The projections of these events onto the electron and proton axes are shown in Figs. 2(b) and 2(c), respectively. In these histograms the curves shown are the distributions expected for the best-fit value of the axial-vector–to–vector ratio stated below. These distributions were obtained from a Monte Carlo calculation which included the characteristic generation of two solutions in the zero-constraint fit and which included the geometric acceptance criteria. In Fig. 2(d) the contours of relative probability density on the Dalitz plane show the characteristic peaking at the low and high baryon-energy limits for the pure axial-vector ($A$) and pure vector ($V$) baryon currents, respectively.

We used 148 events contributing 285 solutions to our likelihood function for the axial-vector–to–vector ratio in the baryon current. With proper consideration of the two-solution ambiguity we obtain the ratio

$$|g_1/f_1| = 0.72^{+0.19}_{-0.14}$$

at the 68% confidence level. With 95% confidence we obtain the limits $0.48 \leq |g_1/f_1| \leq 1.22$. If we neglect the effect of weak magnetism, our ratio becomes 0.69. Filthuth[5] has recently reviewed the latest available data on the baryon leptonic decays in the context of the Cabibbo theory.[6] The best fit for the single-angle Cabibbo theory[5] predicts an axial-vector–to–vector ratio $g_1/f_1 = 0.74$ for the leptonic $\Lambda$ decay, in good agreement with our experimental result.

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[2] C. Baglin et al., Nuovo Cimento 35, 977 (1965); R. P. Ely et al., Phys. Rev. 131, 868 (1963).

[3] R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958); E. C. G. Sudarshan and R. E. Marshak, in Proceedings of the Padua-Venice Conference on Mesons and Recently Discovered Particles, September, 1957 (Società Italiana di Fisica, Padua, Italy, 1958); P. K. Kabir, Development of Weak Interaction Theory (Gordon and Breach Publishers, Inc., New York, 1963), p. 118.

[4] We have neglected the two time-reversal-noninvariant second-class components, scalar and axial magnetism. We have also ignored the first-class induced pseudoscalar component since its effect is small even relative to that of weak magnetism.

[5] H. Filthuth, in Proceedings of the Topical Conference on Weak Interactions, CERN, Geneva, Switzerland, 14-17 January 1969 (CERN Scientific Information Service, Geneva, Switzerland, 1969), p. 131. The best fit of the single-angle Cabibbo theory to the data is given by the angle $\theta = 0.235$ and the axial-vector coupling coefficients $g_1^F = 0.49$ and $g_1^D = 0.74$.

[6] N. Cabibbo, Phys. Rev. Letters 10, 531 (1963).

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# A MEASUREMENT OF THE BRANCHING RATIO $(K_L^0\to\pi\mu\nu)/(K_L^0\to\pi e\nu)$ *

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We present the results of a study of $K_L^0$ decays observed in the CERN 1.1-m$^3$ heavy-liquid bubble chamber. About 75 000 frames were scanned, and yielded some 7500 examples of isolated $K_L^0$ decays to charged particles. Based on a sample of 4000 events in a restricted fiducial region, the following branching ratios were found:

$$N(K_L^0\to\pi^\pm\mu^\mp\nu)/N(K_L^0\to\pi^\pm e^\mp\nu) = 0.648 \pm 0.030,$$

$$N(K_L^0\to\pi^+\pi^-\pi^0)/N(K_L^0\to\text{all charged}) = 0.157 \pm 0.010.$$

The CERN 1.1-m$^3$ heavy-liquid bubble chamber was exposed to a neutral beam taken at 30° from an internal beryllium target in the CERN proton synchrotron. Approximately $2\times10^{11}$ protons/pulse with a momentum of 19.2 GeV/$c$ impinged on the target, giving rise to a flux at the bubble chamber of 50 $K_L{}^0$, $1.8\times10^3$ $\gamma$ rays (with energy >1 GeV), and $9.0\times10^3$ neutrons (with kinetic energy >0.3 GeV) per pulse. The distance from the target to the center of the bubble chamber was 22.5 m, and the beam was collimated to a circular profile 2 cm in diameter at the chamber. In order to avoid all possible background and regeneration effects, the beam path was in vacuo ($4\times10^{-2}$-mm pressure of air) both inside the chamber and for 13 m before it. The beam had a momentum spectrum ranging from 0.3 to 3.0 GeV/$c$, peaking at about 1.0 GeV/$c$.

