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

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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 $0.87 \pm 0.15$ 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.

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The decays $K_L \to \pi^0 l^+ l^-$ 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 $K_1 \to \pi^0 l^+ l^-$, 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 $\eta$ 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 $5.1 \times 10^{-9}$ 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 $7 \times 10^{-11}$, 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 $3.5 \times 10^{12}$ 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 $\mu$m 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 m² to
1.77 × 1.77 m²) 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 m² section of the
calorimeter had a cross-sectional area of 2.5 × 2.5 cm²,
and those in the outer region (out to 1.9 × 1.9 m²) had a
5 × 5 cm² 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 $\pi^0$
mass resolution in $K_L \rightarrow \pi^+\pi^-\pi^0$ was ~1.3 MeV/c².
Nine photon veto assemblies (lead scintillator sand-
wiches) 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 calorim-
eter, 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 down-
stream of the calorimeter, were taken as a function of
momentum from $K_L \rightarrow \pi^+\pi^-\pi^0$ and data and are on the order
of $2 \times 10^{-3}$. 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 op-
positely charged particles with a common vertex that de-
posit little energy in the calorimeter and created two hits
at MU3 from these muons. The $\pi^0$ creates two electro-
magnetic 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
$K_L \rightarrow \pi^+\pi^-\pi^0$ where both $\pi^\pm$ either decay upstream of
the calorimeter (decay in flight) or punch through to MU3.
The second is $K_L \rightarrow \pi^+\mu^-\nu$ with one decay in flight
or punch-through and accidentally coincident calorimeter
activity that appears as a $\pi^0$. The third and largest
background is the radiative muonic Dalitz decay $K_L \rightarrow
\mu^+\mu^-\gamma\gamma$ when $m_{\gamma\gamma} = m_{\pi^0}$. Because of the low ex-
pected [12] branching ratio, $K_L \rightarrow \pi^0\pi^+\pi^-\nu$ is not a
large background.

Two triggers were used for this analysis. To deter-
mine the number of $K_L$ decays in the data, we identi-
fied $K_L \rightarrow \pi^+\pi^-\pi^0$ decays in a minimum bias trigger.
This trigger required hits in the trigger hodoscopes and
the drift chambers which were consistent with two coinci-
dent 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 sig-
nal 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 mo-
mentum was well measured. The two-muon system was
required to have a mass less than 350 MeV/c² to reduce
backgrounds from $K_L \rightarrow \pi^+\mu^-\nu$. We required two non-
adjacent 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 require-
ment 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 $\chi^2$ 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 ac-
cceptance) of each other at the bend plane of the magnet.
The mass of the two unassociated clusters under the hy-
thesis that they were produced by photons from the de-
cay vertex was required to be between 135 ± 6 MeV/c²
(±2.5σ). These clusters both had to have been found by
the trigger cluster counter.

A number of kinematic criteria were studied to sup-
press background from $K_L \rightarrow \mu^+\mu^-\gamma\gamma$ decays. The
kinematics of this decay are very different from the analo-
gous $K_L \rightarrow e^+e^-\gamma\gamma$ background to $K_L \rightarrow \pi^0e^+e^-$, and
the branching ratio is lower. Consequently, the methods
[13,14] which are effective in the $e^-$ case are less effec-
tive in the $\mu^-$ case. Although kinematic cuts do reduce
$K_L \rightarrow \mu^+\mu^-\gamma\gamma$ background, the corresponding ac-
cceptance loss in light of the other backgrounds is not ad-
vantageous. Requirements of this kind were not applied.

We suppress backgrounds from $K_L \rightarrow \pi^+\pi^-\pi^0$ and
$K_L \rightarrow \pi^-\pi^+\nu$ by using

$$R_{\mu\mu} = \frac{(m^2_K - m^2_{\mu\mu} - m^2_{\pi^0})^2 - 4m^2_{\mu\mu}m^2_{\pi^0} - 4m^2_{\pi^0}p^2_{\pi^0\mu\mu}}{p^2_{\pi^0\mu\mu} + m^2_{\mu\mu}}$$

(1)
where $m_K$ is the kaon mass, $m_{\mu\mu}$ the mass of the two-muon system, $m_{\pi^0}$ the $\pi^0$ mass, and $p_{\perp\mu\mu}$ is the two-muon systems’ momentum perpendicular to the kaon momentum. This quantity is proportional to the $\pi^0$ 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 $R_{\mu\mu}$ to lie between −0.01 and 0.10 GeV$^2$/c$^4$. This cut keeps 89.2% of the signal and rejects 73% of $K_L \to \pi^\pm \mu^+ \nu$ decays with coincident photons and 95% of the $K_L \to \pi^\pm \pi^\mp \pi^0$ 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 decay, 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 $\mathcal{B}(K_L \to \mu^+\mu^-\gamma\gamma) = (10.4\pm7.5_{\text{STAT}}\pm0.7_{\text{SYS}}) \times 10^{-9}$ 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 $\mathcal{B}(K_L \to \mu^+\mu^-\gamma\gamma)$; a value of $\mathcal{B}(K_L \to \mu^+\mu^-\gamma\gamma) = (9.1\pm0.8) \times 10^{-9}$ was used.

