L. S. Rochester, Phys. Rev. Letters 17, 573 (1966).

[5]S. R. Deans and W. G. Holladay, Phys. Rev. 161, 1466 (1967), and references therein.

[6]C. Lovelace, in Proceedings of the International Conference on Elementary Particles, Heidelburg, Germany, 1967, edited by H. Filthuth (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968); P. Bareyre, C. Bricman, and G. Villet, Phys. Rev. 165, 1730 (1968).

[7]C. A. Heusch, C. Y. Prescott, and R. F. Dashen, Phys. Rev. Letters 17, 1019 (1966).

[8]C. A. Heusch and C. Y. Prescott, Nucl. Instr. Methods 29, 205 (1964).

[9]For details of experimental method and data analysis, see L. S. Rochester, thesis, California Institute of Technology, 1968 (unpublished).

[10]W. B. Richards et al., Phys. Rev. Letters 16, 1221 (1966); and W. B. Richards, University of California Radiation Laboratory Report No. UCRL-16195, 1965 (unpublished).

[11]Lovelace's list of resonances (Ref. 6) found in πN phase-shift analyses mentions, for the $I=\frac{1}{2}$ channel, only one candidate in good standing which might show up in our energy region, in addition to the F_{15} and D_{15} states around 1680 MeV. This is the S_{11} (1709), with an elasticity of Γ_{el}/Γ_{tot} of 0.786 in $\pi N \to \pi N$. Whether this state, with a total width of $\Gamma \approx 300$ MeV, can account for the apparent shoulder observed in this experiment around 1.1 GeV remains to be established. A general tendency for forward peaking of the cross section is expected with increasing energy because of diagrams in the t channel (vector-meson exchange).

MEASUREMENT OF THE BRANCHING RATIO $(K_L \to \gamma\gamma)/(K_L \to 3\pi^0)$†*

M. Banner,‡ J. W. Cronin, J. K. Liu, and J. E. Pilcher
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 16 August 1968)

We have measured the branching ratio $(K_L \to \gamma\gamma)/(K_L \to 3\pi^0)$ to be $(2.24 \pm 0.28) \times 10^{-3}$. Combined with a recently reported branching ratio $(K_L \to 3\pi^0)/(K_L \to \text{all modes}) = 0.209 \pm 0.011$, we find $(K_L \to \gamma\gamma)/(K_L \to \text{all modes})$ to be $(4.68 \pm 0.64) \times 10^{-4}$.

An experiment to measure $K_L \to \pi^0\pi^0$ and $K_L \to \gamma\gamma$, previously reported in preliminary form,[1] has been repeated with an improved apparatus. We report here the results obtained for the decay rate of $K_L \to \gamma\gamma$.

The apparatus consisted of a pair spectrometer placed parallel to a K_L beam at the Princeton-Pennsylvania Accelerator. The spectrometer has been described in Ref. 1. In principle, a measurement of the energy spectrum of single γ rays in the c.m. system allows one to distinguish between the decay modes $K_L \to \gamma\gamma$, $K_L \to \pi^0\pi^0$, and $K_L \to 3\pi^0$. However, no kinematic check that the γ rays came from K_L is possible. To provide such a check, steel-plate spark chambers have been added to convert the additional γ rays.

Figure 1(b) shows a view of the apparatus looking upstream along the beam line. We have surrounded the remaining three sides of the beam with spark chambers. Each chamber consists of three 0.86-g/cm^2 aluminum plates nearest the beam, followed by 20 2.5-g/cm^2 stainless steel plates. The total thickness of each chamber, as measured along its normal, is 3.6 radiation lengths. The spark chambers extend along the beam for 10 feet, as is shown in the plan view of Fig. 1(a), and were viewed in small-angle stereo. The precision of spark location was 0.1 in. perpendicular to the beam, and 0.5 in. parallel to the beam.

