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SEARCH FOR THE DIRECT DECAY $K^+ \to \pi^+ + \gamma + \gamma$*

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The mechanism causing the $K^+ \to \pi^+ + \pi^0$ decay has been the subject of considerable theoretical speculation. If the two pion final state were a pure isospin 2 state, and if the weak interaction satisfied the $|\Delta T| = 1/2$ law, this decay would be forbidden. Indeed, the amplitude for this decay is about twenty times smaller than the amplitude for the $K_s^0 \to 2\pi$ decay which does not violate the $|\Delta T| = 1/2$ selection rule. It is of interest therefore to attempt to determine the actual mechanism through which the $K^+ \to \pi^+ + \pi^0$ decay occurs.

It has been suggested that the $K^+ \to \pi^+ + \pi^0$ decay may occur because the 2π final state may not be a pure isospin state on account of the π^+, π^0 mass difference. In this picture the weak interaction is thought to obey the $|\Delta T| = 1/2$ law exactly. The rate of $K^+ \to \pi^+ + \pi^0$ decay is then determined by the extent to which the final two pion state is not constrained to be a pure $T = 2$ state. We have attempted to test this hypothesis by searching for examples of the $K^+ \to \pi^+ + \gamma + \gamma$ decay in

*This work was performed under the auspices of the U.S. Atomic Energy Commission.

which the invariant mass of the two gamma rays is far from the π^0 mass. If we imagine that the two gamma rays constitute a virtual π^0 intermediate state, the mass difference between the π^+ and this virtual π^0 is much greater than the real π^+, π^0 mass difference. It follows that the effect suggested above as a mechanism causing the $K^+ \to \pi^+ + \pi^0$ decay would be greatly enhanced. We would therefore expect a large rate for $K^+ \to \pi^+ + \gamma + \gamma$.

Cabibbo and Gatto,[1] and more recently Hara and Nambu,[2] Fujii,[3] and Okubo, Marshak, and Mather[4] have suggested that the $K^+ \to \pi^+ + \pi^0$ amplitude may become very large when the π^0 is not on the mass shell. The authors of references 2, 3, and 4 came to this conclusion by applying current algebra techniques to non-leptonic K meson decays. At first glance, the conjecture that the amplitude becomes large off the mass shell may appear to be in contradiction to the experimental observation[5] that the radiative decay $K^+ \to \pi^+ + \pi^0 + \gamma$ occurs with the frequency of ordinary inner bremsstrahlung. If the $K^+ \to \pi^+ + \pi^0$ amplitude is due to an electromagnetic correction to the weak interaction, and is therefore of order e^2, one might think that the $K^+ \to \pi^+ + \pi^0 + \gamma$ amplitude, which would be of order e, would be large in comparison with the non-radiative amplitude. Experimental results,[5] however, indicate that this is not so.

Cabibbo and Gatto,[1] however, showed that it is possible to introduce a large off-the-mass shell $|\Delta T| = 1/2$ amplitude which does not give rise to abundant radiative decay. The form of the amplitude proposed by Cabibbo and Gatto has been adopted by Hara and Nambu,[2] Fujii,[3] and Okubo, Marshak, and Mathur.[4] If the $K^+ \to \pi^+ + \pi^0$ amplitude becomes very large off the mass shell, it will give rise to a number of observable decays. In particular decays of the form $K^+ \to \pi^+ + \gamma + \gamma$ where the invariant mass of the two gamma rays is not equal to the π^0 mass should be observed.

As a rough method of describing our results, we shall assume that the $K^+ \to \pi^+ + \gamma + \gamma$ process is dominated by a single diagram in which there is a π^0 intermediate state. We shall assume that the amplitude for $\pi^0 \to 2\gamma$ does not vary off the mass shell, and that the amplitude for $K^+ \to \pi^+ + \pi^0$ varies in the following manner:

$$M(q^2) = M(m_{\pi^0}^2)\left[1 - \xi\,\frac{q^2 - \bar{m}_{\pi^0}^2}{m_{\pi^0}^2}\right]$$

In this expression, $M(m_{\pi^0}^2)$ is the on-mass-shell amplitude for $K^+ \to \pi^+ + \pi^0$ decay, $\bar{m}_{\pi^0}$ is the complex mass of π^0, $\bar{m}_{\pi^0} = m_{\pi^0} + i\,\frac{\Gamma(\pi^0 \to 2\gamma)}{2}$. q is the invariant mass of the two gamma rays.

Cabibbo and Gatto, and Fujii have related the parameter ξ to the amplitude for $K_S^0 \to \pi^+ + \pi^-$ decay. Fujii finds that,

$$|\xi| \cong \frac{M(K^0 \to \pi^+ + \pi^-)}{M(K^+ \to \pi^+ + \pi^0)} \cong 20 .$$

In order to compare our results with this prediction, we have calculated the differential spectrum of the π^+ energy in the $K^+ \to \pi^+ + \gamma + \gamma$ decay for various values of ξ . The result is as follows:

$$\frac{1}{\Gamma(K^+ \to \pi^+ + \pi^o)} \frac{d\Gamma(K^+ \to \pi^+ + \gamma + \gamma)}{dE_{\pi^+}} =$$

$$\frac{2}{\pi} \frac{M_K}{m^3_{\pi^o}} \Gamma(\pi^o \to 2\gamma) \frac{P^+_\pi}{P_\Theta} q^4 \left| \frac{1}{q^2 - m^2_{\pi^o} + \frac{\Gamma(\pi^o \to 2\gamma)^2}{4} - i m_{\pi^o} \Gamma(\pi^o \to 2\gamma)} - \frac{\xi}{m^2_{\pi^o}} \right|^2 .$$

