Search for the Decay $K_L \to \pi^0 \mu^+ \mu^-$

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(Received 23 December 1999)

We report on a search for the decay $K_L \to \pi^0 \mu^+ \mu^-$ carried out as a part of the KTeV experiment at Fermilab. This decay is expected to have a significant CP violating contribution and a direct measurement will either support the Cabibbo-Kobayashi-Maskawa mechanism for CP violation or point to new physics. Two events were observed in the 1997 data with an expected background of 0.87 ± 0.15 events, and we set an upper limit $\mathcal{B}(K_L \to \pi^0 \mu^+ \mu^-) < 3.8 \times 10^{-10}$ at the 90% confidence level.

PACS numbers: 13.20.Eb, 11.30.Er, 14.40.Aq

The decays $K_L \to \pi^0 l \bar{l}$ are interesting decays for the study of CP violation and can be used to search for new physics. There are three expected contributions to the amplitude: a CP conserving contribution which proceeds through the $\pi^0 \gamma^* \gamma^*$ intermediate state, an indirectly CP violating contribution from $K_1 \to \pi^0 l \bar{l}$, and a directly CP violating contribution from electroweak penguin and W box diagrams [1–3]. Branching ratio predictions in theories containing exotic (e.g., supersymmetry) particles that contribute to the penguin amplitudes are significantly higher [4].

The sizes of the three contributions depend on the flavor of the final state lepton. The greatest theoretical interest is in the $K_L \to \pi^0 \nu \bar{\nu}$ case, where the direct CP violating amplitude dominates and a theoretically clean measurement [5] of the Wolfenstein [6] parameter η should be possible. However, measuring a final state with two neutrinos and a single pion is experimentally challenging, and the current experimental limit [7] remains 4 orders of magnitude above the standard model expectation of $\sim 3 \times 10^{-11}$.

In contrast, $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ are comparatively straightforward to detect, although all three amplitudes are present in these modes. This Letter presents a new limit on $\mathcal{B}(K_L \to \pi^0 \mu^+ \mu^-)$; the existing limit [8] is 5.1×10^{-9} at the 90% C.L. For the data taken by KTeV in 1997 and discussed here, a single event observed in the muon mode would correspond to a branching ratio of 7×10^{-11}, which approaches the standard model expectation [9,10] of $\mathcal{B}(K_L \to \pi^0 \mu^+ \mu^-) \sim (0.44–1.00) \times 10^{-11}$. The expectation is that the CP violating amplitude contribution to the branching ratio will be $\sim 0.8 \times 10^{-12}$.

The KTeV detector has been described elsewhere [7,11]. An 800 GeV proton beam, with typically 3.5×10^{12} protons per 19 s Fermilab Tevatron spill every minute, was targeted at a vertical angle of 4.8 mrad on a 1.1 interaction length (30 cm) BeO target. Photons were converted by 76 mm of lead immediately downstream of the target. Charged particles were then removed with magnetic sweeping. Collimators defined two 0.25 μsr beams that entered the KTeV apparatus 94 m downstream of the target. The 65 m vacuum ($\sim 10^{-6}$ Torr) decay region extended to the first drift chamber. The spectrometer consisted of a dipole magnet surrounded by four (1.28×1.28 m^2 to 1.77×1.77 m^2) drift chambers with ~ 100 μm position resolution in both horizontal and vertical directions. Helium filled bags occupied the spaces between the drift chambers; the magnetic field imparted a ± 205 MeV$/c$ horizontal momentum kick. The spectrometer had a momentum resolution of $\sigma(P)/P = 0.38\% \oplus 0.016\% P$, where P is in GeV$/c$. The electromagnetic calorimeter consisted of 3100 pure CsI crystals. Each crystal was 50 cm (27 radiation lengths, 1.4 interaction lengths) long. Crystals in the central 1.2×1.2 m^2 section of the calorimeter had a cross-sectional area of 2.5×2.5 cm^2, and those in the outer region (out to 1.9×1.9 m^2) had a 5×5 cm^2 area. The calorimeter's energy resolution for photons was $\sigma(E)/E = 0.45\% \oplus 2\%/\sqrt{E}$, where E is in GeV, and its position resolution was ~ 1 mm. The π^0 mass resolution in $K_L \to \pi^+\pi^-\pi^0$ was ~ 1.3 MeV$/c^2$. Nine photon veto assemblies (lead scintillator sandwiches) detected particles leaving the fiducial volume. Two scintillator hodoscopes in front of the calorimeter were used to trigger on charged particles. The hodoscopes and the calorimeter had two holes (15×15 cm at the calorimeter) to let the neutral beams pass through without interaction. The muon filter, located behind the calorimeter, was constructed of a 10 cm thick lead wall followed by three steel walls totaling 511 cm thickness. Scintillator planes with 15 cm segmentation in both horizontal and vertical directions (MU3) were located after the third steel wall. The segmentation was comparable to the multiple scattering angle of 10 GeV muons at MU3. Pion punch-through probabilities, including decays downstream of the calorimeter, were taken as a function of momentum from $K_L \to \pi^\pm e^\mp \nu$ data and are on the order of 2×10^{-3}. The data acquisition system reconstructed events online, and the results were used to filter the data.