These spark chambers were triggered along

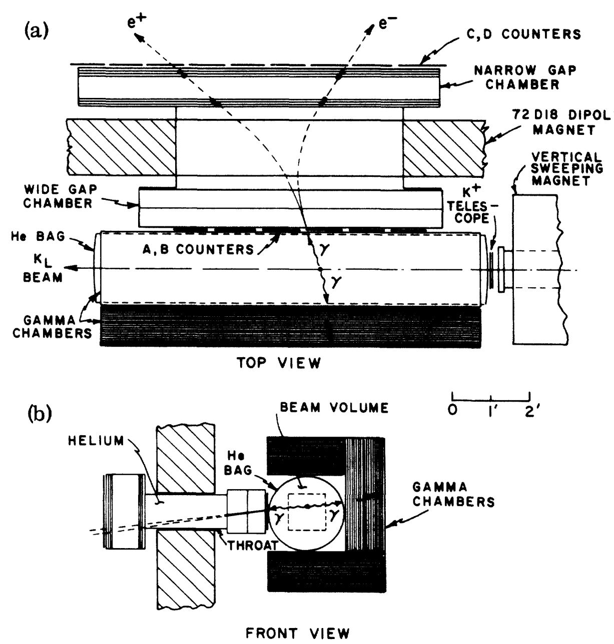

FIG. 1. (a) Plan view of apparatus. (b) End view of apparatus.

with the spectrometer every time the logic indicated a γ ray had been detected in the spectrometer. We did not demand in the trigger that a γ ray convert in the steel chambers. The velocity of the decay particles was measured using the 67.3-nsec time structure present in the accelerator beam. A helium bag in the beam reduced problems of neutron and K_L interactions in the decay volume.

In the experiment reported here, we observed 7351 converted γ rays in the spectrometer. For these events we verified that the efficiency per gap of each steel chamber was always greater than 90%. In addition, the spatial reconstruction was verified by measurement of cosmic-ray tracks that passed through both the spectrometer and the steel chambers. The correspondence between the two coordinate systems was within 0.1 in.

Of the 7351 good events, 643 were found to have a transverse momentum greater than 165 MeV/c. The cut in transverse momentum was chosen to eliminate almost all the $3\pi^0$ decays. A cut in center-of-mass energy was not made since about 1% of the $3\pi^0$ events were expected to have an apparent energy greater than 165 MeV because of time-of-flight ambiguities.

The 643 selected events were scanned and measured twice by physicists. The criterion for a converted γ ray in a steel chamber was the presence of at least two contiguous sparks, even though the expected γ ray energy was >240 MeV. A fit to $K_L \to \gamma\gamma$ was attempted for each such γ ray, providing it did not convert in the first two gaps. Occasionally a fit was found for two separate γ rays, but in each case these could be traced to the same shower.

In the fitting of events, only the conversion points were used for those γ rays converting in the steel chambers. The K_L decay point was assumed to lie along the line of the spectrometer γ ray projected back into the beam. Points were chosen along this trajectory at 0.5-in. intervals across the beam volume. For each point, the direction of a γ ray in a steel chamber was taken to be along the line drawn from this point to its conversion point. The decay point was chosen to give the best collinearity in the c.m. system with the restriction that the point be no more than 2 in. outside the beam volume. The resulting collinearity distribution is shown in Fig. 2(a). The spectrometer momentum measurement has not been used in the fitting. Figure 2(b) shows the transverse momentum distribution of those events which show a collinearity $-1.00 \leq \cos\theta_{\gamma\gamma} < -0.99$. Figure 2(c) shows the energy distribution of these events in the c.m. system using the time-of-flight information for each event.

For the branching-ratio calculation, we used events with $215 < E_{\text{c.m.}} < 270$ MeV, $P_\perp > 165$ MeV/c, and $-1.00 \leq \cos\theta_{\gamma\gamma} < 0.99$. Here $E_{\text{c.m.}}$ and $P_\perp$ refer to the c.m. energy and transverse momentum of the spectrometer gamma ray, respectively. There were 116 events which satisfied these conditions. A Monte Carlo study using the observed number of $\pi^0\pi^0$ decays indicated that we can expect to find one $K_L \to \pi^0\pi^0$ event in this region. The decay $K_L \to \pi^0\pi^0$ is discussed in the following paper. The final number of $\gamma\gamma$ events is then found to be 115 ± 11.

