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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 $\text{Br}(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) < 1.0 \times 10^{-10}$ and $\text{Br}(K_L \to \pi^0\pi^0\mu^+\mu^-) < 9.2 \times 10^{-11}$ 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.

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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 $\text{Br}(K^\pm \to \pi^\pm\mu^+\mu^-) = 8.1\times10^{-8}$ [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 $\text{Br}(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-)$ for a pseudoscalar X^0 has been made [5], while 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 $\text{Br}(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\gamma\gamma) < 2.4 \times 10^{-7}$, which 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 (NMSSM) was investigated at e^+e^- colliders by CLEO [9] and BaBar [10,11,12] and at the TeVatron (D0) [13]. No evidence for an NMSSM light pseudoscalar Higgs boson was found.

The $K_L \to \pi\pi X^0$ modes have an extremely limited phase space. The phase space of $K_L \to \pi^0\pi^0 X^0$ is ten times larger than the phase space available to $K_L \to \pi^+\pi^- X^0$, motivating the search for the former over the latter. We have searched for $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ 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

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$X^0 \to \mu^+\mu^-$ Model	Br($K_L \to \pi^0\pi^0 X^0$)
Pseudoscalar ($\Re(g_P)$) [2]	$(8.3^{+7.5}_{-6.6})\times10^{-9}$
Axial Vector ($\Re(g_A)$) [2]	$(1.0^{+0.9}_{-0.8})\times10^{-10}$
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}

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

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. Immediately downstream of the vacuum region was a spectrometer composed of an analysis magnet between two pairs of drift chambers. The momentum resolution of the spectrometer is given by $\sigma_P/P = 0.38\% \oplus 0.016\%P$, with P in units of GeV/c.

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 $\sigma_E/E \simeq 0.4\% \oplus 2\%/\sqrt{E[GeV]}$ 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 $(1.69 + 0.17P$ [GeV/c]$)\times10^{-3}$, 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 [14, 15].

Between the 1997 and 1999 runs, the beam's duty factor was doubled and the proton intensity on the target was increased by a factor of 2 to 3. The momentum kick imparted by the magnetic field to charged particles was reduced from 0.205 GeV/c to 0.150 GeV/c, giving an increased acceptance for kaon decay modes with charged decay products.

The signal modes and normalization mode ($K_L \to \pi^0\pi^0\pi^0_D$, where one photon was lost down the beam hole and $\pi^0_D \to e^+e^-\gamma$) 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. The requirement on the number of clusters for the 1999 data-taking period was applied to compensate for the increased event rate due to a relaxed requirement on the number of missing hits in the muon counting planes. 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 a cluster in the CsI calorimeter and to deposit less than 1 GeV of energy in the CsI calorimeter, 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 they 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 $K_L \to \pi^0\pi^0\mu^+\mu^-$ simulation was modeled as a four body decay using a constant matrix element. The $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ 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 $M_{\mu\mu\gamma\gamma\gamma\gamma}$, $p^2_T(\mu\mu\gamma\gamma\gamma\gamma)$ and $|p^2_T(\mu\mu) - p^2_T(\gamma\gamma\gamma\gamma)|$ resolutions calculated in the simulation. Here p^2_T is measured transverse to the direction of the K_L, determined by the line connecting the BeO target and the vertex. For a well-measured decay, $p^2_T(\mu\mu\gamma\gamma\gamma\gamma)$ and $|p^2_T(\mu\mu) - p^2_T(\gamma\gamma\gamma\gamma)|$ should be close to zero. The signal region for the decay $K_L \to \pi^0\pi^0\mu^+\mu^-$ was defined as 0.495 GeV/c^2 $\leq M_{\mu\mu\gamma\gamma\gamma\gamma} \leq$ 0.501 GeV/c^2 and $p^2_T \leq 1.3\times10^{-4}$ (GeV/c)^2. An additional signal region for the $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ decay was defined as 213.8×10^{-3} GeV/c^2 $\leq M_{\mu\mu} \leq 214.8\times10^{-3}$ GeV/c^2 and $|p^2_T(\mu\mu) - p^2_T(\gamma\gamma\gamma\gamma)| \leq 7.0\times10^{-4}$ (GeV/c)^2. The 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 [16]. Figure 1 shows p^2_T vs. invariant mass plots of the $K_L \to \pi^0\pi^0\mu^+\mu^-$ and

