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MAGNITUDE OF THE K_1^0-K_2^0 MASS DIFFERENCE USING STRONG INTERACTIONS*

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Experiments to determine the magnitude δ of the K_1^0-K_2^0 mass difference have used two essentially different methods. These are as follows:

(I) Strong interactions.[1,2]—Starting with a sample of K^0 at time $t=0$, one detects the subsequent time development of $\bar{K}^0$ by means of secondary strong interactions. Three published strong-interaction experiments[3-5] give the following results (the units are inverse K_1^0 lifetime): $\delta<10$, $\delta=1.9\pm0.3$, and $\delta=1.5\pm0.2$.

(II) Coherent regeneration.[1,6]—Starting with a K_2^0 beam, one detects $\pi^+\pi^-$ decays from K_1^0 coherently regenerated in matter. Five published coherent-regeneration experiments[7-11] give the following results: $\delta=0.84_{-0.22}^{+0.29}$, 0.55 ± 0.10, 0.82 ± 0.12, 0.82 ± 0.14, and 0.50 ± 0.10. Thus there has been a discrepancy of more than a factor of two between the average of the values of δ obtained through strong interactions and those obtained through coherent regeneration.[12]

In this paper we report a new measurement of δ using the strong-interaction method. The K^0 are produced in the Alvarez 72-inch hydrogen bubble chamber by associated-production reactions involving a visible Λ decay:

$$\pi^-+p\to\Lambda+K^0,\quad \Lambda\to p+\pi^-\ \text{(5860 events)},\qquad (1a)$$

and

$$\pi^-+p\to\Sigma^0+K^0,\quad \Sigma^0\to\gamma+\Lambda,\quad \Lambda\to p+\pi^-\ \text{(1360 events)}.\qquad (1b)$$

The time development of $\bar{K}^0$ intensity is detected through the secondary interactions

$$\bar{K}^0+p\to\Lambda+\pi^+\quad\text{(25 events)},\qquad(2a)$$
$$\to\Sigma^0+\pi^+\quad\text{(19 events)},\qquad(2b)$$
$$\to\Sigma^++\pi^0\quad\text{(9 events)},\qquad(2c)$$
$$\to\Lambda+\pi^++\pi^0\quad\text{(4 events)},\qquad(2d)$$
$$\to\Sigma^++\pi^++\pi^-\quad\text{(1 event)},\qquad(2e)$$
$$\to\Lambda+\pi^++\gamma\quad\text{(1 event)}.\qquad(2f)$$

Our statistics are limited (59 events), but we believe that the experiment is free of sources of systematic bias. We find (in units τ_1^{-1}, with $\tau_1=0.88\times10^{-10}$ sec)

$$\delta=0.65\pm0.30.\qquad(3)$$

Our result (3) is in poor agreement with previous determinations of δ using strong interactions,[4,5] and in good agreement with determinations using coherent regeneration.[7-11]

We conclude that the strong-interaction and coherent-regeneration methods give compatible results. A least-squares average of our result (3) and those of the five coherent-regeneration experiments gives $\delta=0.64\pm0.06$, with $\chi^2=7.3$ giving a χ^2 probability of 0.20.

The events are described in Table I. Their time distribution is shown in Fig. 1. Our likelihood function for δ is shown in Fig. 2, together with the results of other determinations.

Table I. Summary of 59 events. t and T are the actual and the potential $\bar{K}^0$-interaction proper times in 10^{-10} sec. P_{K^0} is the K^0 lab momentum in MeV/c. Under "Type," the first symbol gives the hyperon produced with the K^0; symbols after the comma give the $\bar{K}^0$-p interaction products; parentheses indicate an invisible Λ decay; $\Sigma_0{}^+$ and $\Sigma_+{}^+$ mean $\Sigma^+ \rightarrow \pi^0 + p$ and $\pi^+ + n$, respectively.

