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Search for $X(214)$ in $K_L^0 \to \pi^0\pi^0 X(X \to \mu^+\mu^-)$ using Back-Anti counter at the E391a experiment

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We have searched for a light pseudoscaler particle "$X(214)$" which is suggested by HyperCP experiment in the $K_L^0 \to \pi^0\pi^0 X(X \to \mu^+\mu^-)$ decay process using the E391a detector at KEK. In our analysis, signal event "$X(214)$" has not observed with the 3.58×10^9 K_L^0 decays, and we set an upper limit for the branching fraction of $K_L^0 \to \pi^0\pi^0 X(X \to \mu^+\mu^-)$ to be 1.6×10^{-6} at the 90% confidence level. Also we have examined $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ 4-body process. We set an upper limit for the branching fraction of $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ to be 9.3×10^{-7}.

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The HyperCP experiment reported observation of three events in $\Sigma^+ \to p\mu^+\mu^-$ decays where the $\mu^+\mu^-$ effective mass was clustered around 214 MeV/c^2 [1]. This was quite unlikely to occur in the 3-body decay, and could be interpreted as the quasi-2-body $\Sigma^+ \to pX$ and subsequent $X \to \mu^+\mu^-$ decay with an intermediate state X of a mass around 214.3 MeV/c^2.

Several phenomenological discussions have been made for this object, and have suggested that $X(214)$ is most likely be a pseudoscalar particle, which decays dominantly to the $\mu^+\mu^-$ and $\gamma\gamma$ final states. Also this particle could be produced in other processes such as $K \to \pi\pi X$. Among these discussions, D.S.Gorbanov and V.A.Rubakov [2] proposed the "sgoldstino" model and predicted the braching fraction of $K_L^0 \to \pi^0\pi^0 X(214)$ in the $X(214) \to \mu^+\mu^-$ and $X(214) \to \gamma\gamma$ final states to be $\approx 1.2\times10^{-8}$ and $\approx 1.2\times10^{-4}$, respectively. Another model proposed the possibility of light pseudoscaler Higgs boson [3], but the prediction of the branching fraction was not given for the $K_L^0 \to \pi^0\pi^0 X(214)$ decay. Also possibility of the very light gauge U-boson of the extra $U'(1)$ gauge model in the supersymmetry framework was discussed [4].

E391a collaboration has reported a search for $K_L^0 \to \pi^0\pi^0 X(214)$ in the $X(214) \to \gamma\gamma$ final state, and set the upper limit of the branching fraction to be 2.4×10^{-7} [5]. To examine the prediction for $X(214) \to \mu^+\mu^-$ final state in the above discussion on the Kaon sector and motivated by the fact that $\mu^+\mu^-$ system of this mass region has not yet be fully explored and worth be studied in its own right, we performed a search of the particle $X(214)$ in the $K_L^0 \to \pi^0\pi^0 X$ ($X \to \mu^+\mu^-$) decay process with the E391a detector at KEK.

The study was done using the data sample taken in the period from Oct. to Nov. 2005, or Run-III. The E391a detector was primarily designed to search for $K_L^0 \to \pi^0\nu\overline{\nu}$ process [6], and was equipped with CsI calorimeter for detection of γ from π^0 decays and hermetic veto counters to ensure that no other visible particles exist (Fig. 1). To avoid background from the beam particle interaction with air, most of the dector components are placed in the vacuum vessel. The CsI calorimeter consists of 496 blocks of $7\times7\times30$ cm^3 pure CsI crystal. At the center of the calorimeter, there is a beam hole of 12×12 cm^2 to allow the beam particles pass through. The main barrel (MB) and front barel (FB) counters, consisted of sandwitch of lead and scintillation counters with $13.5X_0$ and $17.5X_0$ respectively, forms cylinder wall surrounding the K_L decay volume. Collar shaped counters (CC00, CC02−07) were placed around the beam line for vetoing photons in the beam axis area. Charged particles which hit the CsI calorimeter were rejected by charge veto (CV) scintillation counter hodoscope which covers the front area of 50 cm upsrtream and outer wall of the beam hole area.

