to separate usefully the contributions to their orbits of λ_p and J_2. A covariance analysis based on expected improvement in measurement accuracy and in the modeling of planetary topography indicates that the uncertainty of J_2 would be reduced to about 3×10^{-6} and that of λ_p to about 0.3%.

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*Department of Earth and Planetary Sciences.

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[1]I. I. Shapiro, Phys. Rev. Lett. 13, 789 (1964), and Massachusetts Institute of Technology Lincoln Laboratory Technical Report No. 368, DDC No. 614232, 1964 (unpublished).

[2]The radar observations of Mars, at the present state of analysis, cannot contribute usefully to this test.

[3]These include observations from the Millstone Hill radar of the Massachusetts Institute of Technology Lincoln Laboratory and from the Goldstone radars of the Jet Propulsion Laboratory. The latter were kindly sent to us by R. M. Goldstein, J. H. Lieske, and W. G. Melbourne.

[4]See, for example, H. P. Robertson, in *Space Age Astronomy,* edited by A. J. Deutsch and W. E. Klemperer (Academic, New York, 1962), p. 228.

[5]The existing radar observations of Venus do not allow the advance of its orbital perihelion, or Earth's, to be determined with an accuracy useful for testing general relativity.

[6]I. I. Shapiro, M. E. Ash, R. P. Ingalls, W. B. Smith, D. B. Campbell, R. B. Dyce, R. F. Jurgens, and G. H. Pettengill, Phys. Rev. Lett. 26, 1132 (1971). [Note that the result of the first radar time-delay test of general relativity $(1+\gamma)/2\simeq 0.9\pm0.2$ was misprinted as 0.09 ± 0.2 in this reference.]

[7]D. B. Campbell, R. B. Dyce, R. P. Ingalls, G. H. Pettengill, and I. I. Shapiro, Science 175, 514 (1972); A. E. E. Rogers, R. P. Ingalls, and L. P. Rainville, Astron. J. 77, 100 (1972).

[8]R. P. Ingalls and L. P. Rainville, Astron. J. 77, 185 (1972).

[9]We use the definition of longitude adopted in *Proceedings of the Fourteenth General Assembly of the International Astronomical Union,* edited by C. De Jager and A. Jappel (D. Reidel, Dordrecht, Holland, 1971), p. 28. In this system, the Sun was above the zero meridian at the time of Mercury's first perihelion passage in 1950.

[10]Prior determinations of the perihelion advance of Mercury's orbit, based solely on optical observations, yielded the equivalent of $\lambda_p\simeq 1.00\pm0.01$ [G. M. Clemence, Astron. Papers Amer. Ephemeris Nautical Almanac 11, Part 1 (1943); see also R. L. Duncombe, *ibid.* 16, Part 1 (1959)].

[11]By the same token, given that $\lambda_p\equiv 1$, our data show that $J_2 < 5\times10^{-6}$.

Measurement of $|\eta_{00}|/|\eta_{+-}|$†

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We have measured the quantity $|\eta_{00}|/|\eta_{+-}|$ which is defined in terms of K_L and K_S decay rates by the ratio $[\Gamma(K_L\to\pi^0\pi^0)\Gamma(K_S\to\pi^+\pi^-)/\Gamma(K_L\to\pi^+\pi^-)\Gamma(K_S\to\pi^0\pi^0)]^{1/2}$. We find $|\eta_{00}|/|\eta_{+-}|=1.03\pm0.07$.

In the study of CP nonconservation in K_L decay[1] the crucial question has become the following: Does a single parameter in the mass matrix account for all the CP-nonconservation phenomena observed? If the ratio $|\eta_{00}|/|\eta_{+-}|^2$ were found to be different from unity, such a single parameter could not describe the CP-invariance violation. From an experimental point view, the principal difficulty in the determination of this ratio has been the measurement of the decay rate $\Gamma(K_L\to\pi^0\pi^0)$ with sufficient precision.

