$K^*(892)$, $0.84 < M(K^+\pi^-) < 0.94$;

$\Delta^{++}(1236)$, $M(p\pi^+) < 1.5$;

ρ, $0.66 < M(\pi^+\pi^-) < 0.86$;

ω, $0.75 < M(\pi^+\pi^-\pi^0) < 0.81$.

[10]The reflection of the decay angular distribution of the $\Delta^{++}(1236)$ produces the broad enhancement at a mass of about 2.8 GeV in Fig. 1(c). It also produces a broad enhancement of about the same number of events under the L region.

[11]An explanation for the $K\pi\pi$ peaking at threshold for any fixed $K\pi$ mass can be found in the double-Regge-pole model, which gives a good qualitative fit to the threshold enhancements that we see.

[12]We have investigated the momentum transfer and decay angular distribution of this threshold enhancement as a function of $K\pi$ mass and find no significant anomalies in the L region.

[13]See Refs. 1 and 3; also note that some other experimenters observed the absence of a $K^*(890)\pi$ decay mode for the L enhancement. [J. Andrews, J. Lach, T. Ludlum, J. Sandweiss, H. D. Taft, and E. L. Berger, Phys. Rev. Letters 22, 731 (1969).]

[14]G. F. Chew and A. Pignotti, Phys. Rev. Letters 20, 1078 (1968).

MEASUREMENT OF THE BRANCHING RATIO $K_L{}^0 \to 2\pi^0/K_L{}^0 \to 3\pi^0$ †

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The rate of the CP-nonconserving decay $K_L{}^0 \to 2\pi^0$ has been measured relative to that of $K_L{}^0 \to 3\pi^0$ using a monoenergetic K beam and a nearly 4π solid-angle detector system employing lead-plate spark chambers and shower counters. The measured branching ratio 1.31% ±0.18% (statistical) ±25% (systematic) leads to a value for the CP-nonconservation parameter $|\eta_{00}|^2$ of $(14.1 \pm 3.4) \times 10^{-6}$.

We report a measurement of the branching ratio $(K_L{}^0 \to 2\pi^0)/(K_L{}^0 \to 3\pi^0)$ which is then used to determine the CP-nonconservation parameter $|\eta_{00}|^2$. A number of measurements of this important parameter have been published, but their disagreement, and the unusual experimental difficulties of the measurement, encourage further efforts. Some of the previously published values for $|\eta_{00}|^2$ are[1-6] $(18_{-6}^{+11}) \times 10^{-6}$, $(24 \pm 5) \times 10^{-6}$, $(-2 \pm 7) \times 10^{-6}$, $(5.1 \pm 1.2) \times 10^{-6}$, $(4.8 \pm 1.9) \times 10^{-6}$, and $(13 \pm 4) \times 10^{-6}$. Other results lying between these disparate values have emerged at topical conferences and in preliminary reports, but these have not yet reached publication.

This experiment was designed to detect all $K_L{}^0 \to 3\pi^0$ as well as $K_L{}^0 \to 2\pi^0$ decays and to provide internal checks on possible systematic errors. Important features included (a) a "monochromatic" $K_L{}^0$ beam, (b) a counter trigger which strongly rejected neutron-induced events while accepting $3\pi^0$ and $2\pi^0$ decays with nearly equal efficiency, (c) a thick lead-plate spark-chamber detector which subtended nearly 4π solid angle for $K_L{}^0 \to 2\pi^0$ decays, and (d) normalization to $K_L{}^0 \to 3\pi^0$ decays, which were observed mainly as five-shower and six-shower events. Photon energies were measured by spark counting.

