New Determination of the K_1^0 Branching Ratio*

JOHN L. BROWN, JOHN A. KADYK, AND GEORGE H. TRILLING
Lawrence Radiation Laboratory and Department of Physics, University of California, Berkeley, California

AND

BYRON P. ROE, DANIEL SINCLAIR, AND JOHN C. VANDER VELDE
Department of Physics, University of Michigan, Ann Arbor, Michigan

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Using the 12-in. xenon bubble chamber, we have redetermined the branching ratio of the decay modes $K_1^0 \to 2\pi^0$ and $K_1^0 \to \pi^+ + \pi^-$. Exposure of the chamber to an 800-MeV/c separated K^+ beam produced a large number of K^0 particles by charge exchange in the xenon, leading to about 3500 K_1^0 decays. The $K_1^0 \to 2\pi^0$ decay mode is recognized by observation of the electron pairs formed by conversion of the γ rays from π^0 decay. From an analysis of these data, we have determined the K_1^0 branching ratio to be $(K_1^0 \to 2\pi^0)/[(K_1^0 \to 2\pi^0)+(K_1^0 \to \pi^+ + \pi^-)] = 0.335 \pm 0.014$. This result is in very good agreement with the value of 0.337 predicted by the $|\Delta \mathbf{T}| = 1/2$ rule.

I. INTRODUCTION

THE question of the validity of the $|\Delta \mathbf{T}| = 1/2$ rule in nonleptonic weak interactions has been studied extensively. Experimental evidence from many sources exists which is in good agreement with this rule; however, the results of some recent experiments have tended to discredit it. The major experimental results that seem to be correctly predicted by the $|\Delta \mathbf{T}| = 1/2$ rule within the errors of measurement are the decay branching ratios[1] of the Λ^0 and K_1^0, the relative rates[2] and energy spectra[3] of the τ^+ and $\tau^{+\prime}$ modes in K^+ decay, and the ratio of the decay asymmetry parameters for the two nonleptonic modes of the Λ^0.[4] Furthermore, the decay rate for the mode $K^+ \to \pi^+ + \pi^0$, forbidden by the rule, is indeed 1/700 of the corresponding $K_1^2 \to 2\pi$ rate. This rate, small as it is, is still about 25 times the normal electromagnetic correction of order α^2. The recent data which seem to disagree with the predictions of the rule are:

(1) The predicted closure of the Σ triangle requires that the magnitude of the asymmetry parameter in $\Sigma^+ \to p + \pi^0$ decay be unity, whereas the measured value[5] is $0.79_{-0.09}^{+0.08}$.

(2) The measured ratio

$$W(K_2^0 \to \pi^+\pi^-\pi^0)/W(K^+ \to 3\pi)$$

is about half of the value predicted by the rule, the quoted odds against agreement[6] being 100:1.

These recent results suggest the desirability of more precisely experimentally testing the $|\Delta \mathbf{T}| = 1/2$ rule. In this paper, we describe a new measurement of the K_1^0 branching ratio of substantially higher precision than previous measurements, which adds information bearing upon the validity of the $|\Delta \mathbf{T}| = 1/2$ rule.

The K_1^0 branching ratio was determined with the 12-in. xenon bubble chamber,[7] in which the $K_1^0 \to 2\pi^0$ mode is detected with high efficiency by observation of the conversion of the γ rays from π^0 decay into visible electron pairs.[8] The chamber was exposed at the Bevatron to a well-separated K^+ beam of about 800-MeV/c momentum.[9] Charge exchange of the K^+ at this momentum occurs frequently (about 5% of all beam tracks), and is, therefore, an efficient way of producing a large number of K^0 particles. Since the contamination of the beam by other strongly interacting particles is small ($\lesssim 2\%$), the K^+ charge exchange is identified reliably by requiring that all prongs from the interaction of a beam particle stop inside the chamber without decaying. This method of identifying a charge-exchange interaction thus provides a convenient signature for K^0 production. During this experiment, approximately

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[6] G. Alexander, S. P. Almeida, and F. S. Crawford, Jr., Phys. Rev. Letters **9**, 69 (1962).

[7] J. L. Brown, in *Proceedings of an International Conference on Instrumentation for High-Energy Physics, Berkeley, 1960* (Interscience Publishers, Inc., New York, 1961), p. 110.

[8] In this context, Compton electron recoils are also included in the category of visible electron pairs.