We have measured the ratio $|\eta_{00}|/|\eta_{+-}|$ using a K_L beam of mean momentum 6 GeV/c produced by the alternating gradient synchrotron at Brookhaven National Laboratory. In this experiment we have determined *all* the parameters required to extract the ratio $|\eta_{00}|/|\eta_{+-}|$. We observed both neutral and charged decays with our apparatus. A simple conversion sufficed to pass from one mode to the other, so that the rates of $K_L \to \pi^0\pi^0$ and $K_L \to \pi^+\pi^-$ in vacuum could each be observed. The introduction of an 8-in.-thick uranium regenerator in the decay volume permitted us to measure the rates $K_S \to \pi^0\pi^0$ and $K_S \to \pi^+\pi^-$. If we designate the regenerated K_S intensity immediately downstream of the regenerator as $|\rho'|^2$ times the *incident* K_L intensity, we find

$$\frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{\Gamma(K_L \to \pi^0\pi^0)[|\rho'|^2\Gamma(K_S \to \pi^+\pi^-)]}{\Gamma(K_L \to \pi^+\pi^-)[|\rho'|^2\Gamma(K_S \to \pi^0\pi^0)]}.$$

We note that the regenerated intensity $|\rho'|^2$ cancels in the ratio, as do efficiency factors not explicitly indicated.

We wish to emphasize two other features of the experiment. First, we made a precise measurement of the transverse momentum of one of the γ rays from the $K_L \to \pi^0\pi^0$ decay and required it to be larger than 170 MeV/c, thus reducing the contamination of $3\pi^0$ events in the final sample to a negligible level. Second, the *only* time an efficiency calculation was required to evaluate the result was in the subtraction of the incoherently regenerated $K_S \to \pi^0\pi^0$ events. The result is insensitive to large errors in this subtraction because the incoherent regeneration is itself a small fraction of the coherent regeneration. The fraction of incoherent regeneration was measured directly from the charged decays.

Figure 1 shows the apparatus used to detect $K \to \pi^0\pi^0$. One of the four γ rays from the decay was converted in a 0.1-radiation-length converter sandwiched between scintillation counters. The energy and direction of this γ were determined

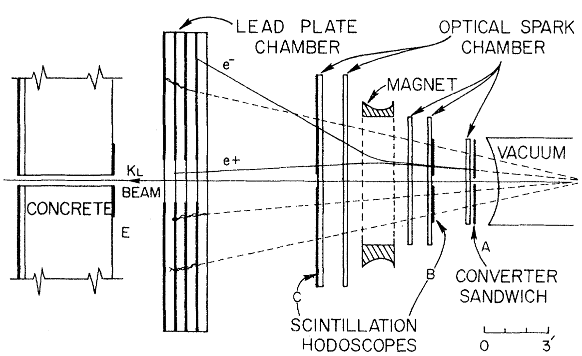

FIG. 1. Schematic view of apparatus used to detect $K \to \pi^0\pi^0$.

by a pair spectrometer consisting of five optical spark chambers and a 72 D 18 magnet with an 18-in. gap and a field integral of 680 kG cm. The momentum, direction, and transverse momentum of this γ were measured with standard deviations of 3%, 3 mrad, and 5 MeV/c, respectively.

Planes of scintillation hodoscopes B and C placed symmetrically with respect to the magnet center were used to trigger on γ rays with high transverse momentum. The inward-deflected e^+ or e^- was required to pass the plane C at a larger transverse distance from the beam than it had at plane B. This requirement greatly suppressed the $K_L \to \pi^0\pi^0\pi^0$ decays in the trigger.

Given a detected spectrometer γ, there is a 15% probability that the remaining three γ rays will pass through the magnet aperture and convert in a large optical spark chamber. The spark chamber contained forty lead plates totaling 6 radiation lengths. A bank of scintillation counters was placed after each 10-gap module. The neutral-mode trigger consisted of the spectrometer γ in coincidence with a count in any one or more of these scintillators on the opposite side of the beam.

