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Further Observation of the Decay $K_L{}^0 \rightarrow \mu^+\mu^-$*

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A new search for the decay $K_L{}^0 \rightarrow \mu^+\mu^-$ has been performed at the Brookhaven National Laboratory alternating-gradient synchrotron. We used the experimental technique employed by Carithers *et al.*, with some modifications to suppress the background further and eliminate possible systematic effects. The analysis of this experiment yields three events satisfying criteria for this decay mode.

The experimental observation by Carithers *et al.* of six events satisfying criteria for the decay $K_L{}^0 \rightarrow \mu^+\mu^-$ gives a value for the branching ratio $\Gamma(K_L{}^0 \rightarrow \mu^+\mu^-)/\Gamma(K_L{}^0 \rightarrow \text{all}) = 14^{+13}_{-7} \times 10^{-9}$ (90% confidence-level errors).[1] This is in contradiction with the result from Clark *et al.*, in which no $K_L{}^0 \rightarrow \mu^+\mu^-$ candidates were found, thus placing an upper limit for this branching ratio of 3.3×10^{-9} at the 90% confidence level.[2] In this Letter we report the final results of a new search for the decay $K_L{}^0 \rightarrow \mu^+\mu^-$.

Three modifications were made to the spectrometer used by the original Columbia/CERN/New York University experiment shown in Fig. 1 of Ref. 1 [which we will refer to as $K_{\mu 2}$(I)]:

(1) A new high-resolution horizontal hodoscope has been added to the system in order to improve background rejection in the identification of muons. This array of 23 scintillator elements, each $2\frac{1}{2}$ in. wide and 84 in. long, is mounted behind a 2-in.-thick steel plate and placed downstream from the other muon detectors. The overall size of the hodoscope is sufficient to detect most $K_L{}^0 \rightarrow \mu^+\mu^-$ decays which penetrate the hadron absorber. The efficiency of each of the three muon hodoscope planes (horizontal, vertical, and new horizontal) was found to be 97% from a carefully selected sample of $K_{\mu 3}$ decays.

(2) The spectrometer magnet was operated at 240 MeV/c transverse momentum ($P_\perp$). This was chosen to be different from $P_\perp = 210.6$ MeV/c used in the $K_{\mu 2}$(I) experiment for the following reasons. (a) Increased bending power tends to compress the $\mu^+\mu^-$ invariant-mass spectrum due to the

background process $K_L{}^0 \to \pi\mu\nu \to \mu\mu\nu\bar{\nu}$ so that there will be more separation between the signal and the background events. (b) If the result from Carithers *et al.*,[1] were indeed due to some geometric peculiarity of the apparatus, then by increasing the bending one expects that the apparent $K_L{}^0 \to \mu^+\mu^-$ signal due to this peculiarity would be moved away from the K^0 mass.

(3) The front part of the hadron and electron absorber (heavy concrete) has been moved back ($3\frac{1}{2}$ ft) against the rear concrete section in order to reduce backscattering into the last multiwire proportional chamber.

The performance of the spectrometer was continuously monitored using the Brookhaven National Laboratory on-line data facility. We will refer to the present experiment as $K_{\mu 2}$(II).

Data were recorded under the same trigger conditions as used in the $K_{\mu 2}$(I) experiment, demanding in addition that two trajectories were left-right separated in all three multiwire proportional chambers. The new muon hodoscope was not required in the trigger. In the analysis, both $\mu^+\mu^-$ *and* $\pi^+\pi^-$ candidates were required to satisfy the following criteria: (a) decay vertex within a fiducial volume in the vacuum chamber; (b) extrapolated secondary trajectories within the active area of both the vertical and new horizontal muon hodoscopes; (c) momenta of secondary trajectories between 2 and 7 GeV/c, and $K_L{}^0$ momentum less than 12 GeV/c; (d) no signal in any Cherenkov counter element that lies along the trajectory of a secondary particle; (e) the horizontal bending of each trajectory inward towards the center line of the apparatus.

