Measurement of the Branching Ratio of the Decay $K_L^0 \to \mu\mu$

T. Akagi,[1] R. Fukuhisa,[2] Y. Hemmi,[3] T. Inagaki,[4] K. Ishikawa,[2],[a] T. Kishida,[2] M. Kobayashi,[4] T. K. Komatsubara,[2] M. Kuze,[2],[b] F. Sai,[2],[c] T. Sato,[4] T. Shinkawa,[4] F. Suekane,[4],[d] K. Takamatsu,[4] J. Toyoura,[2],[e] S. S. Yamamoto,[2] and Y. Yoshimura[4]

[1]*Department of Physics, Tohoku University, Sendai 980, Japan*
[2]*Department of Physics, University of Tokyo, Tokyo 113, Japan*
[3]*Department of Physics, Kyoto University, Kyoto 606, Japan*
[4]*National Laboratory for High Energy Physics (KEK), Tsukuba 305, Japan*

(Received 22 July 1991)

We observed 177.8 $K_L^0 \to \mu\mu$ events after background subtraction of 1.2 events in an experiment to search for the decays $K_L^0 \to \mu e$ and ee at the KEK 12-GeV Proton Synchrotron. Normalizing to the decay $K_L^0 \to \pi^+\pi^-$, the branching ratio $B(K_L^0 \to \mu\mu) = [7.9 \pm 0.6(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-9}$ was obtained.

PACS numbers: 13.20.Eb

The decay $K_L^0 \to \mu\mu$ is a quark-flavor-changing neutral-current process, and the study of this process has played a profound role in developing the standard model [1]. This decay proceeds through the second-order electroweak interaction, and a precise measurement of its branching ratio would provide a constraint on the parameters of the standard model. Both short- and long-distance effects contribute to this decay. The absorptive part of the decay amplitude is dominated by the long-distance effect of a two-real-photon intermediate state, and the unitarity bound [2] of $B(K_L^0 \to \mu\mu) \geq (6.83 \pm 0.28) \times 10^{-9}$ was calculated from the measured branching ratio of the decay $K_L^0 \to \gamma\gamma$. In order to extract the short-distance effect, which is important for the determination of the standard-model parameters [3], such as the top quark mass and the Kobayashi-Maskawa (KM) matrix element ($\mathrm{Re}V_{td}$), the dispersive part of the long-distance effect coming from a two-virtual-photon intermediate state needs to be estimated. Several theoretical attempts [4] have been made to estimate it. Since the present estimates are too ambiguous to clearly extract the short-distance effect, further experimental and theoretical investigations are needed to solve this problem. The recent experiments at BNL [5–7] and KEK [8] have given more precise measurements of the branching ratio of the decay $K_L^0 \to \mu\mu$ than the previous ones [9]. In this Letter, we report a new measurement using our entire data.

The detector system and the track-reconstruction routine have been described previously [8,10]. Here, the analysis of the decay $K_L^0 \to \mu\mu$ and the correction procedures for the differences in the detector response between the decays $K_L^0 \to \mu\mu$ and $K_L^0 \to \pi^+\pi^-$ will be described.

The data taking was performed simultaneously for the four decays $K_L^0 \to \mu e$, ee [10], $\mu\mu$, and $\pi^+\pi^-$. The basic trigger required a coincidence between an $H1$ counter and the corresponding $H2$ counter (parallel coincidence) for the decay $K_L^0 \to \mu\mu$ as well as the other leptonic decays in both arms. A less stringent coincidence including the $H2$ counter adjacent to the corresponding $H2$ counter on the beam pipe side (semiparallel coincidence) was used for the decay $K_L^0 \to \pi^+\pi^-$. Since both decays are kinematically similar, the acceptances were not much different from each other. The trigger for the decay $K_L^0 \to \pi^+\pi^-$ required semiparallel coincidence without additional particle identification and was prescaled typically by a factor of 500. For the decay $K_L^0 \to \mu\mu$, a muon signal in each arm was required in the trigger as well as in an off-line analysis. Another difference between the two modes was the fact that pions undergo nuclear interaction. The largest effect of the nuclear interaction came from the interaction in the region between $H1$ and $H2$ hodoscopes. The corrections for the pion and muon decays in flight were different from each other, and were included in the calculation of the acceptances. In the calculation a pion track was traced, including its secondary muon track for the decay $\pi \to \mu\nu$.

