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Observation of the Decay $K_L^0 \to e^+e^-e^+e^-$.

Abstract

Two events with the characteristics of the decay $K_L^0 \to e^+e^-e^+e^-$ have been observed with a negligible expected background from which a branching ratio of $(4 \pm 3) \times 10^{-8}$ is derived. This result is consistent with values estimated from theoretical models based on the double internal conversion of the decay $K_L^0 \to \gamma\gamma$.

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Introduction

The weak nonleptonic decay $K_L^0 \mapsto \gamma\gamma$ is well established experimentally. Results have been reported recently [1,2] on the related Dalitz decay $K_L^0 \mapsto e^+e^-\gamma$ which proceeds dominantly via an intermediate $\gamma\gamma^*$ state. We have searched the same data set as used in Ref. [1] for the decay with two virtual photons which is expected to yield events of the type $K_L^0 \mapsto e^+e^-e^+e^-$.

The mechanism for the production of electron pairs in neutral meson decay was first developed for the pion [3] but has since been extended to other mesons including the long lived kaon [4]. The branching ratio for $K_L^0 \mapsto e^+e^-e^+e^-$ is expected to be around 3.5×10^{-8}, using the value for the $K_L^0 \mapsto \gamma\gamma$ branching ratio which was measured earlier [5]. So far, the decay $K_L^0 \mapsto e^+e^-e^+e^-$ has not been observed; the present 90% C.L. upper limit is 2.6×10^{-6} [6].

Experimental set-up and data taking

The data were taken in 1988 at the CERN Super Proton Synchrotron in an experiment designed to measure the direct CP violation parameter ϵ'/ϵ . The beam and detector for the experiment have been described in detail in Ref. [7]. The detector consists of two drift chambers, a transition radiation detector (TRD), a liquid argon/lead sandwich electromagnetic shower calorimeter (LAC) and an iron/scintillator sandwich hadronic calorimeter (HAC). The detector elements are used in the same way as in the $K_L^0 \mapsto e^+e^-\gamma$ analysis, the drift chambers and LAC are used to measure the positions and energies of the electrons and the TRD and HAC are used to remove events which contain charged pions.

Event selection and analysis

We use the same trigger and initial offline selection as in the $K_L^0 \mapsto e^+e^-\gamma$ analysis after which we are left with a sample of events containing at least 45 GeV in the LAC, at least 4 space points reconstructed in each wire chamber and less than 6 GeV total energy in the hadronic calorimeter. Events with 6 or more electromagnetic showers are cut away by the trigger to suppress the mode $K_L^0 \mapsto 3\pi^\circ$. 5×10^4 events remain.

A complete reconstruction of these events is performed. Four tracks are reconstructed by linking spacepoints from the two wirechambers. The spacepoints are required to be at least 3 cm from each other. Each track is required to extrapolate to a separate electromagnetic shower in the LAC to within $2\,cm$ and all four tracks are required to converge upstream of the detector. The four electromagnetic showers must be separated by at least 5 cm in the LAC. Events with additional showers are not accepted.

The transverse (x, y) and longitudinal (z) positions of the decay vertex are reconstructed from the four tracks by minimizing the quantity

$$\chi^2 = \sum_{i=1}^{4} \frac{(x_i - x)^2 + (y_i - y)^2}{\sigma_i^2}$$

x_i and y_i are the coordinates of track i at the vertex position z. σ_i is the resolution in the transverse distance from track i to the vertex taking the chamber resolution (750 μm) and multiple scattering into account. The invariant mass of the decaying kaon is calculated using the distance between the longitudinal vertex position z and the front face of the LAC (z_{LAC})

$$M_{K^0} = \frac{\sqrt{\sum_{i=1}^{3} \sum_{j=i+1}^{4} E_i E_j d_{ij}^2}}{z_{\mathrm{LAC}} - z}$$

d_{ij} is the distance between two showers i and j in the LAC with energies E_i and E_j. The resolution σ in the K_{L}^0 mass is about 7 MeV.

The events are now required to satisfy the following selection criteria:

(1) The total kaon energy must be between 50 GeV and 190 GeV.

(2) The decay vertex must be in the fiducial region between 0 and 50 m measured from the final defining collimator.

(3) Each shower in the LAC must have energy between 3 GeV and 100 GeV

(4) The centre of gravity of the showers must be within 7 cm of the beam axis.

