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Search for a New Neutral Boson in the Rare Decay $K_L \to \pi^0\pi^0\mu^+\mu^-$ from KTeV

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The KTeV E799 experiment has conducted a search for the rare decay $K_L \to \pi^0\pi^0\mu^+\mu^-$, which includes a search for the light neutral boson X^0 that decays to $\mu^+\mu^-$. A possible new light neutral boson X^0 was reported by the HyperCP experiment with a mass of 214.3 MeV/c^2. In this paper we report no evidence of $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ and set an upper limit on the branching ratio for $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ of 9.44×10^{-11} at the 90% confidence level. In addition, an upper limit on the branching ratio for $K_L \to \pi^0\pi^0\mu^+\mu^-$ of 8.63×10^{-11} at the 90% confidence level is also presented.

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In this report, we present the first attempt to detect the rare decay modes $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$, where X^0 is a neutral boson of mass 214.3 MeV/c^2. Based on an observation of three events in a study of the decay $\Sigma^+ \to p\mu^+\mu^-$, the HyperCP collaboration reported the possible observation of an X^0 boson of mass 214.3 MeV/c^2 decaying into $\mu^+\mu^-$ [1].

Using a two-quark flavor changing coupling model, in which the X^0 couples to the $\bar{d}s$ and the $\mu^+\mu^-$, theoretical estimates of the $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ branching ratio were determined to be $(8.3^{+7.5}_{-6.6})\times10^{-9}$ for a pseudoscalar X^0 and $(1.0^{+0.9}_{-0.8})\times10^{-10}$ for a axial vector X^0 [2]. In this model, the scalar and vector X^0 were ruled out as explanations for the HyperCP hypothesis of the X^0 particle by using a constraint from $K^\pm \to \pi^\pm\mu^+\mu^-$, which has a measured branching ratio of 8.1×10^{-8} [3]. Another similar model predicts a branching ratio for $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ of 8.02×10^{-9}, where the X^0 is a neutral pseudoscalar spin zero boson [4]. An alternate model proposes the light pseudoscalar Higgs boson from the next-to-minimal supersymmetric standard model (NMSSM) as an explanation of the HyperCP result [5]. However, there is currently no prediction for the branching ratio of $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ using NMSSM. In addition, a theoretical study on the rare decay $K_L \to \pi^0\pi^0\mu^+\mu^-$ has not yet been performed within the framework of the standard model.

The search for the $K_L \to \pi^0\pi^0\mu^+\mu^-$ mode was performed by analyzing 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 70 m long vacuum tank, which was evacuated to 1 μTorr. Immediately downstream of the vacuum region was a spectrometer, which was composed of an analysis magnet sandwiched between two pairs of drift chambers.

The two vital elements to this analysis were the pure CsI electromagnetic calorimeter and the muon ID system, which were located at 186.0 m and 188.5 m from the BeO target respectively. The CsI electromagnetic calorimeter was constructed of 3100 pure CsI crystal blocks arranged into a 1.9×1.9 m^2 array, in which each crystal was 27 radiation lengths long. Two holes are located near the center of the calorimeter to allow for passage of the neutral beams. The muon ID system was composed of a lead wall, three particle filters and three scintillator counter planes designed to identify muons by filtering out other charged particles. In total, the lead wall and three filters amounted to 31 nuclear interaction lengths of material. A more detailed description of the KTeV detector can be found in [6, 7].

The 1997 and 1999 runs differed in the following ways. The spill length was doubled from 20 seconds in the 1997 run to 40 seconds in the 1999 run. The proton intensity on the BeO neutral kaon production target was increased from $2-4\times10^{12}$ protons per spill in the 1997 run to $6-10\times10^{12}$ protons per spill in the 1999 run. Another important difference between the 1997 and 1999 runs was the magnetic field in the spectrometer. In the 1997 run, the magnetic field produced a momentum kick of 205 MeV/c to charged particles in x-z plane of the spectrometer. In the 1999 run, the magnetic field was changed to yield a momentum kick of 150 MeV/c in the x-z plane to increase acceptance for select neutral kaon decay modes.

