Search for the Rare Decays $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$

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The KTeV E799 experiment has conducted a search for the rare decays, $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$, where the X^0 is a possible new neutral boson that was reported by the HyperCP experiment with a mass of (214.3 ± 0.5) MeV/c^2. We find no evidence for either decay. We obtain upper limits of Br$(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) < 1.0 \times 10^{-10}$ and Br$(K_L \to \pi^0\pi^0\mu^+\mu^-) < 9.2 \times 10^{-11}$ at the 90% confidence level. This result rules out the pseudoscalar X^0 as an explanation of the HyperCP result under the scenario that the $\bar{d}sX^0$ coupling is completely real.

The HyperCP Collaboration has reported the possible observation of an X^0 boson of mass (214.3 ± 0.5) MeV/c^2 decaying into $\mu^+\mu^-$ based on three observed events in a search for the decay $\Sigma^+ \to p\mu^+\mu^-$ [1]. The confidence level within the standard model for all three events to overlap within the HyperCP dimuon mass resolution of 0.5 MeV/c^2 is less than 1%. As the X^0 would presumably be a strange-to-down neutral current, it is natural to look for it in the kaon sector, specifically in the mode $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$. This Letter presents the first attempt to detect the rare decay modes $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$.

Using a two-quark flavor changing coupling model in which the X^0 couples to $\bar{d}s$ and $\mu^+\mu^-$, theoretical estimates of the $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ branching ratio were determined for a pseudoscalar X^0 and an axial vector X^0 [2]. Reference [2] uses the known value Br$(K^\pm \to \pi^\pm\mu^+\mu^-) = 8.1 \times 10^{-8}$ [3] to rule out the possibility of a scalar or vector X^0 as explanations of the HyperCP anomaly. These predictions assume real $\bar{d}sX^0$

couplings, g_P; for a complex coupling with a dominant imaginary term, $|\Im(g_P)| > 0.98|g_P|$, the predicted upper limit is much smaller [4]. Another prediction of Br$(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-)$ for a pseudoscalar X^0 has been made [5]. Finally, the branching ratio for $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\gamma\gamma$ has been estimated using an sgoldstino model [6]. These results are summarized in Table I.

The E391a Collaboration has reported [7] an upper limit Br$(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\gamma\gamma) < 2.4 \times 10^{-7}$, which

TABLE I. Summary of predicted branching ratios for $K_L \to \pi^0\pi^0 X^0$.

$X^0 \to \mu^+\mu^-$ model	Br$(K_L \to \pi^0\pi^0 X^0)$
Pseudoscalar $[\Re(g_P)]$ [2]	$(8.3^{+7.5}_{-6.6}) \times 10^{-9}$
Axial vector $[\Re(g_A)]$ [2]	$(1.0^{+0.9}_{-0.8}) \times 10^{-10}$
Pseudoscalar $[|\Im(g_P)| > 0.98|g_P|]$ [4]	$<7 \times 10^{-11}$
Pseudoscalar $[\Re(g_P)]$ [5]	8.02×10^{-9}
Sgoldstino $(X^0 \to \gamma\gamma)$ [6]	1.2×10^{-4}

rules out the sgoldstino model of this decay. The possibility [8] that X^0 could be a light pseudoscalar Higgs boson of the next-to-minimal supersymmetric standard model was investigated at e^+e^- colliders by CLEO [9] and *BABAR* [10–12] and at the Tevatron (D0) [13]. No evidence for a next-to-minimal supersymmetric standard model light pseudoscalar Higgs boson was found.

The $K_L \rightarrow \pi\pi X^0$ modes have an extremely limited phase space. The phase space of $K_L \rightarrow \pi^0\pi^0 X^0$ is 10 times larger than the phase space available to $K_L \rightarrow \pi^+\pi^- X^0$, motivating the search for the former over the latter. We have searched for $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ and $K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ in data from the 1997 and 1999 runs of KTeV E799 II at Fermi National Accelerator Laboratory.