[9] G. Goldhaber, S. Goldhaber, J. Kadyk, T. Stubbs, D. Stork, and H. Ticho, Bevatron Internal Report, 1960 (unpublished). W. Chinowsky, G. Goldhaber, S. Goldhaber, W. Lee, T. O'Halloran, T. F. Stubbs, W. Slater, D. H. Stork, and H. K. Ticho, in *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester*, edited by E. C. G. Sudarshan, J. H. Tinlot and A. C. Melissinos (Interscience Publishers, Inc., New York, 1960), p. 451. T. F. Stubbs, H. Bradner, W. Chinowsky, G. Goldhaber, and S. Goldhaber, Phys. Rev. Letters **7**, 188 (1961).

12 000 charge exchanges have been observed, of which about 7000 lie within a specified central fiducial volume. There are, therefore, approximately 3500 K_1^0 decays in the entire sample.

II. ANALYSIS OF DATA

A. General Procedure

The K_1^0 events were found by scanning along each incoming beam track for interactions, and examining each such event to see if it fulfilled sufficient conditions for a charge exchange, viz., all prongs from the interaction must stop in the chamber without decaying. Only those charge exchanges were used which lay within a central fiducial region, restricted to be several centimeters from each chamber wall. This guaranteed a high efficiency for detection and identification of K_1^0 decays, since the average flight path before decay was only about 2 cm. To further insure that beam contamination have minimal importance, we required that beam particles enter the chamber within a restricted region and have minimum bubble density and small multiple scattering. These latter requirements discriminated against protons and low-momentum pions and muons in the beam. We restricted ourselves in the analysis to those photographs having ten or fewer beam particles, in order to reduce possible confusion caused by many events occurring in the same picture. Each picture was scanned independently by at least two scanners, who were instructed to look first for charge exchanges, and if any were found, to look for the characteristic decays $K_1^0 \to \pi^+ + \pi^-$ and $K_1^0 \to 2\pi^0 \to 4\gamma$. In addition to noting these events, the scanner was also required to count and record the number of beam tracks in every picture to be sure this number was not greater than ten, and to help emphasize the procedure of along-the-track scanning.

It was found that the individual scanning efficiency for finding charge exchange and K_1^0 decay events was between 80 and 90%. The scanning efficiency of each nonphysicist scanner was continually monitored by physicists, who studied on every fifth roll all charge exchanges found by either of the two previous scanners, whether or not the charge exchange was accompanied by a detected K_1^0 decay. In addition, part of the film was fully scanned by physicists to be sure that very few events were missed by both scanners, and this was indeed found to be the case.

In order to obtain a final result for the K_1^0 branching ratio, a number of corrections had to be made to the number of events found by the scanners, such as corrections for scanning efficiency, events lying outside their appropriate fiducial volume, γ-ray conversion efficiencies, etc. Although most of these corrections are reasonably small, the level of precision involved here requires the examination of a fairly large number of effects. These investigations are described in detail in the following two sections, and the results presented in tabular form to show what corrections are involved, the magnitude of each, and how it affects the final result. This is done separately for the $2\pi^0$ and the $\pi^+ + \pi^-$ decay modes, since in general, these involve quite different corrections. Because of the low level of background, the net effects of the various corrections lead to fairly small changes in the raw numbers obtained from the scan. Therefore, these effects can be evaluated to an accuracy comparable to that implied by the statistics of the experiment by measuring only a random sample from the events found in the scan rather than all the events. This permits a substantial saving in measuring labor.

The description of the analysis which follows in Secs. II B and II C applies without qualification to 83% of the data, and the numbers of events appearing in Tables I through VII are based on that fraction of the film. The remaining 17% of the data was analyzed by methods that differ only slightly from the general procedure outlined below. Since we believe both procedures are valid, and the separate results are in agreement, we have combined the numbers of events obtained from these two groups of data to derive the final branching ratio.