Event	Type	t	P_{K^0}	T
516228	$\Lambda, \Lambda\pi^+$	6.85	123.6± 4.8	29.79
522520	$\Lambda, \Sigma^0\pi^+$	9.07	541.7± 5.6	17.54
553409	$\Lambda, (\Lambda)\pi^+$	25.14	625.5± 9.7	27.40
575094	$\Lambda, \Sigma^0\pi^+$	9.43	293.8± 3.7	20.99
591168	$\Lambda, \Lambda\pi^+$	42.00	604.8± 5.4	42.53
683291	$\Lambda, \Lambda\pi^+$	38.46	140.2± 1.6	49.87
683475	$\Lambda, \Sigma_0^+\pi^0$	3.82	224.5± 5.3	15.31
694525	$\Lambda, (\Sigma^0)\pi^+$	15.50	124.4± 2.3	36.28
699421	$\Lambda, \Sigma^0\pi^+$	14.97	573.9± 6.1	20.02
703249	$\Lambda, \Lambda\pi^+$	9.78	549.5± 3.8	10.20
714468	$\Sigma^0, \Lambda\pi^+$	20.16	297.1± 2.8	34.41
742199	$\Lambda, \Lambda\pi^+$	5.38	401.1± 8.8	8.56
771175	$\Lambda, (\Lambda)\pi^+$	7.52	239.2± 3.5	9.14
815263	$\Lambda, \Sigma_+^+\pi^0$	12.24	557.7± 5.1	30.51
818498	$\Lambda, \Lambda\pi^+$	11.99	369.4± 6.0	13.85
836282	$\Lambda, \Sigma^0\pi^+$	5.00	265.7±12.4	19.56
839268	$\Lambda, \Sigma_+^+\pi^0$	3.26	378.0± 4.9	15.65
867230	$\Lambda, \Lambda\pi^+$	15.11	590.6± 7.3	17.38
1352419	$\Lambda, \Lambda\pi^+\pi^0$	2.06	740.0± 5.6	6.03
1353067	$\Lambda, \Sigma_+^+\pi^0$	1.65	630.4± 5.3	14.58
1354371	$\Lambda, (\Lambda)\pi^+$	1.32	493.1± 7.4	6.62
1358016	$\Lambda, \Lambda\pi^+$	6.74	745.7± 6.9	25.19
1368592	$\Lambda, (\Sigma^0)\pi^+$	4.20	815.0± 6.2	13.46
1372223	$\Lambda, \Sigma^0\pi^+$	2.36	766.9± 6.4	3.61
1380336	$\Lambda, (\Sigma^0)\pi^+$	3.08	86.7± 3.7	10.44
1382488	$\Sigma^0, \Sigma^0\pi^+$	57.47	117.6± 7.8	70.50
1385110	$\Lambda, \Lambda\pi^+$	1.85	717.0± 6.3	6.73
1405053	$\Lambda, \Lambda\pi^+\gamma$	4.42	563.3± 5.2	12.67
1405102	$\Sigma^0, \Sigma^0\pi^+$	5.94	315.5±14.8	8.45
1440184	$\Lambda, \Lambda\pi^+$	2.72	299.8± 6.7	22.07
1446440	$\Sigma^0, \Sigma^0\pi^+$	101.90	75.5± 4.2	165.79
1461434	$\Lambda, \Sigma^+\pi^+\pi^-$	7.64	651.7± 7.3	8.19
1462557	$\Lambda, \Lambda\pi^+\pi^0$	21.55	768.9± 7.0	22.71
1487194	$\Lambda, \Lambda\pi^+$	9.93	262.9± 3.6	12.90
1494222	$\Lambda, \Sigma_+^+\pi^0$	2.28	655.5± 6.5	12.21
1708440	$\Sigma^0, \Lambda\pi^+$	8.93	280.4± 2.4	45.53
1714443	$\Lambda, \Sigma^0\pi^+$	10.38	263.7±11.0	30.23
1715360	$\Lambda, \Sigma^0\pi^+$	9.44	191.5± 3.5	39.57
1716304	$\Sigma^0, \Sigma^0\pi^+$	39.43	318.5±15.4	75.05
1722436	$\Lambda, \Lambda\pi^+\pi^0$	9.05	516.5± 6.2	13.22
1725518	$\Lambda, (\Lambda)\pi^+$	7.67	540.6± 5.5	11.41
1741572	$\Lambda, (\Sigma^0)\pi^+$	8.55	496.1± 5.5	14.06
1754399	$\Lambda, (\Lambda)\pi^+$	3.86	586.1± 5.3	28.61
1754465	$\Lambda, \Lambda\pi^+\pi^0$	6.51	573.8±12.2	11.31
1772600	$\Lambda, \Lambda\pi^+$	32.67	136.1±17.1	32.69
1773159	$\Lambda, \Sigma_+^+\pi^0$	4.70	623.2± 9.6	23.37
1775496	$\Lambda, \Sigma^0\pi^+$	23.13	321.3± 4.1	27.58
1789342	$\Lambda, (\Lambda)\pi^+$	3.43	221.4± 3.1	29.28
1821055	$\Lambda, \Lambda\pi^+\pi^0$	2.95	602.0± 5.3	18.67
1828522	$\Sigma^0, \Sigma^0\pi^+$	2.82	335.0±26.0	5.18
1829392	$\Lambda, \Lambda\pi^+$	7.81	630.8± 3.9	23.89
1837574	$\Lambda, (\Sigma^0)\pi^+$	21.80	144.2± 3.1	26.87
1846420	$\Lambda, \Sigma_+^+\pi^0$	4.64	489.6± 6.0	8.52
1849021	$\Lambda, \Lambda\pi^+$	16.37	144.8± 3.9	25.52
1857266	$\Lambda, \Lambda\pi^+$	17.20	447.1± 6.9	19.26
1859078	$\Sigma^0, \Sigma^0\pi^+$	16.97	305.1±22.5	77.19
1859410	$\Sigma^0, \Lambda\pi^+$	96.85	225.7± 5.7	106.21
1868172	$\Lambda, \Sigma_0^+\pi^0$	27.38	546.5± 4.6	30.40
1878338	$\Lambda, \Sigma_+^+\pi^0$	14.40	301.6± 3.5	19.50