The muon identifier, which was placed at the end of the detector system in each arm, consisted of four iron blocks with thicknesses of 10, 50, 30, and 30 cm, each of which was followed by a scintillator hodoscope. The first two hodoscopes were horizontally segmented by six scintillators, each of which was viewed from both sides. The last two hodoscopes were vertically segmented by eight scintillators viewed from one side. A matrix coincidence between a counter in the first hodoscope and the corresponding counter or one of the adjacent counters in the second hodoscope was required for the trigger. In the off-line analysis, a muon identifier signal whose timing was within 3 ns with respect to the $H1$-$H2$ coincidence was searched for along the extrapolated track obtained from the track reconstruction routine in both the horizontal and vertical planes.

Since the $K_L^0 \to \pi^+\pi^-$ triggered events contained a considerable number of events from the K_{l3} decays, the response of the particle-identification counters to the pion and that to the muon were calibrated by using well-identified pions from the decay $K_L^0 \to \pi e\nu$ and muons from the decay $K_L^0 \to \pi\mu\nu$, respectively. The rangemomentum relation using the four layers of the hodoscopes in the muon identifier was utilized for muon identification. The muon identification was made by requiring the presence of a proper muon signal in the muon identifier and the absence of electron signals in both the electromagnetic shower counter and the gas Cherenkov counter. For pion identification, the absence of a proper signal in both the gas Cherenkov counter and the muon identifier was required. The efficiency of the muon identifier was determined as a function of particle momentum.

The nuclear interaction rate for the pion was determined as a function of momentum by studying the data from a run in which at least one hit on the $H1$ was required in one arm and semiparallel coincidence and an electron signal were required in the other arm. After a track was tagged as a pion from the decay $K_L^0 \to \pi e \nu$ in the off-line analysis, the track was extrapolated to the $H2$ position. The interaction rate in the region between $H1$ and $H2$ was estimated from the fraction of the loss of signals in the corresponding $H2$ counters. A Monte Carlo calculation based on the FLUKA program [11] reproduced well the interaction rate.

We investigated other small but possible effects on the relative yields of the decays $K_L^0 \to \mu\mu$ and $K_L^0 \to \pi^+\pi^-$. The dead-time effect on the $\pi^+\pi^-$ mode was $(1.3 \pm 0.3)\%$ smaller than that on the $\mu\mu$ mode [12]. To investigate the effect due to accidental hits in the detector, randomly triggered events were collected for various beam conditions and were superposed onto events produced by a Monte Carlo calculation in the same data format as that of the actual raw data. They were analyzed using the same track reconstruction routine. A decrease in the tracking efficiency for the $K_L^0 \to \pi^+\pi^-$ event with increasing beam intensity, which was observed to be 10% to 20%, was well reproduced from these superposed Monte Carlo data. However, the effect on the relative acceptances due to accidental hits was found to be small. The effect due to dead sense wires, typically 10 out of 4864, was very small. These corrections, which were 1% as a whole, were included in the acceptance calculation. The inefficiency in the electronic latching of a bit to tag a $\mu\mu$ trigger was negligibly small ($<0.3\%$).

In order to get a high-quality track, cuts on the track fitting were made: $\chi^2 < 4$ and $(|p_u - p| + |p_d - p|)/p < 0.06$, where p_u, p_d, and p are the momenta of a track measured in the upstream and downstream halves of the spectrometer and in the whole spectrometer. After applying the cuts to reject the background unassociated with the K_L^0 decays which were described in the preceding Letter [10], we obtained clean samples of the $\mu\mu$ and $\pi^+\pi^-$ events. Figure 1(a) shows a scatter plot of the effective mass ($M_{\mu\mu}$) vs θ^2 for the $\mu\mu$ events, where θ is the angle between the momentum vector of the $\mu\mu$ system and the target-to-vertex direction. Figures 2(a) and 2(b)

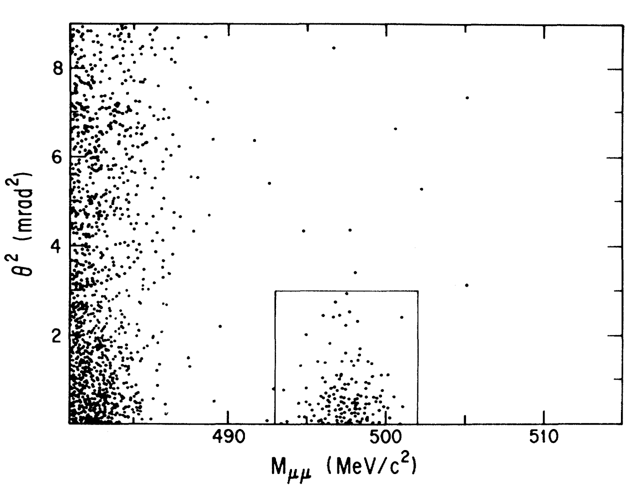

FIG. 1. Scatter plot of the $\mu\mu$ effective mass ($M_{\mu\mu}$) vs θ^2. A box indicates the boundary of the fiducial region: $493 < M_{\mu\mu} < 502$ MeV/c^2 and $\theta^2 < 3$ mrad^2.