(5) The longitudinal development of each electron shower must be consistent with being an electron (to remove pion tracks). i.e. (a) At least 65% of the total energy must be collected in the first 12 radiation lengths of the LAC and (b) energy in the HAC immediately behind the shower must be less than 2 GeV.

(6) The reconstructed kaon mass must be between 484 and 512 MeV ($\pm 2\sigma$).

(7) The χ^2 for the reconstructed vertex must be less than 11 (95% C.L.).

(8) The TRD signals for each track must be consistent with being an electron (ie the pulse height associated with the track must be at least 1.5 times that of a minimum ionizing particle).

Seven events remain after cuts (1) to (5). Figure 1 shows χ^2 plotted against the kaon mass for these events. The three events which are not shown in the plot have $\chi^2 > 200$. The events which pass cut (8) are shown as solid circles. Two events remain after all cuts.

As a check of the overall sensitivity of the detector, we have searched for events containing four electron showers associated with tracks and extra electromagnetic showers which are not associated with any tracks (photons). There are two such events. One of them has four additional photons which is consistent with the decay $K_L^0 \mapsto \pi^\circ\pi^\circ\pi^\circ_{DD}$ where π°_{DD} is a pion which decays to a final $e^+e^-e^+e^-$ state. The reconstructed pion masses are 134.9, 135.2 and 134.9 MeV/c^2 respectively. The other event is a $K_L \mapsto \pi^\circ_D\pi^\circ_D$ in which the two π°_D decay to $e^+e^-\gamma$. The reconstructed pion masses are 133.5 and 134.6 MeV/c^2 respectively. The first of these events was accepted by a calibration trigger in which the rejection of 6 photon events was suppressed. The expected number of events originating from all such modes involving π° decay is 2.0.

Background

Table 1 summarises the backgrounds to the decay $K_L^0 \mapsto e^+e^-e^+e^-$. The background from the first four entries listed are estimated from a Monte-Carlo calculation. The background from $K_L^0 \mapsto \pi^+\pi^-\pi^\circ_D$ has been estimated by analysing the data set without applying the electron identification cuts (5) and (8). No additional events enter the signal region. The last background listed in Table 1 comes from the accidental coincidence of two $K_L^0 \mapsto e^\pm\pi^\mp\nu$ events in which the two decays occur within 100ns of each other and are accepted as a single event. The background due to this process has been estimated by inspecting events outside the signal region in Fig. 1 and extrapolating to the signal region. The above method of releasing the electron identification cuts also shows that the background from this process is negligible.

Results

We conclude that background is negligible and that the process $K_L^0 \mapsto e^+e^-e^+e^-$ has been observed. The normalisation has been determined from the number of $K_L^0 \mapsto \pi^\circ\pi^\circ_D$ events with the subsequent decay $\pi^\circ_D \mapsto ee\gamma$ of one of the pions (see Ref. [1]). A total of 6.7×10^8 kaons decayed in the fiducial region of the detector during the livetime of the experiment. The acceptance for $K_L^0 \mapsto e^+e^-e^+e^-$ is computed from a Monte-Carlo simulation to be 7.8% assuming the differential cross-section from Ref. [4]. From the above numbers, we derive a branching ratio for the process $K_L^0 \mapsto e^+e^-e^+e^-$ of $(4 \pm 3) \times 10^{-8}$. This result is in good agreement with the theoretical expectation [4].