$K_L{}^0$ mesons were produced from the reaction $\pi^- p \to K^0\Lambda^0$ just below $K^0\Sigma^0$ threshold; their decay was observed in the photon-converting chambers nearly surrounding an air-filled, 1-m^3 cubical volume centered 6 m from the hydrogen target. Those entering the decay volume had a momentum of 530 ± 50 MeV/c (full width at half-maximum). The momentum distribution was calculated from the measured π^- spectrum at the H_2 target and agrees with measurements of $K_L{}^0$ momentum from $\pi^+\pi^-\pi^0$ decays in which both showers are observed. To convert and reject photons from the hydrogen target, a filter, consisting of layers of lead and scintillator, was placed between the target and the chamber system. The lead thickness (10 cm) was optimized to remove photons and retain $K_L{}^0$'s.

The rear (down-beam) spark chamber presented about 8 radiation lengths, and the four side-wall chambers about 7, to photons entering with normal incidence. For each chamber the first four-gap module had Al plates for identification of entering charged particles. In front of each side chamber, and following the Al module in the rear chamber, were planes of plastic scintillator also detecting charged particles and providing an anticoincidence signal when desired. Trigger counter units, each composed of scintillator and Cherenkov radiator (Lucite), were arrayed in two banks after the first and second radiation lengths of lead modules in the rear chamber (see Fig. 1).

Loss of photons through the open face of the cube was largely reduced by the tunnel-shaped gamma-ray shower counter shown in Fig. 1. The walls of this structure, consisting of lead sheets with scintillation and Cherenkov counters, presented 6-8 radiation lengths for photon detection, thus contributing to the recognition of correct photon multiplicity in events not delivering all their photons into the spark chambers.

The trigger conditions for pulsing the spark chambers were (1) a signal from the π^- beam counter system, indicating that a pion had entered the hydrogen target and did not remain in the beam beyond it, (2) no response from the gamma filter counters, (3) no response from the scintillators in front of the lead chambers, and (4) coincident response of at least two of the trigger units embedded in the rear chamber and separated by two or more intermediate units. This chamber design and triggering system allowed the recognition of about 95% of the $K_L^0 \rightarrow 3\pi^0$ background simply by the observation of five or more showers. The application of kinematical relationships, aided by the known interval of K_L^0 momentum and by spark counting, provided the identification of the $K_L^0 \rightarrow 2\pi^0$ events.

Various modes of operation contributed to the understanding and calibration of the system. In

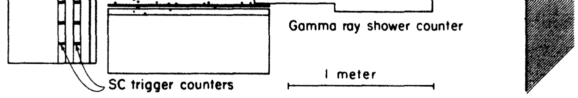

FIG. 1. Vertical section through detecting system. Vertices of all four-shower events having no tunnel counts are projected on this plane. $2\pi^0$ events have a similar distribution. The fiducial volume boundaries are 5 cm from the chambers.

addition to the principal triggering condition described above, associated with neutral final states yielding two or more showers, we also changed conditions so as to trigger on charged final states of K_L^0 decay by requiring two or more nonadjacent S counters and two or more R counters in coincidence (see Fig. 1). Data with C and Be regenerators were taken in both neutral and charged final-state modes. Brief periods of running with empty H_2 target and runs with random chamber triggering during Bevatron beam pulses indicated a negligible number of non-target-associated events and a low probability (≈4%) for accidental tracks in the chamber system.

A total of 464 000 neutral-free decay and 170 000 charged-free decay pictures were taken. The neutral decay pictures show 20 000 K decays in the fiducial volume with the rest mostly blank or with gammas clearly from chamber or lead-filter interactions. Of these, ~1000 (primarily four-shower, but including some five-shower events) were selected for measurement. The charged-decay pictures, two thirds of which have been analyzed, show 5000 leptonic and 1000 $\pi^+\pi^-\pi^0$ decays in the fiducial volume.

