reported here is predominantly an $\eta\pi^0$ effect.[12] An $\eta\pi^0$ final state would have 72% of its signal in the neutral spectrum, yet we observe only 27 ± 16 and 27 ± 16 events above background in the neutral spectrum for the $M^0(940)$ and the δ^0, while we would expect 481 ± 111 and 553 ± 113, respectively, based on the observed enhancements in the two-charge spectrum.

Regarding $\pi^+\pi^-\pi^0$ effects, we note that at least part of the $M^0(940)$ enhancement involves two charged particles and at least one neutral and is consistent with $\pi^+\pi^-\pi^0$ or $\pi^+\pi^-\gamma$ final states.[13]

The original CERN missing-mass experiment[14] reported a mass and width of 962 ± 5 MeV and $\Gamma \lesssim 5$ MeV for an enhancement referred to as the δ^-. We suggest that the δ^0 observed in the present experiment is the neutral member of an isotopic multiplet of which the δ^- is the singly charged negative member.[15]

We have observed three distinct mesons, namely, the well-known $\eta'(958)$ and the previously unobserved δ^0 and $M^0(940)$. Both the δ^0 and the $M^0(940)$ appear predominantly in final states that have two charged particles, and a substantial fraction of the $M^0(940)$ appears in a final state which has two charged particles and at least one neutral particle. Neither of these mesons decays predominantly to $\eta\pi^0$. We associate the δ^0 reported here with the $I \geq 1$ δ^- effect observed previously.[14]

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[1]The efficiency of similar neutron counters has been measured by C. Wiegand *et al.*, Rev. Sci. Instrum. 33, 526 (1962). See also R. Kurz, UCRL Report No. UCRL-11339 (unpublished).

[2]When two errors are given, the first is statistical and the second is systematic.

[3]A. Rittenberg *et al.*, Rev. Mod. Phys. 43, S1 (1971).

[4]W. B. Richards *et al.*, Phys. Rev. D 1, 10 (1970); E. Hyman *et al.*, Phys Rev. 165, 1437 (1968).

[5]See, for example, R. K. Rader, UCRL Report No. UCRL-19431, 1969 (unpublished).

[6]The angle cuts reflect our counter geometry. The intersection of the front array and the cylindrical array corresponds to an angle of 17° with respect to the center of the hydrogen target. The upstream end of the cylindrical array corresponds to an angle of 130°.

[7]The two-charge and four-charge events of Fig. 3(a) presumably correspond to the $\eta\pi\pi$ decay of the η'. This final state preferentially populates those spectra for which θ_{lab} is small because of the low Q of the decay.

[8]To minimize binning effects, all masses and widths at 2.4 GeV/c were determined from data in 1-MeV bins.

[9]We have arbitrarily increased the statistical errors on the branching ratios by 50% to account for systematic effects.

[10]M. Aguilar-Benitez *et al.*, Phys. Rev. Lett. 25, 1635 (1970).

[11]B. Maglich *et al.*, Phys. Rev. Lett. 27, 1479 (1971).

[12]The neutral member of an isospin multiplet whose charged member decays predominantly via $\eta\pi^\pm$ need not decay predominantly via $\eta\pi^0$. For example, if the $\eta\pi^\pm$ decay is electromagnetic, then $\eta\pi^0$ decay may be forbidden by C conservation.

[13]In a good mass-resolution experiment B. D. Hyam *et al.*, Nucl. Phys. B7, 1 (1968), observed a 4.5σ enhancement at 946 ± MeV, $\Gamma < 15$ MeV.

[14]W. Kienzle *et al.*, Phys. Lett. 19, 438 (1965).

[15]The masses of the δ^- and δ^0 may differ by a small amount because of electromagnetic effects.

Search for the Decay $K^+\rightarrow\pi^+\gamma\gamma$†

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A search has been made for the rare decay mode $K^+\rightarrow\pi^+\gamma\gamma$ using a heavy-liquid bubble chamber. No events were found. A test was made of the Fujii model which uses an off-mass-shell extrapolation of the $K_{\pi2}$ amplitude to make predictions for this decay. The experimental upper limit on the branching ratio is reported to be 2.2×10^{-5}, and this result is consistent with the Fujii model. This result is inconsistent with the branching ratio predicted by the Fujii model.

This paper presents the relevant details and the results of an experimental bubble-chamber search for the decay $K^+\rightarrow\pi^+\gamma\gamma$. This experiment is the first one to search for this decay in the lower end of the pion spectrum. This region is important as several theoretical models of the decay have predicted that the majority of these decays will have pions with a kinetic energy below 60 MeV.