Monte Carlo calculations have shown that 0.828 ± 0.032 of all $K_L \to \gamma\gamma$ events detected in the spectrometer with $215 < E_{\text{c.m.}} < 270$ MeV will show a materialized γ in a steel chamber and satisfy the fitting criteria. The 17% inefficiency is due to 10% of the events with no conversion in a steel chamber, and 7% with a conversion in one of the first two plates. Less than 1% of all events fail to fit. The fraction of all $K_L \to \gamma\gamma$ events which are detected in the spectrometer with $215 < E_{\text{c.m.}} < 270$ MeV and $P_\perp > 165$ MeV/c is calculated to be 0.884 ± 0.019. The total number of $K_L \to \gamma\gamma$ events observed in the spectrometer is then $N_{\gamma\gamma} = 157 \pm 16$.

We wish to emphasize that the Monte Carlo calculations referred to above made use of geometrical quantities and the absolute pair-production cross section[2]; they did not require application of shower theory.

The solid curves in Figs. 2(b) and 2(c) are the distributions from the Monte Carlo calculations normalized to 116 events for $E_{\text{c.m.}} > 215$ MeV. This calculation for the spectrometer γ ray took into account the incident K_L momentum spectrum, the bremsstrahlung loss in the converter, scattering in the converter and foils of the spark chambers, and the relative pair-production cross section in the thin radiator as a function of γ energy. It also included our estimate of measurement errors. It did not include the fact that at steep angles the sparks do not necessarily follow the trajectory of the particle, nor could it account for unknown errors of reconstruction. Therefore the data themselves were used to determine the actual resolution. The full width at half-maximum of the $K_L \to \gamma\gamma$ peak was observed to be 20 MeV, whereas the calculation had predicted 14 MeV. In addition, the centers of the ex-

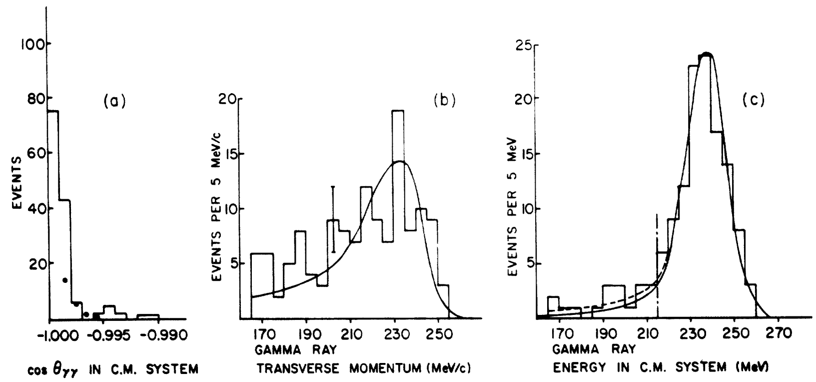

FIG. 2. (a) Collinearity distribution of $K_L \rightarrow \gamma\gamma$ events. The solid dots are the results of a Monte Carlo calculation for the expected distribution. The experiment indicates an angular resolution of ± 0.030 rad, while the Monte Carlo predicts ± 0.025. (b) Distribution of transverse momentum of spectrometer γ ray for the prediction. (c) Distribution of energy of the spectrometer γ ray in the c.m. system. The solid curve is the Monte Carlo prediction adjusted to match the experimental resolution; the dashed curve is the background expected from decays $K_L \rightarrow \pi^0\pi^0$.

perimental $E_{\text{c.m.}}$ and $P_\perp$ peaks were shifted down by 1% from their expected positions. We attribute these facts to a fault in the reconstruction calculation, as evidenced by the fact that cosmic rays passing through the spectrometer under zero-field conditions had an 8-mrad shift between their directions in the two spectrometer spark chambers. This error has no significant effect on our conclusions. The measured resolution has been used in all subsequent calculations. It is important to note that the distributions in $P_\perp$ and $E_{\text{c.m.}}$ do not show any evidence of a tail on the high-energy side. The good agreement between the calculated and observed distributions for both $P_\perp$ and $E_{\text{c.m.}}$ indicates that our measured time-of-flight resolution (2-nsec full width at half-maximum) does not have to be increased.