The signature we searched for is two tracks from oppositely charged particles with a common vertex that deposit little energy in the calorimeter and created two hits at MU3 from these muons. The π^0 creates two electromagnetic showers in the calorimeter with $m_{\gamma\gamma} = m_{\pi^0}$ and which are unassociated to tracks.

There are three important backgrounds. The first is $K_L \to \pi^+\pi^-\pi^0$ where both $\pi^\pm$ either decay upstream of the calorimeter (decay in flight) or punch through to MU3. The second is $K_L \to \pi^\pm\mu^\mp\nu$ with one decay in flight or punch-through and accidentally coincident calorimeter activity that appears as a π^0. The third and largest background is the radiative muonic Dalitz decay $K_L \to \mu^+\mu^-\gamma\gamma$ when $m_{\gamma\gamma} = m_{\pi^0}$. Because of the low expected [12] branching ratio, $K_L \to \pi^0\pi^\pm\mu^\mp\nu$ is not a large background.

Two triggers were used for this analysis. To determine the number of K_L decays in the data, we identified $K_L \to \pi^+\pi^-\pi^0$ decays in a minimum bias trigger. This trigger required hits in the trigger hodoscopes and the drift chambers which were consistent with two coincident charged particles passing through the detector. Events with a reconstructed vertex from oppositely charged tracks were recorded with a prescale factor of 500:1. For the signal trigger further requirements were made. Two or more hits in MU3 were required, and activity in the photon veto counters rejected events. The trigger system counted the number of calorimeter clusters over ~ 1 GeV in a narrow (20 nsec) time gate; for the signal mode, at least one such cluster was required. We also required that the calorimeter energy reconstructed online and associated with each track be less than 5 GeV. The signal trigger was not prescaled.

Muons passing through the calorimeter typically deposit ~ 400 MeV, and so in searching offline for the signal we required that the clusters associated to the tracks had less than 1 GeV of energy. Track momenta were required to be greater than 10 GeV$/c$ to ensure that they penetrated to MU3 and less than 100 GeV$/c$ to ensure that the momentum was well measured. The two-muon system was required to have a mass less than 350 MeV$/c^2$ to reduce backgrounds from $K_L \to \pi^\pm\mu^\mp\nu$. We required two nonadjacent hits in both views of MU3. We did not compare the MU3 hit positions to the extrapolation of the tracks to MU3, because the major backgrounds passed this requirement as well as the signal did.

To suppress $\pi^\pm$ decays in flight, we required that the reconstructed vertex occurred in the beam volume of the decay region and had a χ^2 of 10 for 1 d.o.f. or less, and that the track segments upstream and downstream of the spectrometer magnet passed within 1 mm (94% signal acceptance) of each other at the bend plane of the magnet. The mass of the two unassociated clusters under the hypothesis that they were produced by photons from the decay vertex was required to be between 135 ± 6 MeV$/c^2$ ($\pm 2.5\sigma$). These clusters both had to have been found by the trigger cluster counter.

