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†Permanent address: University of Sussex, Brighton, England.

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CHARGE ASYMMETRY IN THE MUONIC DECAY OF THE K_2^0 †

D. Dorfan, J. Enstrom, D. Raymond, M. Schwartz, and S. Wojcicki
Stanford University and Stanford Linear Accelerator Center, Stanford, California

and

D. H. Miller and M. Paciotti
University of California, Berkeley, California
(Received 11 September 1967)

We report herewith the observation and measurement of a charge asymmetry in the muonic decay of the long-lived neutral K meson (K_2^0). In particular we find the decay rate R_{μ^+} into $\pi^-\mu^+\nu$ to be larger than the decay rate R_{μ^-} into $\pi^+\mu^-\bar{\nu}$ with the ratio determined as

$$R \equiv R_{\mu^+}/R_{\mu^-} = 1.0081 \pm 0.0027.$$

This result, obtained at the Stanford Linear Accelerator Center (SLAC), is a prima facie demonstration of CP noninvariance in K_2^0 decay. It is consistent with theoretical expectations based upon an analysis of experimental data which have been obtained since the first such demonstration by Christenson, Cronin, Fitch, and Turlay.[1]

The analysis of K_2^0 decay in terms of parameters characterizing the CP nonconservation has been carried out by a number of authors.[2-4] It is most convenient to make use of the four parameters η_{+-}, η_{00}, ϵ, and ϵ' as follows:

(1) η_{+-} is the ratio

$$\eta_{+-} = \frac{\text{Amplitude } (K_2^0 \to \pi^+\pi^-)}{\text{Amplitude } (K_1^0 \to \pi^+\pi^-)},$$

(2) η_{00} is the ratio

$$\eta_{00} = \frac{\text{Amplitude } (K_2^0 \to \pi^0\pi^0)}{\text{Amplitude } (K_1^0 \to \pi^0\pi^0)}$$

(3) ϵ determines the extent to which K_2^0 is not an eigenstate of CP, viz.

$$|K_2^0\rangle = \frac{(1+\epsilon)|K^0\rangle - (1-\epsilon)|\bar{K}^0\rangle}{[2(1+|\epsilon|^2)]^{1/2}},$$

where $|\bar{K}^0\rangle = CPT|K^0\rangle$.

(4) $\epsilon' = 2^{-\frac{1}{2}} \mathrm{Im}(A_2/A_0) e^{i(\frac{1}{2}\pi - \delta_0 + \delta_2)}$, where

$$A_2 = \langle 2\ \pi\text{'s in stationary } I=2 \text{ state} | H_{wk} | K^0\rangle,$$

$$A_0 = \langle 2\ \pi\text{'s in stationary } I=0 \text{ state} | H_{wk} | K^0\rangle,$$

and δ_0 and δ_2 are the appropriate $\pi\pi$ phase shifts. η_{+-} and η_{00} can be expressed in terms of ϵ and

ϵ' as

$$\eta_{+-} = \epsilon + \epsilon'; \quad \eta_{00} = \epsilon - 2\epsilon'.$$

To the extent that the $\Delta I = \frac{3}{2}$ decay of the K_1^0 and the CP-nonconserving amplitudes for decays into states other than two pions can both be ignored, we can obtain the phase of ϵ from the relation

$$\tan \arg\epsilon = 2\frac{[m_{K_2} - m_{K_1^0}]}{\gamma_{K_1^0} - \gamma_{K_2^0}}.$$

In this relation, $m_{K_1^0}$ and $m_{K_2^0}$ are the masses of the K_1^0 and K_2^0, respectively; $\gamma_{K_1^0}$ and $\gamma_{K_2^0}$ are their decay rates.

