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

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October 25, 1967

ABSTRACT

As a part of our Bevatron spark chamber study of K^+ decays at rest we have searched through our data for examples of the direct decay $K^+ \to \pi^+ + \gamma + \gamma$. No events were found. Candidates were recognized by the relation of the conversion points of two gamma rays to the momentum of a charged particle. The charged particle was assumed to be a pion. Its momentum was determined from its range in an aluminum plate spark chamber. Our apparatus was sensitive to pions having a kinetic energy between 60 and 90 MeV. The gamma rays were detected by a lead plate spark chamber. If we assume the hypothetical direct decay process $K^+ \to \pi^+ + \gamma + \gamma$ to be distributed according to a phase space model, we can set an upper limit for the branching ratio of the K^+ into this channel of 1.1×10^{-4}. Following the suggestion of Fujii,[3] we have interpreted our result as a limit on the off-the-mass shell variation of the $K^+ \to \pi^+ + \pi^0$ amplitude. If this amplitude is assumed to be of the form

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

* Work performed under the auspices of the U. S. Atomic Energy Commission.

our result requires that $|\xi| < 30$. In this expression q is the invariant mass of the two gamma rays. Our results are incompatible with the suggestion of Lapidus[9] that the $K^+ \to \pi^+ + \gamma + \gamma$ mode may be related to the $\eta \to \pi^0 + \gamma + \gamma$ mode through a σ meson intermediate state model. The rate of $K^+ \to \pi^+ + \gamma + \gamma$ predicted by Lapidus is more than an order of magnitude greater than what we obtain from our upper limit of the branching ratio. We note however that this conclusion depends on the presently reported value[6] of the branching ratio of $\eta \to \pi^0 + \gamma + \gamma$ decay.

I. INTRODUCTION

The mechanism causing the $K^+ \rightarrow \pi^+ + \pi^0$ 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 $K_S^0 \rightarrow 2\pi$ 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 $K^+ \rightarrow \pi^+ + \pi^0$ decay occurs.

It has been suggested that the $K^+ \rightarrow \pi^+ + \pi^0$ 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 $K^+ \rightarrow \pi^+ + \pi^0$ 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 $K^+ \rightarrow \pi^+ + \gamma + \gamma$ decay in 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, this virtual particle has a mass different from the π^+ mass even more than the π^0. It follows that the effect suggested above as a mechanism causing the $K^+ \rightarrow \pi^+ + \pi^0$ decay would be greatly enhanced. We would therefore expect a large rate for $K^+ \rightarrow \pi^+ + \gamma + \gamma$.

We have also used our results on the frequency of $K^+ \rightarrow \pi^+ + \gamma + \gamma$ decays to set a limit on the applicability of the so-called σ and ϵ meson intermediate state models to K^+ and η decays.

II. RESULTS

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:

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

In this expression, $M(m^2_{\pi^0})$ 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 $K^0_s \to \pi^+ + \pi^-$ 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:

$$\frac{1}{\Gamma(K^+ \to \pi^+ + \pi^0)} \frac{d\Gamma(K^+ \to \pi^+ + \gamma + \gamma)}{dE_{\pi^+}} =$$

$$\frac{2}{\pi} \frac{M_K}{m^3_{\pi^0}} \Gamma(\pi^0 \to 2\gamma) \frac{P^+_\pi}{P_0} q^4 \left| \frac{1}{q^2 - m^2_{\pi^0} + \frac{\Gamma(\pi^0 \to 2\gamma)^2}{4} - i m_{\pi^0} \Gamma(\pi^0 \to 2\gamma)} - \frac{\xi}{m^2_{\pi^0}} \right|^2$$

In this expression P_θ is the momentum of the π^+ in $K^+ \to \pi^+ + \pi^0$ decay. For the purpose of comparing this calculation with our experimental results we have assumed that $\Gamma(\pi^0 \to 2\gamma) = 7.4 \pm 0.15 \times 10^{-6}$ MeV as given in the table of Rosenfeld et al.[6]

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 evidence for the existance of this decay mode. 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]

Our result can be interpreted in another way. 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:

$$K^+ \to \sigma + \pi^+$$
$$\quad \hookrightarrow \pi^{\stackrel{+}{0}} + \pi^{\stackrel{-}{0}}$$

$$\eta \to \sigma + \pi^0$$
$$\quad \hookrightarrow \pi^{\stackrel{+}{0}} + \pi^{\stackrel{-}{0}}$$

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:

$$\eta \to \pi^0 + \gamma + \gamma$$

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,

$$\eta \to \pi^0 + \gamma + \gamma .$$
$$K^+ \to \pi^+ + \gamma + \gamma$$

are simply related. The model of Lapidus requires that the decay $K^+ \to \pi^+ + \gamma + \gamma$ 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 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_ϵ = 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.