A number of kinematic criteria were studied to suppress background from $K_L \to \mu^+\mu^-\gamma\gamma$ decays. The kinematics of this decay are very different from the analogous $K_L \to e^+e^-\gamma\gamma$ background to $K_L \to \pi^0 e^+e^-$, and the branching ratio is lower. Consequently, the methods [13,14] which are effective in the $e^\pm$ case are less effective in the $\mu^\pm$ case. Although kinematic cuts do reduce $K_L \to \mu^+\mu^-\gamma\gamma$ background, the corresponding acceptance loss in light of the other backgrounds is not advantageous. Requirements of this kind were not applied.

We suppress backgrounds from $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi^\pm\mu^\mp\nu$ by using

$$\mathrm{R}_{\parallel}^{\mu\mu} \equiv \frac{(m_K^2 - m_{\mu\mu}^2 - m_{\pi^0}^2)^2 - 4m_{\mu\mu}^2 m_{\pi^0}^2 - 4m_K^2 p_{\perp\mu\mu}^2}{p_{\perp\mu\mu}^2 + m_{\mu\mu}^2}, \tag{1}$$

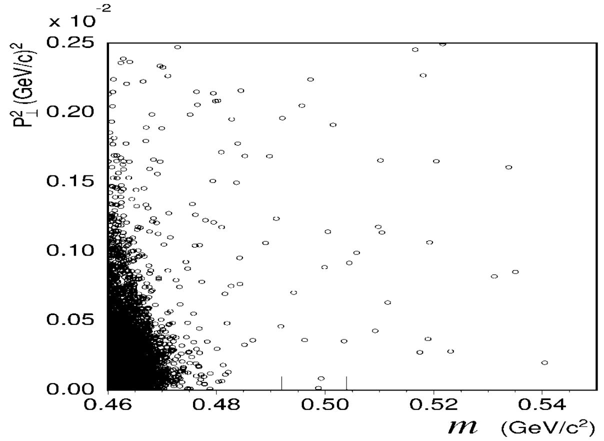

FIG. 1. Reconstructed $P_\perp^2$ vs m after all other selection criteria, for the data. The box indicates the signal region; events in the lower left are predominantly $K_L \to \pi^+\pi^-\pi^0$ with $\pi^\pm$ decays in flight.

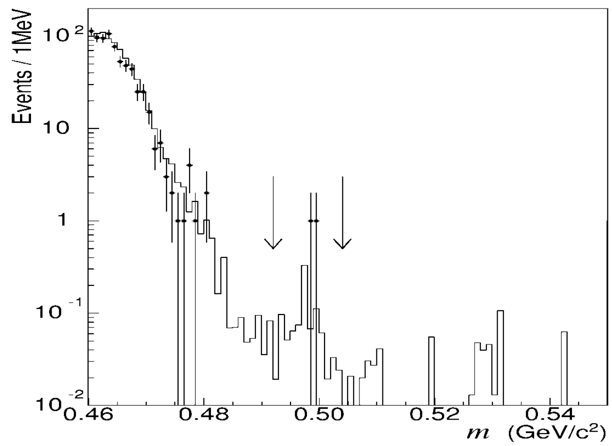

FIG. 2. Reconstructed m after all other selection criteria, for the data (dots), and the total background estimate (line). The arrows indicate the range of values of m accepted. The small bump in the background at the K_L mass is from $K_L \to \mu^+\mu^-\gamma\gamma$.

where m_K is the kaon mass, $m_{\mu\mu}$ the mass of the two-muon system, m_{π^0} the π^0 mass, and $p_{\perp\mu\mu}$ is the two-muon systems' momentum perpendicular to the kaon momentum. This quantity is proportional to the π^0 momentum squared in the K_L flight direction in the frame colinear with the K_L but where the $\mu^+\mu^-$ pair has no longitudinal momentum. We required $R_\parallel^{\mu\mu}$ to lie between -0.01 and 0.10 GeV$^2/c^4$. This cut keeps 89.2% of the signal and rejects 73% of $K_L \to \pi^\pm\mu^\mp\nu$ decays with coincident photons and 95% of the $K_L \to \pi^+\pi^-\pi^0$ decays.