Figure 3(a) shows the $P_\perp$ distribution for all events measured in the spectrometer. Among these are approximately 157 $K_L \rightarrow \gamma\gamma$ events; in the paper that follows, we find approximately 100 $K_L \rightarrow \pi^0\pi^0$ events with $P_\perp > 165$ MeV. We have established that the remaining 386 events with $P_\perp > 165$ MeV are mainly background from interactions of K_L or neutrons in the helium gas and in the walls of the steel chambers. A distribution of $P_\perp$ typical of interactions was obtained by the insertion of a tungsten target in the beam volume. This distribution has been used, along with the distributions expected for $K_L \rightarrow \pi^0\pi^0$ and $K_L \rightarrow \gamma\gamma$ events, to compute the dashed curve, which has been normalized for $P_\perp > 165$ MeV. Figure 3(b) shows the subtracted spectrum, and the solid dots are the Monte Carlo predictions. From this curve we find that a total of 6077 ± 85 $3\pi^0$ and $\pi^+\pi^-\pi^0$ decays (designated $N_{3\pi}$) were observed.

Once the number of $\gamma\gamma$ and 3π events has been established, the branching ratio $R = (K_L \rightarrow \gamma\gamma)/(K_L \rightarrow 3\pi^0)$ depends only on the relative detection efficiency for the two processes. It does not depend on the absolute conversion efficiency in the thin radiator of the spectrometer. By Monte Carlo calculations, the efficiency ratio $\bar{\epsilon}/\epsilon_{\gamma\gamma}$ is found to be 0.0241 ± 0.0007. Here $\bar{\epsilon}$ is the weighted efficiency to observe a single γ ray in the spectrometer from either $K_L \rightarrow \pi^+\pi^-\pi^0$ or $K_L \rightarrow 3\pi^0$, and $\epsilon_{\gamma\gamma}$ is the corresponding efficiency for

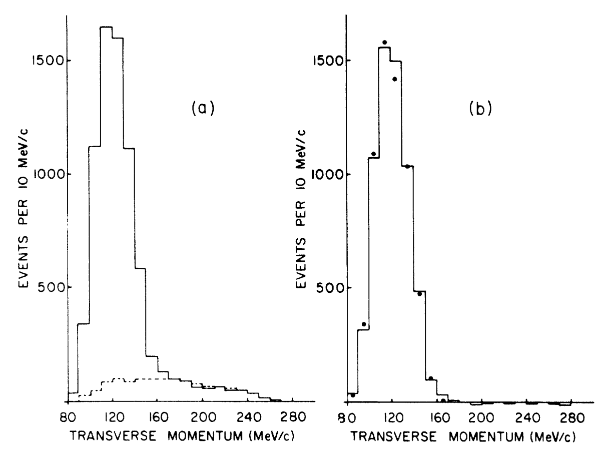

FIG. 3. (a) Distribution of transverse momentum of the spectrometer γ ray for the entire experiment. The dashed curve is the composite spectrum of $K_L \rightarrow \pi^0\pi^0$, $K_L \rightarrow \gamma\gamma$, and background. (b) Distribution of transverse momentum with the dashed curve of (a) subtracted. The solid dots show the Monte Carlo prediction of the distribution for $K_L \rightarrow 3\pi^0$ and $K_L \rightarrow \pi^+\pi^-\pi^0$.

$K_L \to \gamma\gamma$. The former is defined by

$$\bar{\epsilon} = (6\epsilon_{3\pi^0} + 2R'\epsilon_{\pi^+\pi^-\pi^0})/(6+2R'),$$

where $R' = 0.60 \pm 0.03$ is the branching ratio $(K_L \to \pi^+\pi^-\pi^0)/(K_L \to 3\pi^0)$ recently reported by the CERN-Orsay-Ecole Polytechnique collaboration.[3] The integers 6 and 2 correspond to the fact that $3\pi^0$ and $\pi^+\pi^-\pi^0$ yield six and two γ rays, respectively.