In the event that the weak interactions obey the $\Delta S = \Delta Q$ rule, the charge ratio is given by

$$R = 1 + 4\,\mathrm{Re}\epsilon.$$

From the measured intensity of the two-pion decay of the K_2^0,[1,5-9] and from studies of the interference of this decay with regenerated K_1^0's,[5,10,11] it is possible to obtain two solutions for ϵ. They yield two possible charge ratios[12]

$$R_a = 1.0064 \pm 0.0014, \quad R_b = 0.9997 \pm 0.0003.$$

The error in R_a is largely attributable to uncertainty in the phase of η_{+-} which we have taken as $80° \pm 15°$. We have taken the values for the other measured parameters[8,13] as follows:

$$\eta_{+-} = 1.96 \pm 0.09 \times 10^{-3}, \quad \eta_{00} = 4.3 \pm 0.3 \times 10^{-3},$$

$$\arg\epsilon = 42.5°.$$

The experimental arrangement for producing a beam of K_2^0's is shown in Fig. 1(a). The electron beam at 15 GeV with an average intensity of 1.5 μA is allowed to impinge on a 30-cm beryllium target. A hole through a 12-ft thick shielding wall at 3° to the electron beam allows the passage of secondary particles produced in the target. In order to remove the large electromagnetic component, characteristic of electron machines, we place 12 in. of lead in the beam just before an 18-in.×72-in. sweeping magnet. A second sweeping magnet is located as shown. At this point the neutral beam is collimated to a vertical size of 6 in. and a horizontal size of 9 in. The experimental apparatus, shown in Fig. 1(b), begins at a distance of 230 ft from the target.

An anticoincidence counter (A), 20 in.×20 in.×$\frac{1}{4}$ in., precedes a $2\frac{1}{2}$-m decay region and serves to eliminate counts caused by charged particles originating either in the shielding walls or from decays prior to the decay region.

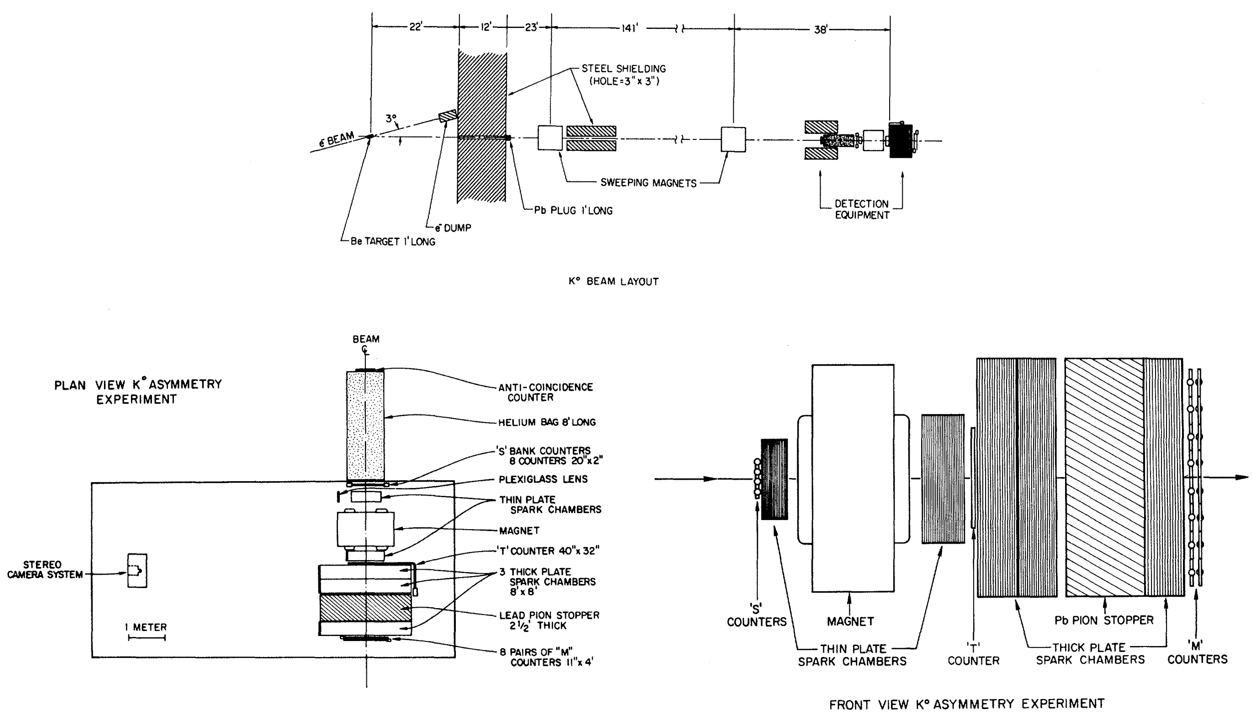

FIG. 1. (a) Beam Layout at SLAC. (b) Arrangement of experimental equipment.