The K_L decays occurred in a 10-ft-long vacuum tank. The regeneration data were taken with the uranium regenerator at each of five discrete locations spaced uniformly through the decay region. The trigger requirement for the regenerator runs was the same as for the vacuum decays except for the addition of a $\frac{1}{16}$-in.-thick anticoincidence counter placed on the downstream face of the regenerator.

The relative K_L flux was monitored at all times by a telescope viewing the production target at an angle of 30°. The stability of this principal monitor was checked by auxiliary monitors. One of the auxiliary monitors recorded charged K^0 decays from the beam. Careful bookkeeping permitted the number of monitor counts associated with a given set of measured events to be determined to better than 3%.

The spectrometer γ rays were measured by a cathode-ray-tube scanner. The lead-plate chamber photographs were measured by two independent scanners for all events with a γ ray having transverse momentum between 160 and 270 MeV/c. In all, 20 000 free-decay events and 60 000 regenerator events were so examined.

We used the following information to reconstruct the events: (1) the energy and direction of the spectrometer γ, (2) the conversion points of the three other γ's, and (3) the decay vertex. The decay vertex was established by the intersection of the spectrometer γ-ray trajectory with the beam which was a 0.8-in.-wide$\times$8-in.-high vertical ribbon.

This information provides two constraints for the hypothesis $K_L \to \pi^0\pi^0$, with the assumption that the K_L is moving in the beam direction. Two important cuts were made on the lead-plate chamber: (i) Only conversions which produced a shower of length greater than 10 gaps were retained; (ii) only events which had exactly three converted γ's surviving the first cut were reconstructed. The first cut reduced the number of accidental extra γ's to 5.5% for the vacuum events and 7% for the regenerator events. The second cut eliminated a small contamination of $K_L \to \pi^0\pi^0\pi^0$ events.[3,4]

The first constraint is purely geometrical. We minimized the quantity $\chi^2 = [(M_{12}/M_4 - 0.271)/\sigma]^2 + [(M_{34}/M_4 - 0.271)/\sigma]^2$ with respect to the assumed $\beta(1-\beta^2)^{-1/2}$ of the decaying particle. Here M_{12} and M_{34} are the effective masses of the paired γ's, while M_4 is the effective mass of all four γ's. σ was chosen to be 0.01 from calculations. An event was accepted if $\chi^2 \leq 10$. There are three ways to pair the γ's; the pairing with the minimum χ^2 was chosen. The momentum and mass of the selected events were then proportional to the measured momentum of the spectrometer γ ray.

The yields of the five regenerator positions have been appropriately weighted to give a decay-point distribution identical to the vacuum-decay distribution with a yield $\langle|\rho'|/|\eta_{00}|^2\rangle$ times the vacuum-decay yield.[5] $\langle|\rho'|^2/|\eta_{00}|^2\rangle$ is the value of this quantity averaged over the momentum spectrum. This method of comparison of the vacuum and regenerated events neglects a small contribution due to the interference with CP-nonconserving K_L decays. An identical effect occurs for the charged decay if $\arg\eta_{00} = \arg\eta_{+-}$.[6]

Figures 2(a) and 2(b) show the resulting mass distributions for the regenerator and vacuum decays, respectively. Figures 2(c) and 2(d) show the distributions of the transverse momentum of the spectrometer γ ray. These are plotted for events surviving the final mass cut (400 to 600 MeV/c^2). The sharp cutoff at 230 MeV/c is a prominent feature of these distributions. Two finer features should be noted. The vacuum events in the interval 160 to 170 MeV/c show evidence of the $K_L \to 3\pi^0$ decays which are removed by the 170-MeV/c cut. In the weighted regenerator distribution the small tail that extends beyond