To ensure that we observed all the products of a K_L decay, we required that the total squared momentum transverse to the K_L flight direction ($P_\perp^2$) be less than 100 MeV$^2/c^2$, and that the reconstructed mass (m) of the K_L be between 492 and 504 MeV$/c^2$. With these requirements, which were selected by examining Monte Carlo simulation results and data outside the signal region before examining the data for $K_L \to \pi^0\mu^+\mu^-$ candidates, the overall acceptance for the signal was 5.0%. The simulation distributed the products of the decay uniformly in phase space.

Figure 1 shows the $P_\perp^2$ vs m distributions for the data, and Fig. 2 shows the mass distribution after the $P_\perp^2$ requirement for the data and the backgrounds as estimated from the simulation. The correspondence between the data and the simulation is good, and is also good in the distributions of $m_{\mu\mu}$, $P_\perp^2$, track momentum, vertex position and (for $K_L \to \pi^+\pi^-\pi^0$) of $m_{\gamma\gamma}$. The background levels in the signal region are given in Table I; they are calculated from the simulations, published [15] branching ratios, and the number of K_L decays in the data sample. All Monte Carlo samples were over 10 times the data sample. The background from $K_L \to \pi^+\pi^- + 2\gamma$ (Acc) and $K_L \to \pi^+\pi^-\gamma + \gamma$ (Acc) was negligible.

KTeV has found evidence for the decay $K_L \to \mu^+\mu^-\gamma\gamma$ in the data studied here. Based on four events observed with a background of 0.155 ± 0.081 events, we determined [16] that $\mathcal{B}(K_L \to \mu^+\mu^-\gamma\gamma) = (10.4^{+7.5}_{-4.5}{}_{\mathrm{STAT}} \pm 0.7_{\mathrm{SYS}}) \times 10^{-9}$ with an $m_{\gamma\gamma} > 1$ MeV$/c^2$ cutoff. The small statistics of that event sample meant that this background was more precisely estimated from QED and the measured $\mathcal{B}(K_L \to \mu^+\mu^-\gamma)$; a value of $\mathcal{B}(K_L \to \mu^+\mu^-\gamma\gamma) = (9.1 \pm 0.8) \times 10^{-9}$ was used.

To normalize any possible signal's branching ratio, we identified $K_L \to \pi^+\pi^-\pi^0$ decays in as similar a manner to the $K_L \to \pi^0\mu^+\mu^-$ identification as possible. Apart from the trigger differences, the calorimeter energy requirement for clusters associated to tracks was changed to less than 0.9 times the momentum measured with the spectrometer; the MU3 and $R_\parallel^{\mu\mu}$ requirements were removed, and $m_{\pi^\pm}$ rather than $m_{\mu^\pm}$ was used in calculating kinematic quantities. The acceptance for the normalization mode was 8.1%. There were $(268 \pm 0.4_{\mathrm{STAT}} \pm 0.4_{\mathrm{MC}} \pm 4.3_{\mathrm{BR}}) \times 10^9$ K_L decays between 90 and 160 m from the target with K_L momentum between 20 and 220 MeV$/c$.

TABLE I. Summary of expected backgrounds in the signal region. "Acc" refers to particles from other sources which were accidentally time coincident with the interesting decay; "*D*" and "*P*" refer, respectively, to decay in flight or punch-through. Limits are 90% C.L.; uncertainties are due to uncertainties in published branching ratios, simulation statistics, and the statistics of the normalization mode.

Decay mode	Expected No. of events
$K_L \to \mu^+\mu^-\gamma\gamma$	0.373 ± 0.032
$K_L \to \mu^+\mu^-\gamma + \gamma$(Acc)	<0.029
$K_L \to \pi^+\pi^-\pi^0$ (*DD*)	0.252 ± 0.095
$K_L \to \pi^+\pi^-\pi^0$ (*DP*)	0.007 ± 0.007
$K_L \to \pi^+\pi^-\pi^0$ (*PP*)	0.007 ± 0.007
$K_L \to \pi^\pm\mu^\mp\nu + 2\gamma$(Acc) (*D*)	0.161 ± 0.093
$K_L \to \pi^\pm\mu^\mp\nu + 2\gamma$(Acc) (*P*)	0.063 ± 0.037
$K_L \to \pi^0\pi^\pm\mu^\mp\nu$ (*D*)	0.009 ± 0.009
$K_L \to \pi^0\pi^\pm\mu^\mp\nu$ (*P*)	<0.009
Total	0.87 ± 0.15