B. $K_1^0 \to \pi^+ + \pi^-$ Decays

To be included in our sample, the $K_1^0 \to \pi^+ + \pi^-$ decays had to satisfy the following restrictions, designed to insure high scanning efficiency and minimize the number of fake events: (1) The K^+ charge exchange that produced the K_1^0 had to be at least 3 cm from any chamber boundary. (2) The incoming K^+ track had to lie within 12 deg of the beam direction. (3) The K_1^0 decay point had to lie at least 2 cm from any chamber boundary. (4) The K_1^0 flight path before decay had to be less than 10 cm (about five mean lives). (5) The $K_1^0 \to \pi^+ + \pi^-$ flight path had to be longer than 0.5 cm. (6) The secondary pions from $K_1^0 \to \pi^+ + \pi^-$ decay had to go at least 0.3 cm before stopping or interacting. (7) The $K_1^0 \to \pi^+ + \pi^-$ decay had to pass the relevant kinematic requirements. Of these seven restrictions the first four were also applied to the $K_1^0 \to 2\pi^0$ decays; hence for the branching-ratio determination no correction need be made for events excluded by these four rules. The last three criteria, however, were applied only to $K_1^0 \to \pi^+ + \pi^-$ decays; hence it was necessary to correct for the real events removed by their application.

To reduce the labor involved, only about 25% of all the $\pi^+\pi^-$ events recorded by the scanners was measured. Corrections deduced from this sample were then applied to all the film. Results of this sampling are given in Table I. Note that most rejected events were actually real $K_1^0 \to \pi^+ + \pi^-$ events; they were discarded simply because they failed to pass one or more of the geometric criteria. By adding the two numbers in the last column of Table I, we find that the number of $K_1^0 \to \pi^+ + \pi^-$ events satisfying all seven criteria is 1420 ± 56. The quoted error reflects both the inherent statistical error

TABLE I. $K_1{}^0 \to \pi^+ + \pi^-$ scanning results.

	Events in 25% sample			Events in all film	
Number of scanners	Uncorrected	Passing all criteria	Fraction passing all criteria	Uncorrected	Passing all criteria
Both	415	287	0.69	1842	1274
One	215	38	0.18	828	146

($\pm$38) and that due to our sampling procedure ($\pm$41). This raw number now must be corrected for scanning efficiency, and for the restrictions deliberately imposed by the application of the last three criteria listed at the beginning of this section.

1. *Correction for Short Decay Lengths*

The correction factor, C_1, for events with decay lengths less than 5 mm can be calculated from the measured events that passed all the criteria, as follows:

$$C_1 = \frac{1}{N} \sum_{i=1}^{N} F_i,$$

with

$$F_i = \frac{1-e^{-T_i/\tau}}{e^{-t_i/\tau} - e^{-T_i/\tau}},$$

where N is the number of measured events, T_i is the maximum potential time for the ith event (corresponding to a potential flight path of 10 cm, or the maximum potential path, whichever is smaller), t_i is the minimum flight time for ith event, corresponding to a flight path of 5 mm, τ is the $K_1{}^0$ lifetime, taken to be 0.87×10^{-10} sec.[10] The error in C_1 can be determined by using

$$\delta C_1 = N^{-1/2} [\langle F^2 \rangle - C_1{}^2]^{1/2},$$

with

$$\langle F^2 \rangle = \frac{1}{N} \sum_{i=1}^{N} F_i^2.$$

From 315 measured events we found $C_1 = 1.363 \pm 0.010$. There is an additional error, not included, due to uncertainty in the $K_1{}^0$ lifetime. If the true lifetime differs from 0.87×10^{-10} sec by an amount $\delta\tau$, then the true branching ratio $B(K_1{}^0)$ (see Sec. III) will differ from our result by the amount

$$\delta B(K_1{}^0) = 0.20(\delta\tau/\tau) B(K_1{}^0).$$

This is negligible in comparison to our other uncertainties, unless the true value of τ differs from the value quoted above by an amount much larger than the quoted errors.[10]

2. *Correction for Short Pion Secondaries*

The $K_1{}^0 \to \pi^+ + \pi^-$ decays with short secondaries are difficult to identify kinematically because of the inherently large angular errors. For this reason, we discarded events with secondaries that interacted or stopped in less than 3 mm. From an examination of the secondaries of a number of $K_1{}^0 \to \pi^+ + \pi^-$ decays, we found that the interaction cross section for the pions produced by our $K_1{}^0$ events was geometric, i.e., the interaction mean free path was $\sim$60 cm. To determine the fraction of events that have a secondary of range less than 3 mm, we used our observed $K_1{}^0$ momentum distribution and assumed that the $K_1{}^0$ decayed isotropically in its rest system. We found that 0.38% of all $K_1{}^0$ decays would produce short stopping secondaries. Adding these two results together, we find $C_2 = 1.014 \pm 0.004$. The error has been assigned to cover an arbitrary 1-mm uncertainty in the 3-mm cutoff.