The KTeV E799 experiment produced neutral kaons via collisions of 800 GeV/c protons with a BeO target. The particles created from interactions with the target passed through a series of collimators, absorbers and sweeper magnets to produce two nearly parallel K_L beams. The K_L beams then entered a 65 m long vacuum tank, which was evacuated to 1 μTorr. A doubling of the spill length and an increase in instantaneous luminosity between the 1997 and 1999 data-taking periods resulted in a factor of 2–3 increase in per-spill protons on target in 1999. A 10.3 in. beryllium absorber was introduced in the 1999 data-taking period to reduce neutron backgrounds.

Immediately downstream of the vacuum region was a spectrometer composed of an analysis magnet between two pairs of drift chambers. The momentum kick imparted by the magnetic field was reduced from the 1997 value of 0.205 GeV/c to 0.150 GeV/c in 1999 to increase the acceptance for low momentum charged particles. The momentum resolution of the spectrometer in 1997 was $\sigma_P/P = 0.38\% \oplus 0.016\% P$ [14], and in 1999 the momentum resolution was $\sigma_P/P = 0.52\% \oplus 0.022\% P$.

The electromagnetic calorimeter was constructed of 3100 pure CsI crystal blocks arranged into a 1.9×1.9 m^2 array. Each CsI crystal was 27 radiation lengths long. Two holes were located near the center of the calorimeter to allow for passage of the beams. The electromagnetic calorimeter had an energy resolution of $\sigma_E/E \simeq 0.4\% \oplus 2\%/\sqrt{E[\text{GeV}]}$ and the position resolution was about 1 mm. The muon ID system used a Pb wall, three steel filters, and three scintillator counter planes to identify muons by filtering out other charged particles. The muon ID system contained 31 nuclear interaction lengths of material and had a charged pion fake rate of $(1.69 + 0.17P[\text{GeV}/c]) \times 10^{-3}$, where P is the track momentum. A photon veto system detected photons outside the detector acceptance. The upstream section of the photon veto system had five lead-scintillator counter arrays located inside the vacuum decay region. The downstream section of the photon vetos had four lead-scintillator arrays that framed the outside of the last three drift chambers and the CsI

calorimeter. A more detailed description of the KTeV detector and photon veto system can be found in [15–17].

The signal modes and normalization mode ($K_L \rightarrow \pi^0\pi^0\pi^0_D$, where one photon was lost down the beam hole and $\pi^0_D \rightarrow e^+e^-\gamma$) were collected by different triggers. The triggers required in-time energy clusters in the calorimeter of at least 1 GeV. The signal mode required one (two) such clusters for the 1997 (1999) data-taking periods. Two hits were required in the two most downstream stations of the muon system in 1997; in 1999, the number of hits required in the middle station was reduced to one. The normalization mode trigger required at least four in-time clusters and two tracks.

Both tracks were required to form a good vertex within the vacuum decay region, to match (within 7 cm) a cluster in the CsI calorimeter and to deposit less than 1 GeV of energy in the CsI calorimeter, which is consistent with a muon hypothesis. 99.9% of muons with a track momentum over 7.0 GeV/c satisfied the last three requirements. Each of the three scintillator counting planes in the muon ID system were required to register at least one hit. The invariant $\mu^+\mu^-$ mass, $M_{\mu\mu}$, was required to be less than 0.232 GeV/c^2, which is slightly above the kinematic limit given by M_K-$2M_\pi$.