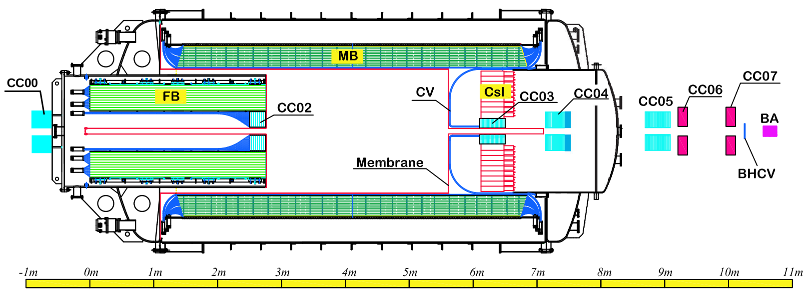

Figure 1: Schematic cross sectional view of the E391a detector. "0 m" in the scale corresponds to the entrance of the detector.

On the downstream beam axis region outside of the vacuum vessel, we have beam hole charge veto (BHCV) and Back-Anti counter (BA). BHCV consists of eight 3 mm thick plastic scintillation counters, which are arranged to fully cover the downstream area of beam hole (Fig. 2). BA counter for the Run-III period consisted of 5 layers of PWO scintillation crystal array and array of quartz blocks, aiming for good energy deposit resolution and γ/neutron separation (Fig. 3). Each PWO layer is segmented in 2(horizontal) $\times$ 8(vertical) with crystal blocks of $3 \times 3 \times 12$ cm^3, while quartz layer is segmented in 7(vertical). The total thickness of the BA counter is $18.1X_0$ and $0.90\lambda_I$. In the BA, the electromagnetic shower deposites most of its energy from the first to third layers, and be well discriminated from hadron and muon events.

This study was made using data sample taken in the Run-III period of the E391a experiment, which accumulated $3.58{\times}10^9$ K_L^0 decays in the detector volume. Data aquisition was made with hardware trigger requiring two or more shower clusters in the CsI calorimeter with cluster energy $>$ 60 MeV, and no obvious activity in the CV and other veto counters.

The signature of the decay $K_L^0 \to \pi^0\pi^0 X(214)$ $(X(214) \to \mu^+\mu^-)$ is 4γ clusters from $2\pi^0$ in the CsI calorimeter and 2 minimum ionizing particles (MIPs) from $\mu^+\mu^-$ in the downstream beam counters. Those hits should satisfy in-time requirement to separate the backgrounds. Since the Q-value of the $K_L^0 \to \pi^0\pi^0 X(214)$ and subsequent decay $X(214) \to \mu^+\mu^-$ are very small, the $\mu^\pm$ tracks will go through the beam hole, and will hit BHCV and BA. Dimuon will be identified by the correlated hits on five PWO layers giving energy deposit consistent with the passage of 2MIPs particles. BHCV also gives dE/dx information for the muon tracks.