3. *Correction for Kinematic Criteria*

The following kinematic criteria were imposed on $K_1{}^0 \to \pi^+ + \pi^-$ events:

(1) The plane determined by the π^+ and π^- directions had to contain the charge-exchange point, within measurement errors. (2) For about 25% of the events in which one pion stopped without interacting, the observed range had to agree with the predicted range, within measurement errors.

Real $K_1{}^0 \to \pi^+ + \pi^-$ events will occasionally fail these criteria because of mismeasurement, misestimation of errors, or because the $K_1{}^0$ scatters before decaying. By examination of the coplanarity distribution of the measured events and careful re-examination of all the events that failed the above kinematical requirements, we concluded that a correction factor, $C_3 = 1.025 \pm 0.012$, had to be applied to allow for such effects.

4. *Scanning Efficiency*

A naive comparison of the number of events found by one scanner only and by both scanners leads one to conclude that the single-scan efficiency was 94%. It is well known that this calculation, based on the assumption that all events are equally likely to be missed by either scanner, leads only to an upper limit for the scanning efficiency. A more meaningful figure can be found from a small sample (15 rolls) which was very carefully scanned by physicists. The physicist's scan of these rolls produced two events missed by both scanners, who between them found 77 events. If one assumes that the joint scanning efficiency of the two scanners plus the physicist was unity, the correction for scanning efficiency is $C_4 = 1.026 \pm 0.018$. The quoted error reflects only the statistical error in two events.

Multiplying the uncorrected number of events by these four correction factors (summarized in Table II)

[10] This value represents a weighted average of the values $\tau = (0.86 \pm 0.03) \times 10^{-10}$ sec [G. Alexander, S. P. Almeida, and F. S. Crawford, Jr., Phys. Rev. Letters **9**, 69 (1962)] and $\tau = (0.90 \pm 0.05) \times 10^{-10}$ sec [A. F. Garfinkel, Nevis Cyclotron Laboratory Report NEVIS-104, 1962 (unpublished)].

TABLE II. Summary of corrections to $K_1{}^0 \to \pi^+ + \pi^-$ events.

Events satisfying all criteria	1420 ± 56
Correction for flight path <0.5 cm	1.363 ± 0.010
Correction for short pion secondaries	1.014 ± 0.004
Correction for kinematic failures	1.025 ± 0.012
Correction for scanning efficiency	1.026 ± 0.018
Corrected number of events	2063 ± 94

we find that the total number of $K_1{}^0 \to \pi^+ + \pi^-$ events is

$$N(K_1{}^0 \to \pi^+ + \pi^-) = 2063 \pm 94.$$

C. $K_1{}^0 \to 2\pi^0$ Decays

1. Scanning Results

One recognizes the $2\pi^0$ decay mode by observing the conversion to electron pairs in the liquid xenon of 2, 3, or 4 of the γ rays associated with the decay of the π^0's. After finding a charge exchange fulfilling the criteria described in Sec. II A, the scanners looked for two or more electron pairs which corresponded to γ rays having copunctal flight paths, the intersection point being the $K_1{}^0$ decay point. In addition, the scanners noted all events having only a single electron pair pointing *directly* to the charge exchange; these latter events were used to determine the number of charge-exchange events induced by the π^+ which occurred as a small contamination of the beam (See Sec. II C-4).

In addition to real $K_1{}^0 \to 2\pi^0$ decays, the events found by the scanners included a small admixture of a variety of background processes of which the main ones are:

(a) K^+ decays in flight by the mode $K^+ \to e^+ + \pi^0 + \nu$. In some cases, the electron may be mistaken for a prong, or in others, if it produces a sizeable shower, it may be taken to arise from the close conversion of a γ ray.

(b) $\bar{K}^0$ interaction giving rise to a π^0 which leads to two electron pairs.

(c) Charge-exchange interactions in which an additional π^0 was created, and the K^0 did not decay within the chamber.

(d) Charge-exchange interactions by π^+ mesons contaminating the beam.