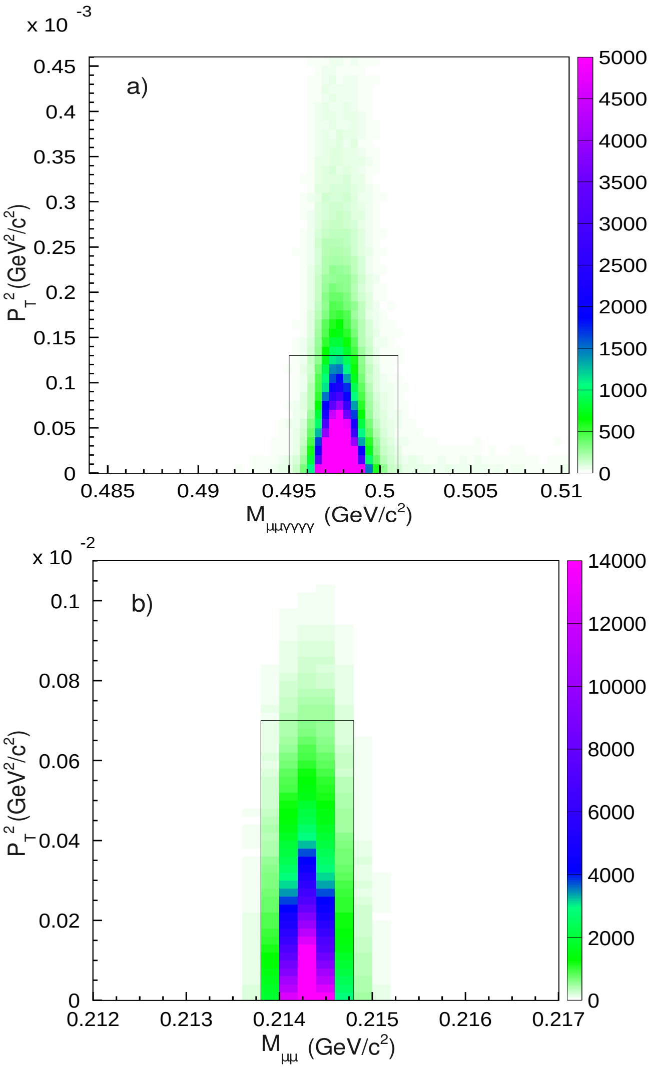

FIG. 1: a) p_T^2 vs. $M_{\mu\mu\gamma\gamma\gamma\gamma}$ plot for the 1997 $K_L \to \pi^0\pi^0\mu^+\mu^-$ simulation, where the boxed signal region contains 90% of all events. b) $|p_T^2(\mu\mu) - p_T^2(\gamma\gamma\gamma\gamma)|$ vs. $M_{\mu\mu}$ plot for the 1997 $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ simulation, where the boxed signal region contains 95% of all events. Both plots are shown after all analysis requirements were applied.

$K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ signal mode simulation respectively.

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. Accidental activity was included in the simulation of all background mode events.

Small branching ratio backgrounds such as the dimuon modes, $K_L \to \pi^0\pi^\pm\mu^\mp\nu_\mu$, and $K_L \to \pi^+\pi^-\gamma$ were simulated extensively. Statistically significant simulations with large branching ratio modes such as $K_L \to \pi^\pm\mu^\mp\nu_\mu$, $K_L \to \pi^+\pi^-\pi^0$ and $K_L \to \pi^+\pi^-$ was not feasible. Accidental activity coupled with a background mode to reproduce the signal mode topology will push p_T^2 above the signal region and force the invariant mass, $M_{\mu\mu\gamma\gamma\gamma\gamma}$, to values higher than the K_L mass. Simulations and kinematics indicate the background to be negligible, which 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-measured 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 chosen to be between 0.494 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 [17].

The flux, F_K, 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 efficiency. Uncertainty in the normalization mode requirements was studied by varying selection requirements of the normalization mode to eliminate disagreements between simulation and data. The uncertainty from disagreements between signal mode and normalization modes was estimated by varying the selection requirements of the signal mode and normalization mode simulations. 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 counting planes [18]. A systematic uncertainty associated with the muon counting plane inefficiency was determined by counting the number of in-time hits registered in each view of the last two muon counting planes from a clean sample of $K_{\mu 3}$ decays [19]. 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 $K_L \to \pi^0\pi^0\mu^+\mu^-$ and $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$ respectively. The 1997 and 1999 normalization mode acceptances were 4.21×10^{-6} and 3.26×10^{-6} respectively [17]. While signal mode acceptance would drop in scenarios where the X^0 does not decay immediately, it would not be sharply reduced for values of $c\tau < 3$ mm. F_K was 6.85×10^{11}. The single event sensitivity was 3.97×10^{-11} for $K_L \to \pi^0\pi^0\mu^+\mu^-$ and 4.34×10^{-11} for $K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-$. Figure 2 displays the results of the blind analysis; no events are inside the signal regions after opening the signal boxes