III. EXPERIMENTAL DETAILS

A cross section of our apparatus is shown in Fig. 1. This apparatus was designed primarily for a study of the $K^+_{\mu 3}$ decay mode and the results of the experiment described here are based on a re-analysis of the data taken for that experiment. As the apparatus will be described in detail in a later paper, we shall give only a brief outline of it here.

The kaon stopper at the center of Fig. 1, which consisted of a scintillation counter box filled with carbon dust, was placed at the second focus of a 500 MeV/c single-stage separated K^+ beam at the Bevatron. K^+ mesons, which entered the apparatus in a direction perpendicular to the figure, were identified by a variety of scintillation counters and a Cerenkov counter in the beam. The counting system is not shown in the figure. There were two spark chambers in the K^+ beam immediately before the stopper to assist in the determination of the stopping point of the K meson.

The set of counters T2, T3, $\bar{C}$, T4, and $\overline{T5}$, which we shall call the pion telescope, was used to identify charged particles from K^+ decay.

The spark chamber trigger requirement was a T2-T3-T4-$\bar{C}$-$\overline{T5}$ fast coincidence occurring in the interval from $6\text{-}35 \times 10^{-9}$ seconds after a K-stop signal. The water Cerenkov counter in the pion telescope served to reject electrons from the K^{+}_{e3} decay mode, and products of gamma ray conversions. Pions with insufficient energy to go beyond the $\overline{T5}$ anti-coincidence counter were not detected in the Cerenkov anticoincidence counter. The aluminum degrader shown in the figure was variable and could be adjusted to make the range interval between T4 and $\overline{T5}$ correspond to an initial pion kinetic energy from 50 to 150 MeV.

The gamma rays were detected in 36 module spark chambers surrounding the kaon stopper. The plates in these modules consisted of a sandwich of a 0.8 mm thick lead sheet between two 0.3 mm thick aluminum plates. The two modules closest to the kaon stopper were made with thin aluminum plates in order to permit the identification of charged particles entering the chamber from outside. There were no counters associated with the gamma ray chambers. The initial direction of the pion was determined by measuring the tracks in the three thin spark chambers SC1, SC2, and SC3 in Fig. 1. The range of the pion was determined by measuring its depth of penetration into the 28 module aluminum plate spark chamber between T4 and $\overline{T5}$. The film taken in this experiment was scanned on the MIT SPASS automatic scanning system. All the spark chambers were scanned by this system except the aluminum plate range chamber which was scanned by hand on the LRL SCAMP machine.

In order to isolate events of the type $K^{+} \rightarrow \pi^{+} + \gamma + \gamma$ we take the range and direction of the charged particle in the pion telescope and the direction of one of the gamma rays and compute the expected direction of the second gamma ray. This direction is uniquely predicted if the event is an example of $K^+ \rightarrow \pi^+ + \gamma + \gamma$. We compute the angle α between the predicted direction and the measured direction of the second gamma ray. We then repeat the procedure using the second gamma ray to predict the direction of the first. We use the average of the angles α from these two computations as a measure of the deviation from $K^+ \rightarrow \pi^+ + \gamma + \gamma$ kinematics.

In order to show that our apparatus would be sensitive to $K^+ \rightarrow \pi^+ + \gamma + \gamma$ events, we adjusted the amount of degrader in the pion telescope so that 108.6 MeV pions from the reaction $K^+ \rightarrow \pi^+ + \pi^0$ would stop between T4 and $\overline{T5}$. The distribution in $\cos \alpha_{av}$ of these events is shown in Fig. 2.