Events in categories (a) and (b) above are readily identified on the scanning table and were eliminated by the following procedure. Every purported $K_1{}^0 \to 2\pi^0$ decay noted by the scanners was studied by at least one physicist. As a further check about 40% of the events were looked at by two physicists. As a result of this study, we believe that all but a negligible fraction of the background arising from K^+ decays in flight and from K^0 interactions was eliminated.

Events in categories (c) and (d) above are not readily identified on the scan tables. In this connection it should be noted that the finite decay length of the K^0, absent from these background events, is not of much help in purifying the sample. This follows from the fact that, because of the sizeable measuring errors in determining the directions of the pairs, and the rather low momenta of most $K_1{}^0$, a substantial fraction of the real $K_1{}^0 \to 2\pi^0$ events have decay lengths that are not significantly distinguishable from zero. Corrections arising from this sort of background were made statistically and are discussed in Sec. II C-5.

TABLE III. Scanning results.

Type	Both scanners	One scanner
4γ	287	29
3γ	401	65
2γ	259	87

Table III shows the distribution of decay events found in the scan according to the number of γ rays converting, 2γ, 3γ, or 4γ, and according to whether the event was found by *both* of the original scanners, or only one. This division allows one to estimate the scanning efficiency. As will be seen later, the events found by both scanners are real more frequently than those found by only one scanner.

2. Measuring Results

All 2γ, 3γ, and 4γ events (referring to the number of γ-ray conversions) in about 30% of the rolls were measured. In addition to the general restrictions imposed upon the charge exchange and the allowable fiducial region (the first four restrictions in Sec. II B), it was required that only electron pairs with vertices further than 2 cm from any wall of the bubble chamber be counted as converted γ rays, and that their flight paths intersect within a small region in space appropriate to the measuring errors. The results of the measurement are given in Table IV. Many of the events which are counted under "fail" were eliminated not because they were not real events, but because one of the fiducial-volume requirements was not satisfied. The fraction of scanned events which satisfied all requirements was high, and only a small correction was needed to account for the events in the unrescanned rolls which did not belong in the sample. To make this correction we can write

$$N_j = \sum_{i=2,3,4} N_j{}^i + \sum_{i=2,3,4} N^i (N_j{}^i / \sum_{k=f,2,3,4} N_k{}^i),$$

where N_j is the maximum-likelihood estimate of the number of real events in the sample having j γ-ray conversions, with $j=2, 3, 4$; N^i is the number of events

TABLE IV. Measurement results.

Scan classification	Both scanners 4γ	3γ	2γ	Fail	One scanner 4γ	3γ	2γ	Fail
4γ	70	11	0	2	6	0	0	3
3γ	9	96	7	8	2	8	1	2
2γ	0	9	76	13	0	3	17	10

TABLE V. Numbers of events corrected for measurements and scanning efficiency.

Type	After measurement corrections Both scanners	One scanner	Scan efficiency correction	Total
4γ	272	29	10	311
3γ	383	49	10	442
2γ	224	55	25	304

in the unmeasured rolls having i γ-ray conversions, according to the scanning results, with $i=2$, 3, 4; and $N_j{}^i$ is the number of events in *measured* rolls, which had i γ-ray conversions in the scanning results but, after measurement, had $j=2$, 3, 4 γ conversions, or failed $(j=f)$.

The results of this estimate are shown in Table V. The scanning efficiency correction takes account of the real events that were missed by both scanners. These numbers were computed from the results of 24 rolls which were completely and carefully scanned by physicists, and in which five new events were found, compared with 105 found by the scanners. It should be noted that this is a considerably larger correction than would be obtained from the first two columns of Table V and the assumption that events are missed randomly by scanners. As pointed out before, this assumption leads only to an upper limit for the scanning efficiency. Of course, the correction based upon the 24 rolls assumes that the physicist scan and the two nonphysicist scans have jointly found *all* the events.

3. *Correction for Gamma Conversion Efficiency*

The results of the preceding section give the correct number of $K_1{}^0 \to 2\pi^0$ decays resulting in 2, 3, and 4 electron pairs, except for a correction for π^+ beam contamination, which will be discussed in the following section, and for other relatively minor corrections. The number of decays yielding 0 or 1 electron pair can be computed, in principle, from a knowledge of the mean free path for pair production in xenon, as a function of γ-ray energy and the potential path available for each γ-ray. The conversion mean free path is readily computed from theory to a precision of about 1%. The number of expected γ-ray conversions was then found by a Monte Carlo analysis based on observed $K_1{}^0 \to \pi^+ + \pi^-$ events. The actual directions and energies of the K^0 particles were used, but the pions were assumed to be π^0's, and both the K^0 and π^0 were allowed to decay isotropically in their own rest frames. The conversion or nonconversion of each γ ray was then determined on a statistical basis, using the known γ-ray energy and potential path. A large number of such calculations were made, resulting in the conversion probabilities shown in the first column of Table VI.