For $\mu^+\mu^-$ candidates, each secondary particle was required to be detected by the correct counter element in each of the three muon hodoscopes (horizontal, vertical, and new horizontal). To reduce possible contamination from pion or electron penetration of the hadron absorber, $\mu^+\mu^-$ candidates were required to register in at least two distinct muon counters from each hodoscope (horizontal, vertical, and new horizontal hodoscopes). No more than a total of seven muon counters were allowed to be registered. For $\pi^+\pi^-$ candidates, no muon counter may be hit.

Resolution of the spectrometer was studied by means of $K_L{}^0 \to \pi^+\pi^-$ events. The quality of the $K_L{}^0 \to \pi^+\pi^-$ data was examined using a χ^2 analysis involving the following variables which describe an event: (a) vertical kink angle[3] for each secondary trajectory (two degrees of freedom); (b) closest distance of approach of the two secondary trajectories in the decay region (one degree of freedom); (c) the angle between the vector sum of the momenta of the two secondaries and the incident $K_L{}^0$ beam direction (θ) (this variable contains two degrees of freedom corresponding to two orthogonal projections transverse to the beam direction); (d) invariant mass of the secondary particles.

A $\chi^2(3)$ of three degrees of freedom is constructed from the variables (a) and (b) characterizing any "good two-prong" event. A cut of $\chi^2(3) \le 6.25$ is imposed on both $\pi^+\pi^-$ and $\mu^+\mu^-$ candidates. This cut eliminates only 10% of the good events, while strongly suppressing background from $\pi \to \mu\nu$ decays.

The remaining data are presented in terms of the invariant mass and an angular variable $\theta^2/\sigma_\theta{}^2 \equiv \chi^2(2)/2$.[4] Figure 1(a) shows a scatter plot of $\theta^2/\sigma_\theta{}^2$ versus invariant mass for 300 $\pi^+\pi^-$ candidates; Fig. 1(b) depicts the mass histogram for all $\pi^+\pi^-$ candidates with $\theta^2/\sigma_\theta{}^2 \le 3$, corresponding to a cut at the 95% confidence level. Fitting this invariant-mass spectrum by a Gaussian distribution yields a central mass value $M_K = 499.4$ MeV and a width $\sigma_{M_K} = 1.6$ MeV.

A 95% confidence level cut ($|M_{\pi\pi} - M_K| \le 3.2$ MeV) is imposed on the $\pi^+\pi^-$ invariant-mass spectrum leaving 15 110 $K_L{}^0 \to \pi^+\pi^-$ events. This corresponds to 0.967×10^6 $K_L{}^0 \to \pi^+\pi^-$ events since the trigger suppresses the collection of $K_L{}^0 \to \pi^+\pi^-$ candidates by a factor of 64.

All $\mu^+\mu^-$ candidates with $\chi^2(3) \le 6.25$ are presented in the scatter plot of $\theta^2/\sigma_\theta{}^2$ versus $M_{\mu\mu}$ shown in Fig. 2(a). Selections in $\chi^2(3)$, $\chi^2(2)$, and $M_{\mu\mu}$ identical to those for the $\pi^+\pi^-$ candidates. Three $\mu^+\mu^-$ candidates survive these cuts. Generally, the background density in the $M_{\mu\mu}$ versus θ^2/σ^2 plane is similar to or less than the $K_{\mu 2}$(I) results.[1] The $\mu^+\mu^-$ invariant mass projection for $\theta^2/\sigma_\theta{}^2 \le 3$ shows a clear separation between the background events and $K_L{}^0 \to \mu^+\mu^-$ signal, shown in Fig. 2(b). Thus we consider these three events as $K_L{}^0 \to \mu^+\mu^-$ events. This new result confirms the existence of the process $K_L{}^0 \to \mu\mu$.