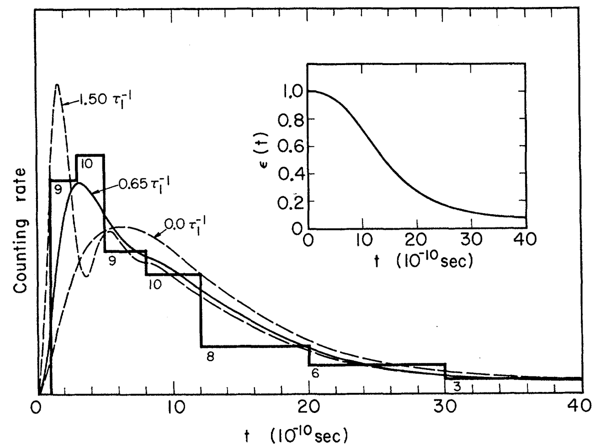

FIG. 1. Time distribution of 59 $\bar{K}^0$-p interactions. The histogram is labeled with the number of events in each interval. (No events were found between $t = 0$ and 1×10^{-10} sec; four events with $t > 40 \times 10^{-10}$ sec are not shown.) The smooth curves correspond to $\delta = 0.65\tau^{-1}$ (our best-fit value), to $\delta = 0$, and to $1.5\tau_1{}^{-1}$ with $\tau_1 = 0.88 \times 10^{-10}$ sec. Their shapes are given by $\bar{I}(t)$ of Eq. (6), times the detection-probability factor $\epsilon(t)$, where $\epsilon(t)$ is the fractional number of K^0 production events having potential time T greater than t.