The signal modes and normalization mode were collected by different triggers. Both signal modes used $K_L \to \pi^0\pi^0\pi^0_D$ as the normalization mode, where one of the π^0s undergoes the Dalitz decay $\pi^0_D \to e^+e^-\gamma$. The signal mode trigger was changed in the 1999 run from the requirement of two hits in each view of the final pair of muon ID system counting planes to one missing hit in either the x or y view of the last two muon ID system counting planes. In order to counteract this effect, the number of hardware clusters was increased from a minimum of one to two for the 1999 run. Every crystal in a hardware cluster has at least 1 GeV of deposited energy from a track or a photon. The normalization mode trigger, which demanded two charged tracks and at least four electromagnetic clusters, was loosened midway through the 1997 run by changing the minimum thresholds for energy in the electromagnetic calorimeter. These changes to the minimum thresholds were kept intact for the 1999 run.

The presence of four photons and lack of phase space available to the signal modes forces the vast majority of all possible backgrounds into a $M_{\mu\mu\gamma\gamma\gamma\gamma}$ region above the K_L mass. This allowed for background issues to be effectively addressed with a loose set of cuts, which also yielded good signal acceptance. Both charged tracks were required to form a good vertex within the vacuum decay region, to match a cluster in the CsI calorimeter, to have $E/p \leq 0.9$ and deposit less than 1 GeV of energy in the CsI calorimeter. E was the energy of the cluster associated with the track, while p was momentum. In addition, the track momentum was constrained to values greater than 7.0 GeV/c. The latter three requirements are consistent with minimum ionizing muons. In addition, each of the three scintillator counting planes in the muon ID system were required to register at least one hit. A loose requirement on the invariant $\mu^+\mu^-$ mass, $M_{\mu\mu} \leq 232$ MeV/c^2, was also implemented.

The number of clusters in the CsI calorimeter not associated with tracks was required to be equal to four. Due to the narrow opening angle of the $\mu^+\mu^-$, the z-vertex determined from the charged tracks was poor compared to the z-vertex constructed using two $\gamma\gamma$ vertices associated with the $\pi^0\pi^0$. Reconstruction of the $\pi^0\pi^0$ was performed by analyzing each possible $\gamma\gamma$ pair in order to find the combination with the best agreement of the position of two neutral vertices determined from each pair of photons under the hypothesis that they originated in a π^0 decay. The z-vertex for the event is then calculated as a weighted average of z-vertex values for each $\gamma\gamma$ in the π^0 pairing with the minimum pairing chi-squared of the z-vertex. This z-vertex was required to lie within the range of 90 to 160 m from the target, which encompasses the full length of the vacuum decay region. Each $\gamma\gamma$ mass in a given event, $M_{\gamma\gamma}$, is extracted as a byproduct of the neutral z-vertexing procedure and was required to be within 9 MeV/c^2 of the π^0 mass. Further details can be found in [8].

Any K_L decay mode with two minimum ionizing tracks and at least one photon was simulated in the Monte Carlo (MC) and analyzed as a potential source of background. If the minimum ionizing track was a $\pi^\pm$, then cases of both $\pi^\pm$ punch through to the muon ID system and $\pi^\pm$ decay were simulated in the MC as two separate sources of background. Backgrounds in these scenarios lack a minimum of two photons needed to have the signal mode topology. Overlap of these modes with accidental events provide the extra photons needed to fill this void. These backgrounds have an $M_{\mu\mu\gamma\gamma\gamma\gamma}$ greater than the K_L mass. Approximately eleven billion background events were generated. After all signal mode analysis cuts there were zero background events remaining in the signal regions from the considered backgrounds.