Within the chamber, the vacuum pipe was of aluminum and had an internal diameter of 4 cm. The wall was 2.5 mm thick. A lead collar was fitted to the pipe just within the chamber, and greatly reduced the background of tracks from $K_L{}^0$ decays occuring before the chamber. Tracks that emerged from the pipe on the far side from the cameras were observed through a mirror placed some 35 cm behind the pipe. The chamber was filled with heavy Freon, $CF_3Br$, in which the radiation length was 11 cm and the collision length was 58 cm. The magnetic field in the chamber was 27.0 kG.

75 000 frames were scanned for those on which there was a single decay of the type $K_L{}^0\rightarrow$ charged particles in a region defined by the first track exiting the pipe not less than 5 cm from the lead collar and the second not more than 70 cm from the collar. The scan rules also rejected those frames on which there was evidence for any decays giving rise to tracks just outside this region. Events were accepted with one or two charged tracks, of either sign, together with up to three gamma rays that could be associated with a possible origin for the charged tracks. Two independent scans were made and all frames found by either scan were checked and classified by physicists. About 7500 events remained after physicist classification.

The criteria used in the identification of particles were that (i) an electron (positron) could be identified by shower effects, or by the curvature of the track; (ii) gamma rays could be recognized through electron pairs or Compton electrons; (iii) charged pions could be identified through the occurrence of an interaction, or of a single scatter with a momentum transfer greater than 0.1 GeV/$c$,[1] or of a $\pi$-$\mu$-$e$ decay chain; and (iv) the remaining nonelectronic tracks could not be distinguished between $\pi$ or $\mu$, but the decay of such a track to an electron was recorded.

After identification of the individual tracks, events were assigned to the categories shown in Table I. At this level, 6% of events were flagged as difficult to classify. These events were subsequently examined and classified by teams of two

Table I. Event classification.

| Class | Class characteristics | No. in class |
|---|---|---|
| $K^0_{e3}$ | One electron track, one non-electron track of opposite sign which may be identified as a pion. No $\gamma$ rays other than those consistent with bremsstrahlung. | 1897 |
| $K^0_{\mu3}$ | Two non-electron tracks, one of which may be identified as a pion. No $\gamma$ rays. | 1309 |
| $K^0(\pi^+\pi^-\pi^0)$ | Two non-electron tracks and 1 or 2 $\gamma$ rays associated with the likely decay point. | 558 |
| $\pi^+\pi^-$ | Two identified pion tracks and no $\gamma$ rays. | 8 |
| $e^+e^-$ | Two identified electron tracks. | 41 |
| Single tracks | One track of any nature with or without associated $\gamma$ rays. | 167 |
| $K^0_{e3}+\gamma$ | As $K^0_{e3}$, but with one associated $\gamma$ ray not consistent with bremsstrahlung.[a] | 19 |
| Others | Tracks with same charge or unassociated; events with tenuous $\gamma$ association. | 6 |
| TOTAL | | 4005 |

[a] Ref. 2.

or more physicists, using as a basis the individual appearance of an event. 16 events remained which were ambiguous between $K_{\mu 3}$ and $K_{e3}$ decays, and these were assigned following a final inspection of the individual events together with a consideration of the overall properties of this group. An evaluation of the possible systematic bias in this procedure has been made, and is included as part of the correction in item 2 of Table II.

The numbers in Table I represent those events placed in each category when the first track was required to emerge from the pipe within a fiducial region 35 cm long, beginning 20 cm from the lead collar. This fiducial region was chosen to ensure reliable particle identification and high gamma-detection efficiency. The final results were shown to be insensitive to the precise choice of fiducial region.

A number of systematic effects were considered, which can influence both the efficiency of detecting events and the efficiency for identifying those events found. These effects are summarized in Table II. The scanning efficiencies and identification efficiencies have been obtained[3] by careful rescanning of film by different combinations of scanners and physicists from the two establishments collaborating in this work. The corrections due to stopping of pions and muons, and to electron-loss processes, are given in items 4-7 of Table II. The effect of the fiducial volume geometry on preferential detection of the different decay modes is given in item 10. These corrections and the gamma-detection efficiency have been derived from a study of the data and a Monte Carlo simulation of the experiment. The flux of gammas randomly associated with events has been estimated from the number of events found of the type $\pi\pi 3\gamma$. The final totals after application of the corrections are given in line 11. From these we may immediately derive the two branching ratios:

$$R_1 = N(K_L{}^0 \to \pi^\pm \mu^\mp \nu)/N(K_L{}^0 \to \pi^\pm e^\mp \nu)$$
$$= 0.648 \pm 0.030,$$
$$R_2 = N(K_L{}^0 \to \pi^+ \pi^- \pi^0)/N(K_L{}^0 \to \text{all charged})$$
$$= 0.157 \pm 0.010.$$

