

with whom we started a similar treatment of  $\text{He}^3$ .

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## Experimental Measurement of $K_L^0 \rightarrow \mu^+ \mu^-$ \*

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Using a spark-chamber magnet spectrometer and applying very stringent requirements to eliminate background contamination, we find three events of the rare process  $K_L^0 \rightarrow \mu^+ \mu^-$  corresponding to a branching ratio relative to  $K_L^0 \rightarrow \pi^+ \pi^-$  of  $4.2^{+5.1}_{-2.6} \times 10^{-6}$ . Using the branching ratio  $(K_L^0 \rightarrow \pi^+ \pi^-)/(K_L^0 \rightarrow \text{all}) = 0.21\%$ , we calculate the branching ratio to be  $8.8^{+10.7}_{-5.5} \times 10^{-9}$  (90% confidence level) for the  $K_L^0 \rightarrow \mu^+ \mu^-$  decay.

The rate for the decay  $K_L^0 \rightarrow \mu^+ \mu^-$  has been in question for several years. Since the rate for  $K_L^0 \rightarrow \gamma\gamma$  is known,<sup>1</sup> a straightforward calculation results in a lower bound of  $4.3 \times 10^{-9}$  for the branching ratio for the  $2\mu$  process.<sup>2,3</sup> Clark *et al.*<sup>4,5</sup> searched for the  $2\mu$  decay and reported<sup>6</sup> at a 90% confidence level an experimental upper bound of  $3.3 \times 10^{-9}$ , significantly below this lower limit. Carithers *et al.*<sup>7,8</sup> found nine events corresponding to a branching ratio of  $12^{+8}_{-4} \times 10^{-9}$  in clear disagreement with the first experiment. A third experiment is necessary to resolve this experimental discrepancy.

This experiment was performed in a 250- $\mu\text{sr}$  solid angle neutral beam at the Brookhaven National Laboratory alternating-gradient synchrotron (see Fig. 1). The external proton beam ( $\sim 10^{11}$  protons/pulse) incident upon an Ir target yielded  $\sim 10^4$   $K_L^0$  decays per pulse in the decay region. Charged particles and  $\gamma$  rays were removed by a sweeping magnet preceded by 10 radiation lengths of Pb. The spectrometer consist-

ed of 22 spark chamber planes (eight planes had magnetostrictive readout; all others used capacitive readout<sup>9</sup>); a magnet (46 cm  $\times$  46 cm  $\times$  183 cm wide gap; field integral 209 MeV/c); and trigger counters (UHL, UHR, and the downstream hodoscope banks). The downstream banks, separated by 173 cm, were used to impose the "picket-fence" requirements (PFR, PFL) that only downstream tracks with projected angles in the  $x$ - $z$  plane less than  $\pm 44$  mrad with respect to the beam line be accepted.

To suppress potential neutron-related backgrounds the neutral beam was in vacuum from the sweeping collimator to the downstream end of the decay region and was dumped into a re-entrant cavity downstream of the muon detector. All counters and absorbers were placed outside the beam.

There were two types of triggers: (1) a sixfold coincidence, two-track trigger from which the normalization  $K_{\pi\pi}$  events were obtained ( $2T \equiv \text{UHR} \cdot \text{UHL} \cdot \text{PFR} \cdot \text{PFL}$ ), and (2) a tenfold coincidence

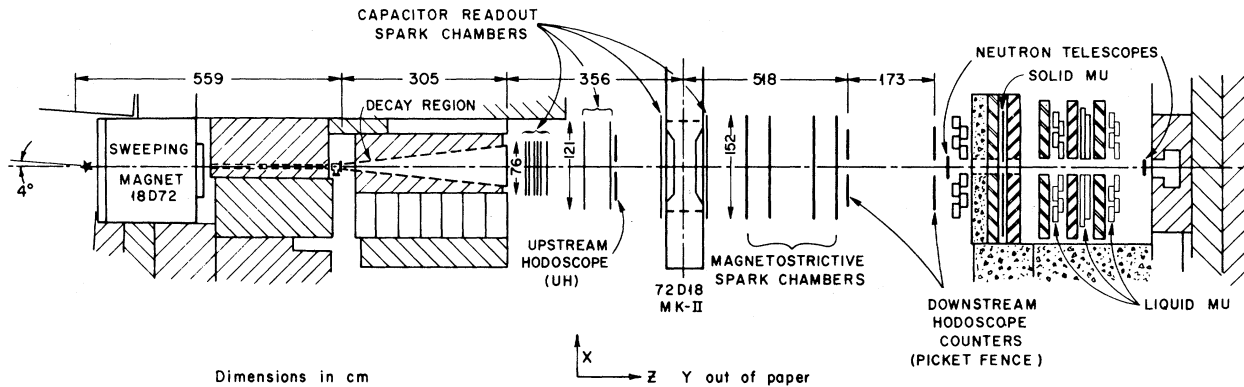


FIG. 1. Experimental layout.

