OBSERVATION OF THE TWO-PHOTON DECAY OF THE K_2^0 MESON†

L. Criegee,‡ J. D. Fox,§ H. Frauenfelder, A. O. Hanson,
G. Moscati,‖ C. F. Perdrisat, and J. Todoroff
Department of Physics, University of Illinois, Urbana, Illinois
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The decay $K_2^0 \to 2\gamma$ has been observed to occur with a branching ratio of $(1.3 \pm 0.6) \times 10^{-4}$.

An arrangement of spark chambers and scintillation shower detectors was used to investigate the two-photon decay mode of the K_2^0 meson. We found 29 candidates for this decay mode. However, 12 ± 7 of these events can originate from the $K_2^0 \to \pi^0 + \pi^0 + \pi^0$ mode and the CP-nonconserving $K_2^0 \to \pi^0 + \pi^0$ decay. Monte Carlo simulations indicate that 5 ± 2 of the 12 events are likely to originate from the $3\pi^0$ decays, leaving 7 ± 7 events which may be ascribed to $2\pi^0$ decays. The corresponding branching ratios are

$$\text{Rate } (K_2^0 \to 2\gamma)/\text{Rate } (K_2^0 \to \text{all modes}) = (1.3 \pm 0.6) \times 10^{-4},$$

$$\text{Rate } (K_2^0 \to 2\pi^0)/\text{Rate } (K_2^0 \to \text{all modes}) = (1.2_{-1.2}^{+1.5}) \times 10^{-3}.$$

For the $K_2^0 \to 2\gamma$ decay branching ratio, theoretical predictions range from 5×10^{-3} to 1.5×10^{-5}.[1] For the mode $K_2^0 \to 2\pi^0$, the predictions range from 0.8×10^{-3} to 3.2×10^{-3}.[2]

The neutral K mesons were produced by 30-BeV protons on an internal Be target at the Brookhaven National Laboratory AGS and collimated at 30°. Photons were filtered out of the beam with 4 cm of lead located close to the target; charged particles were removed with a sweeping magnet following the lead. The beam at the position of the detectors, 20 m from the target, was 10 cm wide and 15 cm high.

The detector arrangement is shown in Fig. 1. Decay photons were converted in two spark chambers, 30 cm square and 25 cm deep, each containing two radiation lengths of lead. The energies of the resultant showers were measured (to about 30%) with lead-and-scintillator shower detectors (S_L and S_R) behind each spark chamber. The number of triggers on charged, $2\pi^0$, and $3\pi^0$ decays was reduced by anti counters A_1, A_2, and A_3. These counters consisted of scintillator in front of the spark chambers, lead and scintillator elsewhere.

The spark chambers were triggered and stereoscopic pictures taken for events in which the counters C_L and C_R and shower detectors

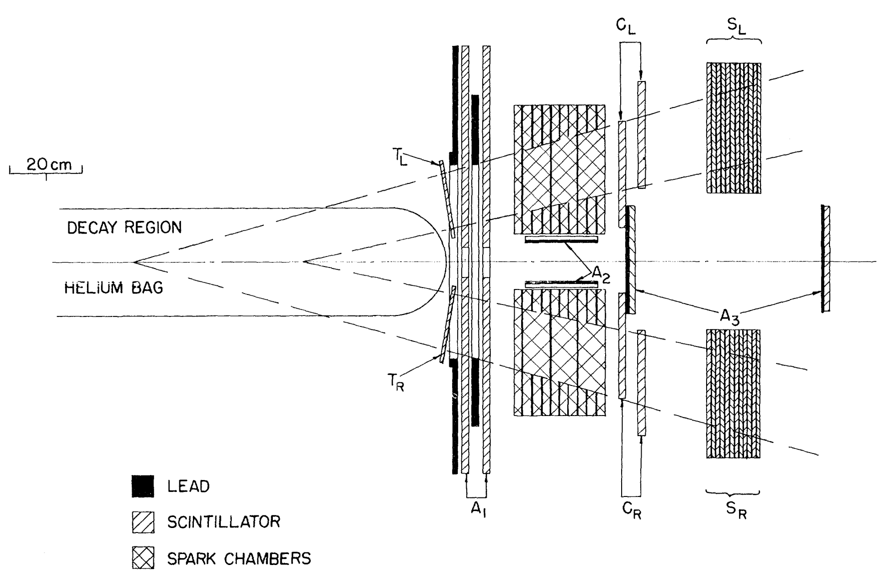

FIG. 1. Geometry of the $K_2^0 \to 2\gamma$ experiment (horizontal view). A_1, A_2, and A_3 are lead-loaded anti counters. C are triggering counters for ionizing particles. S are shower detectors and T are counters for the monitoring on the charged K_2^0 decays.