The K^0's were produced via reactions (1) by incident π^- of 1035 and 1170 MeV/c. All single- and double-vee events were analyzed. Then all single-vee events were carefully re-examined on the scanning table. Scanners search along the calculated direction of the missing neutral for recoils, interactions, or decays that may have been missed in the initial scan. We consider ΛK^0 production, Eq. (1a), and $\Sigma^0 K^0$ production, Eq. (1b), separately.

ΛK^0 production.—The missing-K^0 direction is known typically to within ±0.4 deg in dip and azimuth, and the missing-K^0 momentum to ±1.5%. We scan along the missing-K^0 direction using a protractor, and provisionally accept all interaction candidates within ±5 deg in azimuth of the predicted direction. We believe our scanning efficiency is essentially 100%. Those $\bar{K}$-p interaction candidates that involve visible hyperon decays $\Lambda \rightarrow p + \pi^-$, $\Sigma^+ \rightarrow p + \pi^0$, or $\Sigma^+ \rightarrow n + \pi^+$ have no background. We also accept $\bar{K}^0 + p \rightarrow \pi^+ + (\Lambda)$ or $\pi^+ + (\Sigma^0)$ where the parentheses indicate that the Λ decay is invisible (the 11 events 553 409, etc., in Table I). In that case the π^+ "recoil" is sometimes indistinguishable on the scanning table from a proton recoil arising from an n-p scatter due

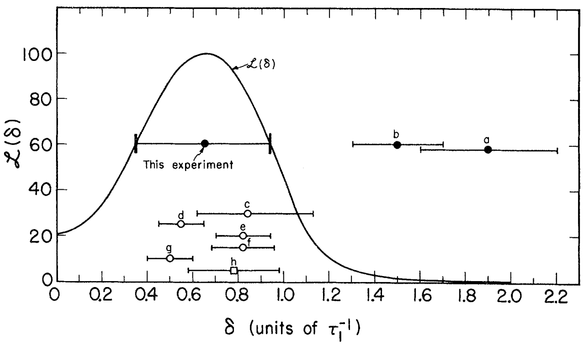

FIG. 2. Likelihood function and results of this and other experiments. The smooth curve is $\mathcal{L}(\delta)$ for this experiment; the standard deviation ±0.30 corresponds to a decrease of $\mathcal{L}$ by a factor $\exp(-\frac{1}{2})$ from its maximum value at $\delta = 0.65\tau_1^{-1}$. At $\delta = 1.5\tau_1^{-1}$, $\mathcal{L}$ is smaller than its maximum value by a factor of 70. For $\delta > 2$, $\mathcal{L}(6)$ is less than its maximum value by three orders of magnitude. The results of the strong-interaction experiments are shown as solid points: a (Ref. 4), b (Ref. 5), and this experiment. The results of the regeneration experiments are the open circles: c (Ref. 7), d (Ref. 8), e (Ref. 9), f (Ref. 10), and g (Ref. 11, assuming $\varphi_{12} = 0$). The open square h (Ref. 12) is the result of the leptonic-decay experiment.

to neutron background. There are about 900 such candidates (i.e., about $\frac{1}{5}$ of the missing K^0's have a random recoil proton lying within ±5 deg). We measure the neutral "track" from the production point to the recoil and reduce the amount of background by rejecting recoils that give a neutral differing by more than five standard deviations from the predicted K^0 di-reaction.[13] The remaining 300 events are fitted (1 constraint) to Reactions (2a) and (2b), assuming invisible Λ decay. They are also fitted to the topologically similar reactions

$$K(\text{neutral}) + p \rightarrow K(\text{neutral}) + p, \tag{4}$$

and

$$K^0 + p \rightarrow K^+ + n, \tag{5}$$

where in (4) the final neutral K decays invisibly or leaves the chamber. Of the 11 accepted $(\Lambda)\pi^+$ and $(\Sigma^0)\pi^+$ events, 9 are unambiguous from their kinematical fits; 2 are kinematically ambiguous with Reaction (5), but were easily resolved by gap counting. An additional 6 events are kinematically ambiguous with Reaction (5) and are not resolvable by gap counting; these are not used. 12 unambiguous charge-exchange events (5) were found. We do not use them because to do so we would have to assume CPT invariance, which is otherwise not necessary in this experiment.[14] In addition, 54 three-body leptonic decays were found.[15] For the reasons discussed,[12] we use none of these in our determination of δ.