Four clusters in the calorimeter without associated tracks were required. The resolution of the z vertex determined from the two $\gamma\gamma$ vertices associated with a $\pi^0\pi^0$ was better than the resolution of the z vertex from the two muons. We considered each possible $\gamma\gamma$ pair to find the combination with the best agreement between the positions of the two $\gamma\gamma$ decay points under the hypothesis that each originated from a π^0 decay. A minimum pairing chi-squared χ^2_z was calculated to determine the best agreement between the positions of the two $\gamma\gamma$ decay points. A weighted average of z vertex values for each $\gamma\gamma$ in the pairing with the minimum χ^2_z was used as the decay vertex for the event. This vertex was then required to be located within the length of the vacuum decay region. A $\gamma\gamma$ mass $M_{\gamma\gamma}$ was calculated for the event using the decay vertex from the minimum χ^2_z pairing. $M_{\gamma\gamma}$ was required to be within 0.009 GeV/c^2 of the π^0 mass.

The $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ simulation was modeled as a four body decay using a constant matrix element. The $K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ simulation was modeled as a three body decay with a flat phase space, where the X^0 underwent a prompt decay to $\mu^+\mu^-$.

The signal regions for the 1997 and 1999 data were based on the $M_{\mu\mu\gamma\gamma\gamma\gamma}$, $p_T^2(\mu\mu\gamma\gamma\gamma\gamma)$, and $|p_T^2(\mu\mu) - p_T^2(\gamma\gamma\gamma\gamma)|$ resolutions calculated in the simulation. Here p_T^2 is measured transverse to the direction of the K_L, which is determined by the line connecting the BeO target and the vertex. For a well-measured decay, $p_T^2(\mu\mu\gamma\gamma\gamma\gamma)$ and $|p_T^2(\mu\mu) - p_T^2(\gamma\gamma\gamma\gamma)|$ should be close to zero. The K_L signal region for the decay $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ was defined as 0.495 GeV/$c^2 \leq M_{\mu\mu\gamma\gamma\gamma\gamma} \leq 0.501$ GeV/c^2

and $p_T^2 \leq 1.3 \times 10^{-4}$ $(\text{GeV}/c)^2$. The X^0 signal region for the $K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ decay was defined as 213.8×10^{-3} $\text{GeV}/c^2 \leq M_{\mu\mu} \leq 214.8 \times 10^{-3}$ GeV/c^2 and $|p_T^2(\mu\mu) - p_T^2(\gamma\gamma\gamma\gamma)| \leq 7.0 \times 10^{-4}(\text{GeV}/c)^2$. The
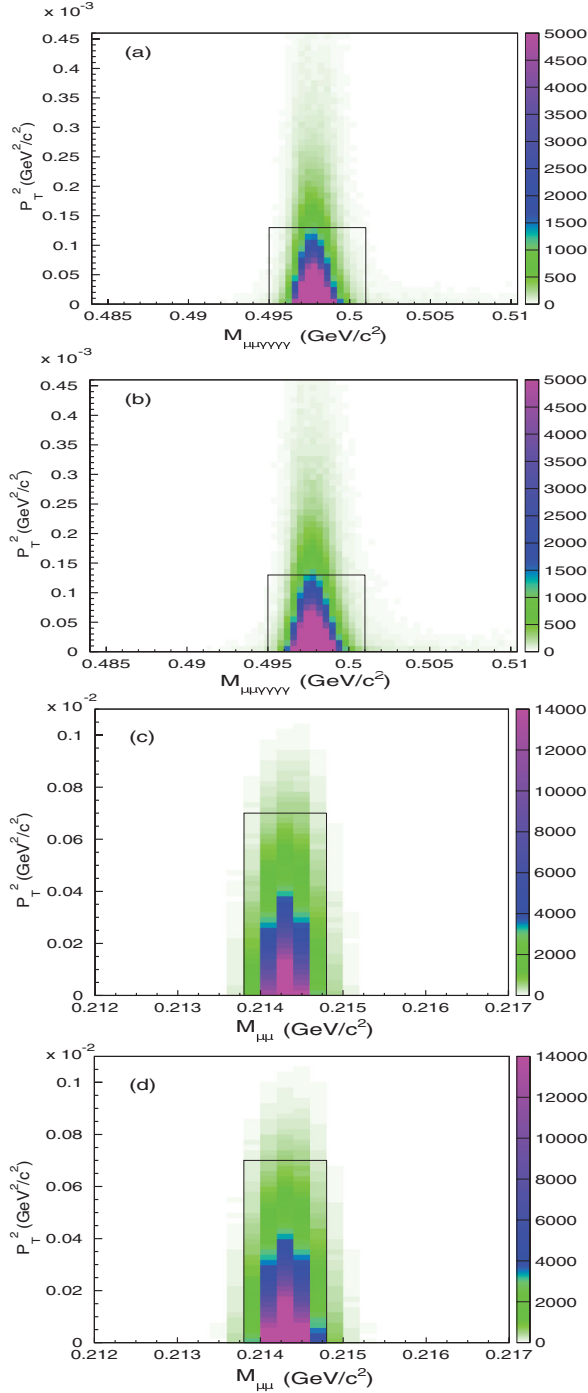