The efficiency of the chamber system was obtained by a Monte Carlo program using a library of case histories of showers of known energies obtained from observation of $K_L^0 \rightarrow \pi^+\pi^-\pi^0$ decays. Until the regenerator data and all of the $\pi^+\pi^-\pi^0$ decays are processed, the library is being supplemented at the low- (<25 MeV) and high- (>220 MeV) energy ends by synthetic events whose shower structure, spark counts, and angular errors are deduced by extrapolation from the existing library. These extrapolations were checked and limits on their uncertainty set by comparing the resulting Monte Carlo predictions with the neutral-decay data. Preliminary measurements of regenerated $K_S^0 \rightarrow 2\pi^0$ decays give an estimate of detection efficiency consistent with these methods. The low soft-photon background permitted use of a two-spark minimum for shower identification, although regenerator studies indicated that $2\pi^0$ events seldom gave showers with less than four or five sparks.

A vertex, or decay point, was determined for each four-shower event, thus establishing the direction of the K_L^0 from the H_2 target and the directions of the four photons. The first approximation to the vertex was obtained by extrapolating backward into the decay volume along lines determined by the initial portions of the showers to locate an optimum intersection. This point was then varied by a search procedure so as to minimize a fitting parameter related to the lateral displacements of the initial sparks of each shower from straight lines drawn from the variable decay point through the first spark of each shower.

Two different methods of analysis were used. They gave mutually consistent values for the number of $2\pi^0$ four-shower events in the data.

Method A. —We utilized knowledge of the $K_L{}^0$ momentum vector to transform the photon directions into the K rest frame. From momentum and energy conservation and the K mass we calculated the photon energies. The photons were then paired in the available combinations as if each pair came from a π^0, and using these calculated energies to resolve the quadratic ambiguity, a unique direction for each π^0 was determined. A weighting factor $W(\theta_1, \theta_2)$ was calculated for each pairing case, based upon the probability that the observed opening angles θ_1 and θ_2 between photons of each pair should arise from π^0's of the requisite momentum. The case with the largest value of W was selected as the preferred pairing. The relative directions of the two π^0's were then found by calculating $\cos\theta_{\pi\pi}$, which should be -1 for a $2\pi^0$ decay observed with correct pairing and no experimental error. A distribution of the values of $\cos\theta_{\pi\pi}$ was collected from all four-shower events, and cuts were made by assigning a minimum value to the weight W and then a maximum value to $\cos\theta_{\pi\pi}$. The results from analysis by method A are shown in Fig. 2.

Method B. —Here we made no initial assumption about the momentum or mass of the primary particle from which the four photons derived, but required that they came from an intermediate state of two π^0's; also, we used spark-count information. The photon momenta were calculated from four kinematic relationships, two from conservation of transverse momentum and two of the form $(m_{\pi^0})^2 = 2p_ip_j(1-\hat{p}_i\cdot\hat{p}_j)$. All pairings giving physically possible photon energies were kept at this stage.

At this point we introduced a vertex search operation that varied the vertex position by small amounts from its initial location until a minimum was found for the fitting parameter

$$\chi^2 = \sum_{i=1}^{4}\left\{\left[\frac{1}{0.4}\ln\frac{E_{S_i}}{E_{K_i}}\right]^2 + \left[\frac{\Delta\theta_i}{\langle\Delta\theta(E_{S_i})\rangle}\right]^2\right\},$$

where E_{S_i} = energy of ith shower inferred from spark count, E_{K_i} = energy of this shower obtained by kinematic calculation using the vertex position

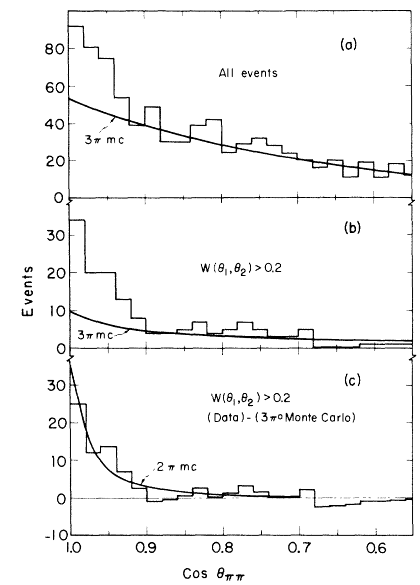

FIG. 2. Distribution in $\cos\theta_{\pi\pi}$ for all events, for events passing the opening-angle cut, and for events with $3\pi^0$ background subtracted. Solid lines show Monte Carlo predictions.