$\Sigma^0 K^0$ production.—The missing-K^0 direction is poorly known (because of the undetected γ from $\Sigma^0 \rightarrow \Lambda + \gamma$). We rescan these pictures only for secondary interactions (2a) and (2b) involving visible Λ decay into $p + \pi^-$, making no attempt to find either Σ^+ decays or π^+ recoils not associated with a vee. The pictures are clean (about 20 beam π^- per picture), and we believe the second-scan efficiency is 100% for these events. The background is negligible, and there are no spurious or ambiguous events.

We do not use any events where the Λ produced in association with the K^0 in Reaction (1) does not decay visibly. If we did, we could only guarantee 100% scanning efficiency for K interactions, independent of time t, by scanning the entire film many times. As it is, no bias is introduced if some associated-production events are not detected, provided we find all K interactions associated with our sample of visible Λ's from Reactions (1). Another reason for demanding visible Λ's in Reaction (1) is that we thereby completely eliminate the possibility of an ambiguity between two possible production vertices. A third reason is that the information from the Λ decay eliminates some kinematical ambiguities that might otherwise remain.[16]

For a K^0 produced at proper time $t = 0$, the probability of a detectable $\bar{K}^0$ interaction at time t is proportional (independent of assumptions of CP or CPT invariance) to[17]

$$\bar{I}(t) = \exp(-\lambda_1 t) + \exp(-\lambda_2 t) - 2[\cos(\delta t)]\exp[-\tfrac{1}{2}(\lambda_1 + \lambda_2)t], \tag{6}$$

for $0 \leq t \leq T$, where T is the potential proper time (the largest value of t for which the interaction can occur within the fiducial volume). For $t > T$, $\bar{I}(t)$ is zero. Given a detected $\bar{K}^0$ interaction which we label with subscript i, and given T_i, λ_1, λ_2, and δ, then the a priori probability that the interaction occurred at t_i within Δt is given by

$$\mathcal{L}_i = \bar{I}(t_i)\Delta t \Big/ \int_0^{T_i} \bar{I}(t)\,dt.$$

We form the likelihood function $\mathcal{L}(\delta) = \Pi\, \mathcal{L}_i$, where the product Π extends over our 59 events. This function is plotted in Fig. 2 and gives our result (3).

We would like to express our appreciation to Robert L. Golden for his help during the early part of the experiment, to Edward A. Romascan and Thomas H. Strong for their help in writing computer programs, and to our scanners and measurers, especially Arlene D. Bindloss, for their excellent work. It is a pleasure to thank Luis W. Alvarez for his interest and support.

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[8]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. 140, B74 (1965), use coherent regeneration and find $\delta = 0.50 \pm 0.10$, later corrected to 0.55 ± 0.10 to take into account constructive interference of $\pi^+\pi^-$ from regenerated $K_1 \to \pi^+ + \pi^-$ with the $\pi^+\pi^-$ from the CP-nonconserving decay $K_2 \to \pi^+ + \pi^-$ [V. L. Fitch, communication to Weak Interaction Conference, Argonne, Illinois, October 1965 (unpublished)].

[9]T. Fujii, J. V. Jovanovich, F. Turkot, and G. T. Zorn, Phys. Rev. Letters 13, 253, 324 (1964), find $\delta = 0.82 \pm 0.12$, using coherent regeneration.