The decays of interest take place in a helium-filled bag to reduce interactions of primary beam particles. Following the decay region are a series of counters and spark chambers to enable identification of a decay of interest. In sequence, the instrumentation includes the following:

(1) A hodoscope consisting of eight horizontal scintillation counters, each having a height of 2 in., a horizontal width of 20 in., and a thickness of $\frac{1}{4}$ in. These counters (called S_1 through S_8) serve to identify the simultaneous presence of two particles emerging from the decay region.

(2) A thin-plate spark chamber of 30-in. height and 26-in. width, having a total of 17 plates in the beam direction. Each plate is constructed of $\frac{1}{4}$-in. polyurethane foam faced with 0.002-in. aluminum foil. The total thickness of the chamber is 1.5 g/cm^2.

(3) A 16-in. wide aperture magnet bending in a vertical plane. The pole face of the magnet is 29 in. in height and 36 in. along the beam direction. Data were taken at various current settings corresponding to field integrals of 9.4, 11.3, and 13.1 kG m.

(4) Another thin-plate spark chamber of 54-in. height, 36-in. width, and identical thickness to the first.

(5) A large scintillation counter (T) covering the exit aperture of the magnet. For the first half of the experiment the counter was 30 in. high, 32 in. wide, and $\frac{1}{2}$ in. thick, and was viewed by eight 2-in. phototubes. For the second half of the experiment the height was increased to 40 in. and the scintillator was viewed by one 5-in. phototube.

(6) Two large (5-ton) aluminum spark chambers. These chambers are each constructed of 11 1-in. plates with effective area of 91 in. by 91 in.

(7) A 30-in. thick lead wall. The purpose of this wall is to supply the bulk of the material necessary to remove the pions through nuclear interactions. Muons with momentum of more than about 1.55 BeV/c will, on the other hand, penetrate the shield unaffected except for energy loss and Coulomb scattering.

(8) Another 5-ton spark chamber similar to those described above.

(9) Eight pairs of scintillation counters (M_1 through M_8), each 11 in. high and 48 in. wide. The counters are set as shown with 1 in. of plywood between the two counters in each pair. Muons which have succeeded in penetrating the spark chambers and lead wall will thus produce a coincidence count within the struck pair.

An event of interest is characterized by the time coincidence of two or more S counters, the T counter, and an M pair. For all magnet settings used, a muon arriving at counters M_1, M_2, M_3, M_6, M_7, or M_8 has uniquely determined sign, and so those counters can be used for a rigorous sign decision. Muons arriving at M_4 or M_5 have their sign determined with 91.7% accuracy as determined through a study of typical pictures taken with the spark chambers when triggered by the above counter conditions (see Fig. 2). The accuracy of sign decision results from the fact that the transverse momentum transfer in the magnet is more than the maximum transverse momentum of the muon.

It should also be pointed out that the dimensions of the M-counter bank are such as to intercept more than 98% of those muons entering the apparatus which have sufficient energy to meet the range requirement.

The function of the spark chambers as such was largely one of calibration and diagnosis. By taking a relatively small number of pictures, it was possible to determine the nature of spurious triggers and to investigate quantitatively various sources of potential bias.

Normal operation of the SLAC machine yields 360 bursts of beam per sec, each 1.6 μsec long. This rather poor duty cycle leads to a number of accidentals which must be subtracted from the data. The dominant source of accidentals in this experiment is the chance coincidence of a real K_2^0 decay where no muon penetrates the apparatus with an M pair triggered by an unrelated track. The majority of the latter arise from K_2^0 and neutron interactions in the heavy spark chambers and lead wall. For each K_2^0 which decays and initiates a trigger in the S and T counters, we expect about 2000 interactions in the aluminum or lead with an average of many thousand secondaries. The measured accidental rate in counters M_4 and M_5 is about 15% of the real rate in those counters, reasonably consistent with the expected flux. Counter M_1 has a high accidental rate caused by unrelated particles coming over the lead shield. These and other significant accidentals are continuously monitored and subtracted out for each M pair individually.