In this expression P_Θ is the momentum of the π^+ in $K^+ \to \pi^+ + \pi^o$ decay. For the purpose of comparing this calculation with our experimental results we have assumed that $\Gamma(\pi^o \to 2\gamma) = 7.4 \pm 0.15 \times 10^{-6}$ MeV as given in the table of Rosenfeld et al.[6]

As a part of our Bevatron spark chamber study of K^+ decays at rest we have searched for examples of the $K^+ \to \pi^+ + \gamma + \gamma$ decay in which the kinetic energy of the π^+ was between 60 and 90 MeV. We did not find any statistically significant evidence for the existence of such decays. If we interpret our observations using the above described model we find that $|\xi| < 30$. Our experiment therefore does not rule out the prediction of Fujii.[3]

We have also used our results on the frequency of $K^+ \to \pi^+ + \gamma + \gamma$ decays to set a limit on the applicability of the so-called σ and ϵ meson intermediate state models to K^+ and η decays. Brown and Singer[7] have suggested that many K and η decays are mediated by a spin zero, isospin zero, even parity meson, the σ . The following decay sequences are thought to occur:

$$K^{+} \rightarrow \sigma + \pi^{+}$$
$$\quad \hookrightarrow \pi^{\substack{+\\0}} + \pi^{\substack{-\\0}}$$

$$\eta \rightarrow \sigma + \pi^{0}$$
$$\quad \hookrightarrow \pi^{\substack{+\\0}} + \pi^{\substack{-\\0}}$$

Invariant mass plots of pion pairs in the above decays have indicated that the best fit to the σ model of Brown and Singer is made when it is assumed the $m_{\sigma} \cong 400$ MeV, and $\Gamma_{\sigma} \cong 100$ MeV.[8] Because of the large width of the hypothetical σ it has not been possible to conclusively identify it in the above reactions.

It has been observed[6] that the η meson decays with considerable frequency into the mode:

$$\eta \rightarrow \pi^{0} + \gamma + \gamma$$

Lapidus[9] has suggested that the observation of this decay mode can be used to establish the branching ratio of the σ meson into two gamma rays. If this model is correct, the two modes,

$$\eta \rightarrow \pi^{0} + \gamma + \gamma$$

$$K^{+} \rightarrow \pi^{+} + \gamma + \gamma$$

are simply related. The model of Lapidus requires that the decay $K^{+} \rightarrow \pi^{+} + \gamma + \gamma$ be about 1% of all K^{+} decays.

In order to compare our results with this prediction, we have computed the fraction of σ meson mediated $K^+ \to \pi^+ + \gamma + \gamma$ decays that would be detected by our apparatus. In making this calculation we have used a Breit-Wigner distribution function:

$$\frac{d\Gamma(K^+ \to \pi^+ + \gamma + \gamma)}{dE_{\pi^+}} = \lambda \frac{P_{\pi^+} q^4}{\left(q^2 - m^2 + \frac{\Gamma_\sigma^2}{4}\right)^2 + m_\sigma^2 \Gamma_\sigma^2}$$

m_σ is the mass of the σ, assumed to be 400 MeV, and Γ_σ is its width, assumed to be 100 MeV. λ is a constant. Our result, which is relatively insensitive to the assumed σ meson parameters, is that if the $K^+ \to \pi^+ + \gamma + \gamma$ decay proceeds via a σ meson intermediate state, the total branching ratio of the K^+ meson into this channel is less than 3.3×10^{-4}. This is more than an order of magnitude lower than the prediction of the Lapidus model. We would like to point out, however, that the σ intermediate state model would not be in disagreement with our results if the branching ratio for $\eta \to \pi^0 + \gamma + \gamma$ were much smaller than the current experimental results indicate $(20.5 \pm 3.5)\%$.[6]

Various other 0^+ meson intermediate state models have been considered in the literature. Oneda[10] suggested an ϵ model ($m_\epsilon = 700$ MeV). For this model our results limit the total branching ratio to be less than 1.8×10^{-4}.

Finally, if we assume that the hypothetical $K^+ \to \pi^+ + \gamma + \gamma$ decay is governed by a phase space model, that is, if the distribution of the π^+ is as follows:

$$\frac{d\Gamma(K^+ \to \pi + \gamma + \gamma)}{dE_\pi} = \lambda\, P_{\pi^+}$$

where λ is a constant, our experimental result limits the total branching ratio of the K^+ into this mode to be less than 1.1×10^{-4} .

The vector-meson-dominant model,[11,12] and the η-pole model[13] both predict branching ratios for $K^+ \to \pi^+ + \gamma + \gamma$ that are much lower than the upper limits that we have been able to set in this experiment.

We have observed 29 events which are acceptable candidates for the reaction $K^+ \to \pi^+ + \gamma + \gamma$. A study of the background indicates that there should be 30 ± 3 background events among the candidates. Our branching ratio limits are based on the assumption that there are fewer than 11 $K^+ \to \pi^+ + \gamma + \gamma$ events in our sample. A more detailed description of this experiment can be found in UCRL-17887.[14]

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