S_L and S_R were in coincidence and in which there were no signals from A_1, A_2, or A_3. The pulse heights from S_R and S_L were measured by two digital voltmeters and were printed out after each event.

79 000 pictures were scanned and 4000 were selected for further analysis. These had one photon shower in each chamber, with each shower satisfying the criteria that either (1) the opening angle between the initial pair be <2°, or (2) if the opening angle be >2°, one of the electrons of the pair be of low enough energy to be stopped in the following lead plate. Each of these events was considered to be a two-photon decay of a single particle.

The coordinates of the first and last sparks were measured for each track and reconstructed in space. The best plane through the four sparks and parallel to the beam was determined. The two decay angles, as calculated in this plane, together with the two measured shower energies, were fitted to a two-photon decay kinematics and were used to define the invariant mass of the decaying particle. Events that gave a χ^2 above a given value, and those for which the reconstructed decay point fell outside

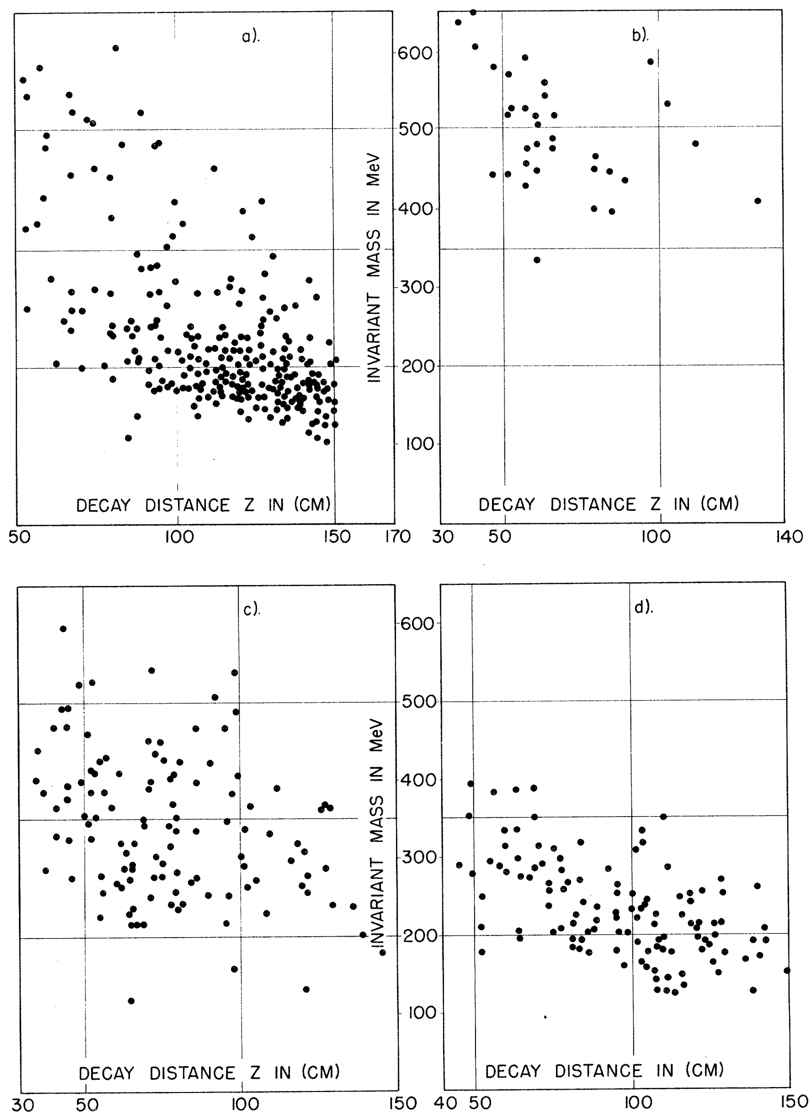

FIG. 2. Reconstructed invariant mass associated with two-photon events, as a function of the decay distance Z: (a) for the experimental events satisfying two-photon kinematics within the experimental resolution; (b) for simulated 2γ events satisfying the same criteria as those for the experimental events; (c) for simulated $2\pi^0$ decays; (d) for simulated $3\pi^0$ decays.