FIG. 1 (color).   (a), (b) p_T^2 vs $M_{\mu\mu\gamma\gamma\gamma\gamma}$ for the 1997 and 1999 $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ simulations, respectively. The boxed signal region contains 90% of all events. (c), (d) $|p_T^2(\mu\mu) - p_T^2(\gamma\gamma\gamma\gamma)|$ vs $M_{\mu\mu}$ for the 1997 and 1999 $K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ simulations, respectively. The boxed signal region contains 95% of all events. The four plots are shown after all analysis requirements were applied.

bound on $M_{\mu\mu}$ was determined from the conservative hypothesis that the observations made by HyperCP reflect the natural width of the X^0 [18]. Figure 1 shows p_T^2 vs invariant mass plots from the $K_L \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ and $K_L \rightarrow \pi^0 \pi^0 X^0 \rightarrow \pi^0 \pi^0 \mu^+ \mu^-$ signal mode simulations.

Every K_L decay mode with two minimum ionizing tracks and at least one photon was considered as a potential source of background. Accidental time-coincident activity created from particle interactions in the vacuum window, neutrons from the target, cosmic rays, beam interactions, or another kaon decay in flight, can overlap with the primary kaon decay in an event to reproduce the signal mode topology. We have simulated all known backgrounds to the extent that it is possible. Accidental activity was included in the simulation of all background mode events. Small branching ratio backgrounds such as $K_L \rightarrow \pi^0 \pi^{\pm} \mu^{\mp} \nu_\mu$ [19] and $K_L \rightarrow \pi^+ \pi^- \gamma$ were simulated with the full statistics of the data. Large branching ratio modes such as $K_L \rightarrow \pi^{\pm} \mu^{\mp} \nu_\mu$ were also studied extensively, although simulated samples with statistics similar to the data were not feasible. We find that when accidental activity reproduces the signal mode topology, p_T^2 and the invariant mass $M_{\mu\mu\gamma\gamma\gamma\gamma}$ are pushed to values well above the signal region. The conclusion that the background is negligible is confirmed in the data.

The normalization mode shares the topological trait of four photons and two tracks with the signal mode and has a well-understood branching ratio. The vertex in the normalization mode analysis was required to be located within the vacuum decay region. The signal region for the 1997 data was defined by 0.494 $\text{GeV}/c^2 \leq M_{ee\gamma\gamma\gamma\gamma} \leq 0.501$ GeV/c^2 and $p_T^2(ee\gamma\gamma\gamma\gamma) \leq 0.00015$ GeV^2/c^2. The signal region for the 1999 data was a contour that was derived from a joint probability distribution of $M_{ee\gamma\gamma\gamma\gamma}$ and $p_T^2(ee\gamma\gamma\gamma\gamma)$ signal resolutions from simulations.

The flux F_K obtained from the normalization mode, is the estimated number of K_L decays in the vacuum decay region. Uncertainties in F_K originated from the branching ratio used to calculate F_K and the muon ID system

TABLE II.   Summary of systematic uncertainties on the apparent K_L flux, labeled as F_K.