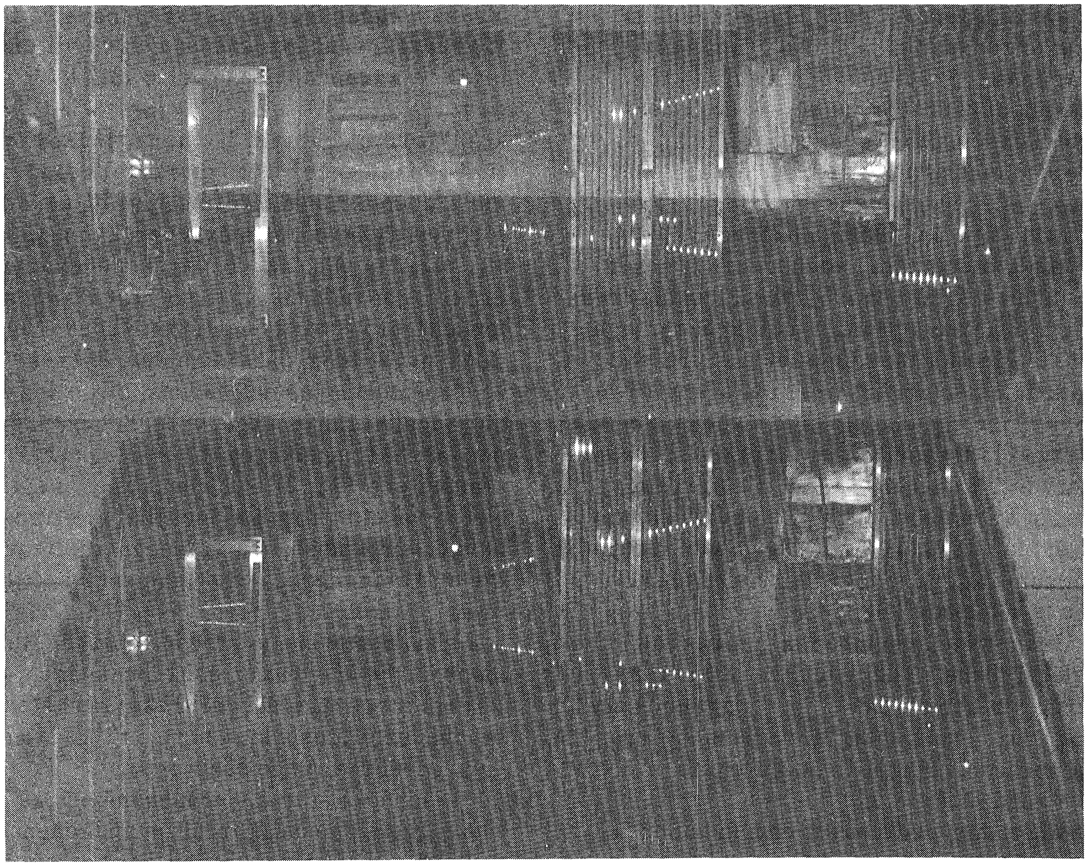

FIG. 2. Photograph of typical event.

Inasmuch as the data have been logged in eight bins, corresponding to the eight M-counter pairs, we can in principle make seven independent determinations of the charge asymmetry by normalizing to the same total number of events for each magnet polarity. In Table I we tabulate the number of counts in each bin, after subtraction of accidentals, for each magnet polarity. The "down" runs are then corrected proportionally to yield the same total number of events as the "up" runs. Asymmetries are then calculated by taking the ratio (or inverse ratio) of "up" to "down" counts in each bin and correcting for the fraction of wrong decisions. Combing all of the data yields a charge ratio before further correction of 1.0095 ± 0.0026. The statistical error has been appropriately increased due to the statistical nature of the subtraction of accidentals.

It should be noted here that essentially the same result is obtained from each magnet polarity individually by just taking the ratio of $M_1+M_2+M_3+M_4$ to $M_5+M_6+M_7+M_8$. This is the result of the geometric symmetry of the apparatus about the beam line.