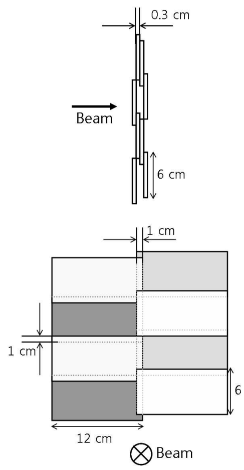

Figure 2: Side view and front view of BHCV

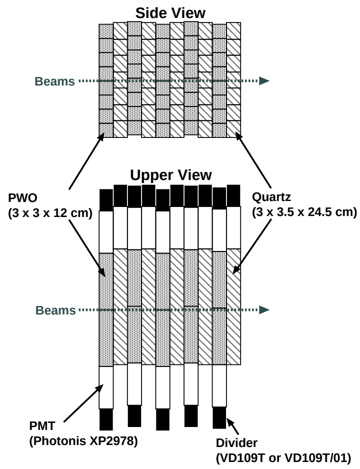

Figure 3: Side view and top view of BA

To define the event selection criteria and estimate the acceptance for the $K_L^0 \to \pi^0\pi^0 X(214)$ $(X(214) \to \mu^+\mu^-)$ signal, GEANT-3 Monte Carlo (MC) simulation was made, and processed with the same reconstruction code as the real data. Total K_L^0 flux generated is 3×10^8 and they make 3-body phase space decay. About 2% of them make a decay in the decay volume. The generated events were overlayed with accidental hits on the counter system, which were sampled by special trigger runs. Also $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ direct decay events were generated with the same statistics assuming 4-body phase space decay. To study the properties of major backgrounds, $K_L^0 \to \pi^0\pi^0$ (incident K_L^0 flux $4.99{\times}10^9$) and $K_L^0 \to \pi^0\pi^0\pi^0$ (incident K_L^0 flux $1.5{\times}10^9$) were generated with the same detector condition as the signal event.

To reconstruct $K_L^0 \to \pi^0\pi^0 X(214)$ ($X(214) \to \mu^+\mu^-$) process, we first selected events with 4γ clusters found in CsI, which satisfied the condition of having common π^0 decay vertex point in the detector decay volume ($V_z > 200$ cm). Remarkable point is that since the Q-value of $K_L^0 \to \pi^0\pi^0 X(214)$ decay is small. Effective mass of reconstructed 4γ shows a sharp peak within the $250-300$ MeV/c^2 region, while background process such as $\pi^0\pi^0\pi^0$ decay shows rather broad mass distribution up to 400 MeV/c^2 (Fig. 5). This gives us a distinct kinematical signature of the $K_L^0 \to \pi^0\pi^0 X(214)$ signal. Hereafter we refer this 4γ effective mass region (250 MeV/c^2 $< M(4\gamma) <$ 300 MeV/c^2) as the "signal region".

Then we required dimuon hits in the beam hole counters. Fig. 4 shows the deposit energy in BHCV and in a PWO layer of BA for RunIII data and signal MC. The deposit energy scale of the RunIII data was caribrated by observed MIP peak in the "muon enriched" data. Muon enriched test run was carried out by switching off the sweeping magnet allowing long lived charged particles (i.e. muon) in the K_L beam line. By extrapolating the energy scale of single muon peak at the muon enriched run, we defined the "dimuon cut" to accept 2MIPs for both MC and real data sample. Since BHCV counters are overlapped to avoid cracks, we only required that BHCV gives signal consistent with 2MIPs or more with no upper bound (0.8 MeV $< E_{dep.}$ in 3 mm thick plastic scintillator; Fig. 4(a)). Enegy deposit consistent with 2MIPs was required to all the PWO layers of BA (0.055 GeV $< E_{dep.} <$ 0.15 GeV in 3 cm thick PWO; Fig. 4(b)). We rather set loose requirement on higher bound to avoid overkilling of the dimuon candidate due to extra hits by random background.

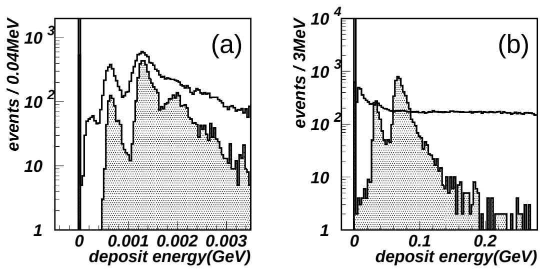

Figure 4: Energy deposit on (a) BHCV and (b) a PWO layer of BA for real data (open histogram) with a superposition of signal Monte Carlo (shaded histogram).

