[6]S. Koslov, footnote a of Table I.

[7]G. Shapiro (private communication) has independently considered this possibility.

[8]J. W. M. DuMond (private communication). We are grateful to Professor DuMond for having called our attention to this very important feature.

[9]The uncertainty of 0.00022 being now reduced to 0.00005.

[10]G. Shapiro, at Columbia University also evaluated with D. Tycko the second-order vacuum polarization contribution on the IBM 650 computer, with the same result as we quote on the first line of the table.

THREE-BODY DECAYS OF K_2^0 AND K_1^0*

Frank S. Crawford, Jr., Marcello Cresti,† Roger L. Douglass, Myron L. Good, George R. Kalbfleisch, and M. Lynn Stevenson
Lawrence Radiation Laboratory, University of California, Berkeley, California
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In the course of our associated-production experiment using the Berkeley 10-inch liquid hydrogen bubble chamber, we have seen nine "anomalous" K^0 decays. Within their limited statistical accuracy these events (a) are consistent with equal leptonic decay rates for K_1^0 and K_2^0, (b) are in good agreement with decay rates predicted[1] by the "extended" $\Delta I = \frac{1}{2}$ rule, and (c) yield a new value for the K_2^0 lifetime.

In the entire experiment we find[2] 497 decays of the type $K_1^0 \to \pi^+ + \pi^-$ (that is, $N_{+-} = 497$), from K^0 produced via $\pi^- + p \to \Lambda + K^0$ or $\Sigma^0 + K^0$. The production and decay points are required to lie within a well-defined fiducial volume in the chamber. Of the nine K^0 decays which fail to fit $\pi^+\pi^-$ decay, one (previously reported[2]) fits $\pi^+\pi^-\pi^0$ decay ($N_\tau = 1$) and eight fit leptonic decay into $\pi^\pm\mu^\mp\nu$ and $\pi^\pm e^\mp\nu$ ($L = 8$). The incident π^- momentum is known precisely.[3] Therefore the K^0 momentum is known from its production angle. (There are actually four possibilities, corresponding to Λ and Σ^0 production, and to forward and backward c.m. production.) For given rest-mass assignments to the two charged decay fragments, and from their measured momenta, we can determine the missing energy and momentum, and therefore the rest mass of the neutral decay fragment. The errors are such that it is fairly easy to distinguish between the $\pi^+\pi^-\pi^0$ decays (135-Mev neutral rest mass) and the leptonic decays (zero neutral rest mass) and to eliminate all but one possible K^0 momentum. However, the four leptonic modes are not easily distinguishable among themselves, since the total energies of the charged decay fragments are determined largely by the momenta rather than by the rest masses. With a larger sample of data, a statistical separation would be possible.

A leptonic K^0 decay can escape detection by simulating a $\pi^+\pi^-$ decay. From the available phase space and known measurement errors, we estimate that less than 10% of the three-body decays are thus masked. No corresponding correction was made to L.

The events are listed in Table I and a photograph of one of the decays is shown in Fig. 1.

The "true" number of K^0 produced in the experiment is 2020 ± 100.[2] According to CPT invariance, half of these (K_1^0) should be short-lived ($N_1 = 1010$) and half (K_2^0) long-lived ($N_2 = 1010$).[4] Gell-Mann[5] has shown that if CP invariance holds, and if the weak interactions are not such as to allow $\Sigma^+ \to n + e^+ + \nu$, then K_1^0 and K_2^0 should undergo leptonic decay at the same rate,

$$\Gamma_{1L} = \Gamma_{2L}. \tag{1}$$

(The oscillatory interference terms between K_1^0 and K_2^0 disappear in the sum over both signs of electric charge of the decay products.)

There are two ways in which we can check the prediction (1). The first is to look at the time

Table I. K^0 three-body decays. T is the K^0 proper potential time and t the proper lifetime.

Event	p_K (Mev/c)	T (10^{-10} sec)	t (10^{-10} sec)
203 999	615	2.60	1.29
235 805	760	1.20	0.56
288 517	670	2.87	1.54
359 058	680	3.60	1.21
385 627	684	2.87	0.67
416 759	656	3.79	1.63
448 646[a]	298	4.89	2.32
499 237	240	9.16	3.81
501 242	120	13.22	0.20

[a]Decays into $\pi^+\pi^-\pi^0$. (The remaining eight decays are leptonic.)