Table I. Comparison of experimental and Monte Carlo events.

Mass-bin label	Mass (MeV)	No of experimental events	No of Monte Carlo events, normalized to one event in bin B $3\pi^0$	$2\pi^0$	2γ
A	200-350	105	20	1.5	0
B	350-500	20	1	1	1
C	>500	9	0	0.1	1

of the beam cross section, were eliminated. The remaining events are shown in Fig. 2(a) as a function of Z, the distance from the spark chambers to the decay point. The analysis was carried out by comparing the invariant masses associated with the two observed photons with those computed for 2γ, $2\pi^0$, and $3\pi^0$ decays simulated by a Monte Carlo program and satisfying identical triggering and scanning criteria.

The events generated by the Monte Carlo program were assigned spark positions and pulse heights distributed about their initial values with a spread representing the reconstruction errors and the finite resolution of the shower detectors. They were then reconstructed and calculated in the same way as were the experimental points. The Monte Carlo program used a K_2^0-momentum distribution as reported by Carpenter et al.[3] Each event was given a weight proportional to the probability that it would show a single photon converted in each spark chamber, have an acceptable shower type, and, in the case of the $2\pi^0$ and $3\pi^0$ decays, fail to give an anti signal. These Monte Carlo results are shown in Fig. 2(b), 2(c), and 2(d). A comparison of the numbers of experimental events in three mass bins with the Monte Carlo results is shown in Table I.

Table I indicates that the $3\pi^0$ decays contribute about 5 ± 2 events between 350 and 500 MeV, and nothing above 500 MeV. The $2\pi^0$ decays contribute mainly in the region between 350 and 500 MeV and very little above 500 MeV. After subtracting the $3\pi^0$ contribution, 9 experimental events have a mass above 500 MeV and 15 between 350 and 500. Using the ratios given by Monte Carlo calculations for $2\pi^0$ and 2γ events in these two mass bins (Table I), we compute that the 9 events with mass above 500 MeV correspond to 8.3 2γ events and 0.7 $2\pi^0$ events. Since the mass distribution for 2γ events is symmetrical around 500 MeV, 17 ± 6 of the 29 events above 350 MeV are taken to be 2γ decays. This assignment, in conjunction with 5 ± 2 events expected from the $3\pi^0$ background, leaves 7 ± 7 events which may have originated from $2\pi^0$ decays.

The total number of K_2^0 decays in all modes was determined by recording decays into charged particles with counters (T) and (C) shown in Fig. 1. Six-fold coincidences $(CT)_L(CT)_R$ were counted by a gated scaler turned on by the AGS beam-spill signal and turned off at each triggering signal. The efficiency of the (CT) counter system was calculated with a Monte Carlo program, using Dalitz plots for $(\pi\mu\nu)$ and $(\pi e\nu)$.[3,4] The 79 000 pictures discussed in this report correspond to $(4.6\pm 0.5)\times 10^8$ K_2^0 decays in all modes per meter decay path.

The triggering probability per K_2^0 decay per meter along the decay path as obtained from the Monte Carlo computations and corrected for an estimate of the scanning efficiency was $(2.9\pm 0.8)\times 10^{-4}$ for the 2γ, $(1.25\pm 0.4)\times 10^{-5}$ for the $2\pi^0$ decays. These efficiencies, together with the interpretation that of the 29 events selected in this experiment, 17 are likely to be 2γ decays and 7 may be $2\pi^0$ decays, result in the branching ratios and errors stated in the first paragraph.

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‡Present address: Deutsches Elektronen-Synchrotron, Hamburg, Germany.

§Present address: Brookhaven National Laboratory, Upton, New York.

‖Present address: Physics Department, University of São Paulo, Box 8105, São Paulo, Brazil (Fulbright travel grant recipient).