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

$|p^2_{T,\mu\mu} - p^2_{T,\pi\pi}|$ resolutions calculated using the two signal mode MCs. Here p^2_T is measured relative to the direction of the K_L determined by the line connecting the BeO target center and the decay vertex. The signal mode MC for $K_L \to \pi^0\pi^0\mu^+\mu^-$ was modeled as a four body decay using a constant matrix element. The signal mode MC for $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ was modeled as a three body decay with a flat phase space, where the X^0 decayed immediately to $\mu^+\mu^-$. For the 1997 and 1999 data, the signal region for the K_L decay was determined from resolution studies to be rectangular with 0.495 GeV/c$^2 \leq M_{\mu\mu\gamma\gamma\gamma\gamma} \leq$ 0.501 GeV/c^2 and $p^2_T \leq$ 0.00013 (GeV/c)^2. This region shall be referred to as the first signal box. In both data sets, the signal region for the X^0 decay was chosen to be rectangular with 213.8 MeV/c$^2 \leq M_{\mu\mu} \leq$ 214.8 MeV/c^2 and $|p^2_{T,\mu\mu} - p^2_{T,\pi\pi}| \leq$ 0.0007 (GeV/c)^2. This region shall be referred to as the second signal box. The constraint on $M_{\mu\mu}$ was determined based on the resolutions of the dimuon mass and $|p^2_{T,\mu\mu} - p^2_{T,\pi\pi}|$, and the X^0 mass defined by the HyperCP collaboration [1]. Figure 1 shows p^2_T vs. invariant mass scatter plots of the $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ signal mode MC respectively. Generation of the signal mode MC with accidental events led to mismeasured events, which were pushed outside the signal mode region as a result.

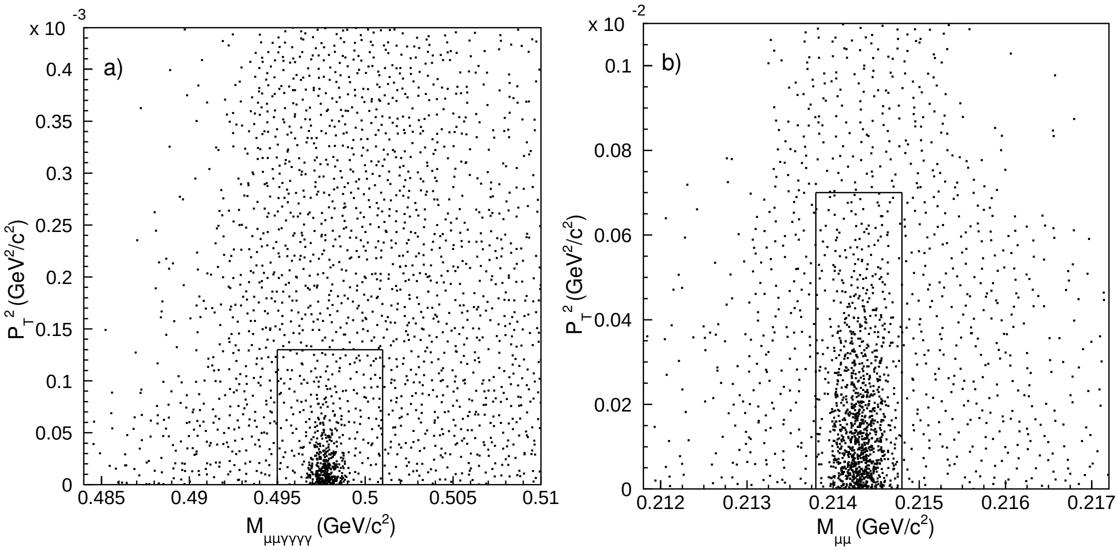

Figure 1: a) p^2_T vs. $M_{\mu\mu\gamma\gamma\gamma\gamma}$ scatter plot for the 1997 $K_L \to \pi^0\pi^0\mu^+\mu^-$ MC. b) $|p^2_{T,\mu\mu} - p^2_{T,\pi\pi}|$ vs. $M_{\mu\mu}$ scatter plot for the 1997 $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ MC. Both plots are shown after all analysis requirements were applied. The boxes indicate the locations of the signal regions.