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[11]V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon, Phys. Rev. Letters 15, 73 (1965), maximize the interference between $(\pi^+\pi^-)_1$ from regenerated K_1's and $(\pi^+\pi^-)_2$ from K_2 decay, by using a sufficiently dilute regenerator. For $\varphi_{12} = 0$, where φ_{12} is the relative phase between $(\pi^+\pi^-)_1$ and $(\pi^+\pi^-)_2$, they find $\delta \approx 0.50 \pm 0.10$. (Other allowed values of φ_{12} give $\delta < 0.50$, so that their measurement actually gives only an upper limit on δ.)

[12]A third method starts with K^0 and detects subsequent three-body leptonic decays [S. B. Treiman and R. G. Sachs, Phys. Rev. 103, 1545 (1956)]. This method depends for its success on correct knowledge of the amount (if any) of $\Delta S = -\Delta Q$ amplitude, the amount (if any) of CP-nonconserving amplitude, and the amount (if any) of CPT-nonconserving amplitude [R. G. Sachs, Phys. Rev. 129, 2280 (1963)]. This method has been used by B. Aubert, L. Behr, J. P. Lowys, P. Mittner, and C. Pascand, Phys. Letters 10, 215 (1964). They find $\delta = 0.78 \pm 0.20$, in good agreement with the values obtained by coherent regeneration.[7-11] They assume CPT invariance and use their results for the $\Delta S = -\Delta Q$ and the CP-nonconserving amplitudes. Because of the large uncertainties in the present knowledge of these amplitudes, and especially because of the large correlation between the value obtained for δ and that obtained for the CP-nonconserving amplitude, we take this result as a consistency check on their attempt to determine the CP-nonconserving amplitude, rather than as a clear determination of δ. (No knowledge as to CPT conservation, CP conservation, $\Delta S/\Delta Q$, or any other selection rule is required in the strong-interaction or coherent-regeneration methods, except as mentioned in Ref. 8.)

[13]When, for part of the film, the azimuthal width of the scanned region was doubled to ±10 deg and the K^0-direction criterion relaxed to seven standard deviations, no new good candidates were found.

[14]The application of Reactions (1), (2), and (5) to test CPT, CP, and T invariance is discussed by F. S. Crawford, Jr., Phys. Rev. Letters 15, 1045 (1965).

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[16]A preliminary result based on 22 events [Proceedings of the International Conference on Fundamental Aspects of Weak Interactions, Brookhaven National Laboratory Report No. BNL-837, 1963 (unpublished), p. 17] included events without a visible Λ decay at the production vertex. This was to our sorrow. One of these events was later discovered to be a Λp scatter followed by $\Lambda \to p + \pi^-$, rather than $\bar{K}^0 + p \to \Lambda + \pi^+$ followed by $\Lambda \to p + \pi^-$, with which it was kinematically ambiguous. Because of the very short time $t = 0.2 \times 10^{-10}$ sec for this spurious "$\bar{K}^0 p$ interaction," the likelihood function $\mathcal{L}(\delta)$ was strongly suppressed for small values of δ. The resulting $\mathcal{L}(\delta)$ had a maximum in the region $0 \leq \delta \leq 3$, and our preliminary result was $\delta = 1.65^{+0.65}_{-0.35}$; indeed, when we (later) calculated $\mathcal{L}(\delta)$ for values of δ greater than 3, we found an even larger maximum at $\delta = 8.0$. When the spurious event was removed, $\mathcal{L}(\delta)$ for the remaining 21 events became flat

(within 1 standard deviation) between $\delta = 0$ and 2, then decreased rapidly with no larger maxima at greater values of δ. A later preliminary sample of 48 events (including events without visible Λ decay at production) gave $\delta = 0.6^{+0.4}_{-0.6}$ [Bull. Am. Phys. Soc. 9, 433 (1964)].

[17]Equation (6) is proportional to the $\bar{K}^0$ intensity in vacuum. The correction to $\bar{I}(t)$ due to coherent regeneration in liquid hydrogen is negligible.