To normalize any possible signal’s branching ratio, we identified $K_L \to \pi^+\pi^-\pi^0$ decays in 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 $R_{\mu\mu}$ requirements were removed, and $m_{\pi^0}$ rather than $m_{\mu^+\mu^-}$ was used in calculating kinematic quantities. The acceptance for the normalization mode was 8.1%. There were $(268\pm0.4_{\text{STAT}}\pm0.4_{\text{MC}}\pm4.3_{BR}) \times 10^9$ $K_L$ decays between 90 and 160 m from the target with $K_L$ momentum between 20 and 220 MeV/c.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Expected No. of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_L \to \mu^+\mu^-\gamma\gamma$</td>
<td>$0.373 \pm 0.032$</td>
</tr>
<tr>
<td>$K_L \to \mu^+\mu^-\gamma + \gamma$(Acc)</td>
<td>$&lt;0.029$</td>
</tr>
<tr>
<td>$K_L \to \pi^+\pi^-\pi^0$ (DD)</td>
<td>$0.252 \pm 0.095$</td>
</tr>
<tr>
<td>$K_L \to \pi^+\pi^-\pi^0$ (DP)</td>
<td>$0.007 \pm 0.007$</td>
</tr>
<tr>
<td>$K_L \to \pi^+\pi^-\pi^0$ (PP)</td>
<td>$0.007 \pm 0.007$</td>
</tr>
<tr>
<td>$K_L \to \pi^+\mu^-\nu + 2\gamma$(Acc) (D)</td>
<td>$0.161 \pm 0.093$</td>
</tr>
<tr>
<td>$K_L \to \pi^+\mu^-\nu + 2\gamma$(Acc) (P)</td>
<td>$0.063 \pm 0.037$</td>
</tr>
<tr>
<td>$K_L \to \pi^0\pi^\pm\mu^\pm\nu$ (D)</td>
<td>$0.009 \pm 0.009$</td>
</tr>
<tr>
<td>$K_L \to \pi^0\pi^\pm\mu^\pm\nu$ (P)</td>
<td>$&lt;0.009$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.87 \pm 0.15$</td>
</tr>
</tbody>
</table>
TABLE II. Systematic and statistical sources of uncertainty. Sources marked with (*) contribute to uncertainty in both the $K_L$ flux and the acceptance for $K_L \rightarrow \pi^0\mu^+\mu^-$ relative to the acceptance for $K_L \rightarrow \pi^+\pi^-\pi^0$; other sources contribute only to the acceptance ratio.

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

In calculating the number of $K_L$ decays in the data and the acceptance for $K_L \rightarrow \pi^0\mu^+\mu^-$ relative to the acceptance for $K_L \rightarrow \pi^+\pi^-\pi^0$, we allowed for the uncertainties summarized in Table II. We calculated the $K_L$ flux using $K_L \rightarrow \pi^+\pi^-\pi^0$ rather than $K_L \rightarrow \pi^+\pi^-\pi^0$ 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 $P_1^2$ 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 $0.87 \pm 0.15$ events, we set [17] an upper limit $\mathcal{B}(K_L \rightarrow \pi^0\mu^+\mu^-) < 3.8 \times 10^{-10}$ 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 $K_L \rightarrow \pi^0e^+e^-$ channel, future $K_L \rightarrow \pi^0\mu^+\mu^-$ searches will have better single event sensitivity for any given sample of $K_L$ decays because the level of irreducible $K_L \rightarrow l^+l^-\gamma\gamma$ background is less. While not yet as sensitive as $B$ decays, where a recent indirect global analysis [18] finds $\eta$ to be below 1, it is valuable to test if the same parametrization is valid for both $B$ and $K$ decays.

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[12] From measured $K_{\mu^4}$ decays and the ratio of lifetimes of $K_L$ and $K^+$, $\mathcal{B}(K_L \rightarrow \pi^0\pi^+\pi^-\nu) \sim 5 \times 10^{-5}$.


[14] A. Alavi-Harati et al., “Search for the Decay $K_L \rightarrow \pi^0e^+e^-$” (to be published).


[16] A. Alavi-Harati et al., “Evidence for the Decay $K_L \rightarrow \mu^+\mu^-\gamma\gamma$” (to be published).


[18] See, for example, F. Parodi, P. Roudeau, and A. Stocchi, LAL-99-03, hep-ex/9903063.