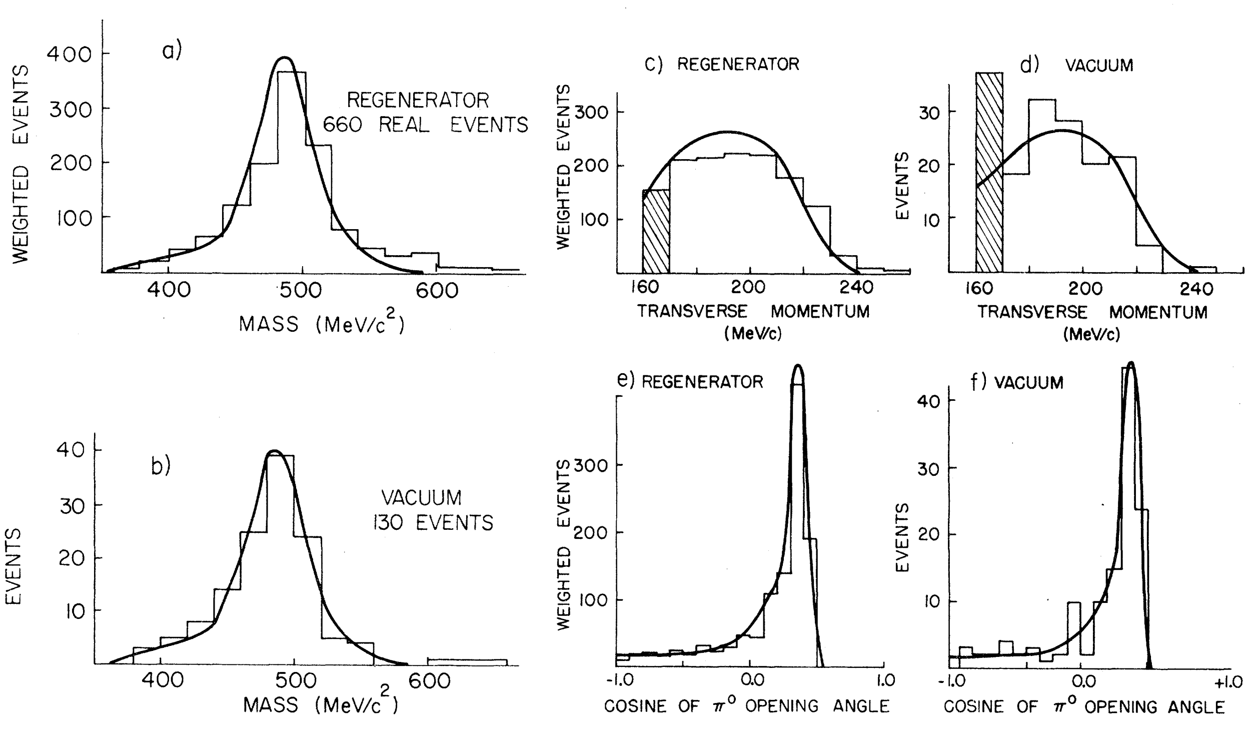

FIG. 2. (a) Mass distribution of regenerated events. (b) Same for vacuum events. (c) Transverse-momentum distribution of spectrometer γ ray for regenerated events. (d) Same for vacuum events. (e) Opening-angle distribution of regenerated events. (f) Same for vacuum events. The smooth curves are the expected distributions on the basis of a Monte Carlo calculation for vacuum events.

the cutoff is due to incoherently regenerated events. Figures 2(e) and 2(f) show the opening angle distribution in the K_L center of mass of the two γ rays not paired with the spectrometer γ ray. These figures show the characteristic opening-angle distribution of a 209-MeV/c pion decay. The regenerator and vacuum events have been analyzed in precisely the same way and the above distributions appear identical except for small features which may be ascribed to incoherent regeneration.

The apparatus was converted to detect $K \to \pi^+\pi^-$ by removing the lead-plate spark chamber and the spectrometer γ-ray converter, and by adding Čerenkov counters to detect $K_L \to \pi e \nu$ decays and a muon filter to detect $K_L \to \pi\mu\nu$. The trigger logic was modified to require two charged particles emerging from the magnet roughly parallel to the beam. Runs were made with the vacuum and regenerator in similar fashion to the neutral mode, but with much improved statistics. The results quoted below are based on 2000 vacuum events and 14 000 regenerated events. The $K_L \to \pi^+\pi^-$ and regenerated $K_S \to \pi^+\pi^-$ events were extracted in standard fashion in 1-GeV/c momentum intervals from 3 to 10 GeV/c. Using these data, the value of $\langle|\rho'|^2/|\eta_{+-}|^2\rangle$ averaged over the spectrum of $K_L \to \pi^0\pi^0$ *events* was found to be 126 ± 6. (Note that this figure directly includes the attenuation of the K_L beam in the regenerator).