Fig. 5 shows 4γ effective mass distribution before and after imposing various BHCV and BA dimuon cut conditions. Among the K_L^0 decays, major decay modes which give 4γ clusters in the CsI are $K_L^0 \to \pi^0\pi^0$ and $K_L^0 \to \pi^0\pi^0\pi^0$. Requiring downstream dimuon cut condition, feed across events from $\pi^0\pi^0$ decays were rigorously rejected (Fig. 5(d)). Once 4γ clusters are required in the analysis, only chance for $K_L^0 \to \pi^0\pi^0$ to mimic $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ is accidental background hit in the BA and BHCV which satisfies all the cut condition, but it is very rare. $K_L^0 \to \pi^0\pi^0\pi^0$ decay has the largest branching fraction which gives 4γ cluster in the CsI. Fig. 5(c) shows that cirtain amount of $3\pi^0$ events survive if the dimuon cut condition of BA is loose, where $\pi^0\pi^0$ events were completely removed (Fig. 5(d)). In $3\pi^0$ event one of the π^0 could generate charged particles in the downstream beam hole region, and those may have a chance to make a feed across to $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$. Hence $K_L^0 \to \pi^0\pi^0\pi^0$ decay will be the dominant physics background source in our analysis.

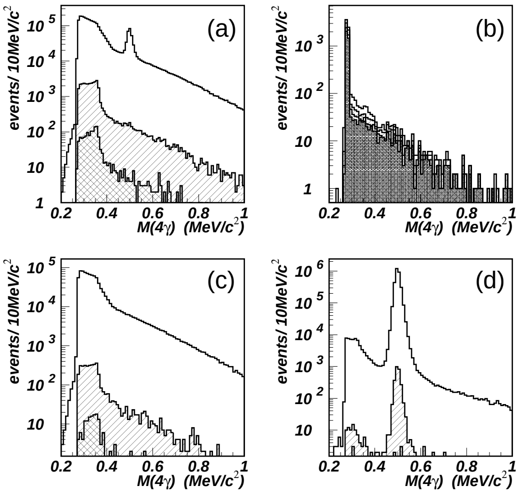

Figure 5: Effects of dimuon cuts on 4γ effective mass distribution for (a) data sample, (b) the signal MC, (c) $3\pi^0$ MC, and (d) $2\pi^0$ MC with several BA cut conditions are shown. Plots are made with the conditions; 4γ clusters are found (open histogram), BHCV hit is consistent with more than 1MIP (hatched histogram), hits on two BA layers are consistent with 2MIPs (double hatched histogram), and all five BA layers are consistent with 2MIPs (dark histogram). We see no event satisfies the last requirement but the signal MC. Vertical scales are arbitrary.

Fig. 6 summarizes the number of survived events after the cuts are imposed step by step on MC and real data. For $K_L^0 \to \pi^0\pi^0 X(214)$ $(X(214) \to \mu^+\mu^-)$ signal MC, acceptance loss in each step is dominantly due to geometrical and accidental loss which is caused by extra random hits on BA. Normalized by the number of generated K_L^0 particles and decay probability in the detector, acceptance of the E391a detector for $K_L^0 \to \pi^0\pi^0 X(214)$ $(X(214) \to \mu^+\mu^-)$ decay was estimated to be 3.9×10^{-4}. Contrary to the signal MC, survived events in the real data drops rapidly with increasing the number of layers required to satisfy the dimuon cut. As a result, no events is left after requiring dimuon cut for BHCV and all of the PWO layers. Physics background contribution to our final data is estimated by assuming that possible background is dominated with $\pi^0\pi^0\pi^0$ decays. We have seen that observed 4γ effective mass distribution of RunIII data and $K_L^0 \to \pi^0\pi^0\pi^0$ agree well after 4γ clusters are found in CsI (Fig.5). Comparison of Fig.5 (a) and (c) also shows that the 4γ effective mass distribution of RunIII data and $3\pi^0$ MC looks similar at each cut condition of BA. Reduction curve of real data and $3\pi^0$ MC (Fig. 6(c)) are very similar, and survived number of events in $3\pi^0$ MC normalized by the number of beam particles are consistent with that of RunIII data at the same BA cut condition. As the estimate of the background contribution, we extrapolated the number of events from $K_L \to \pi^0\pi^0\pi^0$ decay to the final cut condition, and obtained the conservative value of the feed across to the signal region to be less than 0.1.