In comparing these probabilities with the experimental results of Table V, one must note that the number of 2γ events, N_2, is substantially affected by the π^+ contamination in the beam. On the other hand, the numbers of 3γ and 4γ events are only negligibly affected and thus provide a useful basis of comparison between calculation and experiment. From these numbers we find that the actual average conversion efficiency is about 74% instead of 80% as predicted by the Monte Carlo results. This difference, already noted in a previous experiment,[2] arises because some electron pairs, by virtue of their short ionizing path length or their large dip angle, are not recognizable above the background. To correct our conversion efficiencies for this effect we assume that a fraction ξ of the electron pairs are missed because of their unfavorable configuration. If we further suppose that, because of energy correlations in the decay, at most one such electron pair exists in any $K_1{}^0$ decay, we can relate the conversion efficiencies calculated by the Monte Carlo analysis to those actually observed. Specifically, if C_{nt} and C_{ne} are the true and effective conversion efficiencies for n electron pairs, we have

$$C_{4e}=C_{4t}(1-4\xi),$$
$$C_{3e}=C_{3t}(1-3\xi)+4C_{4t}\xi,$$
$$C_{2e}=C_{2t}(1-2\xi)+3C_{3t}\xi,$$
$$C_{1e}=C_{1t}(1-\xi)+2C_{2t}\xi,$$

and

$$C_{0e}=C_{0t}+C_{1t}\xi.$$

By comparing the ratio C_{4e}/C_{3e} with our observed ratio of 4γ and 3γ events, we compute $\xi=0.065$, and the conversion efficiencies given in Column 2 of Table VI. From these we can calculate the numbers of N_1 and N_0 of 1γ and 0γ events. First, however, we consider the corrections due to the small π^+ contamination.

4. *Beam-Contamination Correction*

Although the estimated π^+ contamination is only about 2%, the rather high probability of charge exchange into one or more π^0's leads to a nonnegligible background of events indistinguishable from $K_1{}^0 \to 2\pi^0$ decays. To correct for this contamination, we use two sources of information.

(a) During part of the experiment, the chamber was exposed to a π^+ beam to ascertain what π^+ charge-exchange events occurred. The major result is that

TABLE VI. γ-ray conversion efficiencies.

Type	Monte Carlo results	Corrected efficiencies
4γ	0.389	0.287
3γ	0.380	0.407
2γ	0.174	0.226
1γ	0.049	0.069
0γ	0.008	0.011

TABLE VII. Final numbers of 4, 3, 2, 1, and 0γ events.

Type	Numbers from Table V	π contamination corrections	Numbers after correction	Calculated numbers
4γ	311	-4	307	
3γ	442	-6	436	
2γ	304	-67	237	
1γ				74
0γ				12
			Total	1066

the ratio of $4\gamma:3\gamma:2\gamma:1\gamma$ events is about 1.00:1.42: 15.2:10.7. Unfortunately, our knowledge of the pion contamination in the K^+ beam is not sufficiently precise to permit direct use of the cross sections measured in the π^+ film for making the necessary corrections in the K^0 data.

(b) Instead, we made a study of events with a charge exchange and one electron pair pointing to the interaction vertex. The usefulness of this is easily seen from the following numbers. About 40% of all π^+ charge exchanges lead to a single electron pair, always pointing to the interaction vertex. On the other hand, only 7% of all $K_1^0 \to 2\pi^0$ decays yield a single pair. Furthermore, in only about 45% of these does the pair appear to point to the charge exchange, within the rather large experimental errors. Thus, the π^+ charge exchanges are greater than an order of magnitude more effective in giving 1γ events than $K_1^0 \to 2\pi^0$ decays; hence, the number of such events is very sensitive to contamination. Specifically, the expected number of single-pair events from $K_1^0 \to 2\pi^0$ decays is given by

$$N_1 = 0.45 C_{1e}(N_3+N_4)/(C_{3e}+C_{4e}) = 33 \text{ events},$$

whereas 80 such events were observed. This leaves 47 1γ events due to π^+. From the ratios of the various kinds of events obtained in the π^+ film, we infer that there are $47\times(15.2/10.7)=67$ π^+-induced 2γ events, six 3γ events, and four 4γ events (Table VII, column 2). These events are subtracted from the total.