This analysis employed $K_L \to \pi^0\pi^0\pi^0_D$ as the normalization mode, where $\pi^0_D \to e^+e^-\gamma$. Aside from being located in different triggers, the differences between the normalization mode and the signal modes was the presence of an extra photon and two electrons instead of two muons. The normalization mode was chosen due to its large and well measured branching ratio and to the lack of any previously observed neutral K_L decay modes with two tracks and four photons. As in the signal mode, the four photons which gave the minimum pairing chi-squared of the z-vertex were associated with the π^0 pair for that event. The remaining photon was partnered with the π^0_D state. The z-vertex in the normalization mode analysis was chosen to be between 94 m and 158 m from the target.

Source of Systematic Error on F_K	$\frac{\Delta F_K(1997)}{F_K(1997)}$	$\frac{\Delta F_K(1999)}{F_K(1999)}$
Variation of Kinematic Requirements	+1.26%	+2.24%
p_z Weighting	——	1.87%
Cracks in Muon Counting Planes	0.50%	0.50%
Energy Loss in Muon Filters	0.40%	0.40%
$BR(K_L \to \pi^0\pi^0\pi^0)$	0.61%	0.61%
Total Systematic Error	+1.54%	+3.05%

Table 1: Summary of systematic errors on the K_L flux, labeled as F_K.

The only noticeable background to the normalization mode was when a photon from $K_L \to \pi^0\pi^0\pi^0$ underwent pair production in the vacuum window or detector material upstream of the first drift chamber. Only very loose cuts on the normalization mode invariant mass ($M_{ee\gamma\gamma\gamma\gamma}$), p_T^2 and $M_{\gamma\gamma}$ were needed to extract the normalization mode signal and eliminate the photon conversion background. $M_{ee\gamma\gamma\gamma\gamma}$ was required to be between 473 and 523 MeV^2, while $p_T^2 \leq 0.001$ GeV^2/c^2 and $M_{\gamma\gamma}$ was situated within 14 MeV/c^2 of the π^0 mass. After generating approximately a MC equivalent of twice the flux of $K_L \to \pi^0\pi^0\pi^0$ (where one of the photons underwent photon conversion), only one $K_L \to \pi^0\pi^0\pi^0$ MC event was found after all analysis requirements were applied. This was negligible compared to the number of $K_L \to \pi^0\pi^0\pi^0$ events found in the data. Therefore, this background did not have a noticeable effect on the K_L flux.

Uncertainties in the K_L flux originated from the branching ratio used to calculate the flux, uncertainty in the kinematical analysis requirements, the resolution of the total z momentum (p_Z), and the efficiency of the muon ID system. The statistical errors on the signal mode MC were less than 0.14% for each decay mode, while the statistical error for both the normalization mode data and MC was less than 0.31%. All systematic errors in this analysis came from the normalization mode. The uncertainty due to kinematical analysis requirements was determined by varying the z-vertex, $M_{ee\gamma\gamma\gamma\gamma}$, p_T^2, $M_{\gamma\gamma}$ and E/p cuts. The uncertainty from p_Z was calculated by applying a set of weights to flatten the data/MC ratio of the p_Z spectrum. Systematic errors in the muon ID efficiency stemmed from modeling of the energy loss in the muon filters and from simulation of gaps between scintillator paddles in the last two muon counting planes [9]. Results from these systematic error studies are given in Table 1.