The decay $K^+\rightarrow\pi^+\gamma\gamma$ is expected to exist as a result of first-order weak and second-order electromagnetic interactions. In principle, the decay could proceed either by inner bremsstrahlung or else by direct emission of photons. However, several authors[1] have pointed out that the inner bremsstrahlung terms must vanish as a result of gauge invariance and the pseudoscalar nature of the mesons. Various theoretical models have been used to estimate the contribution to the direct $K^+\to\pi^+\gamma\gamma$ amplitude from different intermediate states. Fujii[2] considers the contribution from a π^0 intermediate state with the π^0 off the mass shell. In this model the $K^+\to\pi^+\gamma\gamma$ amplitude is an extrapolation of the $K_{\pi 2}$ amplitude. The extrapolation is linear in the difference of the squared mass of the off-mass-shell π^0 in $K^+\to\pi^+\gamma\gamma$ decay and the squared mass of the on-mass-shell π^0 in the $K_{\pi 2}$ decay. The proportionality constant in the extrapolation is ϵ, and Fujii estimates $|\epsilon|\approx 20$ from a consideration of the decays $K_s^0\to\pi^+\pi^-$ and $K^+\to\pi^+\pi^0$. Using this value for ϵ and the differential decay rate for $K^+\to\pi^+\gamma\gamma$ appropriate to this model,[3] one obtains a total branching ratio of 8×10^{-5} for $K^+\to\pi^+\gamma\gamma$. In this model the π^+ spectrum has a sharp peak in the $K_{\pi 2}$ region and a large bump for low-energy positive pions. At the 10^{-6} level there are two contributions to the direct amplitude. One contribution is from the K^+ decay into three pions in which two of the pions are virtual and in which these two virtual pions annihilate to produce two γ's. Secondly, there is a contribution from the K^+ decay into a positive pion and a virtual η particle in which the η decays into two γ's. Vanyashin[4] considers both of these contributions, and he writes a general matrix element for the decay and shows that the pion spectrum is peaked for low pion energies while the photon spectrum will peak at high-energy photons. When specifically considering these two contributions, he concludes that they are about equal and that there is no interference between them. He predicts a total branching ratio of 2×10^{-6}. Fäldt, Petersson, and Pilkuhn[5] obtain a branching ratio of 1.5×10^{-6} with the kinetic energy of the π^+ less than 70 MeV using just the η-pole model.

Chen *et al.*[3] did a counter experiment searching for $K^+\to\pi^+\gamma\gamma$ in which the pion kinetic energy was between 60 and 90 MeV. In Fujii's model their result is that $|\epsilon|<30$, and hence they do not rule out his prediction. Klems, Hildebrand, and Steining[6] report a total-branching-ratio upper limit of 4.5×10^{-5} at the 90% confidence level assuming a phase-space model. As their counter setup was sensitive to pions above the $K_{\pi 2}$ region (pion kinetic energy range 117 to 127 MeV), they were unable to check Fujii's model.

The present experiment searched for the decay in the Michigan 40-in. bubble chamber filled with heavy Freon. The short radiation length of heavy Freon meant there was an 84% chance for a γ to convert in the chamber. The K^+ particles in the 28° beam at the Argonne zero gradient synchrotron were degraded so that three to seven K^+ particles stopped in the chamber per bubble-chamber picture. The decay was searched for over most of its spectrum as the experiment was sensitive in the pion kinetic energy range from 6 to 102 MeV and from 114 MeV to the maximum kinetic limit of 127 MeV. No events were found. In terms of Fujii's parameter ϵ, the result is that $|\epsilon|<11$; and, thus, this experiment is inconsistent with Fujii's prediction. This experiment is still an order of magnitude away from testing the η-pole or π-π annihilation models. Assuming a phase-space model, the result is an upper limit on the total branching ratio of 3.5×10^{-5} at the 90% confidence level.