Systematic Uncertainty on F_K	$\frac{\Delta F_K}{F_K}$
Variation of Normalization Requirements	3.57%
Variation of Signal/Normalization Requirements	5.35%
μ Counting Plane Inefficiency	2.00%
Cracks in Muon Counting Planes	0.50%
Energy Loss in Muon Filters	0.40%
$Br(K_L \to \pi^0\pi^0\pi^0)$ [3]	0.61%
$Br(\pi^0 \to \gamma\gamma)$ [3]	0.03%
$Br(\pi^0 \to e^+e^-\gamma)$ [3]	2.98%
Total Systematic Uncertainty	7.41%

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

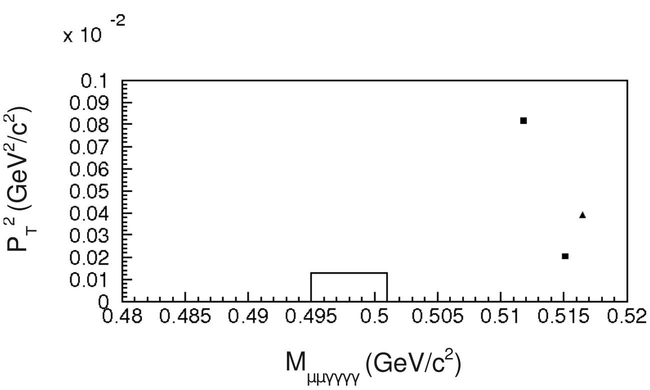

FIG. 2: p_T^2 vs. $M_{\mu\mu\gamma\gamma\gamma\gamma}$ plot for the combined 1997 and 1999 data sets, which are indicated by triangles and squares respectively. The signal box is open.

and no events were found within the available $\mu^+\mu^-$ phase space. Using the method of [20], the 90% confidence level upper limits are $Br(K_L \to \pi^0\pi^0\mu^+\mu^-) < 9.2 \times 10^{-11}$ and $Br(K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-) < 1.0 \times 10^{-10}$.

Our result for $Br(K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-)$ is nearly two orders of magnitude smaller than the expected branching ratios for $K_L \to \pi^0\pi^0X^0 \to \pi^0\pi^0\mu^+\mu^-$ from [2] and [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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[1] H.K. Park *et al.* (HyperCP Collaboration), *Phys. Rev. Lett.* **94**, 021801 (2005).
[2] X.-G. He, J. Tandean, and G. Valencia, Phys. Lett. B **631**, 100 (2005).
[3] K. Nakamura *et al.* (Particle Data Group), J. Phys. G **37**, 075021 (2010).
[4] S. Oh and J. Tandean, JHEP **01**, 022 (2010).
[5] N.G. Deshpande, G. Eilam, and J.Jiang, Phys. Lett. B **632**, 212 (2006).
[6] D.S. Gorbunov and V.A. Rubakov, *Phys. Rev.* **D73**, 035002 (2006).
[7] Y.C. Tung *et al.*, *Phys. Rev. Lett.* **102**, 051802 (2009).
[8] X.-G. He, J. Tandean, and G. Valencia, *Phys. Rev. Lett.* **98**, 081802 (2007).
[9] W. Love *et al.*, *Phys. Rev. Lett.* **101**, 151802 (2008).
[10] B. Aubert *et al.*, arXiv:0808.0017v1 **[hep-ex]**.
[11] B. Aubert *et al.*, *Phys. Rev. Lett.* **103**, 081803 (2009).
[12] B. Aubert *et al.*, *Phys. Rev. Lett.* **103**, 181801 (2009).
[13] V.M. Abazov *et al.*, *Phys. Rev. Lett.* **103**, 061801 (2009).
[14] A. Alavi-Harati *et al.*, *Phys. Rev.* **D67**, 012005 (2003).
[15] C. Bown *et al.*, Nucl. Instrum. Meth. **A369**, 248 (1996).
[16] D.G. Phillips II, PhD Thesis, Univ. of Virginia (2009).
[17] E. Abouzaid *et al.*, *Phys. Rev.* **D78**, 032014 (2008).
[18] B. Quinn, PhD Thesis, Univ. of Chicago (2000).
[19] E. Abouzaid *et al.*, *Phys. Rev. Lett.* **100**, 131803 (2008).
[20] R.D. Cousins and V.L. Highland, Nucl. Instrum. Meth. **A320**, 331 (1992).