in question, $\Delta\theta_i$ = angular deviation of initial direction of ith shower from photon direction line drawn from the vertex, and $\langle\Delta\theta(E_{S_i})\rangle$ = rms value of $\Delta\theta$ observed for showers of this energy. The pairing with the smallest χ^2 is then chosen. ($2\pi^0$ events are correctly paired 90% of the time.) A momentum P and mass M for the primary particle was then calculated. We next required that the momentum fall within the interval 530 ± 100 MeV/c, as allowed for K mesons in our experiment. The solutions surviving this cut were plotted in a frequency distribution as a function of mass (see Fig. 3). A clear $2\pi^0$ peak near the K mass can be seen superimposed upon a background of solutions arising from $3\pi^0$ final states yielding only four visible showers. This $3\pi^0$ distribution peaks in the range 300 to 350 MeV. Monte Carlo calculations show a rapid and uniform fall above 350 MeV. In addition, the distribution for a class of five-shower events that were analyzed as four-shower events, because bremsstrahlung might have been the source of the fifth shower, shows just this shape.

The $2\pi^0$ peak is one bin (20 MeV) low. Analysis shows that a slight departure from linearity in the relationship between spark count and shower energy can account for this, the departure being in the direction of spark-count deficiency at high energy.

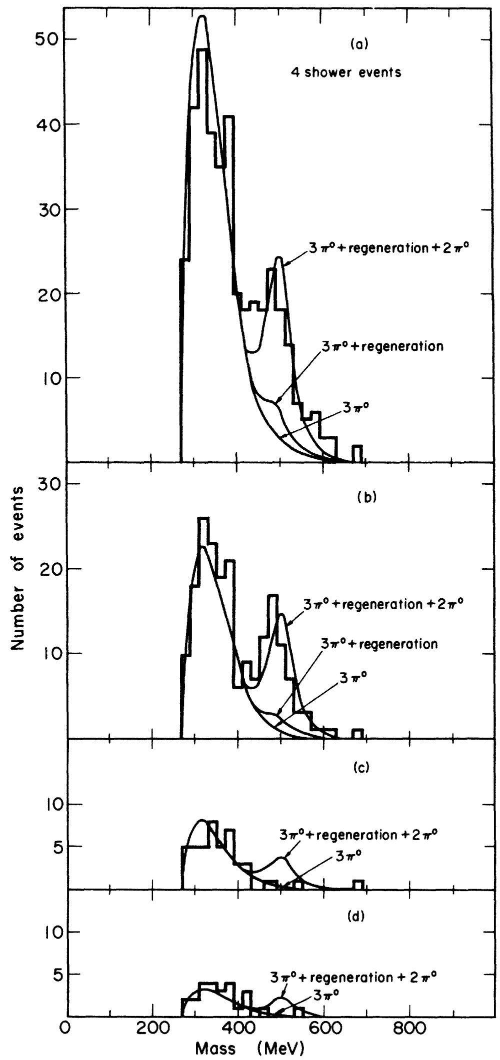

FIG. 3. Mass distributions for (a) all events with 430 MeV/$c \leq P \leq 630$ MeV/c, (b) events from (a) also having $\chi^2 \leq 10$, (c) probable five-shower events analyzed as four-shower events, 430 MeV/$c \leq P \leq 630$ MeV/c, and (d) events from (c) also having $\chi^2 \leq 10$.