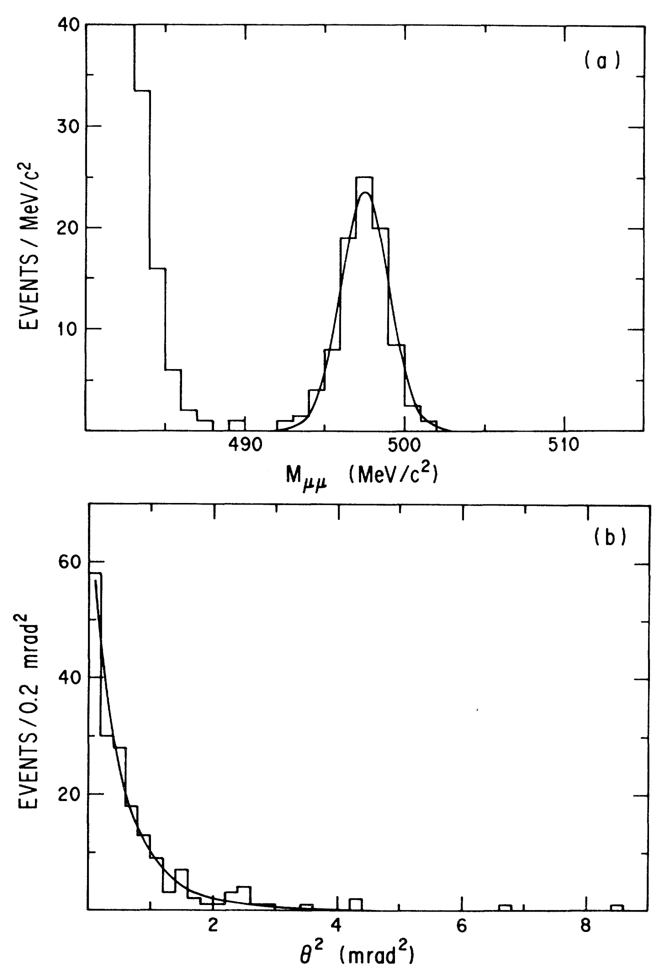

FIG. 2. Distributions of (a) $M_{\mu\mu}$ with $\theta^2 < 3$ mrad^2 and (b) θ^2 with $493 < M_{\mu\mu} < 502$ MeV/c^2. Solid curves are results obtained from a Monte Carlo calculation.

show an $M_{\mu\mu}$ distribution with $\theta^2 < 3$ mrad^2 and a θ^2 distribution with $493 < M_{\mu\mu} < 502$ MeV/c^2, respectively. A peak centered at the K_L^0 mass is clearly separated from the background region. The background events in the region $M_{\mu\mu} < 490$ MeV/c^2 are due to decays in flight in the forward direction and misidentification by the muon identifier of pions from the decay $K_L^0 \to \pi\mu\nu$. The background in the region $M_{\mu\mu} > 490$ MeV/c^2 can be explained by decays in flight in the spectrometer of pions from the decay $K_L^0 \to \pi\mu\nu$ and by double misidentification of both pions and electrons from the decay $K_L^0 \to \pi e\nu$ as muons. The $M_{\pi\pi}$ and θ^2 distributions are shown in Figs. 3(a) and 3(b) for the $\pi^+\pi^-$ events. The mass peak is centered at the K_L^0 mass with a standard deviation of 1.28 MeV/c^2, and events are concentrated around $\theta^2 = 0$ with a 1.0 mrad^2 resolution. The spectra of the mass and θ^2 for both modes were well reproduced by a Monte Carlo calculation, as illustrated by the solid curves in the figures. According to the acceptance calculation, the fractions of events which fell in the fiducial region, $493 < M < 502$ MeV/c^2 and $\theta^2 < 3$ mrad^2, for the decays $K_L^0 \to \mu\mu$ and $K_L^0 \to \pi^+\pi^-$ were estimated to be $(98.2 \pm 0.1)\%$ and $(94.7 \pm 0.1)\%$, respectively.