Potential sources of systematic error and corrections to the asymmetry are discussed later. The only corrections which appear necessary are due to the charge asymmetry in the small number of false events corresponding to an interaction in the S-counter bank and to the washing out of the asymmetry due to pion decays in flight. These corrections change the final charge ratio to

$$R = 1.0081 \pm 0.0027.$$

We have explored experimentally a number of sources of potential systematic error. Inefficiency in the anticoincidence counter A can lead in principle to the acceptance of "events" which originate as interactions in the shielding wall preceding the decay region. We can study any bias this introduces by examining in detail only those "events" which trigger A. We find that only about 25% of all possible triggers originate before A and that they have an

Table I. Tabulation of data after subtraction of accidentals.

M counter	No. of events magnet polarity up[a]	No. of events magnet polarity down	Normalized[b] No. of events magnet polarity down	Percentage of wrong decision	μ^+/μ^- ratio
1	14 500	14 125	14 008	0	1.0351 ± 0.0174
2	42 141	41 881	41 535	0	1.0146 ± 0.0074
3	74 188	74 300	73 685	0.6 ± 0.2	1.0069 ± 0.0056
4	65 902	66 217	65 669	7.8 ± 0.7	1.0041 ± 0.0070
5	63 706	64 599	64 065	8.8 ± 0.6	1.0065 ± 0.0074
6	74 218	75 854	75 226	0.6 ± 0.2	1.0137 ± 0.0056
7	43 136	43 939	43 575	0	1.0102 ± 0.0071
8	13 811	13 954	13 839	0	1.0020 ± 0.0129

[a]We define magnet polarity up as the polarity which gives the upward bend to particles of positive charge.
[b]Normalized to the total number of events with magnet polarity up.

asymmetry of 1.02 ± 0.02. Inasmuch as A is determined experimentally to be no more than 4% inefficient at 300 V below its normal operating point, we conclude that the potential bias here is less than two hundredths of a percent.

Bias due to interactions in the helium was investigated by replacing the helium bag with 6 in. of carbon, increasing its effect by a factor of 250 and observing a charge ratio of 1.029 ± 0.030. The effect of the helium is thus negligible.

A small systematic shift in the charge ratio due to the interaction of neutrons and kaons in the S-bank scintillator is anticipated. In order that we obtain a trigger, one of the particles emerging from the interaction must either decay to a muon or penetrate the shield and another particle must activate a second S counter. The systematic shift results from the charge asymmetry in the emitted prongs (more K^+ than K^-, for example) and differential penetration of K^+ and K^-. We have studied and corrected for this bias as follows:

(a) Data were accumulated with 2 in. and with 3 in. of additional scintillator placed just before the S-counter bank. The probability of any given interaction triggering two S counters is much higher, for geometrical reasons, in this configuration than if the interaction actually took place within an S counter itself. We observed an increase of 14% in the "event" rate for 2 in. of scintillator and 24% for 3 in. of scintillator. The charge ratio in the scintillator-induced events was determined to be 1.34 ± 0.11.

(b) Through a study of 14 000 pictures taken with the spark chambers, we determined that 0.70% of the triggers were due to interactions in the S bank. Of these events, 51 gave positive triggers and 47 gave negative triggers.

Combining the information obtained from the above two measurements reduces the charge ratio by 0.0017 ± 0.0006.

Occasionally we expect an unaccompanied muon, presumably from a K_2^0 decay where the pion missed the S bank, to eject a delta ray as it traverses an S counter. This delta ray will bend back in the fringing field and trigger a neighboring S counter, giving rise to an "event." A study of the sample pictures indicates that 0.89% of our triggers arise from this source. We have measured independently the charge ratio corresponding to unaccompanied muons without delta rays and find it to be 1.009 ± 0.014. We have calculated the extent to which a bias is introduced because of the unique sign of the delta ray and have found it to be negligible. Furthermore, of the 124 events in the sample pictures which fit this hypothesis, we find 61 positive muons and 63 negative muons. We conclude that these "events" do not constitute a significant bias.

We have studied the extent to which positive and negative pions, arising from various decay modes of the K_2^0 can differentially penetrate the shielding wall giving rise to an apparent charge asymmetry. A study of the 14 000 sample photographs of decay "events" yielded 176 examples of such penetrations, with no statistically signifcant difference between positive and negative pions. Furthermore, these pions gave wrong sign decisions 30% of the time, washing out, to this extent, any possible asymmetry. This indicates a contribution of less than 0.08% to the final charge ratio from pion penetration. As a confirmation we performed the following subsidiary experiment.