We have evaluated the amount of incoherently regenerated events contained in the neutral sample by determining the corresponding amount in the charged data. We find there the ratio

$$dN_{\mathrm{inc}}(0)/N_{\mathrm{coh}} = (1.17 \pm 0.03) \times 10^{-4}\ (\mathrm{MeV}/c)^{-2}\ dP_\perp^2.$$

If we characterize the incoherent distribution with an exponential form

$$dN_{\mathrm{inc}} = A \exp(-aP_\perp^2)\, dP_\perp^2,$$

we find $a = (1.43 \pm 0.10) \times 10^{-4}\ (\mathrm{MeV}/c)^{-2}$. Here N_{inc} and N_{coh} are the numbers of incoherent and coherent events and $P_\perp$ is the transverse momentum of the incoherently regenerated K_S with respect to the beam. To evaluate the fraction of incoherent events in the neutral regenerator sample, we required the knowledge of the efficiency of the apparatus as a function of $P_\perp^2$ for the neutral mode relative to that for the charged mode. Although we are quite confident about the calculation of the relative efficiencies with the Monte Carlo technique, we have arbitrarily tripled the statistical error in order to be totally immune to any questions of dependence on Monte Carlo. Thus we take the fraction of incoherent in the neutral sample to be $(23.6 \pm 4)\%$.

TABLE I. Summary of results.

Charged Mode
$\langle|\rho'|^2/|\eta_{+-}|^2\rangle = 126 \pm 6$
Neutral-mode regenerator
Yield: 1228 ± 50 events for $(18.4 \pm 0.5) \times 10^8$ monitors
Fractional coherent: 0.764 ± 0.040
Normalized rate: 51.0 ± 3.6 events per 10^8 monitors
Neutral-mode vacuum
Yield: 124 ± 11 events for $(286 \pm 6) \times 10^8$ monitors
$3\pi^0$ background: 3 ± 3 events
Normalized rate: 0.425 ± 0.040 events per 10^8 monitor counts
Calculation
$\dfrac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \dfrac{(0.425 \pm 0.040)(126 \pm 6)}{51.0 \pm 3.6} = 1.05 \pm 0.14$

Table I summarizes the calculation of $|\eta_{00}|^2/|\eta_{+-}|^2$. Our final result is $|\eta_{00}|/|\eta_{+-}| = 1.03 \pm 0.07$. This is in good agreement with recent determinations of this ratio[7] and is consistent with the assumption that all CP-invariance violation is accounted for by a single parameter in the mass matrix.

We wish to acknowledge the generous support given to us by the staff of the alternating gradient synchrotron during the operation of this experiment. We also wish to thank the staff of the elementary particles laboratory, Mr. Walter Karp, Dr. John Liu, Dr. James Pilcher, Mr. David Newman, Mr. Victor Bearg, Dr. Evan Snyder, Ms. Sharon Unangst, and our scanners for their invaluable assistance during various stages of the construction, running, and analysis of this experiment.

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[1]K. Winter, in Proceedings of the Sixth International Conference on Elementary Particles, Amsterdam, The Netherlands, 1971 (unpublished).

[2]T. T. Wu and C. N. Yang, Phys. Rev. Lett. 13, 380 (1964).

[3]Monte Carlo calculations show that the number of $\pi^0\pi^0$ fits is quite insensitive to the number of accidental extra γ's. The addition of 15% accidental extra γ's produced 15% more events from fits formed with events in which one real γ has been lost. However, 15% of the events with three real γ's now have an extra γ and so are eliminated by the second cut.