Since the simultaneous production of a π^0 and a K^0 which does not decay in the chamber produces a contamination that is phenomenologically similar to π^+ contamination,[11] the former effect is automatically corrected by the procedure used here for subtracting the effect of π^+ contamination. Therefore, this effect (which is small) need not be considered separately, except to determine what part of the correction is due to π^+-induced events. This was done to estimate the π^+ beam contamination; the result was that 2 to 3% of the K^+ beam was π^+ mesons. This value agrees well with the measurements of other experimenters using the same beam.[9]

[11] This is true only if the production of more than one π^0 in π^+ charge exchange is neglected. From the above-quoted ratio of $4\gamma:3\gamma:2\gamma:1\gamma$ in the π^+ film, this appears to be a good approximation.

5. *Final Number of $K_1^0 \to 2\pi^0$ Decays*

All the necessary corrections can now be used to obtain the final number of $K_1^0 \to 2\pi^0$ events. The final numbers of 2γ, 3γ, and 4γ events are given in Table VII. By using the efficiencies in the last column of Table VI, we infer an additional 86 1γ and 0γ events, making a total of 1066 $K_1^0 \to 2\pi^0$ decays in the sample.

6. *Errors*

A computer program was written to calculate the effect of statistical fluctuations of the many independent input quantities upon the final result. The most significant errors result from the following sources:

(a) The error ΔN in the final number of $K_1^0 \to 2\pi^0$ events which is attributable to statistical fluctuation in the number of 3γ events is $\Delta N=\pm 37$. Here a fluctuation causing N_3 to be too large is reflected in too low an estimate of conversion efficiency. This causes too large an estimate of the number of 0γ and 1γ events. Furthermore, this leads to an underestimate of the π^+ contamination. All these effects are in the same direction insofar as they affect the final number of $K_1^0 \to 2\pi^0$ decays.

(b) Statistical uncertainties in other than 3γ events lead to $\Delta N=\pm 39$.

(c) For the error due to uncertainties in scanning efficiency we have $\Delta N=\pm 18$.

(d) The error due to uncertainty in gamma-ray efficiency is $\Delta N=\pm 11$. The small error here reflects the fact that the calculated number of 1γ and 0γ events is not sensitive to the model used to account for the difference between the observed conversion efficiency and its calculated value. The observed ratio of 3γ and 4γ events leads to 1γ and 0γ contributions in a nearly model-independent way.

Combining these errors, we find

$$N(K_1^0 \to 2\pi^0) = 1066 \pm 58.$$

If *all* events had been measured, instead of only 30%, the error would only have been reduced to $\Delta N=\pm 44$.

III. RESULTS AND CONCLUSIONS

A. Branching Ratio: Comparison with $|\Delta \mathbf{T}|=1/2$ Rule

As pointed out before, all previous numbers were obtained from about 83% of the film. The remaining 17% was analyzed in a similar but not identical manner. The numbers of events that resulted from this portion of the data are added to the previous data to give

$$N(K_1^0 \to \pi^+ + \pi^-) = 414 + 2063 = 2477,$$

and

$$N(K_1^0 \to 2\pi^0) = 184 + 1066 = 1250.$$

The branching ratio is

$$B(K_1{}^0)=N(K_1{}^0\to 2\pi^0)/[N(K_1{}^0\to 2\pi^0)+N(K_1{}^0\to \pi^+ + \pi^-)]$$
$$=0.335\pm 0.014.$$

It is of interest to compare this result with the prediction of the $|\Delta\mathbf{T}|=1/2$ rule, which would require the final two-pion state to be $T=0$. Aside from a phase-space correction due to the $\pi^\pm - \pi^0$ mass difference, the ratio is predicted to be $B(K_1{}^0)=1/3$; with the phase-space correction we have

$$B(K_1{}^0)=0.337 \quad (|\Delta\mathbf{T}|=1/2 \text{ rule}).$$

B. Fraction of K^0 Decays by Two–Pion Modes

An additional measurement of the ratio

$$N(K_1{}^0\to 2\pi)/N(K^0)=[N(K_1{}^0\to 2\pi^0)+N(K_1{}^0\to \pi^+ + \pi^-)]/N(K^0)$$

was made in 47 rolls (about 13% of the film), to serve mainly as a check upon possible spurious effects which might influence the previously quoted results. To obtain this result, a physicist examined all charge exchanges as well as all $K_1{}^0$ decays in the 47 rolls, to be sure they satisfied all criteria. About half of the charge exchanges *without* $K_1{}^0$ decays were measured to determine what fraction did not lie within the appropriate fiducial region, or within 12 deg of the beam direction.