dimuon ( $\mu\mu$ ) trigger which required the solid scintillator and first liquid scintillator hodoscopes on each side of the muon detector (see below) in coincidence with a 2T trigger. The event trigger was the logical or of all  $\mu\mu$  triggers and 1% of the 2T triggers.  $3.5 \times 10^6$  triggers were recorded.

After reconstruction of the events from the spark chamber information, the 2T triggers were further prescaled by a factor of 10. The preliminary square field calculations of the track momenta were improved with a step-by-step integration through the field. The  $\chi^2$  per degree of freedom ( $\chi^2/\text{DOF}$ ) for each track assuming that all sparks were on one smooth trajectory (no multiple scattering) was also determined.

The following cuts were imposed on both samples: geometrical cuts including the distance of

closest approach of the two tracks; kaon proper lifetime  $\geq 10 \times 10^{-10}$  sec; kaon momentum  $\leq 10$  GeV/c;  $1.6$  GeV/c  $\leq$  secondary track momentum  $\leq 7.5$  GeV/c; and  $\chi^2/\text{DOF} \leq 3.5$ .

The  $\chi^2/\text{DOF}$  [see Fig. 2(a)] cut provides an important suppression of backgrounds, primarily  $K_{\mu 3}$  with  $\pi$  decay, by discriminating against kinks in the tracks. The  $\chi^2/\text{DOF}$  cut is demonstrably more sensitive than the vertical kink method used in Refs. 7, 8 since kinks in the horizontal plane also increase  $\chi^2/\text{DOF}$ . The value of the cut was established by tightening it until all Monte Carlo-generated backgrounds were eliminated to a level below the sensitivity of the data.

The  $\chi^2/\text{DOF}$  distribution observed in the data was broader than predicted from the Monte Carlo calculation. This difference is due to minor irregularities in spark position determination.

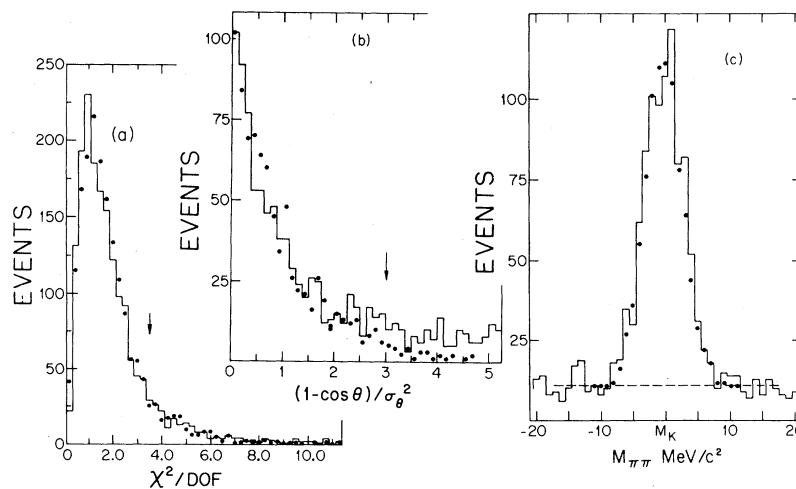


FIG. 2. (a)  $\chi^2/\text{DOF}$ , (b)  $\theta^2/2$ , and (c)  $M_{\pi\pi}$  for normalization events. In each case, the solid curve is the data, and dots represent Monte Carlo results. In (c) the background added to the Monte Carlo result was obtained from a fit to the data.

It was treated in two independent ways. First, the Monte Carlo distribution was scaled to match the data. Alternatively, chamber resolutions were broadened and multiple Coulomb scattering in the upstream hodoscope was increased in the Monte Carlo calculation. In both cases, the value of the  $\chi^2/\text{DOF}$  cut that must be applied to eliminate background is comparable and is insensitive to variations in the Monte Carlo parameters. The Monte Carlo results shown are based on the scaling procedure.