Figure 3 shows the distribution in $\cos \alpha_{av}$ that we observe when we reduce the amount of degrader in the pion telescope in order that pions from the reaction $K^+ \rightarrow \pi^+ + \pi^0$ cannot stop in the range interval between T4 and $\overline{T5}$. During the course of the experiment the degrader was varied so that the pion energy interval from 60 to 90 MeV was covered. There is evidently no peak at $\cos \alpha_{av} = 1$ in our data. From a study of our experimental resolution made with the help of the $K^+ \rightarrow \pi^+ + \pi^0$ data, we estimate that about 80% of the $K^+ \rightarrow \pi^+ + \gamma + \gamma$ events would fall into the interval $0.994 < \cos \alpha_{av} < 1.000$. The uniformly distributed events shown in Fig. 3 are $K^+ \rightarrow \pi^0 + \mu^+ + \nu$ events. A Monte Carlo study of this $K_{\mu 3}$ background has shown that it is distributed uniformly in the interval $0.96 < \cos \alpha_{av} < 1.00$. We have used the number of observed background events in the interval $0.96 < \cos \alpha_{av} < 0.99$ to predict the number of background events expected in the interval $0.994 < \cos \alpha_{av} < 1.000$. We predict 30 ± 3 events. We observe 29 events in this interval. The excess of the observation over the prediction is -1 ± 6 events. We have based our branching ratio limits on the assumption that there are fewer than 11 events in the interval $0.994 < \cos\alpha_{av} < 1.000$.

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REFERENCES

1. N. Cabibbo and R. Gatto, Phys. Rev. Letters 5, 382 (1960).
2. Y. Hara and Y. Nambu, Phys. Rev. Letters 16, 875 (1966).
3. Y. Fujii, Phys. Rev. Letters 17, 613 (1966).
4. S. Okubo, R. E. Marshak, and V. S. Mathur, UR-875-200, University of Rochester, Department of Physics and Astronomy.
5. D. Cline and W. Fry, Phys. Rev. Letters 13, 101 (1964).
6. Rosenfeld, Barbaro-Galtieri, Podolsky, Price, Soding, Wohl, Roos, and Willis, Pev. Mod. Phys. 39, 1 (1967).
7. L. Brown and P. Singer, Phys. Rev. 133, B812 (1964).
8. L. Brown, "Scalar Mesons" in Perspectives in Modern Physics, ed. by R. Marshak, Wiley, 1966, pp 195-210.
9. I. Lapidus, Nuovo Cimento 46, 668 (1966).
10. S. Oneda, Phys. Rev. 158, 1541 (1967).
11. G. Oppo and S. Oneda, Phys. Rev. 160, 1397 (1967).
12. Y. Fujii, Private communication.
13. Fäldt, Peterson, and Pilkuhn, to be published in Nuclear Physics B.