Identical beams of positive and negative pions of 4.5-BeV/c momentum were introduced into the apparatus. 2 ft of iron followed by a bank of additional counters were placed behind the M bank to act as vetoes for any high-energy muons in the beam. Positive and negative pions were determined to penetrate equally to 0.06% from this measurement.

A 1% difference between the energy loss per unit path length of positive and negative muons passing through matter could account for our asymmetry. Although this difference is completely unreasonable theoretically, we have carried out a subsidiary experiment to investigate its possibility. A beam of muons, either positive or negative, with momentum spread of ±8% was introduced into the apparatus. The mean momentum was chosen so as to just barely enable the penetration of the chambers and lead wall. The magnet polarity was then chosen so as to bend the muons downward and the magnitude of the field was made identical for each polarity. A photograph was taken of each muon which succeeded in triggering the M bank. A study of the low-momentum cutoff imposed by the range requirement for 1000 penetrating muons of each sign indicated that the energy loss of positive and negative muons is identical to within 0.3%.

We have studied experimentally the extent to which positive and negative muons scatter differently in passing through our lead shield and have concluded that there can be no bias due to this effect.

The experiment is completely insensitive to the accuracy with which the magnetic field is reversed. This is the result of the fact that essentially every muon with momentum sufficient to penetrate the shield is logged in the M counters with its sign determined almost unambiguously.

The pulse-height distributions on the M counters were carefully checked for variation with magnetic field and none was found.

The experiment is almost completely insensitive to field dependent efficiency variations in the S counters or the T counters. In any case, no such variations were found.

The singles rates in the M counters, largely due to the residue of the K's and neutrons which interact in the chamber, show no significant change upon field reversal.

In conclusion, we have determined that the K_1^0 and K_2^0 are nonorthogonal to the extent that

$$\mathrm{Re}\epsilon = (2.0 \pm 0.7) \times 10^{-3}.$$

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MEASUREMENT OF THE CHARGE ASYMMETRY IN THE DECAY $K_L^0 \to \pi^\pm + e^\mp + \nu$ †

Sheldon Bennett, David Nygren, Harry Saal, Jack Steinberger, and John Sunderland
Columbia University, New York, New York
(Received 30 August 1967)

The charge asymmetry $\delta = (\Gamma_+ - \Gamma_-)/(\Gamma_+ + \Gamma_-)$ for the electron in the decay of the long-lived neutral kaon to pion, electron, and neutrino has been measured. We find asymmetry $\delta = (+2.24 \pm 0.36) \times 10^{-3}$. The result shows that *CP* symmetry is not conserved in this process.

Charge asymmetry in the decay of a neutral boson is possible only if *CP* symmetry is not conserved. The magnitude of this asymmetry in K_L^0 decay is an important parameter in the phenomenology of *CP* nonconservation in *K* decay. We report here a measurement for the processes $K_L^0 \to e^\pm + \pi^\mp + \nu$.

Let Γ_+ and Γ_- be the partial decay rates of the long-lived neutral kaon to positrons and electrons, and define the charge asymmetry δ as

$$\delta = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}.$$

$|\delta|$ can be expected to be no greater than $\sim 4 \times 10^{-3}$ on the basis of existing measurements of *CP* nonconservation in *K* decay.[1] Measurements with sufficient sensitivity for the detection of such a small asymmetry have not been previously reported.

The experiment is performed by means of a neutral beam produced at an internal target in the Brookhaven alternating-gradient synchrotron. The beam is defined by a series of three collimators at 20° to the circulating proton beam and located, respectively, 4, 9, and 19 m from the target. Each collimator has a tapered rectangular aperture such that all internal faces are generated by a common pyramid with its apex at the target. The exit opening is 13.6 cm wide and 20.8 cm high. Before the beam enters the collimators, it traverses 10 radiation lengths of lead to attenuate the γ rays. Between the first two collimators a sweeping magnet bends charged particles aside. The beam traverses a vacuum from the entrance port of the first collimator to the forward end of a 3.75-m-long helium-filled decay region which is flanked on both the right- and left-hand sides by six scintillation counters (see Fig. 1). The decay particles then traverse a helium-filled region and enter a magnet with aperture 150 cm wide and 45 cm high. The faces of the magnet are protected with scintillation counters in anticoincidence.