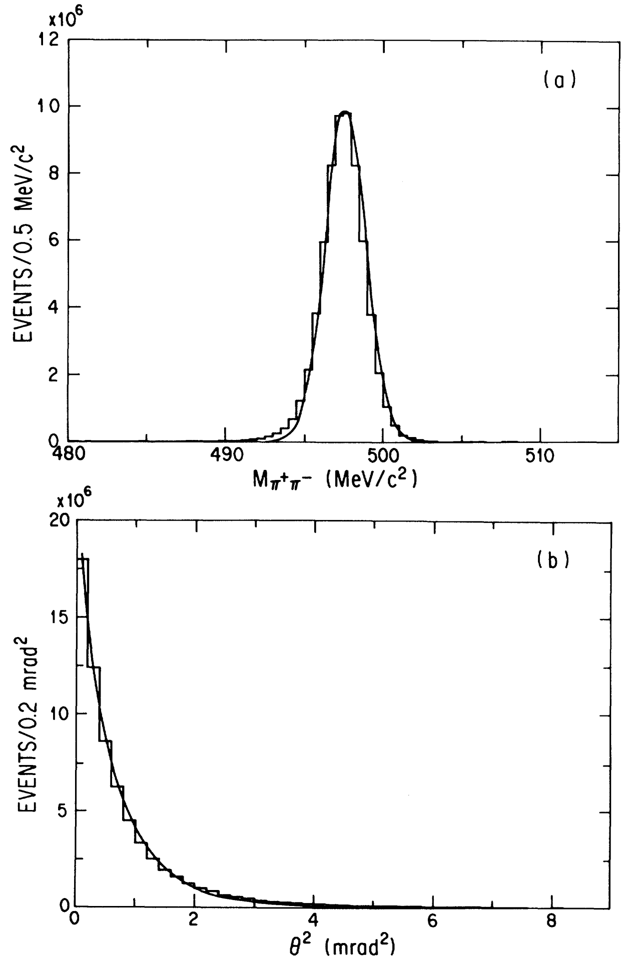

FIG. 3. Distributions, after correcting for the prescaling factor, of (a) $M_{\pi^+\pi^-}$ with $\theta^2 < 3$ mrad^2 and (b) θ^2 with $493 < M_{\pi^+\pi^-} < 502$ MeV/c^2. Solid curves are results obtained from a Monte Carlo calculation.

The number of $\mu\mu$ events in the fiducial region was 179. The number of $\mu\mu$ events in the region $493 < M < 502$ MeV/c^2 and $3 < \theta^2 < 9$ mrad^2 was 5 and the number of real $\mu\mu$ events in the same region was expected to be 2.6. Therefore, the number of background $\mu\mu$ events in the fiducial region was estimated to be 1.2 $[(5-2.6)/2 = 1.2]$. The number of $K_L^0 \to \pi^+\pi^-$ events, $N_{\pi^+\pi^-}$, was determined to be 1.59×10^5 by subtracting the background events from the number of events in the fiducial region. The number of background events in the fiducial region was estimated to be 1.51×10^3 as the average number of events in the 9 MeV/c^2 wide regions adjacent to the mass fiducial boundaries. The numbers of the $K_L^0 \to \mu\mu$ events and $K_L^0 \to \pi^+\pi^-$ events after having been corrected for the prescaling factor were 177.8 $\pm 13.4 \pm 1.2$ and $(6.37 \pm 0.02 \pm 0.06) \times 10^7$, respectively. The first uncertainty in each number is the statistical fluctuation and the second one is the systematic uncertainty from the background subtraction. As a check of the internal consistency of $N_{\pi^+\pi^-}$, it was calculated from the $\pi^+\pi^-$ mass distribution without requiring particle identification, where the background was given by a Monte Carlo calculation for the K_{l3} decays. The result agreed well (to within 1%) with that obtained from the method above.