The invariant mass and  $1 - \cos\theta \simeq \theta^2/2$  were calculated for the remaining events.  $\theta$  is the angle between the kaon momentum vector and the line from the target center to the decay vertex. The distribution in  $\eta \equiv (1 - \cos\theta)/\sigma_\theta^2$  for the normalization events, where  $\sigma_\theta$  is the appropriate momentum-dependent angular resolution ( $\sigma_\theta$  at  $6 \text{ GeV}/c = 0.64 \text{ mrad}$ ), is shown in Fig. 2(b). The  $K_{\pi\pi}$  events fall off exponentially in  $\eta$  with 95% of the decays within  $\eta \leq 3$ . A small  $K_{l3}$  background is evident, as no particle identification has been imposed.

The normalization events after a cut at  $\eta \leq 3$  are presented in Fig. 2(c) as a  $\pi\pi$  invariant-mass distribution, showing a kaon signal and a smooth  $K_{l3}$  background. Fits yield a  $\pi\pi$  mass resolution  $\sigma_{M\pi\pi} = 3.0 \text{ MeV}/c^2$  with  $740 \pm 30$   $K_{\pi\pi}$  events within  $\pm 2\sigma$  of the kaon mass.

The  $K_L^0 \rightarrow \mu^+\mu^-$  candidates were distinguished by the muon detector: an array of shower counters and four hodoscopes providing  $x$ ,  $x$ ,  $y$ , and  $x$  information, respectively, located within an iron muon filter (see Fig. 1). The hodoscopes were a bank of solid scintillator counters at a depth of  $340 \text{ g}/\text{cm}^2$  and three banks of liquid scintillator counters at  $735$ ,  $890$ , and  $1040 \text{ g}/\text{cm}^2$ . Frequent runs were taken in configuration where essentially all of the particles passing through the spectrometer were muons. These data yielded track-momentum-dependent geometrical windows for each muon counter and provided pulse-height distributions for muons passing through the solid muon bank and the shower counters. Counter efficiencies were measured to be 98–99%. With use of the 2T triggers, the stringency of the muon detector minimum range and pulse-height cuts was increased until the  $K_{\pi\pi}$  peak disappeared. ( $\pi$ - $\mu$  decays downstream of the spectrometer and  $\pi$

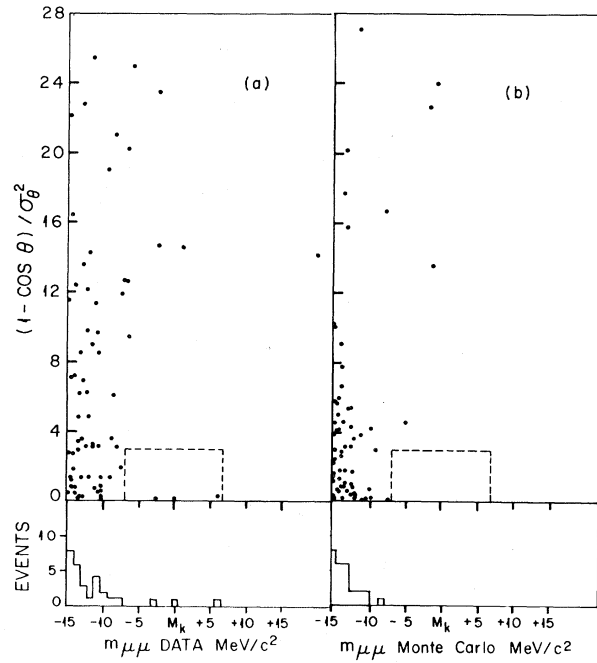


FIG. 3. (a)  $M_{\mu\mu}$  versus  $\theta^2/2$  for  $\mu\mu$  events satisfying all cuts. The dashed lines indicate a  $\pm 2\sigma$  interval in mass and  $\eta < 3.0$ . The  $M_{\mu\mu}$  distribution for events with  $\eta < 3.0$  is shown in projection. (b) Monte Carlo generated events.

punch-through are too infrequent to yield a mass peak in the distribution.) To define a muon it was necessary and sufficient that the track be detected in the first three muon banks. In addition the pulse height in the solid bank was required to be consistent with the observed muon pulse-height distribution. The measured efficiency ( $\epsilon_\mu$ ) for detecting a muon with a momentum greater than  $1.6 \text{ GeV}/c$  is 94%.

The distribution of  $M_{\mu\mu}$  versus  $\eta$  for those  $\mu\mu$  events satisfying all the cuts is presented in Fig. 3(a). A  $\pm 2\sigma$  interval in mass around the kaon mass and the limit in  $\eta$  are also shown. The calculated  $M_{\mu\mu}$  mass resolution,  $\sigma_{M\mu\mu}$ , is  $3.5 \text{ MeV}/c^2$ .