Table II. Corrections and assignment of events to the $K_{e3}$, $K_{\mu 3}$, and $K(+-0)$ class.

| Original class | $K_{e3}$ | $K_{\mu 3}$ | $K(+-0)$ |
|---|---|---|---|
| 1. Identified events | 1897 | 1309 | 558 |
| 2. Scanning and identification efficiency[a] | (95.8±2.1)% | 100% | (93.9±3.7)% |
| 3. $\gamma$ detection efficiency and $\pi^+\pi^-$ decay mode | - | (-0.7±0.1)% | (+1.3±0.3)% |
| 4. Single track + 1 or 2$\gamma$ | (+0.6±0.2)% | - | (+2.0±0.6)% |
| 5. Single tracks | (+1.9±0.5)% | (+0.4±0.1)% | - |
| 6. Electrons on pipe[b] | - | - | (+5.0±3.0)% |
| 7. Pion and muon decay | (-0.1±0.1)% | (+0.6±0.1)% | (+0.5±0.2)% |
| 8. Randomly associated $\gamma$'s | - | - | (-0.5±0.5)% |
| 9. Dalitz pairs | - | - | (+1.7±0.04)%[c] |
| 10. Geometrical efficiency | (+0.0±1.0)% | (+0.0±1.0)% | (-4.2±1.0)% |
| 11. Totals | 2025±67 | 1313±39 | 621±39 |

[a] Normalized to 100% for $K_{\mu 3}$ decays.

[b] Gamma rays from $\pi^+\pi^-\pi^0$ decays passing through the pipe wall can give rise to single electrons leaving the pipe, which would then lead to event rejection at the scanning stage; see Ref. 4.

[c] Ref. 5.

Previous measurements of $R_1$ are given in Table III, together with the best-fit value as given

Table III. Comparison of various values of $R_1$.

| $R_1(K_{\mu 3}/K_{e3})$ | $\Delta R_1$ | Method | Reference |
|---|---|---|---|
| 0.81 | 0.19 | Hydrogen bubble chamber | a |
| 0.73 | 0.15 | Hydrogen bubble chamber | b |
| 0.82 | 0.10 | Spark chamber | c |
| 0.70 | 0.20 | Hydrogen bubble chamber | d |
| 0.81 | 0.08 | Hydrogen bubble chamber | e |
| 0.71 | 0.05 | Heavy liquid bubble chamber | f |
| 0.745 | 0.035 | Fit | g |
| 0.638 | 0.036 | Spark chamber | h |
| 0.648 | 0.030 | Heavy liquid bubble chamber | This work |

[a] R. K. Adair et al., Phys. Letters 12, 67 (1964).

[b] D. Luers et al., Phys. Rev. 133, 1276 (1964).

[c] X. De Bouard et al., Nuovo Cimento 52A, 662 (1967).

[d] C. J. B. Hawkins, Phys. Rev. 156, 1444 (1967).

[e] H. W. K. Hopkins et al., Phys. Rev. Letters 19, 185 (1967).

[f] See Ref. 4.

[g] See Ref. 6.

[h] P. Basile et al., to be published. See also Ref. 12.

in the particle data tables.[6] We note that while $R_2$ is in good agreement with previous measurements,[7] $R_1$ is somewhat lower. We believe this may be because of the ability of the technique to detect decays from all parts of the Dalitz plot with close to 100% efficiency, and to the insensitivity to any assumptions about the form of the interaction. The value of $R_1$ obtained in this work may be used to derive the parameter $\xi_0$, the ratio of the form factors at zero four-momentum transfer, in the expression[8]

$$R_1(K_{\mu 3}/K_{e3}) = 0.6487 + 0.1269\,\mathrm{Re}(\xi_0) + 0.0193\,|\xi_0|^2 + 1.329\lambda_+ + \cdots,$$

where a pure vector coupling and $\mu$-$e$ universality are assumed. The energy dependence of the form factors has been parametrized in the normal manner[9]:

$$f_\pm(q^2) = f_\pm(0)[1 + \lambda_\pm q^2/m_\pi^2].$$

Assuming also time-reversal invariance then $\mathrm{Im}(\xi_0) = 0$, and setting $\lambda_- = 0$ we obtain $\xi_0 = -3.287 \pm 7.198(R_1 - 0.4403 - 1.329\lambda_+)^{1/2}$, whence, using $R_1 = 0.648 \pm 0.03$, and $\lambda_+ = 0.02 \pm 0.015$,[10] $\xi_0 = -6.36 \pm 0.30$ or $-0.22 \pm 0.30$. Results from polarization studies[11] would predict $R_1 = 0.53 \pm 0.03$ using the same phenomenology. The agreement between these two sets of results is at the 5% level; it is possible, as discussed, for example, by Cronin,[12] that a strong contribution from the $\lambda_-$ term may still be required to reconcile the data. A comparison of these data with the $K_{\mu 3}/K_{e3}$ branching ratio from $K^+$ experiments allows a test of the $|\Delta I| = \frac{1}{2}$ (leptonic) rule. The mean value obtained from the measurements of Eichten et al. and Botterill et al.,[13] $R_1(K^+) = 0.636 \pm 0.01$, yields $R_1(+)/R_1(0) = 0.98 \pm 0.05$, in excellent agreement with the prediction of unity.

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[*] A preliminary analysis of part of these data was submitted to the Fourteenth International Conference on High-Energy Physics, Vienna, Austria, September, 1968 (unpublished), Paper No. 242.

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[1] J. Sawicki and H. Yoshiki, Nuovo Cimento 42A, 410 (1966).

[2] The flux of gamma rays randomly associated with events was estimated from events of the type $\pi\pi 3\gamma$, and found to be $(0.23 \pm 0.3)\%$. There should then be $4.5 \pm 5$ events of the type $\pi e \gamma$ in the data, where $\gamma$ arises from a spurious association. The excess of 14.5 events of the type $\pi e \gamma$ actually observed are tentatively assigned to the radiative decay mode $K_L^0 \rightarrow \pi^\pm e^\mp \nu \gamma$, corresponding to a branching ratio $\pi e \nu \gamma / \pi e \nu = (0.75 \pm 0.4)\%$. The error here is purely statistical and does not attempt to include systematic effects of the type likely to arise from incorrect gamma association, which may be considerable. This effect is being studied further.

[3] The absolute scanning efficiencies for the various modes were also obtained using a partial third and fourth scan, and deriving a "visibility function" for each mode (S. E. Derenzo and R. H. Hildebrand, to be published). These efficiencies were in agreement with those obtained in the manner outlined in the text, in which effects not only of scanning efficiency but also of physicist identification efficiency were included.

[4] I. A. Budagov et al., Nuovo Cimento 57A, 182 (1968).

[5] N. P. Samios, Phys. Rev. 121, 275 (1961).

[6] N. Barash-Schmidt et al., Rev. Mod. Phys. 41, 109 (1969).

[7] P. Astbury et al., Phys. Letters 18, 175 (1968); P. Guidoni et al., Argonne National Laboratory Report No. ANL 7130, 1965 (unpublished); C. J. B. Hawkins, Phys. Letters 21, 238 (1966); H. W. K. Hopkins et al., Phys. Rev. Letters 19, 185 (1967).

[8] A. Fujii and M. Kawaguchi, Phys. Rev. 113, 1156 (1959); see also N. Cabibbo, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, California, 1966, (University of California Press, Berkeley, Calif., 1967).

[9] See for example, J. D. Jackson, Brandeis Summer Institute 1962 Lectures in Theoretical Physics, edited by K. W. Ford (W. A. Benjamin, Inc., New York, 1963), Vol. 1., Elementary Particle Physics and Field Theory.

[10] S. H. Aronson and K. Wendell Chen, Phys. Rev. 175, 1708 (1968). A complete list of references to previous measurements is given in this paper.

[11] R. J. Abrams et al., Phys. Rev. 176, 1603 (1968); L. B. Auerbach et al., Phys. Rev. Letters 17, 980 (1966); J. A. Helland et al., Phys. Rev. Letters 21, 257 (1968).

[12] J. W. Cronin in Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, Austria, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 281.

[13] T. Eichten et al., Phys. Letters 27B, 596 (1968); D. R. Botterill et al., Phys. Rev. Letters 21, 766 (1968).