The 1997 (1999) signal mode acceptance was 3.14% (4.03%) and 2.80% (3.74%) for $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ respectively. The total K_L flux was calculated as the summation of the 1997 and 1999 K_L fluxes and was found to be 7.33 $\times 10^{11}$. This flux resulted in a single event senitivity of 3.75 $\times 10^{-11}$ for $K_L \to \pi^0\pi^0\mu^+\mu^-$ and 4.10 $\times 10^{-11}$ for $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$. Figure 2 displays the results of the blind analysis, whereby no events were found inside the signal regions after opening the signal boxes. This yielded 90% confidence level upper limits of $BR(K_L \to \pi^0\pi^0\mu^+\mu^-) < 8.63 \times 10^{-11}$ and $BR(K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-) < 9.44 \times 10^{-11}$ using the methodology adopted in [10].

This letter presents the first experimental study of the decay modes $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$. Our result for $BR(K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-)$ is 88 times smaller than the expected branching ratio with a pseudoscalar X^0 from [2] and 85 times smaller than the ex-

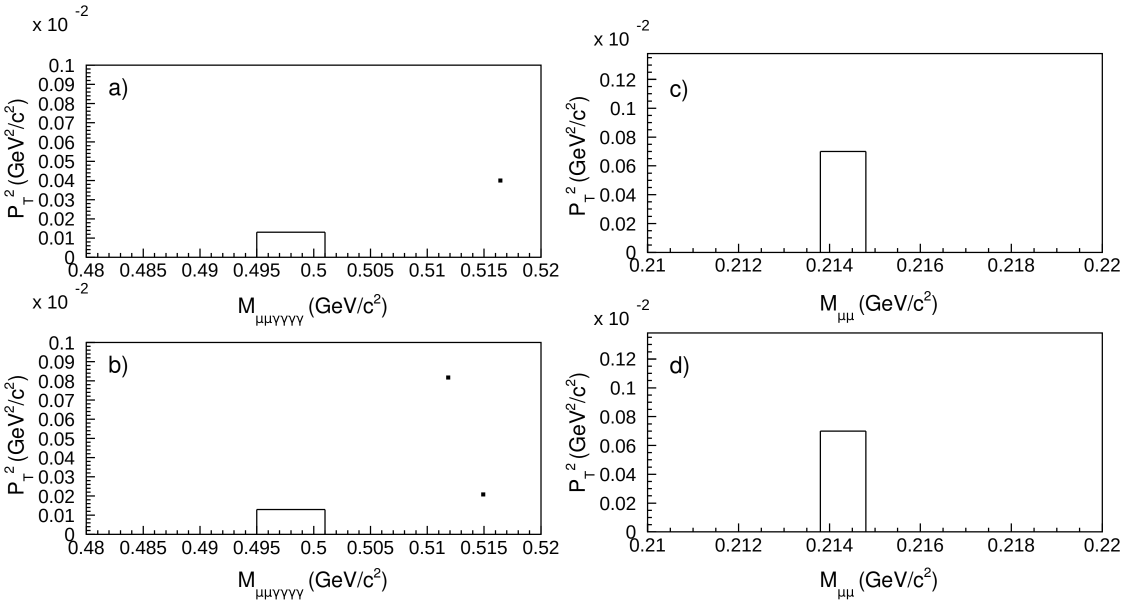

Figure 2: a) p_T^2 vs. $M_{\mu\mu\gamma\gamma\gamma\gamma}$ scatter plot for the 1997 data set b) and 1999 data set. c) $|p^2_{T,\mu\mu} - p^2_{T,\pi\pi}|$ vs. $M_{\mu\mu}$ scatter plot for the 1997 data set and d) 1999 data set.

pected branching ratio with a pseudoscalar X^0 from [4]. This effectively rules out the pseudoscalar X^0 as an explanation of the HyperCP result. In addition, our upper limit challenges the theoretical branching ratio of $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ from [2] with an axial vector X^0. Finally, the scenario in which the X^0 couples to the $\bar{d}s$ and $\mu^+\mu^-$ as a tensor remains to be studied.

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