Three events fall within the rectangle defining  $K_L^0 \rightarrow \mu^+\mu^-$ . These events are due to the rare decay  $K_L^0 \rightarrow \mu^+\mu^-$ . The parameters of the events are given in Table I.

The relative  $\mu\mu/\pi\pi$  geometrical acceptance of the spectrometer ( $A_{\mu\mu}/A_{\pi\pi}$ ) is 1.1. The branching ratio (B.R.) is

$$\frac{K_L^0 \rightarrow \mu^+\mu^-}{K_L^0 \rightarrow \pi^+\pi^-} = \frac{N_{\mu\mu}}{N_{\pi\pi}} \frac{A_{\pi\pi}}{A_{\mu\mu}} \frac{1}{\epsilon_\mu^2} = \frac{3}{740 \times 1000} \times \frac{1}{1.1} \times \frac{1}{(0.94)^2} = 4.2^{+5.1}_{-2.6} \times 10^{-6}.$$

TABLE I. Parameters of the events.

$M_{\mu\mu}$ (MeV/c <sup>2</sup> )	$P_K$ (GeV/c)	$\chi^2/\text{DOF}$ (each track)		$\eta$
495.2	6.65	0.82	3.12	0.088
497.8	3.92	0.67	0.87	0.047
503.8	7.54	1.11	1.36	0.259

Using the B.R.  $(K_L^0 \rightarrow \pi^+\pi^-)/(K_L^0 \rightarrow \text{all})$  of 0.21%<sup>6</sup> the branching ratio for  $(K_L^0 \rightarrow \mu^+\mu^-)/(K_L^0 \rightarrow \text{all})$  is  $8.8_{-5.5}^{+10.7} \times 10^{-9}$  [90% confidence level (CL)].

The three events have an average mass within 1.1 MeV/c<sup>2</sup> of the kaon mass and are at very small  $\eta$  as expected. There is no background near the  $K_{\mu\mu}$ - $\eta$  mass region.

The cuts are very stringent, designed to eliminate background contamination. The worst background is  $K_{\mu 3}$  in which the  $\pi$  decays in the spectrometer. This background is strongly suppressed by the cuts imposed. In Fig. 3(b), the Monte Carlo events which survive all cuts are shown. The events shown are that fraction of the generated events which represent  $K_{\mu 3}$  decays with and without  $\pi$  decay at a sensitivity equal to that of the data ( $\pi$  punch-through probability = 1%). Using the full Monte Carlo sample (at a sensitivity four times that of the data), we estimate that the background from  $K_{\mu 3}$  in the  $K_{\mu\mu}$ - $\eta$  mass region contributes at the level of  $0.7_{-0.6}^{+2.0} \times 10^{-9}$  (90% CL). (In that sample, one Monte Carlo event at 491.7 MeV/c<sup>2</sup> and  $\eta = 0.4$  was found.) Similarly with the conservative value of  $10^{-5}$  for the probability of identifying an  $e$  as a  $\mu$ ,  $K_{e3}$  is expected to contribute background below the  $10^{-9}$  level.

The result is insensitive to reasonable variations in the cuts. If the  $\eta$  cut is tightened to 2.0 (or loosened to 4.0) the B.R. is  $9.6_{-6.6}^{+11.7} \times 10^{-9}$  (or  $8.5_{-5.3}^{+10.3} \times 10^{-9}$ ). If the  $\chi^2/\text{DOF}$  cut is tightened to 1.75 (loosened to 5.25), the B.R. is  $13.7_{-10}^{+22} \times 10^{-9}$  with two events (or  $7.9_{-4.9}^{+9.6} \times 10^{-9}$ ). The  $\chi^2/\text{DOF}$  must be relaxed beyond 7.0 before additional events enter the  $\eta$ -mass region of the data sample. Note that the errors quoted in all cases are

statistical only.

The expected number of events based on the two previous experiments is 4.1 (Refs. 7, 8) or less than 1.1 at the 90% CL (Refs. 4, 5). The probability that this experiment and each of the previous experiments derive from the same parent distribution (as determined by an  $F$ -ratio test<sup>10</sup>) are 31% and 0.7%, respectively.

This result, obtained in a systematically independent manner, strongly supports the conclusion that the rate for  $K_L^0 \rightarrow \mu^+\mu^-$  is non-zero and is consistent with the theoretical lower limit.

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