The ratio of the acceptance for the decay $K_L^0 \to \mu\mu$ to that of the decay $K_L^0 \to \pi^+\pi^-$ was 0.839 ± 0.013. The average values of the corrections for particle identification were 0.763 ± 0.006 and 0.937 ± 0.003 for the $\mu\mu$ and $\pi^+\pi^-$, respectively. The loss due to nuclear interaction for the decay $K_L^0 \to \pi^+\pi^-$ was 0.057 ± 0.006. Using the current value [7] $B(K_L^0 \to \pi^+\pi^-) = (2.03 \pm 0.04) \times 10^{-3}$ we obtained the branching ratio

$$B(K_L^0 \to \mu\mu) = [7.9 \pm 0.6(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-9}.$$

Our value of the branching ratio agrees well with our previously published one: $(8.4 \pm 1.1) \times 10^{-9}$ based on 54 $\mu\mu$ events [8]. It is also in agreement with the value of Heinson *et al.* [13], which is $(7.6 \pm 0.5 \pm 0.4) \times 10^{-9}$. They claim that when combined with their earlier result [6], the average branching ratio becomes $(7.0 \pm 0.5) \times 10^{-9}$, which overlaps with our present value within errors.

We are grateful to the operating crew of the KEK 12-GeV PS. We also thank the KEK Computing Center for processing a large volume of our data. We express our sincere gratitude to the members of the physics departments for their continuous encouragement and support. T.K.K. is a JSPS Fellow for Japanese Junior Scientists.

(a)Present address: 2-2-12, Wakamatsuhigashi, Okazaki

444, Japan.

(b)Present address: Institute for Nuclear Study, University of Tokyo, Tanashi 188, Japan.

(c)Present address: Tokyo Research Laboratory, IBM Ltd., Tokyo 102, Japan.

(d)Present address: Department of Physics, Tohoku University, Sendai 980, Japan.

(e)Present address: Research Laboratory, Mitsubishi Electric Corp., Amagasaki 661, Japan.

[1] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285 (1970); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973); M. K. Gaillard and B. W. Lee, Phys. Rev. D **10**, 897 (1974); M. K. Gaillard, B. W. Lee, and R. E. Shrock, Phys. Rev. D **13**, 2674 (1976).

[2] L. M. Sehgal, Phys. Rev. **183**, 1511 (1969); Phys. Rev. D **4**, 1582 (1971); B. R. Martin, E. de Rafael, and J. Smith, Phys. Rev. D **2**, 179 (1970).

[3] R. E. Shrock and M. B. Voloshin, Phys. Lett. **87B**, 375 (1979); T. Inami and C. S. Lim, Prog. Theor. Phys. **65**, 297 (1981); **65**, 1772(E) (1981).

[4] C. Q. Geng and J. N. Ng, Phys. Rev. D **41**, 2351 (1990); C. S. Kim, J. L. Rosner, and C.-P. Yuan, Phys. Rev. D **42**, 96 (1990); L. Bergström, E. Massó, and P. Singer, Phys. Lett. B **249**, 141 (1990); G. Bélanger and C. Q. Geng, Phys. Rev. D **43**, 140 (1991).

[5] H. B. Greenlee *et al.*, Phys. Rev. Lett. **60**, 893 (1988); S. F. Schaffner *et al.*, Phys. Rev. D **39**, 990 (1989).

[6] R. D. Cousins *et al.*, Phys. Rev. D **38**, 2914 (1988); C. Mathiazhagan *et al.*, Phys. Rev. Lett. **63**, 2185 (1989).

[7] Particle Data Group, J. J. Hernández *et al.*, Phys. Lett. B **239**, 1 (1990).

[8] T. Inagaki *et al.*, Phys. Rev. D **40**, 1712 (1989).

[9] W. C. Carithers *et al.*, Phys. Rev. Lett. **30**, 1336 (1973); W. C. Carithers *et al.*, Phys. Rev. Lett. **31**, 1025 (1973); Y. Fukushima *et al.*, Phys. Rev. Lett. **36**, 348 (1976); M. J. Shochet *et al.*, Phys. Rev. D **19**, 1965 (1979).

[10] T. Akagi *et al.*, preceding Letter, Phys. Rev. Lett. **67**, 2614 (1991).

[11] P. A. Aarnio, J. Ranft, and G. R. Stevenson, CERN Internal Report No. TIS-RP/106-Rev, 1984 (unpublished).

[12] The dead time due to the inhibition of the trigger during data recording time was different for the two modes for the first three quarters of the running period. This difference was due to the fact that the $\pi^+\pi^-$ triggers were inhibited after prescaling, which caused the $\pi^+\pi^-$ triggers to have a periodic structure, thus making the dead time smaller than that for the $\mu\mu$ mode. For the last quarter of the running period the $\pi^+\pi^-$ triggers were inhibited before prescaling, and the dead time was the same for both modes.

[13] A. P. Heinson *et al.*, Phys. Rev. D **44**, R1 (1991).