Special features of the Monte Carlo program deserve mention. Representations of the results of decays of the K_L^0 into $3\pi^0$ and $2\pi^0$ final states in our chamber system were generated from a library of measured case histories of gamma rays of known energy arising from $K_L^0 \to \pi^+\pi^-\pi^0 \to$ two visible showers. The two charged-pion tracks determined the decay vertex and thus the true photon and K_L^0 directions. Kinematic analysis then gave the energy of each photon with an uncertainty small compared with that in neutral decays. By use of the same measuring techniques employed for neutral decay, the shower-direction deviation, the spark count, and the shower geometric structure were obtained for each photon. The mean shower-direction deviation was 11 deg for 100-MeV gammas, 7 deg for 200 MeV, and 5 deg for 300 MeV. These errors increase the $\pi^0 \to 2\gamma$ opening-angle distribution width in the K rest system by 10 deg. The ratio of energy from spark count to energy from kinematics was between $\frac{3}{4}$ and $\frac{4}{3}$ for 50%, $\frac{2}{3}$ and $\frac{3}{2}$ for 69%, and $\frac{1}{2}$ and 2 for 90% of the showers. The spark-count calibration constant found in this way (5.0 MeV/spark for tracks at normal incidence) predicted correctly the total number of sparks observed for six-shower events where the full energy of the K is visible.

The Monte Carlo program used these case histories (via a random table look-up) to provide shower directions and spark counts with realistic errors and correct energy dependences. In addition, the representation of the events was overlaid upon the real structure of the spark-chamber array, thus allowing for efficiency losses due to structural features or to a shortening or loss of a shower in the scintillation and Cherenkov counters. This also determined whether or not such an event would register in the appropriate combination of scintillator and Cherenkov counters to generate a chamber trigger pulse.

The Monte Carlo program correctly predicted the observed gamma penetration depths, shower angular deviations, shower multiplicities, spark counts, and absolute trigger efficiency for $3\pi^0$ events. The percentages of showers of given multiplicity observed for events without tunnel counter signals (80% of all events) were as follows: 7, 4%; 6, 59%; 5, 30%; 4, 6%; and 3, 1%. The seven-shower percentage was slightly larger than that expected from accidental shower rates observed during the random pulsing runs. Using the 7-to-6 ratio to correct the above percentages for accidentals, we get: 6, 60%; 5, 32%; 4, 7%; and 3, 1%. The $3\pi^0$ Monte Carlo predictions are: 6, 59%; 5, 33%; 4, 7%; and 3, 1%.

The Monte Carlo affects the result directly only through the ratio t_3/t_2s_2 = (probability for a $3\pi^0$ decay to trigger)/(probability for a $2\pi^0$ decay to trigger and give four showers). This ratio is quite insensitive to changes in the Monte Carlo program—both to refinements added during its development and to variations deliberately introduced to test its sensitivity to experimental errors. We find $t_3/t_2s_2 = 0.219/(0.156\times 0.715) = 1.96 \pm 0.1$.

The number of $2\pi^0$ decays was calculated with a maximum-likelihood program by fitting the experimental data with a superposition of $2\pi^0$, $3\pi^0$, and air-regenerator Monte Carlo distributions in the relevant variables [method A: $W(\theta_1, \theta_2)$ and $\cos\theta_{\pi\pi}$; method B: P, M, and χ^2]. The regenerated contribution was held fixed at the amount expected for a total diffraction-regeneration cross section of 21 mb per "air nucleus." Method A gives for n_2, the number of $2\pi^0$ four-shower decays in the entire sample, 130 ± 24, with 96 and 51 having $\cos\theta_{\pi\pi} < -0.92$ in Figs. 2(a) and 2(b), respectively. Method B gives $n_2 = 106 \pm 14$ with 75 and 45 having $M > 430$ MeV in Figs. 3(a) and 3(b), respectively. The likelihood function is found to be Gaussian about its maximum; the quoted error is taken at the $e^{-0.5}$ points. The agreement between the two methods further confirms the beam momentum value (used in method A but not in B) and the spark-count calibration (used in B but not in A).