Background $\mu^+\mu^-$ events mainly due to the processes $K_L{}^0 \to \pi\mu\nu$ cannot contribute a peak in the K^0 mass region as was demonstrated in the $K_{\mu 2}$(I) experiment. We will not repeat the argument here since this experiment was performed under similar conditions as the $K_{\mu 2}$(I) experiment. In addition, the new horizontal hodoscope in this experiment further suppresses background $\mu^+\mu^-$ events due to $K_L{}^0 \to \pi\mu\nu$ decays.[5] Results from this experiment with different $P_\perp$ from that of the

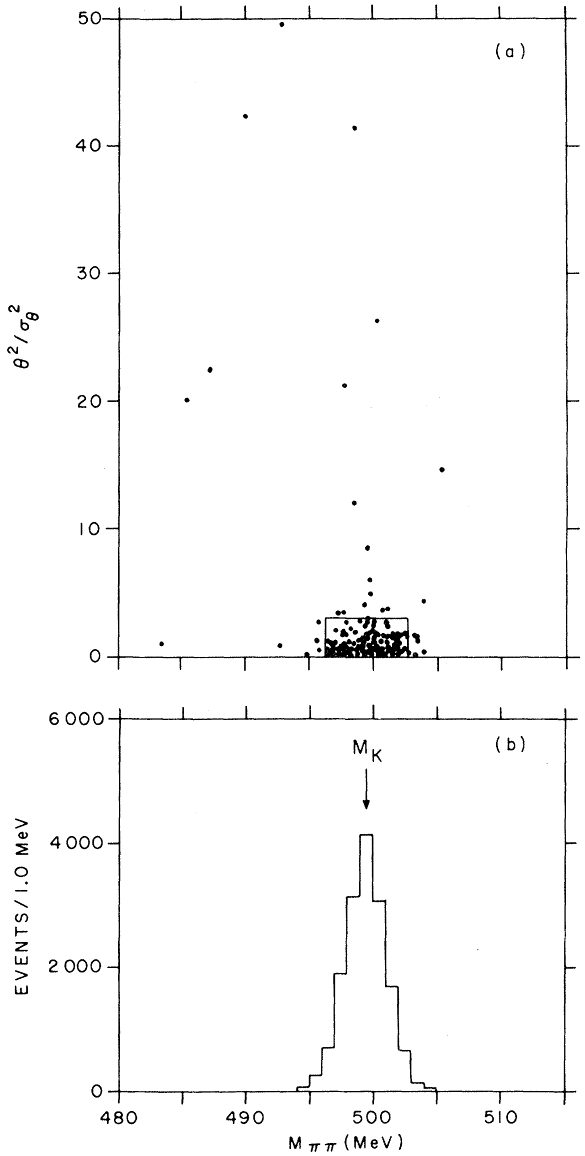

FIG. 1. (a) $M_{\pi\pi}$ versus θ^2/σ_θ^2 for a typical sample of 300 $K_{\pi 2}$ candidates. Box indicates $\theta^2/\sigma_\theta^2 < 3$ and $|M_{\pi\pi} - M_K| < 3.2$ MeV. (b) $M_{\pi\pi}$ for all $K_{\pi 2}$ candidates detected in this experiment with $\theta^2/\sigma_\theta^2 < 3$. See text for details of selection.