From the detection acceptance derived by the MC simulation and the number of K_L^0 decays at the data taking runs, the single event sensitivity (S.E.S) is defined as,

$$S.E.S. = \frac{1}{acceptance \times No.\ of\ K_L^0\ decays}.$$

For the RunIII, the number of K_L^0 decays in the detector volume was 3.58×10^9, and single event

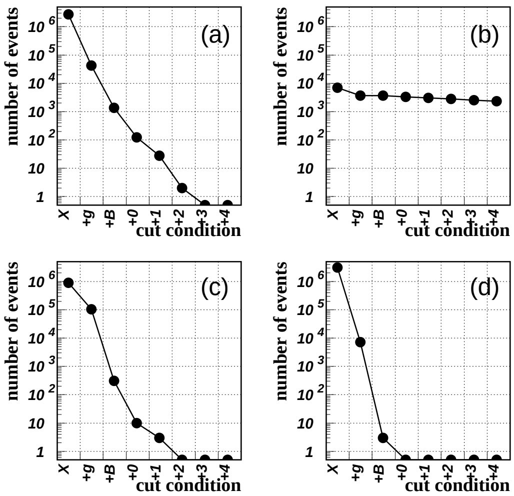

Figure 6: Summary of survived number of events requiring dimuon cut conditions step by step on (a) full data sample, (b) $\pi^0\pi^0 X(\mu^+\mu^-)$ MC, (c) $3\pi^0$ MC, and (d) $2\pi^0$ MC. Titles in the horizontal axis presents cut conditions added at each step, namely, X (4γ cluster are detected), +g (4γ mass and $2\pi^0$ vertex z position), +B (2MIPs signal in BHCV), +0 (2MIPs in BA layer 0), +1 (2MIPs in BA layer 1), +2 (2MIPs in BA layer 2), +3 (2MIPs in BA layer 3), +4 (2MIPs in BA layer 4; i.e. requires all of them).

sensitivity of $K_L^0 \to \pi^0\pi^0 X(214)$ ($X(214) \to \mu^+\mu^-$) decay process is defined as 7.2×10^{-7}. Since we have no observed events in the signal region in the measurement with the single event sensitivity 7.2×10^{-7}, we set the upper limit of the branching fraction of $K_L^0 \to \pi^0\pi^0 X(214)$, $X(214) \to \mu^+\mu^-$ to be 1.6×10^{-6} with 90% confidence level. We have also examined the 4-body $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ decays. By generating $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ event by 4-body phase space model, we got the acceptance of the process to be 6.9×10^{-4} and estimated single event sensitivity 4.0×10^{-7}. From this we get the upper limit of the branching fraction 9.3×10^{-7} with 90% confidence level. Since 4-body phase space decay enhances low mass $\mu^+\mu^-$ region, the 90% limit of the branching fraction of 4-body decay is close to that of low X mass assumption of $\pi^0\pi^0 X(\mu^+\mu^-)$ decay.

We have presented the measurement of the $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ decays in the low mass region of $\mu^+\mu^-$. We found no evidence of $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$. From this we set the upper limit of branching fraction of $K_L^0 \to \pi^0\pi^0 X(214)$, $X(214) \to \mu^+\mu^-$ to be less than 1.6×10^{-6}, and $K_L^0 \to \pi^0\pi^0\mu^+\mu^-$ to be less than 9.3×10^{-7} with 90% confidence level, respectively.

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