The Rare Decay $K_L^0 \to \pi^0 \nu\bar{\nu}$

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1 Problem

The rare decay of the long-lived neutral K meson, $K_L^0 \to \pi^0 \nu\bar{\nu}$, when observed, will be considerable interest towards an understanding of the violation of the combined symmetries of charge conservation and parity (CP violation).

a) Draw a Feynman diagram for this decay process. Deduce the CP quantum number of the final state $\pi^0 \nu\bar{\nu}$ that arises in this decay? Why don't the related decays $K_L^0 \to \pi^0 e^+ e^-$ and $K_L^0 \to \pi^0 \mu^+ \mu^-$ lead to final states with a definite CP quantum number?

b) Draw a (penguin) diagram representing the decay $K^0 \to \pi^0 \nu\bar{\nu}$, and indicate the corresponding CKM matrix factors for the weak interaction, using the Wolfenstein approximation:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix},$$

Use the fact that $K_L \approx K_2 + \epsilon K_1$, where $K_{1,2} = (K_0 \pm \bar{K}_0)/\sqrt{2}$, to express the decay amplitude $A(K_L \to \pi^0 \nu\bar{\nu})$ in terms of the CKM matrix parameters and the parameter ϵ (which measures 'indirect' CP violation in the mixing of K_0 and $\bar{K}_0$).

From what is currently known about CP violation, characterize the expected CP violation $K_L \to \pi^0 \nu\bar{\nu}$ as 'direct' or 'indirect'.

c) **Estimate** the branching fraction for the decay $K_L \to \pi^0 \nu\bar{\nu}$.

2 Solution

a) To determine the CP quantum number of $\pi^0 \nu\bar{\nu}$, we consider the $\nu\bar{\nu}$ system, combined with the π^0 with relative orbital angular momentum $L_{\pi(\nu\bar{\nu})}$. Then

$$CP(\pi^0 \nu\bar{\nu}) = C(\pi^0) P(\pi^0) C(\nu\bar{\nu}) P(\nu\bar{\nu}) (-1)^{L_{\pi(\nu\bar{\nu})}}.$$

We need the facts,

$$C(\pi^0) = +1, \qquad (\pi^0 \to \gamma\gamma),$$

$$P(\pi^0) = -1, \qquad (\text{crossed planes of polarization in } \pi^0 \to e^+e^-e^+e^-),$$

$$C(\nu\bar{\nu}) = (-1)^{L_{\nu\bar{\nu}} + S_{\nu\bar{\nu}}},$$

$$P(\nu\bar{\nu}) = (-1)^{L_{\nu\bar{\nu}} + 1},$$

which last two results are 'well-known' consequences of the Dirac equation for spin-1/2 particles.

First, what is $S_{\nu\bar{\nu}}$? In the rest frame of the $\nu\bar{\nu}$ pair, the neutrino momenta are back to back, but their spins are aligned! Hence $S_{z,\nu\bar{\nu}} = 1 = S_{\nu\bar{\nu}}$.

We don't need to figure out $L_{\nu\bar{\nu}}$, since this cancels out of CP.

But we do need to know $J_{\nu\bar{\nu}}$ to figure out $L_{\pi(\nu\bar{\nu})}$. In the penguin diagram (part b)), we see that the $\nu\bar{\nu}$ pair comes from a virtual Z^0 boson, so we could have $J_{\nu\bar{\nu}} = 0$ or 1. But for the 2-body state, $\nu\bar{\nu}$, we have $L_z = 0$ for z along the particle's motion, so $J_z = 1$ and so we must have $J_{\nu\bar{\nu}} = 1$.

Then from the facts that $J_K = 0$, $J_\pi = 0$ and $J_{\nu\bar{\nu}} = 1$, we deduce that $L_{\pi(\nu\bar{\nu})} = 1$.

Altogether,

$$CP(\pi^0\nu\bar{\nu}) = (+1)(-1)(-1)^{L_{\nu\bar{\nu}}}(-1)(-1)^{L_{\nu\bar{\nu}}}(-1)(-1) = +1.$$

In the case of charged leptons in the final states, we cannot conclude that $S_{l^+l^-} = 1$ only, since massive leptons can have both helicities. Hence the CP quantum number is a mixture of $+1$ and -1.

b) From the penguin diagram,

we deduce that

$$A(K^0 \to \pi^0\nu\bar{\nu}) \propto V_{ts}^* V_{td} \propto (-A\lambda^2)(A\lambda^3)(1 - \rho - i\eta),$$

and therefore,

$$A(\bar{K}^0 \to \pi^0\nu\bar{\nu}) \propto V_{ts} V_{td}^* \propto (-A\lambda^2)(A\lambda^3)(1 - \rho + i\eta).$$

In the diagram, the top quark could also have been a u or c quark. But, the unitarity of the CKM matrix implies that the first and second columns are orthogonal, *i.e.*, $V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$. Since the masses of the u and c quarks are 'nearly' equal, the sum of the terms in the diagram involving u and c quarks nearly cancel, leaving terms of order $V_{ts}^* V_{td}$.

If so,

$$A(K_1 \to \pi^0\nu\bar{\nu}) \propto -A^2\lambda^5(1 - \rho),$$

while

$$A(K_2 \to \pi^0\nu\bar{\nu}) \propto iA^2\lambda^5\eta.$$

Then, since $K_L \approx K_2 + \epsilon K_1$,

$$A(K_L \to \pi^0\nu\bar{\nu}) \propto A^2\lambda^5(i\eta - \epsilon(1 - \rho)).$$

Present knowledge: $\epsilon \approx 10^{-3}$, while $|\eta| \approx |1 - \rho|$. Hence, $A(K_L \to \pi^0\nu\bar{\nu})$ is dominated by $A(K_2 \to \pi^0\nu\bar{\nu})$, which is called 'direct' CP violation.

c) The diagram involves a loop, so a detailed calculation is messy.

For a quick estimate, note that the diagram is second order in the weak interaction $\Rightarrow$ rate $\propto G_F^4$. In addition, the square of the CKM factors yield $A^4\lambda^{10}\eta^2 \approx \lambda^{10}$.

Altogether, $\Gamma(K_L \to \pi^0 \nu\bar{\nu}) \propto G_F^4 \lambda^{10}$.

For comparison, the decay rate of the short-lived K meson is $\Gamma(K_S) \propto G_F^2$ in the same approximation.

The K_L lives about 1000 times as long as the K_L (fact).

Hence $\Gamma(K_L) \approx 10^{-3} G_F^2$, and the branching fraction for $K_L \to \pi^0 \nu\bar{\nu}$ is about $10^3 G_F^2 \lambda^{10} \approx 10^3 (10^{-5})^2 (0.2)^{10} \approx 10^{-14}$.

Supposedly, more detailed calculation yields a branching fraction of 10^{-12}.