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CP-INVARIANCE VIOLATION WITH $\Delta I > \frac{1}{2}$*

Tran N. Truong
Department of Physics, Brown University, Providence, Rhode Island

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The discovery[1,2] of the decay mode $K_L{}^0 \to \pi^+ + \pi^-$ and subsequent experiments establish the violation of CP invariance in K^0 decay. Because of the very small value of $|\eta_{+-}| = [\Gamma(K_L \to \pi^+ + \pi^-)/\Gamma(K_S \to \pi^+ + \pi^-)]^{1/2}$, there have been many suggestions on the origin of this small effect.[3] In particular, it was proposed that CP invariance holds for $\Delta I = \frac{1}{2}$ amplitudes and does not hold for decays which violate this rule.[4-6] In this note we re-examine this possibility, discuss the magnitude of CP-invariance violation, and point out that the small value of $|\eta_{+-}|$ is probably accidental and that the present experimental data are consistent with a large CP-nonconserving $\Delta I > \frac{1}{2}$ amplitude. We suggest the measurement of $\pi^+\pi^-$ asymmetry in the decay $K_2{}^0 \to \pi^+ + \pi^- + \pi^0$ as a possible new test for CP-invariance violation.

The experimental check on this data is difficult since one must look for the effect produced by the interference between $\Delta I = \frac{1}{2}$ and $\Delta I > \frac{1}{2}$ amplitudes; the latter is strongly suppressed. It has been suggested[5] that a sensitive experiment to test this possibility is to measure the neutral-to-charged ratio of the two-pion decay of $K_L{}^0$. This value would be very much different from the value $\frac{1}{2}$ predicted by the $\Delta I = \frac{1}{2}$ rule which is found experimentally valid for $K_S{}^0$ decay.[7,8] Following the notation of Ref. 4, we have

$$\eta_{+-} = a_{+-}{}^L/a_{+-}{}^S = \tfrac{1}{2}[\epsilon + i\sqrt{2}F(\mathrm{Im}A_2)/A_0], \tag{1a}$$

$$\eta_{00} = a_{00}{}^L/a_{00}{}^S = \tfrac{1}{2}[\epsilon - i2\sqrt{2}F(\mathrm{Im}A_2)/A_0], \tag{1b}$$

where

$$\epsilon = \frac{p-q}{p} \simeq \frac{p^2-q^2}{2p^2}.$$

As long as $|A_2/A_0|^2 \ll (\mathrm{Im}A_2)/A_0$, it is a good approximation to put $\epsilon \approx 0$. From Eqs. (1a) and (1b), independent of the magnitude of $(\mathrm{Im}A_2)/A_0$, we have

$$\beta_L = |a_{00}{}^L/a_{+-}{}^L|^2 = 2, \tag{2}$$

to be compared with the value $\frac{1}{2}$ for $K_S{}^0$ decay.[9]

The assumption that $\epsilon \ll (\mathrm{Im}A_2)/A_0$ is valid only if $\Delta I = \frac{1}{2}$ amplitudes[10] and leptonic processes (with violation of $\Delta S = -\Delta Q$ rule) are CP invariant and that there is no superweak interaction of the type discussed by Wolfenstein.[11] In the model of Sachs[12] and Wolfenstein,[11] ϵ is dominant, hence $\beta_L = \frac{1}{2}$, to be contrasted with the value of 2 for CP-invariance violation in $\Delta I > \frac{1}{2}$. If there is a violation of charge-conjugation invariance in electromagnetic interactions,[13] one can also expect $\beta_L \neq \frac{1}{2}$.

We turn next to the question of the magnitude of CP noninvariance in $\Delta I > \frac{1}{2}$ amplitudes. In Ref. 5, for simplicity, it was assumed that $\Delta I = \frac{5}{2}$ amplitude was zero. The magnitude of A_2 can be determined from the rate of $K^+ \to \pi^+ + \pi^0$. The conclusion reached was that the CP-nonconserving phase is small. However, if one takes the branching ratio $B_S = \Gamma(K_S \to 2\pi^0)/\Gamma(K_S \to 2\pi) = 0.335 \pm 0.014$ as given by Brown et al.,[8] which is the most accurate value, it is no long-