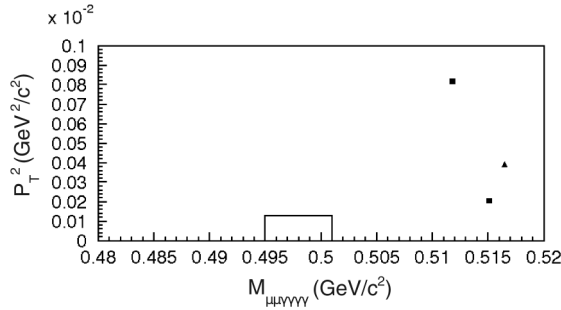| Systematic uncertainty on F_K	$\frac{\Delta F_K}{F_K}$
Variation of normalization requirements	3.57%
Variation of signal and normalization requirements	5.35%
Muon trigger inefficiency	2.00%
Cracks in muon counting planes	0.50%
Energy loss in muon filters	0.40%
Br($K_L \rightarrow \pi^0 \pi^0 \pi^0$) [3]	0.61%
Br($\pi^0 \rightarrow \gamma\gamma$) [3]	0.03%
Br($\pi^0 \rightarrow e^+ e^- \gamma$) [3]	2.98%
Total systematic uncertainty	7.41%

FIG. 2. p_T^2 vs $M_{\mu\mu\gamma\gamma\gamma\gamma}$ plot for the combined 1997 and 1999 data sets, which are indicated by triangles and squares, respectively. The signal box is open.

efficiency. The uncertainty due to normalization mode requirements was studied by varying the selection requirements in the simulation and data and noting the change in the estimated flux. The uncertainty due to differences in the signal and normalization mode simulations was estimated by varying the selection requirements of both modes in the simulation. The statistical uncertainties on the signal mode simulation were less than 0.14% for each decay mode. The statistical uncertainty for the normalization mode simulation was less than 0.37%, while the statistical uncertainty for the normalization mode data was less than 1.14%. Systematic uncertainty in the muon ID efficiency came from modeling of the energy loss in the muon filters and from simulation of gaps between scintillator paddles in the muon planes [20]. A systematic uncertainty associated with the muon trigger inefficiency was determined by selecting clean $K_{\mu3}$ decays from a minimum bias trigger [21]. Results from these systematic uncertainty studies are given in Table II.

The 1997 (1999) signal mode acceptance was 3.14% (4.03%) and 2.80% (3.74%) for $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ and $K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$, respectively. The 1997 and 1999 normalization mode acceptances were 4.21×10^{-6} and 3.26×10^{-6}, respectively [22]. While signal mode acceptance would drop in scenarios for which the X^0 does not decay immediately, it would not be sharply reduced for values of $c\tau < 3$ mm, where τ is the proper decay time. F_K was 2.73×10^{11} in 1997 and 4.12×10^{11} in 1999. The single event sensitivity was 3.97×10^{-11} for $K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$ and 4.34×10^{-11} for $K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$. Figure 2 displays the results of the blind analysis; no events are inside the signal regions after opening the signal boxes and no events were found within the available $\mu^+\mu^-$ phase space. Using the method of [23], the 90% confidence level upper limits are Br($K_L \rightarrow \pi^0\pi^0\mu^+\mu^-$) $< 9.2 \times 10^{-11}$ and Br($K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$) $< 1.0 \times 10^{-10}$.

Our result for Br($K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$) is nearly 2 orders of magnitude smaller than the expected branching ratios for $K_L \rightarrow \pi^0\pi^0 X^0 \rightarrow \pi^0\pi^0\mu^+\mu^-$ from

[2,5], in which X^0 was taken to be a pseudoscalar. This rules out the pseudoscalar X^0 as an explanation of the HyperCP result under the premise that g_P is completely real and also places a tight bound on g_P of $|\Im(g_P)| \gtrsim 0.98|g_P|$ [4]. Finally, our upper limit challenges the axial-vector X^0 explanation of the HyperCP result.

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