EXPERIMENTAL TEST OF TIME-REVERSAL INVARIANCE IN THE DECAY $K_L^0 \to \pi^- + \mu^+ + \nu$*

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In a recent experiment at the Princeton-Pennsylvania Accelerator (PPA), we have investigated the muon polarization transverse to the π-μ plane in the decay

$$K_L^0 \to \pi^- + \mu^+ + \nu. \tag{1}$$

The average transverse polarization in the rest frame of the kaon is limited by time-reversal invariance to $\lesssim 0.01$, where a small nonzero value could result only from electromagnetic final-state interactions.[1] The observation of a transverse polarization larger than 0.01 would then indicate a violation of T invariance in the weak interactions. In view of the discovery[2] of the reaction $K_L^0 \to \pi^+ + \pi^-$, in which CP invariance is violated, experimental tests of T invariance, especially in K^0 decays, are currently of particular interest.

In general, time-reversal invariance requires that the form factors for a decay be real. Reaction (1) may be described by a strangeness-changing current of the form $(f_+ - g_+)(q_K + q_\pi) + (f_- - g_-)(q_K - q_\pi)$, where q_K and q_π are the kaon and pion four-momenta and f and g are the form factors associated with $\Delta S = \Delta Q$ and $\Delta S = -\Delta Q$ transitions, respectively.[3] In any given decay, the muon is completely polarized along some direction which depends upon a single complex parameter $\xi = (f_- - g_-)/(f_+ - g_+)$. The transverse component of this polarization is given by

$$(\vec{P}_\mu{}^T)_{\text{c.m.}} = \operatorname{Im}\xi(\vec{p}_\pi{}^* \times \vec{p}_\mu{}^*)/D, \tag{2}$$

where $D(\xi, \vec{p}_\pi{}^*, \vec{p}_\mu{}^*)$ depends only weakly on ξ.[4] Thus the observation of a transverse polarization in any sample of K decays would indicate a nonzero $\operatorname{Im}\xi$ and therefore a violation of time-reversal invariance.

We have investigated this polarization in an experiment using plastic scintillator counters. As can be seen from Eq. (2), maximum sensitivity to a transverse polarization is exhibited by those decays where the π, μ, and e (which monitors the μ spin) lie in three mutually perpendicular directions when viewed in the K center-of-mass system. Our apparatus is primarily sensitive to those decays which, in addition to this configuration, have their center-of-mass decay plane perpendicular to the K beam. In the laboratory, the π and μ are pitched forward, but the μ spin is not drastically altered. Consequently in the events of interest, all three lab momenta, $\vec{p}_\pi$, $\vec{p}_\mu$, and $\vec{p}_e$, are primarily along the beam direction and can conveniently be detected by counters whose planes are perpendicular to the beam (see Fig. 1).

By using the indicated quadrants of counters, it is possible to distinguish four types of events: (1) μ clockwise from π, electron forward; (2) μ clockwise from π, electron backward; (3) μ counterclockwise from π, electron forward; and (4) μ counterclockwise from π, electron backward. A transversely polarized sample of muons yields an asymmetry of the form

$$A = \frac{n_1 + n_4 - n_2 - n_3}{n_1 + n_2 + n_3 + n_4} \neq 0, \tag{3}$$

where n_i are the number of events of type i.

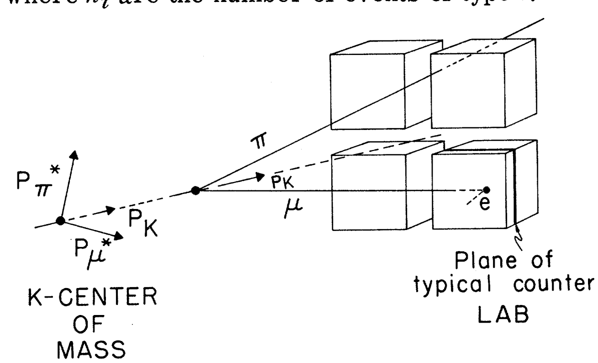

FIG. 1. Schematic representation of the detector.