The decay $K^+\to\pi^+\gamma\gamma$ was searched for as follows. The scanners searched for a stopped K^+ decay with two γ pointing to the origin. The secondary was required to stop and decay in a π-μ-e chain, to have no large-angle scatters, and to have a projected range on the scan table outside of the $K_{\pi 2}$ region. Pion identification was provided by the observation of the muon as a very short track (μ pip) in the π-μ-e decay chain. From a study of the pion endings in τ decays, it was determined that 53% of all pions have a visible μ pip. In contrast, less than 1% of all muon secondaries will have a fake μ pip, and thus, the pion identification is quite clean. Secondaries with strong interactions (large-angle scatters) were discarded in order to insure an accurate measurement of the pion's momentum from the range of the secondary. A total of 542 100 stopped K^+'s in the fiducial volume were scanned. We successfully processed 4100 events (first measured and then analyzed by the programs SHAPE, SQUAW, ARROW, and INDIAN); 2200 of these events were discarded in the program INDIAN as the reconstructed secondary range was in the $K_{\pi 2}$ region. We used the program SQUAW to fit each event to the four-constraint $K^+\to\pi^+\gamma\gamma$ hypothesis using all measured variables plus the two-constraint hypothesis ignoring the measured γ energies. Three cuts were applied to all fits. The first cut accepted only those fits with a χ^2

probability for the $K^+ \to \pi^+\gamma\gamma$ fit greater than 0.01. The second cut was based on the fact that the pion's momentum could be measured by range quite well and any fits in which the fit pion momentum differed by more than 10.5 MeV from the measured momentum were rejected. Finally, any fits with a fit pion momentum in the $K_{\pi 2}$ region from 197 to 211 MeV/c were discarded. There were 47 events in which either the four-constraint or two-constraint fit, or both, passed the above cuts; and these events were then carefully edited on the scan table by a physicist. Only six events satisfied the criteria to be a two γ-π event.

A background study was made to see what types of background are expected at this level. It was found that one of the six events could only be interpreted as an example of $K^+ \to \pi^+\gamma\gamma$ or else as an example of $K^+ \to \pi^+\pi^0\gamma$ where one of the π^0 γ's had failed to convert. Since the radiative $K_{\pi 2}$ branching ratio is at the 10^{-4} level, it was important to determine whether it could reasonably be background for $K^+ \to \pi^+\gamma\gamma$ at the 10^{-5} level. A model of radiative $K_{\pi 2}$ faking $K^+ \to \pi^+\gamma\gamma$ was constructed based on the measurement errors in this experiment and a consideration of 21 radiative $K_{\pi 2}$ events with 3 converted γ's found in another part of the experiment. The model predicted that an experiment of this type had a 30% chance of having a radiative $K_{\pi 2}$ event that would pass editing and all three cuts and hence be background for $K^+ \to \pi^+\gamma\gamma$. Estimates were made of the number of events expected from other sources of background, and it was found reasonable to interpret these six events as three τ' decays in which only two γ's converted in the chamber, one $K_{\mu 3}$ decay in which the muon had a fake μ pip, one $K_{\pi 2}$ decay in flight, and one radiative $K_{\pi 2}$ decay in which one of the three γ's failed to convert.

A real $K^+ \to \pi^+\gamma\gamma$ decay is coplanar. That is, the momenta of the pion and the two γ's are constrained to lie in a plane. No such constraint applies to the background decays and hence the background only accidentally approximates coplanarity. Thus, in order to separate out the background decays mentioned above from any real signal, one can use a more stringent coplanarity constraint than that provided by the rather loose χ^2 cut on the overall fit. To measure how well a given event fits this criterion, we define a box product B by

$$B = \frac{(\vec{p}_{\pi^+} \times \vec{p}_{\gamma_1}) \cdot \vec{p}_{\gamma_2}}{|\vec{p}_{\pi^+}||\vec{p}_{\gamma_1}||\vec{p}_{\gamma_2}|}$$

where all momenta are measured momenta. The range of the box product is -1 to $+1$ and a real event will have a box product consistent with zero. Thus, the final cut rejected events with the absolute value of the box product greater than 0.140. Figure 1 shows the box products for the six remaining events along with the box product for a sample of $K_{\pi 2}$ decays calculated from the pion and two γ momenta. All six remaining candidates were eliminated by this cut.