The magnet is followed on each side in turn by a four-counter hodoscope, a 2-m-long threshold Cherenkov counter filled with 1 atm of ethylene, and a six-counter hodoscope (see Fig. 1). The Cherenkov counters have angular acceptances of ±12° horizontally and ±7.5° vertically. For electrons the average number of photoelectrons collected is 10, corresponding to an efficiency of 99.99 %. The threshold for pions is 3.8 BeV/c, and for muons it is 2.7 BeV/c. None of the pions and ~0.3 % of the muons from K_{L_3} in this experiment (average kaon momentum is ~2.2 BeV/c) exceed these thresholds according to our calculations.

Events are recorded on magnetic tape provided that there are signals from each of the six hodoscopes and from at least one Cherenkov counter. All counters are recorded, as

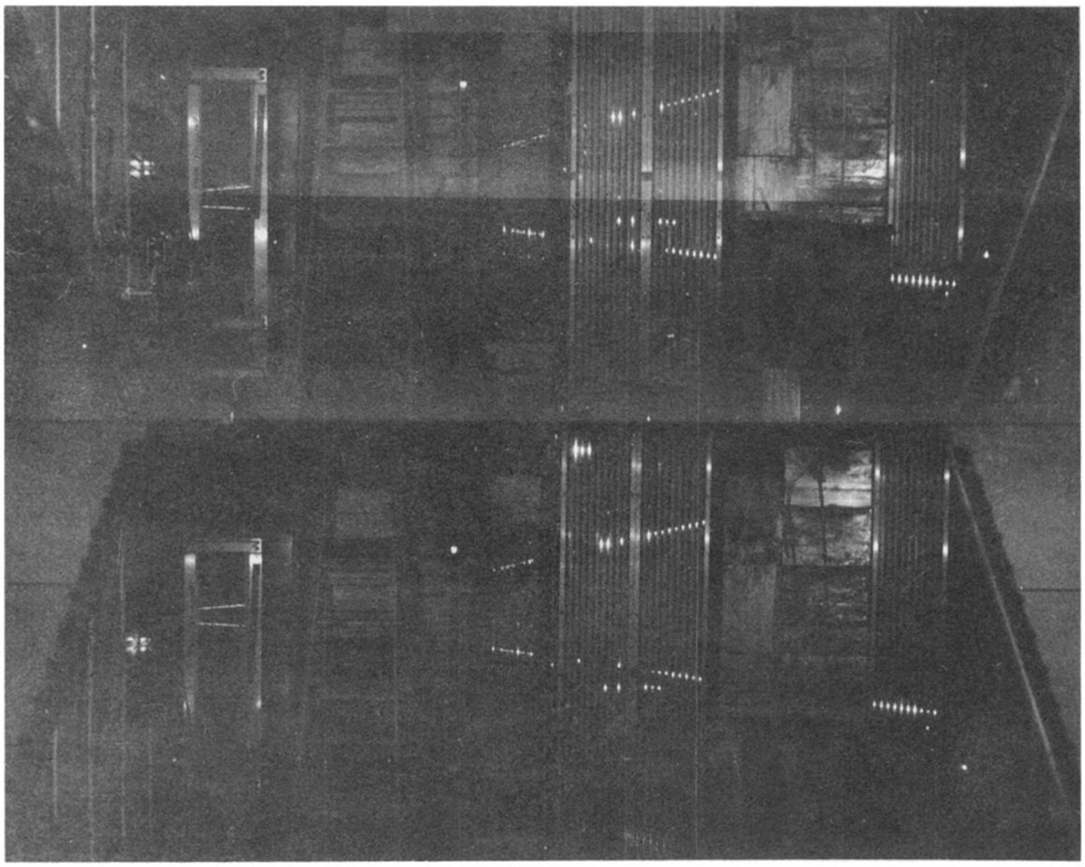

FIG. 2. Photograph of typical event.