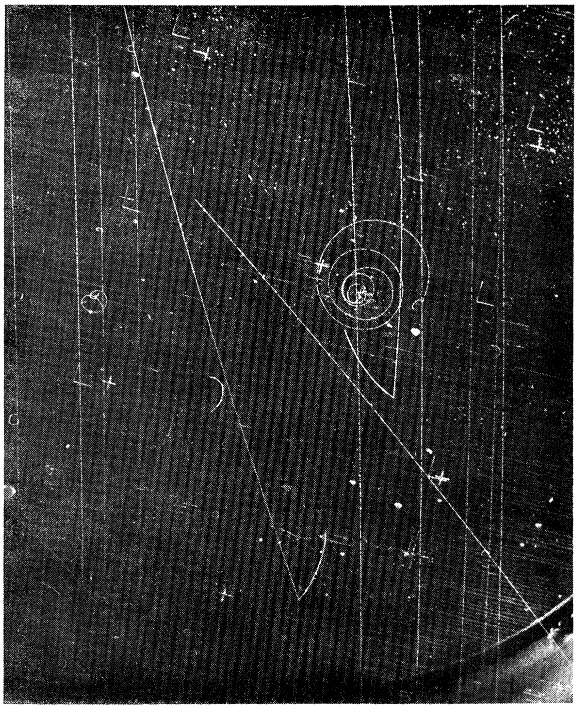

FIG. 1. Event 416 759. The production process is $\pi^- + p \rightarrow \Sigma^0 + K^0$, $(\Sigma^0 \rightarrow \Lambda + \gamma)$. The Λ decay into $p + \pi^-$ occurs closest to the production point. The other vee is best fitted by $K^0 \rightarrow \pi + e + \nu$. A large unbalance in the "visible" transverse momentum is obvious by inspection in the K^0 decay.

distribution of leptonic decays in the chamber. Decays from K_2^0 should be practically uniformly distributed over their potential proper times T. (T is the time interval in the K^0 rest frame between the K^0 production and the escape of the K^0—or of the center of mass of the decay fragments—across the boundary of the fiducial volume.) Therefore the number of leptonic decays from K_2^0 is given by

$$L_2 = N_2 \Gamma_{2L} \overline{T}, \tag{2}$$

where $\overline{T} = 3.21 \times 10^{-10}$ sec is the K^0 average potential time. Decays from K_1^0 should have, for a given T, the proper time distribution

$$dL_1 = N_1 \Gamma_{1L} \exp(-\lambda_1 t) dt, \tag{3}$$

between $t = 0$ and T. We attempt to distinguish L_1 from L_2 by constructing a likelihood function involving the flat distribution (2), and the exponential decay (3). The result is consistent (within one standard deviation) with either 100% K_1^0 or 100% K_2^0 decays. $\overline{T}$ is simply not long enough compared with the K_1^0 lifetime (for which we find $\lambda_1^{-1} = 0.94 \times 10^{-10}$ sec) to provide a sensitive test.

The second method of checking Eq. (1) makes use of the "Columbia" results for the K_2^0 lifetime and leptonic decay fraction measured by Bardon et al.[6] Their lifetime corresponds to the total decay rate

$$\Gamma_2(\mathrm{Col}) = \left(12.3^{+5.2}_{-3.5}\right) \times 10^6 \ \mathrm{sec}^{-1}. \tag{4}$$

They find no other K_2^0 decay modes besides $\pi\mu\nu$, $\pi e \nu$, and $\pi^+\pi^-\pi^0$, and find that 85 to 98% of the decays are into the leptonic modes. From Eq. (2) they can then predict the number of K_2^0 leptonic decays, L_2, expected in our experiment. By subtraction we can find L_1 and check Eq. (1). L_1 is obtained by normalizing to the $\pi^+\pi^-$ decays of K_1^0, since they have the same time distribution. Then

$$L_1 = N_{+-} (\Gamma_{1L} / \lambda_1 R_1), \tag{5}$$

where R_1 is the fraction 0.68 ± 0.04 of K_1^0 that decays into $\pi^+\pi^-$.[2] If we assume $\Gamma_{1L} = \Gamma_{2L}$, we can combine Eqs. (2) and (5) to obtain the total predicted leptonic decay rate,

$$L = \Gamma_{2L} [N_2 \overline{T} + (N_{+-} / \lambda_1 R_1)]. \tag{6}$$

In order to increase the sensitivity, we look only in the first K_1^0 mean life. Then the first term in (6) is reduced by a factor $\tau_1 / \overline{T}$ and the second by $1 - e^{-1}$. From the Columbia result Eq. (4), we then predict $L_1 = 0.5^{+0.2}_{-0.1}$ and $L_2 = 1.1^{+0.4}_{-0.3}$, or $L = 1.6^{+0.7}_{-0.4}$, which is to be compared to our three observed counts that occur between $t = 0$ and 0.94×10^{-10} sec. We thus find $\Gamma_{1L} / \Gamma_{2L} = 3.5^{+3.9}_{-2.7}$. Within the errors, Eq. (1) is satisfied. We will assume that Eq. (1) holds in what follows.