By using the same procedures described in Secs. II B and II C, we determined the number of $K_1{}^0$ decays into $\pi^+ + \pi^-$ and $2\pi^0$'s in this subsample. By a similar sampling procedure, the number of charge exchanges not accompanied by $K_1{}^0$ decays in the sample was computed from the measured number of such events. The results are

$$N(K_1{}^0\to \pi^+ + \pi^-)=345,$$
$$N(K_1{}^0\to 2\pi^0)=177,$$
$$N(K^0)=1009,$$
$$N(K_1{}^0\to 2\pi)/N(K^0)=0.52\pm 0.02.$$

The good agreement between this result and the predicted value[12] of 0.5 gives additional confidence in the validity of our result for $B(K_1{}^0)$.

C. Interpretation and Conclusions

As was noted at the beginning, most of the experimental information on nonleptonic decays of strange particles seems to agree with the predictions of the $|\Delta\mathbf{T}|=1/2$ rule. The notable exceptions are (a) the failure of the "Σ triangle" to close, based upon recent measurements of the asymmetry parameters, and (b) a recent experimental determination of the $K_2{}^0\to \pi^+\pi^-\pi^0$ rate. These two results need to be confirmed before being regarded as conclusive evidence against the $|\Delta\mathbf{T}|=1/2$ rule.

Our experimental result for $B(K_1{}^0)$ of 0.335 ± 0.014 is in excellent agreement with the value 0.337 predicted by the rule. It has been noted at the beginning that the rate for $K^+\to 2\pi$ decay, forbidden by the rule, is indeed very low, but nevertheless considerably larger than one would expect from simple estimates of electromagnetic corrections. There are several possible explanations for the unexpectedly high $K^+\to 2\pi$ rate in the light of the agreement between the present result of 0.335 and the $|\Delta\mathbf{T}|=1/2$ rule prediction for the $K_1{}^0$ decay. Two such explanations are

(1) There is a small admixture of $|\Delta\mathbf{T}|=3/2$ transition in the basic K decay. In this case, in order to yield a $K_1{}^0$ branching ratio in agreement with our experimental result, the difference between the $T=0$ and $T=2$ $\pi-\pi$ phase shifts (for $J=0$, at a total energy corresponding to the K mass) must be limited to the region near 90 deg.[13] Future experiments on pion-pion interactions can test whether this is in fact so.

(2) The $|\Delta\mathbf{T}|=1/2$ rule is exact, but the electromagnetic corrections used in calculating the $K_{\pi 2}{}^+$ decay rate are unusually large. For example, Feinberg and Pais have pointed out that the existence of a particle with $T=1$, $J=0^+$ and a mass near the K^+ mass can enhance the predicted $K_{\pi 2}{}^+$ rate while not appreciably affecting the $K_1{}^0$ branching ratio.[14]

In conclusion, we may summarize the results of the present experiment as follows:

(a) Within our experimental errors, we find no evidence for a reflection of the slight violation of the $|\Delta\mathbf{T}|=1/2$ rule implied by the large $K_{\pi 2}{}^+$ decay rate in the $K_1{}^0\to 2\pi^0$ branching ratio. Whatever mechanism is involved to account for the $K_{\pi 2}{}^+$ rate must have the property of affecting only very slightly the $K_1{}^0\to 2\pi^0$ branching ratio.

(b) The $|\Delta\mathbf{T}|=1/2$ rule seems to work very well for the $K_1{}^0\to 2\pi$ decay. We find no indication from this process of the breakdown of the rule suggested by the experiments on $\Sigma^+\to p+\pi^0$ and $K_2{}^0\to \pi^+ + \pi^- + \pi^0$ decay.

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[12] In making this prediction, we have neglected the effects of the much rarer $K_1{}^0$ leptonic decay modes.

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