We have studied the dependence of $\bar{\epsilon}/\epsilon_{\gamma\gamma}$ upon a number of variables. These included (1) an observed variation in efficiency of the wide-gap chamber for angles of incidence greater than 0.5 rad, (2) a slight deviation of the observed K_L momentum spectrum from that used in the calculation, and (3) variation with respect to the magnetic field of the spectrometer. The latter effect is the only significant one and must be taken into account. If the 2.5-MeV shift of the $E_{\text{c.m.}}$ and $P_\perp$ peaks were due to a 1% increase in the magnetic field, there would be a 6% decrease in the value of $\bar{\epsilon}/\epsilon_{\gamma\gamma}$. Accordingly, we have included an additional 6% error in this efficiency ratio.

The branching ratio R is given by

$$R = (N_{\gamma\gamma}/N_{3\pi})(\bar{\epsilon}/\epsilon_{\gamma\gamma})\tfrac{1}{2}(6+2R').$$

The integer 2 corresponds to the fact that one has two γ rays per $\gamma\gamma$ decay. We thus find

$$(K_L \to \gamma\gamma)/(K_L \to 3\pi^0) = (2.24 \pm 0.28) \times 10^{-3}.$$

Using the recently measured branching ratio $(K_L \to 3\pi^0)/(K_L \to \text{all modes}) = 0.209 \pm 0.011$,[3] we find

$$(K_L \to \gamma\gamma)/(K_L \to \text{all modes}) = (4.68 \pm 0.64) \times 10^{-4}.$$

This result is to be compared with $(7.4 \pm 1.6) \times 10^{-4}$ reported previously,[1] and $(1.3 \pm 0.6) \times 10^{-4}$ reported by Criegee et al.[4]

The possibility of experiments to detect direct interference between $K_L \to \gamma\gamma$ and $K_S \to \gamma\gamma$ has been discussed.[5] The realistic possibilities depend strongly on the rate $K_S \to \gamma\gamma$ which remains to be observed.

We are grateful to Professor M. G. White, Dr. Walter Wales, and all the Princeton-Pennsylvania Accelerator operating crew for their splendid cooperation during this experiment. We wish to thank Dr. P. C. Wheeler, Dr. P. F. Kunz, and Dr. W. Risk for their help during the early stages of this experiment. Finally, thanks go to our scanning staff and to Mrs. Ann David, who patiently put all the cards through the computer.

---

†Work supported by the U. S. Office of Naval Research, Contract No. NOO14-67-A-0151-0001 and by the U. S. Atomic Energy Commission Contract No. AT(30-1)-2137.

*This work made use of computer facilities supported in part by the National Science Foundation, Grant No. NSF-Gp 579.

‡On leave from Département de Physique des Particules Elementaires, Centre d'Etudes Nucléaires, Saclay, France.

[1]J. Cronin, P. Kunz, W. Risk, and P. Wheeler, Phys. Rev. Letters 18, 25 (1967).

[2]H. A. Bethe and W. Heitler, Proc. Roy. Soc. (London), Ser. A 146, 83 (1934).

[3]I. A. Budagov, H. Burmeister, D. C. Cundy, W. Krenz G. Myatt, F. A. Nezrick, H. Sletten, G. H. Trilling, W. Venus, H. Yoshiki, B. Aubert, P. Heusse, I. Le Dong, E. Nagy, C. Pascaud, L. Behr, P. Beillière, G. Boutang, and J. van der Velde, to be published.

[4]L. Criegee, J. D. Fox, H. Frauenfelder, A. O. Hanson, G. Moscati, C. F. Perdrisat, and J. Todoroff, Phys. Rev. Letters 17, 150 (1966). This number has been revised by J. Todoroff (thesis, University of Illinois, unpublished) to $(6.7 \pm 2.2) \times 10^{-4}$.

[5]L. M. Sehgal and L. Wolfenstein, Phys. Rev. 162, 1362 (1967).