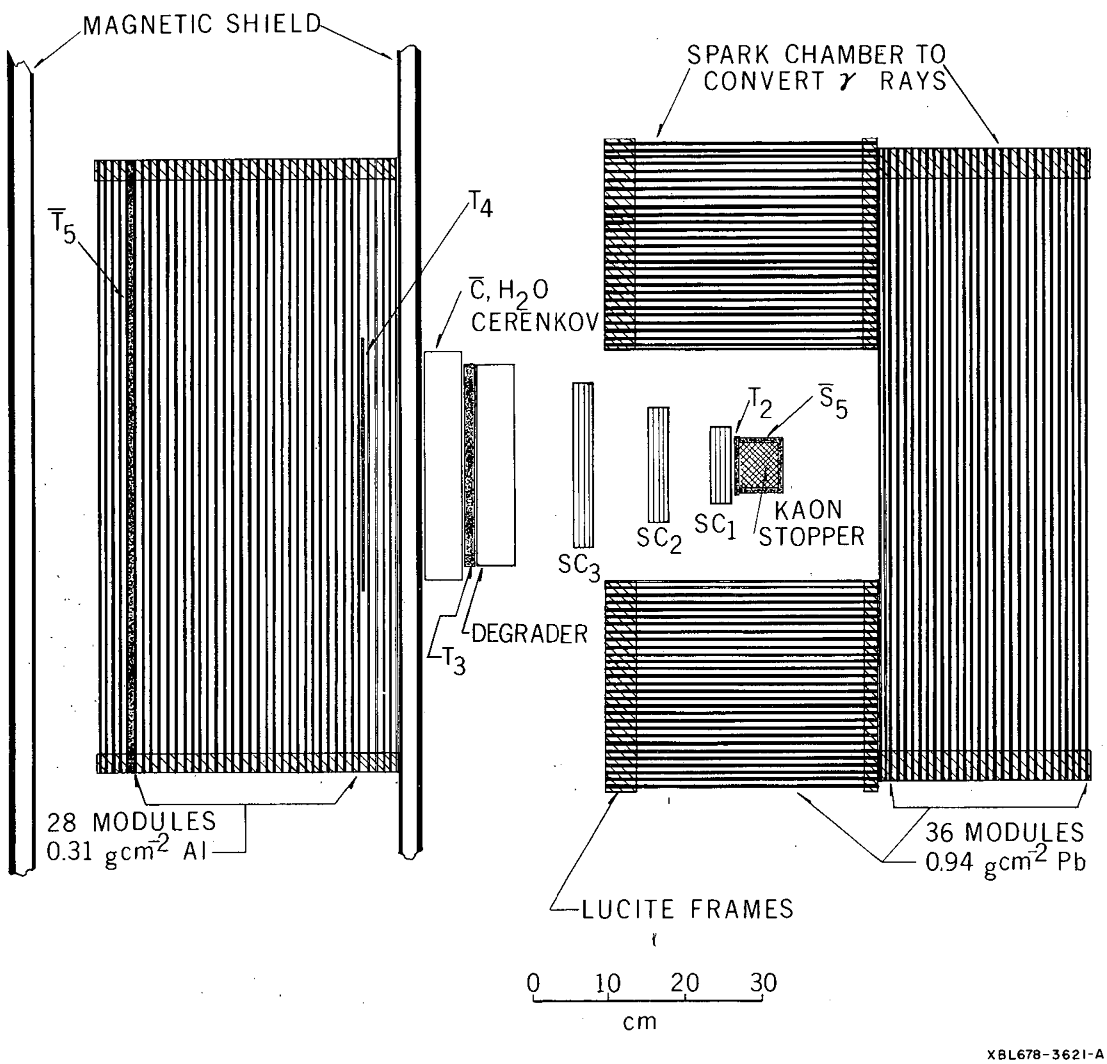

Fig. 1. The apparatus used in this experiment. K^+ mesons entered the stopper in a direction perpendicular to the plane of the diagram.