Two systematic corrections must now be made to this total, one of 1.08 ± 0.01 for loss of events due to a fifth accidental shower or an accidental tunnel count and one of $1/(0.93 \pm 0.07)$ for four-shower selection efficiency which was found to be less than unity for part of the data. A partial triple scan has shown that the scanning efficiency for K's is essentially unity. A further systematic error of ±19 events is also assigned to n_2, compounded quadratically from the (primarily nonstatistical) difference between methods A and B (±16 events), the variations within each method with changes in cuts used to select the sample for maximum-likelihood analysis (±7 events), and the experimental uncertainty in the spark-count calibration and size of angular errors (±8 events). Finally we obtain $n_2 = 133 \pm 18$ (stat.) ± 24 (syst.) as the number of $2\pi^0$ four-shower events in our data.

From this number, the $2\pi^0/3\pi^0$ branching ratio R is found from $R = (t_3/t_2 s_2) \times (n_2/n_3)$, where n_3 is the total number of $3\pi^0$ decays observed, including those with tunnel counts. The ratio does not directly depend on the efficiency assumed for the tunnel counters since (1) the tunnel counter is not used in the trigger electronics, (2) all $2\pi^0$ events with four showers in the chambers by definition can have no gammas detected in the tunnel, and (3) essentially all $3\pi^0$ events show three or more showers in the chambers, making their detection efficiency independent of the tunnel efficiency. The final result for the branching ratio is $R = 1.96(133/19\,967) = 0.0131 \pm 0.0018$ (stat.) ± 0.0025 (syst.).

This value leads to an $|\eta_{00}|^2$ of

$$R \times |\Gamma(K_L^0 \to 3\pi^0)/\Gamma(K_L^0 \to \text{all})| \times |\Gamma(K_S^0 \to \text{all})/\Gamma(K_S^0 \to 2\pi^0)| \times (\tau_S/\tau_L) = [14.1 \pm 1.9 \text{ (stat.)} \pm 2.8 \text{ (syst.)}] \times 10^{-6},$$

where an additional systematic error of ±6 % has been included reflecting the uncertainty in the lifetimes and branching ratios used in this calculation.[7]

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[1]J.-M. Gaillard, F. Krienen, W. Galbraith, A. Hussri, M. R. Jane, N. H. Lipman, G. Manning, T. Ratcliffe, P. Day, A. G. Parham, B. T. Payne, A. C. Sherwood, H. Faissner, and H. Reithler, Phys. Rev. Letters 18, 20 (1967).

[2]J. W. Cronin, P. F. Kunz, W. S. Risk, and P. C. Wheeler, Phys. Rev. Letters 18, 25, 152(E) (1967). This value has been withdrawn.

[3]D. F. Bartlett, R. K. Carnegie, V. L. Fitch, K. Goulianos, D. P. Hutchinson, T. Kamae, R. F. Roth, J. S. Russ, and W. Vernon, Phys. Rev. Letters 21, 558 (1968).

[4]M. Banner, J. W. Cronin, J. K. Liu, and J. E. Pilcher, Phys. Rev. Letters 21, 1107 (1968).

[5]I. A. Budagov, D. C. Cundy, G. Myatt, F. A. Nezrick, G. H. Trilling, W. Venus, H. Yoshiki, B. Aubert, P. Heusse, I. LeDong, J. P. Lowys, D. Morellet, E. Nagy, C. Pascaud, L. Behr, P. Beillière, G. Boutang, M. Schiff, and J. Van Der Velde, Phys. Letters 28B, 215 (1968).

[6]J.-M. Gaillard, W. Galbraith, A. Hussri, M. R. Jane, N. H. Lipman, G. Manning, T. Ratcliffe, H. Faissner, and H. Reithler, Nuovo Cimento 59A, 453 (1969).

[7]N. Barash-Schmidt, A. Barbaro-Galtieri, L. R. Price, A. H. Rosenfeld, P. Söding, C. G. Wohl, M. Roos, and G. Conforto, Rev. Mod. Phys. 41, 109 (1969).