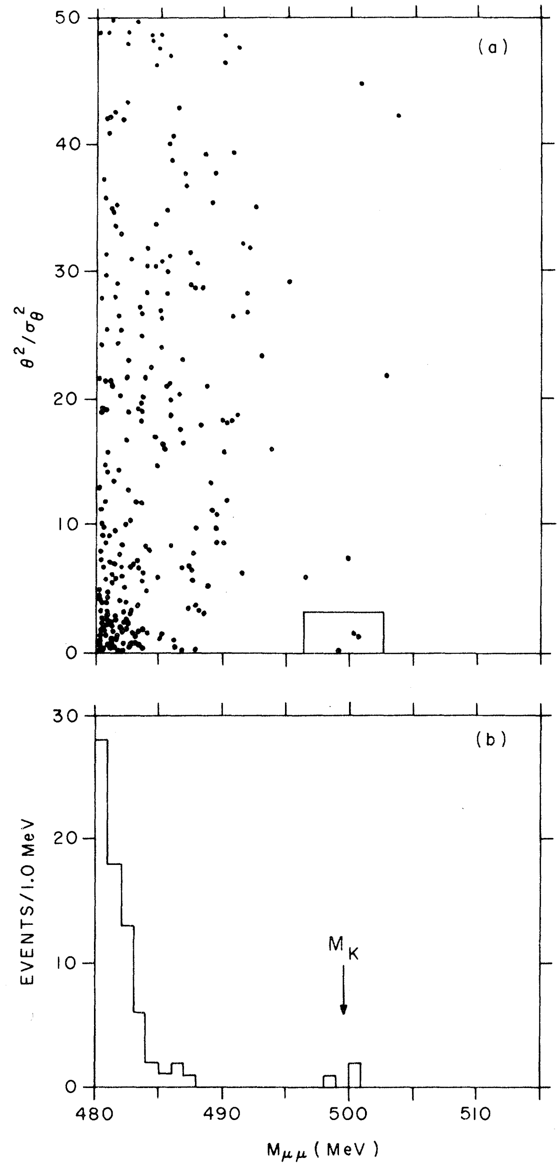

FIG. 2. (a) $M_{\mu\mu}$ versus θ^2/σ_θ^2 for $K_{\mu 2}$ candidates. Box indicates $\theta^2/\sigma_\theta^2 < 3$ and $|M_{\mu\mu} - M_K| < 3.2$ MeV. (b) $M_{\mu\mu}$ for $K_{\mu 2}$ candidates detected in this experiment with $\theta^2/\sigma_\theta^2 < 3$. No candidates at higher $M_{\mu\mu}$. See text for details of selection.

$K_{\mu 2}$(I) experiment suggest that the evidence for $K_L^0 \to \mu^+\mu^-$ is independent of the spectrometer magnet setting.

The branching ratio $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \text{all})$ is determined from

$$\frac{\Gamma(K_L^0 \to \mu^+\mu^-)}{\Gamma(K_L^0 \to \text{all})} = \frac{\Gamma(K_L^0 \to \mu^+\mu^-)}{\Gamma(K_L^0 \to \pi^+\pi^-)} \times \frac{\Gamma(K_L^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \text{all})},$$

where[6]

$$\frac{\Gamma(K_L^0 \to \pi^+\pi^-)}{\Gamma(K_L^0 \to \text{all})} = 2.1 \times 10^{-3},$$

$$\frac{\Gamma(K_L^0 \to \mu^+\mu^-)}{\Gamma(K_L^0 \to \pi^+\pi^-)} = \frac{N_{\mu\mu}}{N_{\pi\pi}} \times \frac{A_{\pi\pi}}{A_{\mu\mu}},$$

and $N_{\mu\mu} = 3$ events, $N_{\pi\pi} = 967\,000$ events, and $A_{\pi\pi}/A_{\mu\mu} = 1.4$ is the relative acceptance[7] of $K_L^0 \to \pi^+\pi^-/$

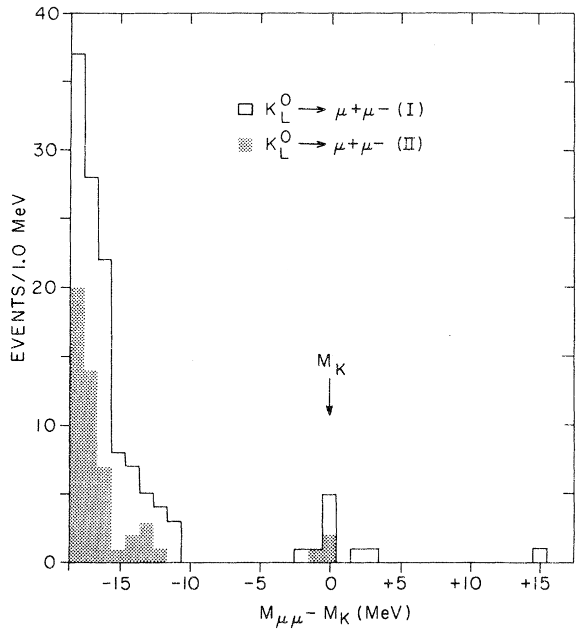

FIG. 3. $M_{\mu\mu} - M_K$ for $K_{\mu2}$(I) and $K_{\mu2}$(II) for $\theta^2/\sigma_\theta^2 < 3$. M_K represents the mass of K_L as measured in each experiment from $K_{\pi2}$ decays.