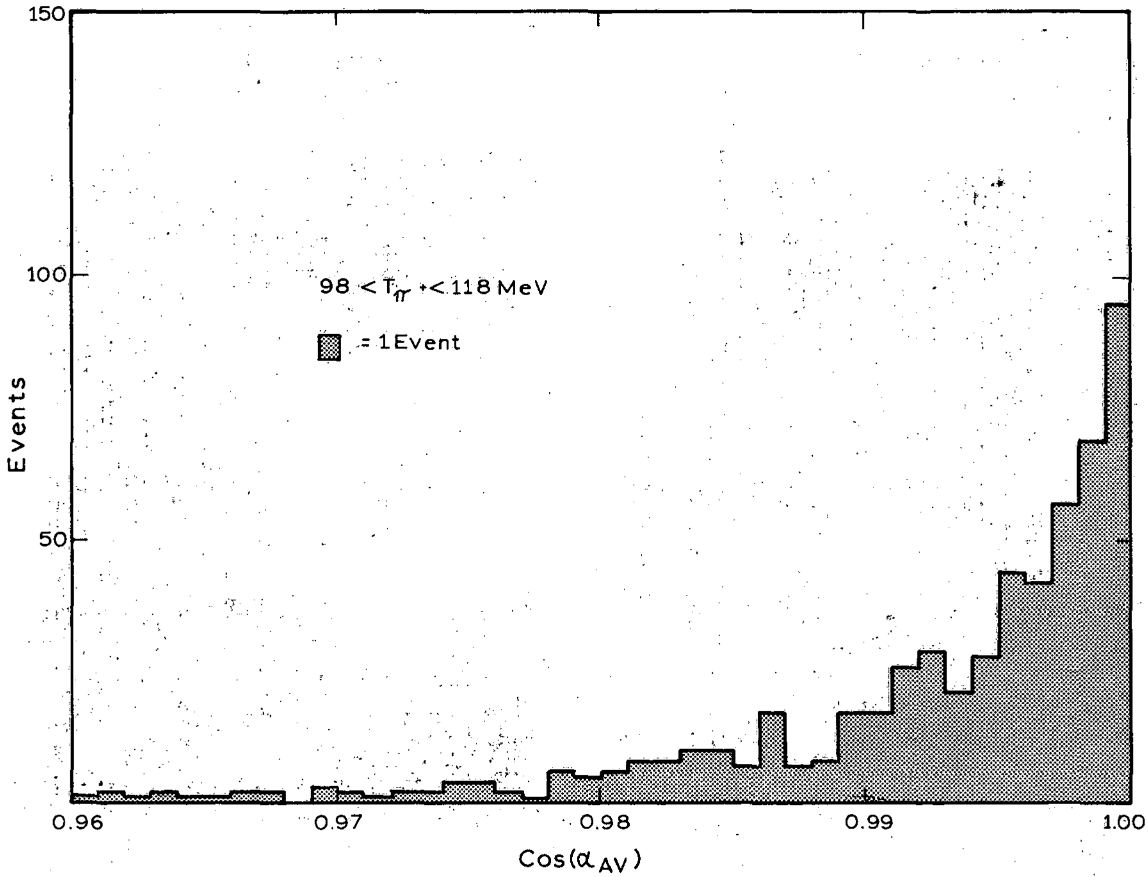

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Fig. 2. Distribution in cos α_{av} of a sample of $K^+ \rightarrow \pi^+ + \pi^0$ events. α_{av} is the average angle between the measured and the predicted direction of one of the gamma rays in $K^+ \rightarrow \pi^+ + \gamma + \gamma$.

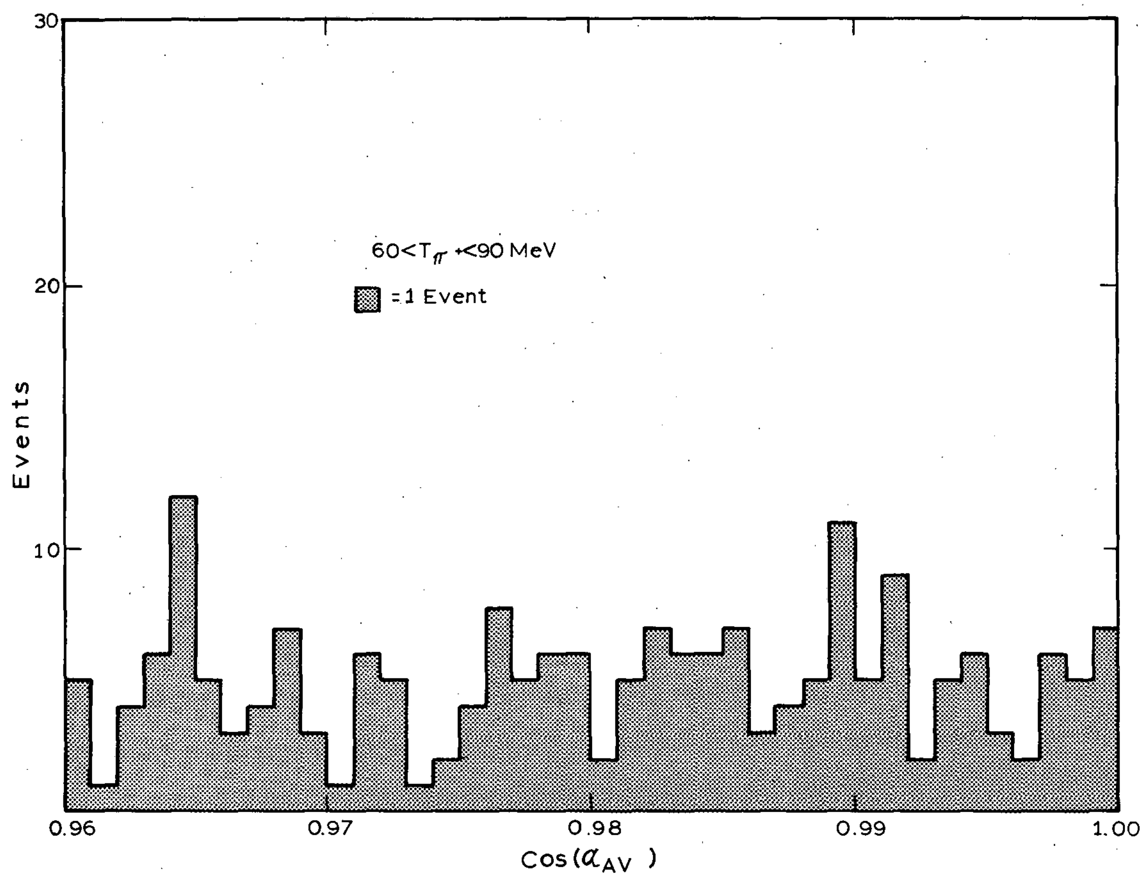

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Fig. 3. Distribution in cos α_{av} of the sample of K decay events in which we searched for examples of the reaction $K^+ \rightarrow \pi^+ + \gamma + \gamma$ with the invariant mass of the two gamma rays not equal to the π^0 mass. Our upper limit on the branching ratio for this mode comes from the conclusion that there are fewer than 11 events in the interval from 0.994 to 1.0.