 and 225 MeV was selected as the signal region. The overall acceptance for photons from the normalizing reaction, $K_L^0\to3\pi^0$, was 0.269 times that for those photons from $K_L^0\to2\pi^0$ that fall into in this interval. As shown in Fig. 1(a), photons from $K_L^0\to\pi^0\nu\bar{\nu}$ also span the interval from 180 to 225 MeV (Ref. 20) although on the average they are somewhat softer than those from $K_L^0\to2\pi^0$. As a result, the experimental efficiency in the 180–225-MeV range for photons from the former decay is about 2% less than that for photons from the latter decay. Furthermore, this interval contains a larger fraction of the photons produced in the latter process than in the former (0.214 vs 0.135). There were 156 events observed in the interval 180–225 MeV. To be conservative, I do not subtract the contribution of $K_L^0\to2\pi^0$ or other backgrounds and use 181 events as an upper limit for $K_L^0\to\pi^0\nu\bar{\nu}$ events. There were 4031 $K_L^0\to3\pi^0$ events in the normalizing sample. A limit on the branching ratio for $K_L^0\to\pi^0\nu\bar{\nu}$ can then be extracted as follows:

$$\begin{aligned} B(K_L^0\to\pi^0\nu\bar{\nu}) &< B(K_L^0\to3\pi^0)(N_{\pi\nu\nu}/N_{3\pi})\\ &\quad\times(\epsilon_{3\pi}/\epsilon_{2\pi})(\epsilon_{2\pi}/\epsilon_{\pi\nu\nu})3\ , \end{aligned}$$

where the ϵ's are the acceptances for single photons from the various processes and the factor 3 is the ratio of the number of photons emanating from $K_L^0\to3\pi^0$ to the number emanating from $K_L^0\to\pi^0\nu\bar{\nu}$. As discussed above $\epsilon_{3\pi}/\epsilon_{2\pi}=0.269$ and $\epsilon_{2\pi}/\epsilon_{\pi\nu\nu}=1.02\times0.214/0.135=1.62$. This then yields

$$B(K_L^0\to\pi^0\nu\bar{\nu})<0.13\ (90\%\ \text{c.l.})\ .$$

A tighter bound can be obtained by subtracting the backgrounds calculated in Ref. 19 as well as the expected contribution from $K_L^0\to\pi^0\pi^0$. This leaves 85±12 events

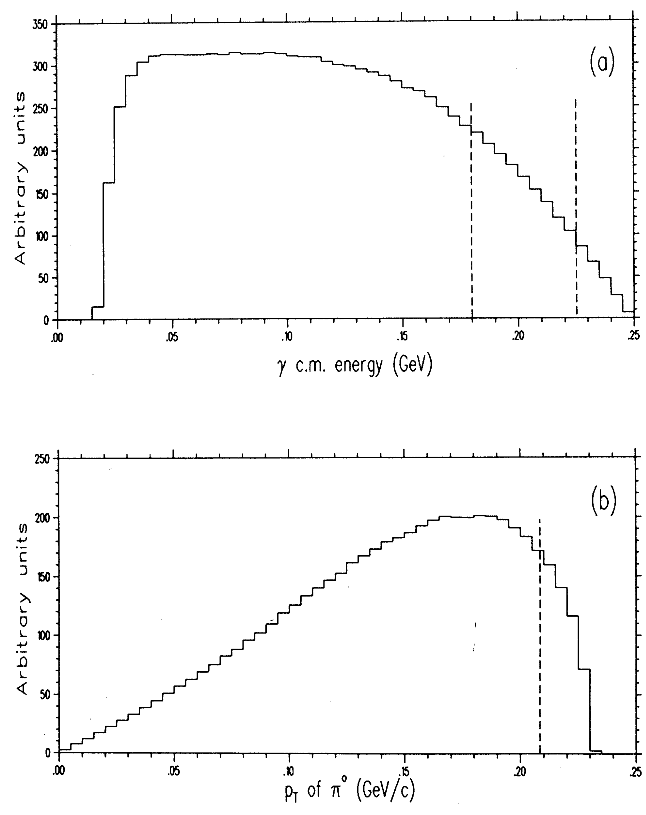

FIG. 1. Distributions of daughters of $K_L^0\to\pi^0\nu\bar{\nu}$. (a) Distribution of gamma energy in the K_L^0 center of mass. Vertical lines indicate region used to obtain the upper limit discussed in the text. (b) Distribution of π^0 p_T. Vertical line indicates maximum p_T of π^0 from $K_L^0\to\pi^0\pi^0$.

in the signal region. The corresponding 90%-C.L. upper limit is then

$$B(K_L^0 \to \pi^0 \nu\bar{\nu}) < 7.6 \times 10^{-3} .$$

There is a window of almost 9 orders of magnitude between this number and the standard-model prediction.

The detection of this decay at the $\sim 10^{-12}$ level is surely a formidable experimental challenge. Searches at the 10^{-10}–10^{-11} level for the kinematically similar (but topologically much more tractable) process $K_L^0 \to \pi^0 e^+ e^-$ have been proposed,[21] and the K_L^0 flux required for these would probably suffice to reach a sensitivity about an order of magnitude worse for $K_L^0 \to \pi^0 \nu\bar{\nu}$. The signature would be an unaccompanied π^0 emerging out of a K_L^0 beam. It might be necessary for triggering (and background rejection) purposes to confine the acceptance to π^0 $p_T > 209$ MeV/c, the maximum p_T allowed for a $K_L^0 \to 2\pi^0$ decay. According to Fig. 1(b), this cut accepts $\sim 9.5\%$ of the signal (more like 7% when a reasonable allowance for resolution effects is made). The only significant decays which can produce π^0's with $p_T > 209$ MeV/c are $K_L^0 \to \pi^0 e^+ e^-$, $\pi^0 \gamma\gamma$, and $\pi^0 \nu\bar{\nu}$. The first is expected to be of order 10^{-11} and is easily eliminated. The second, $K_L^0 \to \pi^0 \gamma\gamma$, is expected[22] at $\lesssim 10^{-6}$ and must therefore be vetoed to at least 10^{-6} ($\sim 10^{-3}$/ photon) which seems possible. If extra gammas can indeed be vetoed at the 10^{-3} level, and the beam is well defined, the dominant background is likely to be that due to π^0 production by beam neutrons off residual gas atoms in the vacuum decay tank. These will have a p_T spectrum which spans the signal region. This background will necessitate extremely good vacuum, and probably the use of neutron-sensitive calorimetry down to small angles with respect to the beam.

To define the kinematics in the presence of background it will be necessary to determine the direction of at least one of the gammas from $K_L^0 \to \pi^0 \nu\bar{\nu}$. If this is done through conversion to e^+e^-, it will cost a factor ~ 10/converted gamma in acceptance. An alternative, which costs a factor ~ 80 in acceptance, is to use only those events in which the π^0 undergoes Dalitz decay. It would certainly be preferable to eliminate the need for either expedient, perhaps through the advent of directional photon detectors.[23] Although the p_T cut mentioned above will limit the acceptance for this decay to less than $\sim 7\%$, the fact that only two gammas need be detected ought to allow a relatively large geometric acceptance, leading to the 10^{-9}–10^{-10} estimate made above.[24]

A measurement of $K_L^0 \to \pi^0 \nu\bar{\nu}$ at the 10^{-12} level seems clearly beyond the present state of the art, but with the development of improved detectors and kaon sources, such a measurement might become possible on a time scale competitive with that for measurements of *CP* violation in the *B* system. In any case a measurement at even the 10^{-8} level would be of great interest.

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