$K_L^0 \to \mu^+\mu^-$. We obtain $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \pi^+\pi^-) = 4.5_{-3}^{+6} \times 10^{-6}$ and $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \mathrm{all}) = 9_{-7}^{+13} \times 10^{-9}$ (90% confidence level errors).[6] This result is in good agreement with that from the $K_{\mu2}$(I) experiment.

Because of the similarities between this experiment and the $K_{\mu2}$(I) experiment, we can combine the results in order to obtain smaller errors on the branching ratio. The K^0 masses from these two experiments are different by 0.8 MeV [$M_K(K_{\mu2}(\mathrm{I})) = 498.6$ MeV versus $M_K(K_{\mu2}(\mathrm{II})) = 499.4$ MeV][8] because of the systematics of different spectrometer magnet settings [$P_\perp(K_{\mu2}(\mathrm{I})) = 210.6$ MeV/c versus $P_\perp(K_{\mu2}(\mathrm{II})) = 240$ MeV/c]. We therefore present the combined $\mu^+\mu^-$ mass spectrum from these two experiments with masses measured relative to their individual K^0 mass as shown in Fig. 3. A clear peak at the K^0 mass is evident. The final averaged branching ratios for the $K_{\mu2}$(I) and $K_{\mu2}$(II) experiments are $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \pi^+\pi^-) = 5.8_{-2}^{+4} \times 10^{-6}$ and $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \mathrm{all}) = 12_{-4}^{+8} \times 10^{-9}$.[6] This value is in excellent agreement with the theoretical lower limit of 6×10^{-9} based on unitarity considerations and the measured $K_L^0 \to \gamma\gamma$ rate.[9]

It is a pleasure to thank the staffs of Brookhaven National Laboratory and Columbia Nevis Laboratory for their contributions to this experiment. The scintillator elements of the new horizontal hodoscope were on loan from the Lindenbaum-Ozaki group at Brookhaven National Laboratory. We wish to express our appreciation for their cooperation.

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[3]The vertical kink angle measures the difference in direction in the vertical plane of the secondary particle trajectory before and after the magnet. The bending due to the magnetic field is in the horizontal plane.

[4]The variable θ contains two degrees of freedom, θ_x and θ_y, corresponding to two orthogonal projections transverse to the beam. Both θ_x and θ_y are Gaussian distributed with $\sigma_{\theta_x} = \sigma_{\theta_y} = \sigma = 0.3$ mrad. $\chi^2(2) = (\theta_x^2/\sigma_{\theta_x}^2 + \theta_y^2/\sigma_{\theta_y}^2)$ is a χ^2 for two degrees of freedom. If $\sigma_\theta^2 \equiv 2\sigma^2$, then $\theta^2/\sigma_\theta^2 = \chi^2(2)/2$ and may be interpreted as a χ^2 per degree of freedom.

[5]The new horizontal hodoscope eliminates ~21% of the $\mu^+\mu^-$ events with $\chi^2(2)/2 < 3$ and $M_{\mu\mu} < 490$ MeV, which are all background events.

[6]We use the values of $|\eta_\pm| = (2.23 \pm 0.05) \times 10^{-3}$ from Messner *et al.*, Ref. 1, and Wahl *et al.*, Ref. 1.

[7]A Monte Carlo calculation of the relative acceptance $A_{\pi\pi}/A_{\mu\mu}$ was performed which included losses due to $\pi \to \mu\nu$ decays, muons scattering out of the absorber, and muon counter efficiencies.

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