TABLE II. Systematic and statistical sources of uncertainty. Sources marked with (*) contribute to uncertainty in both the K_L flux and the acceptance for $K_L \to \pi^0\mu^+\mu^-$ relative to the acceptance for $K_L \to \pi^+\pi^-\pi^0$; other sources contribute only to the acceptance ratio.

Source	Relative uncertainty
$\mathcal{B}(K_L \to \pi^+\pi^-\pi^0)$	1.59% (*)
Data statistics for $K_L \to \pi^+\pi^-\pi^0$	0.16% (*)
Simulation statistics for $K_L \to \pi^+\pi^-\pi^0$	0.14% (*)
Simulation statistics for $K_L \to \pi^0\mu^+\mu^-$	0.16%
Calorimeter scale and resolution	3.33%
Spectrometer scale and resolution	1.12%
Muon identifier	4.20%
Signal trigger requirements	0.80%
Vertex quality requirement	0.22%
Spectrometer wire inefficiency	0.15%
Total	5.77%

In calculating the number of K_L decays in the data and the acceptance for $K_L \to \pi^0\mu^+\mu^-$ relative to the acceptance for $K_L \to \pi^+\pi^-\pi^0$, we allowed for the uncertainties summarized in Table II. We calculated the K_L flux using $K_L \to \pi^\pm\mu^\mp\nu$ rather than $K_L \to \pi^+\pi^-\pi^0$ decays and attributed the difference of 4.20% to the quality of our simulation of muons in the detector. We varied the scale and resolution of the calorimeter and spectrometer in the simulation to conservatively cover the range of variations seen in the data. Apart from uncertainties in published branching ratios, other sources of uncertainty were small.

From Figs. 1 and 2, two events exist in the signal region for the data. Sidebands in both m and $P_\perp^2$ show correspondence between data and background predictions as given in Table III. With the above acceptance and K_L flux, and allowing for a background level of 0.87 ± 0.15 events, we set [17] an upper limit $\mathcal{B}(K_L \to \pi^0\mu^+\mu^-) < 3.8 \times 10^{-10}$ at the 90% confidence level.

This limit is approximately 1 order of magnitude more stringent than the previous limit, and limits $|\eta|$ to $<7\sqrt{f}$ at the 90% confidence level where f is the fraction of the branching ratio attributable to direct CP violation. In comparison to the $K_L \to \pi^0e^+e^-$ channel, future $K_L \to \pi^0\mu^+\mu^-$ searches will have better single event sensitivity for any given sample of K_L decays because the level of irreducible $K_L \to l^+l^-\gamma\gamma$ background is less. While not yet as sensitive as B decays, where a recent indirect global analysis [18] finds η to be below 1, it is valuable to test if the same parametrization is valid for both B and K decays.

TABLE III. Number of observed and predicted events in regions near the signal region. Masses are in MeV/c^2 and $P_\perp^2$ is in (GeV/c)^2.

Region	Prediction	Observed
$480 < m < 492$; $P_\perp^2 < 0.0001$	2.75 ± 0.73	2
$504 < m < 515$; $P_\perp^2 < 0.0001$	0.14 ± 0.08	0
$492 < m < 504$; $0.0001^2 < P_\perp^2 < 0.0005$	2.65 ± 1.53	2
$492 < m < 504$; $0.0005^2 < P_\perp^2 < 0.0010$	2.80 ± 2.59	2

We gratefully acknowledge the support and effort of the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported in part by the U.S. Department of Energy, The National Science Foundation, and The Ministry of Education and Science of Japan. In addition, A. R. B., E. B., and S. V. S. acknowledge support from the NYI program of the NSF; A. R. B. and E. B. from the Alfred P. Sloan Foundation; E. B. from the OJI program of the DOE; K. H., K. S., T. N., and M. S. from the Japan Society for the Promotion of Science.

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