If one assigns isotopic spin $I = 0$ to leptons, then the hypothesis that there is a selection rule $|\Delta \vec{I}| = \frac{1}{2}$ can be "extended" to leptonic decays (e.g., $K^+ \rightarrow \mu^+ + \nu$ then satisfies the rule.) According to either the extended $|\Delta \vec{I}| = \frac{1}{2}$ rule or the "$I = \frac{1}{2}$ current" hypothesis[1,7] (which allows in general $\Delta I = \frac{3}{2}$ as well as $\frac{1}{2}$), the leptonic decay rates of K^+ and K_2^0 are related. One has $\Gamma(K_2^0 \rightarrow e^\pm \pi^\pm \nu) = 2\Gamma(K^+ \rightarrow e^+ \pi^0 \nu)$, and an exactly analogous relation with e replaced by μ. If we add these two relations, the left side becomes the total K_2^0 leptonic decay rate Γ_{2L}. The right side can be evaluated by using K^+ lifetimes[8] and branching ratios[9] as averaged by Gell-Mann and Rosenfeld.[5] The resulting prediction[7] is

$$\Gamma_{2L} = (13.4 \pm 1.4) \times 10^6 \text{ sec}^{-1}. \tag{7}$$

Inserting our observation of $L = 8$ leptonic decays into Eq. (6) yields

$$\Gamma_{2L} = \left(20.4^{+7.2}_{-5.6}\right) \times 10^6 \text{ sec}^{-1}. \tag{8}$$

Our experimental result (8) is consistent with the prediction (7).

We now determine the K_2^0 lifetimes as follows. Corresponding to our one observed K_2^0 decay into $\pi^+\pi^-\pi^0$ ($N_\tau = 1$) there should be an additional 1.5 unobserved decays into $3\pi^0$.[10] (The decay of K_1^0 into $\pi^+\pi^-\pi^0$ should be negligible.[10]) Thus the K_2^0 decay rate into 3π is given by

$$\Gamma_{2\tau} = 2.5 N_\tau / N_2 \overline{T} = 7.7 \times 10^6 \text{ sec}^{-1}, \tag{9}$$

based on one event. Since there are no appreciable K_2^0 decay modes other than into 3π and leptons,[6] the total K_2^0 decay rate is given by adding our results (8) and (9) to obtain [subject to the assumption that Eq. (1) holds]

$$\Gamma_2(\text{UC}) = \left(28^{+10}_{-8}\right) \times 10^6 \text{ sec}^{-1}. \tag{10}$$

According to the $\Delta I = \frac{1}{2}$ rule (but not the $I = \frac{1}{2}$ current rule, except by accident) $\Gamma_{2\tau} = (6.0 \pm 0.4) \times 10^6$ sec^{-1} is predicted from the known K^+ decay rate into 3π.[1,10] After noting[2] the fortuitous agreement with our result (9), we combine this with the prediction (7) to yield a predicted[1] total K_2^0 decay rate

$$\Gamma_2(\Delta I = \tfrac{1}{2}) = (19.4 \pm 1.5) \times 10^6 \text{ sec}^{-1}, \tag{11}$$

in fair agreement with our experimental result (10).

Finally, since our K_2^0 decay rate (10) is in reasonable agreement with the result (4) of Bardon et al., we combine the two results to obtain[11]

$$\Gamma_2(\text{UC, Col}) = (16.3 \pm 3.5) \times 10^6 \text{ sec}^{-1},$$

in excellent agreement with the prediction (11) of the $\Delta I = \frac{1}{2}$ rule.

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†Now at Istituto di Fisica, Universitá di Padova, Padova, Italy.

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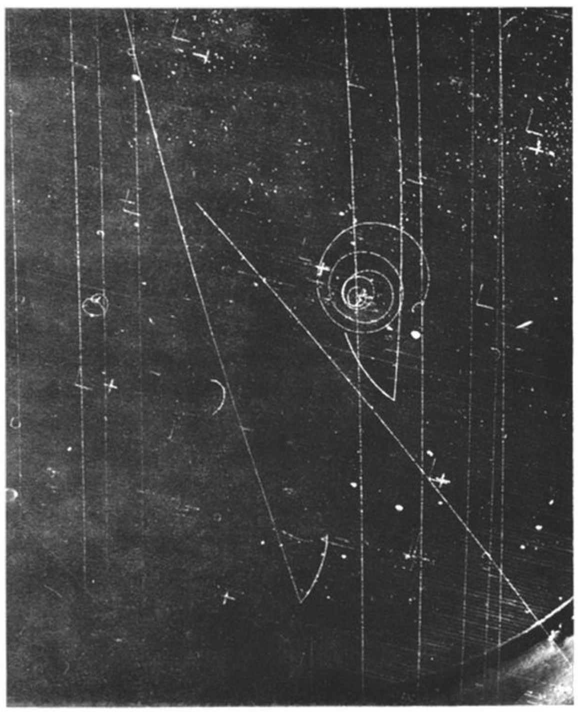
[11] We combine the two lifetimes by constructing a likelihood function (LF) for each experiment and then multiplying them together to form a combined LF. The quoted errors correspond to a decrease of the combined LF by a factor exp(-1/2) from its maximum value. (This corresponds to 1 standard deviation for a Gaussian.) In terms of K_2^0 mean life the result is $\tau_2(\text{UC, Col}) = (6.1^{+1.6}_{-1.1}) \times 10^{-8}$ sec.



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