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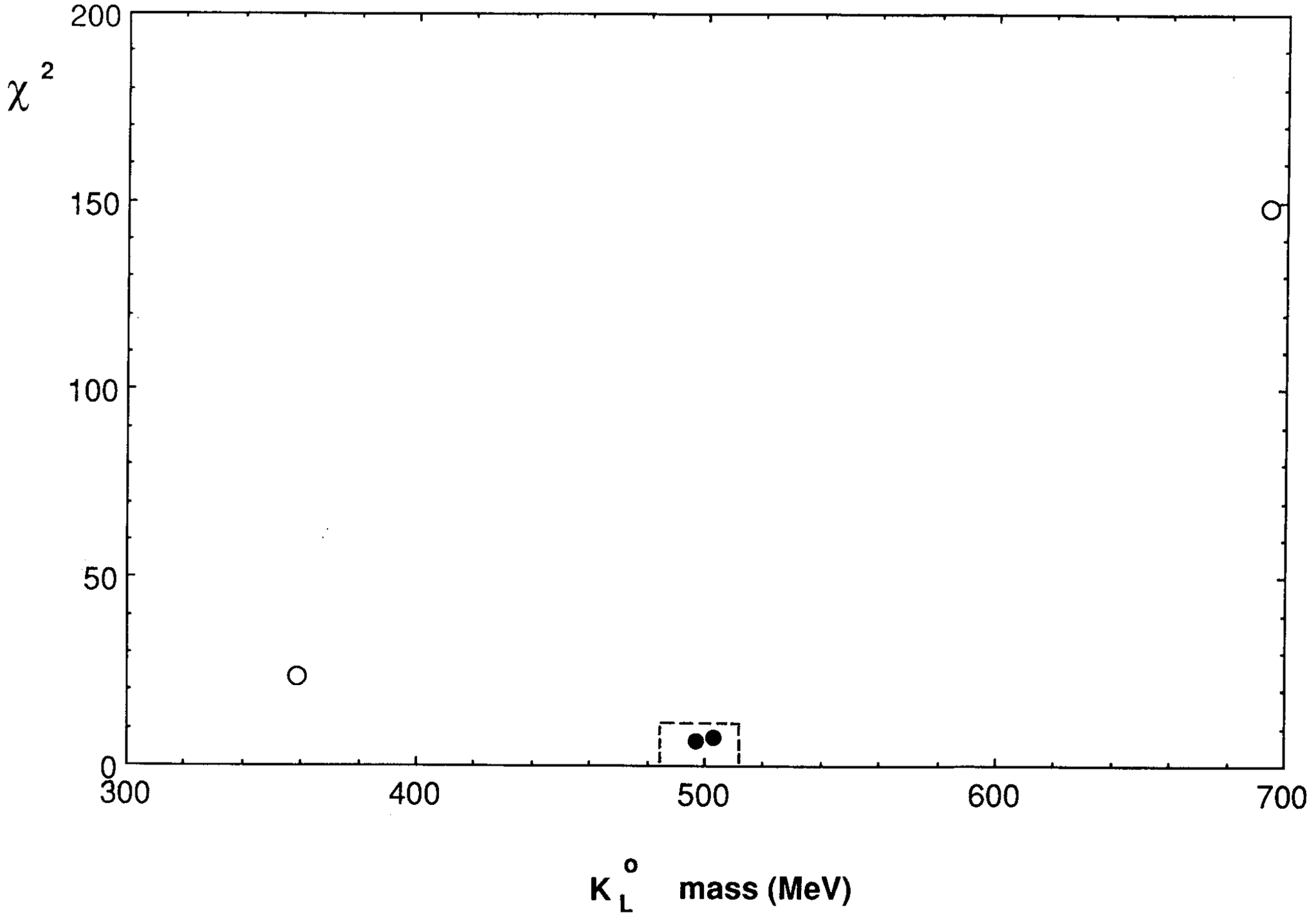
Figure Captions

1) The reconstructed kaon mass plotted against the χ^2 of the vertex fit for events remaining after cuts (1) to (5) (see text). Solid (open) circles are events which pass (fail) the TRD electron identification cut (8). Three events with χ^2 larger than 200 are not shown (all three fail the TRD cut). Cuts (6) and (7) are indicated by the dashed box.

Table 1. List of possible background sources. π°_D (π°_{DD}) indicates a neutral pion which decays into an $e^+e^-\gamma$ ($e^+e^-e^+e^-$) final state.

Type of background	Number of events expected
$K_L \mapsto \pi^\circ\pi^\circ_D\pi^\circ_D$ with 4 missing photons	$< 2 \times 10^{-3}$
$K_L \mapsto \pi^\circ\pi^\circ\pi^\circ_{DD}$ with 4 missing photons	$< 1 \times 10^{-3}$
$K_L \mapsto \pi^\circ_D\pi^\circ_D$ with 2 missing photons	$< 2 \times 10^{-3}$
$K_L \mapsto \pi^\circ\pi^\circ_{DD}$ with 2 missing photons	$< 1 \times 10^{-4}$
$K_L \mapsto \pi^+\pi^-\pi^\circ_D$ with a missing photon and two pions which appear like electrons	$< 2 \times 10^{-3}$
Two superimposed $K_L \mapsto \pi^\pm e^\mp \nu$ decays	$< 3 \times 10^{-4}$



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