[4]Most events of the type $K_L \to \pi^0\pi^0\pi^0$ which fit the $K_L \to \pi^0\pi^0$ hypothesis have more than three γ rays in the lead-plate chamber. These events have transverse momenta very close to the cutoff value of 170 MeV/c. Scaling from ten observed events of this type, we estimate the number of such $K_L \to \pi^0\pi^0\pi^0$ events with three γ rays in the lead-plate chamber to be 3 ± 3 events.

[5]For a given regenerator position, all events were accepted which occurred in a spatial interval bounded by the downstream face of the following regenerator. Each event was then multiplied by a weighting factor $(\Delta/\Lambda_S)[1-\exp(\Delta/\Lambda_S)]^{-1}$, where Δ is the distance between regenerator positions and Λ_S is the mean decay length. A 2% error introduced by the downstream cutoff due to the uncertainty of the vertex position has been corrected.

[6]The value of $\arg\eta_{00}$ was measured to be $43° \pm 19°$ by B. Wolff *et al.*, Phys. Lett. 36B, 517 (1971).

[7]Recent results have been given by P. Darriulat *et al.*, submitted to the Sixth International Conference on High Energy Physics, Amsterdam, The Netherlands, 1971 (unpublished). They find $|\eta_{00}|/|\eta_{+-}| = 1.00 \pm 0.06$. V. V. Barmin *et al.*, Phys. Lett. 33B, 337 (1970), find $|\eta_{00}| = (2.02 \pm 0.23) \times 10^{-3}$. Using $|\eta_{+-}| = (1.95 \pm 0.04) \times 10^{-3}$, $|\eta_{00}|/|\eta_{+-}| = 1.04 \pm 0.12$.

A_1 Production in Charge-Exchange Reactions*

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We have measured the cross section for production of events in the A_1 mass region for two reactions: (1) $\pi^+p \to \pi^+\rho^0 p$ and (2) $\pi^- n \to \pi^-\rho^- p$. The results of these experiments, both conducted at an incident pion momentum of ~ 7 GeV/c, are interpreted within the framework of dual models of inelastic hadron collisions.

One of the most striking phenomena observed in studies of high-energy collisions of hadrons is the copious production of diffractively produced low-mass enhancements such as the A_1 $(\to \pi\rho)$, the Q $(\to \pi K^*)$, and the A_3 $(\to \pi f)$. Although these enhancements appear to possess many resonance-like properties, there has nevertheless been considerable controversy concerning their true nature.

A number of years ago it was suggested that these low-mass enhancements might have a purely kinematic origin.[1] Specifically, Deck showed that in a reaction such as

$$\pi^+ p \to \pi^+ \rho^0 p \tag{1}$$

an enhancement was expected to occur in the $\pi\rho$ mass spectrum near threshold; this enhancement was purported to result from the diffractive elastic scattering of off-mass-shell pions in the π-exchange diagram shown in Fig. 1(a).

More recently, Chew and Pignotti hypothesized that a successful Deck-model description of A_1-like objects would, through an extension of the duality hypothesis, support the contention that these enhancements were mainly resonant in nature.[2] Reggeized versions of the Deck model have subsequently been extensively compared with data at different energies and for different incident channels.[3] The agreement of these models with the data has, through the duality argument, been cited as supporting evidence for the

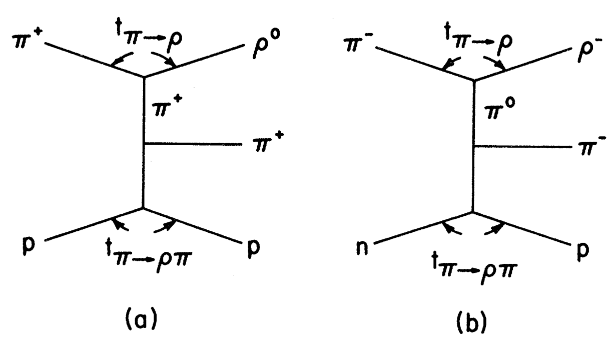

FIG. 1. Pion-exchange diagrams employed in this analysis; (a) applies to Reaction (1) and (b) to Reaction (2). See text for details.