This null result will be discussed in terms of Fujii's model, the η-pole model of Fäldt, Petersson, and Pilkuhn, and phase space. For each model a total detection efficiency was calculated, considering the following corrections. Losses due to the pion having a strong interaction, or the pion leaving the chamber, or the pion being discarded by the range cuts used to eliminate $K_{\pi 2}$ decays are all functions of the pion momentum. Thus, the differential pion spectrum for each model was used to calculate the total percent lost as a result of these causes. For the Fujii model, we used the differential pion spectrum as calculated by Chen *et al.*[3] Fäldt, Petersson, and Pilkuhn[5] give the differential pion spectrum for the η-pole model as

$$d\Gamma/dT_{\pi^+} \propto p_{\pi^+} q^4/(m_\eta^2 - q^2)^2,$$

where q is the invariant mass of the two γ rays. For phase space the spectrum is

$$d\Gamma/dT_{\pi^+} = \lambda p_{\pi^+},$$

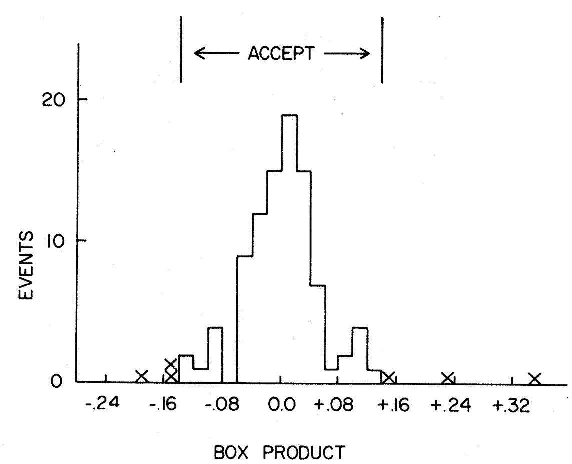

FIG. 1. Coplanarity cut applied to $K^+ \to \pi^+\gamma\gamma$ candidates. The box product is calculated from measured π^+ and γ angles. The crosses correspond to six $K^+ \to \pi^+\gamma\gamma$ candidates. The open histogram corresponds to coplanar $K_{\pi 2}$ decays.

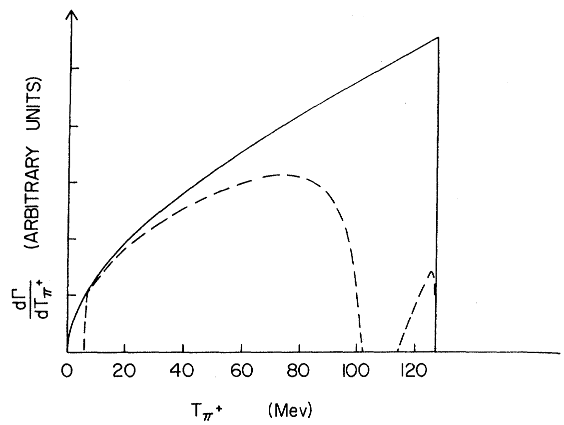

FIG. 2. Pion spectrum for $K^+\to\pi^+\gamma\gamma$. The solid line corresponds to the theoretical distribution assuming a phase-space model for the decay. The dashed line shows the expected spectrum after experimental efficiencies are folded in.

where λ is a constant. Figure 2 shows the phase-space spectrum along with the expected experimental spectrum due to the above losses. Also considered were the probability of seeing a μ pip, the probability of two γ's converting, and losses due to scanning inefficiencies. Losses due to the cuts applied to the events were determined by applying the cuts to a sample of $K_{\pi 2}$ decays treated as examples of $K^+\to\pi^+\gamma\gamma$, and it was found that 93% of the events passed all the cuts. The total detection efficiencies were 19.5%, 20.3%, and 12.2% for the Fujii model, η-pole model, and phase-space model, respectively.

In the Fujii model the branching-ratio upper limit is

$$\frac{\Gamma(K^+\to\pi^+\gamma\gamma,\ T_{\pi^+}<102\text{ MeV})}{\Gamma(K^+\to\text{all})}<2.2\times10^{-5}$$

at the 90% confidence level. This corresponds to a limit on ϵ of $|\epsilon|<11$. Finding a single event in this experiment would have corresponded to $|\epsilon|\approx 7$. Thus, this experiment is inconsistent with Fujii's expectation of $|\epsilon|\approx 20$. For the η-pole model the result is

$$\frac{\Gamma(K^+\to\pi^+\gamma\gamma,\ T_{\pi^+}<70\text{ MeV})}{\Gamma(K^+\to\text{all})}<2.1\times10^{-5}$$

at the 90% confidence level. This is to be compared with the value found by Fäldt, Petersson, and Pilkuhn of 1.5×10^{-6}. Finally, assuming phase space, the limit on the branching ratio over the entire spectrum is

$$\Gamma(K^+\to\pi^+\gamma\gamma)/\Gamma(K^+\to\text{all})<3.5\times10^{-5}$$

at the 90% confidence level.

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