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Estimation of the branching ratio of the decay $K_L^0 \to e^+e^-e^+e^-$ from the $K_L^0 \to e^+e^-X$ process

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Abstract

In an experiment to search for the decay $K_L^0 \to ee$ using the 12GeV Proton Synchrotron at KEK, we observed 18 events with the e^+e^- effective mass greater than $470 MeV/c^2$. They are presumed to come mainly from the decay $K_L^0 \to e^+e^-e^+e^-$. Subtracting the background from the decay $K_L^0 \to ee\gamma$ and the external conversion of γ in the decays $K_L^0 \to \gamma\gamma$ and $K_L^0 \to ee\gamma$, the branching ratio of the decay $K_L^0 \to e^+e^-e^+e^-$ is estimated to be $(6 \pm 2 \pm 1) \times 10^{-8}$. It is consistent with the pervious experimental values.

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The decay $K_L^0 \to e^+e^-e^+e^-$ proceeds predominantly through the double conversion process via the $\gamma^*\gamma^*$ intermediate state. Information on the $\gamma^*\gamma^*$ intermediate state has been thought useful for estimating the long-distance effect[1] in the decay $K_L^0 \to \mu\mu$, the branching ratio of which has been measured with good accuracy recently.[2,3] In addition, the decay $K_L^0 \to e^+e^-e^+e^-$ is likely to be the main background for the search for the decay $K_L^0 \to ee$. The branching ratio of the decay $K_L^0 \to e^+e^-e^+e^-$ was estimated to be 3.4×10^{-8} using the branching ratio of the decay $K_L^0 \to \gamma\gamma$ and a QED calculation.[4,5] Recently, two $K_L^0 \to e^+e^-e^+e^-$ events were observed by Barr et al.[6], which yielded the branching ratio of $(4 \pm 3) \times 10^{-8}$.

We undertook a study of the decay $K_L^0 \to e^+e^-e^+e^-$ as a byproduct of our search for the decay $K_L^0 \to ee$.[7] This search for the decay $K_L^0 \to ee$ was made at the 12GeV Proton Synchrotron in the National Laboratory for High Energy Physics (KEK) using a double-arm detector. Each arm consisted of five drift chambers, two dipole magnets, two scintillator hodoscopes, a gas Čerenkov counter, an electromagnetic shower counter and a muon identifier. The magnetic field strength was adjusted to have a transverse momentum kick of $238MeV/c$ in each arm. The basic trigger required a coincidence between a counter of the first hodoscope and the corresponding counter of the second hodoscope to ensure that the track after the magnets was parallel to the K_L^0 direction for the transverse two body decays of K_L^0. For the e^+e^- events, a gas Čerenkov counter signal and an electron signal from the electromagnetic shower counter were additionally required in both arms. The radiator of the gas Čerenkov counter was $1.5m$ of air at atmospheric pressure. The average number of photo-electrons by an incident electron was five. The electromagnetic shower counter was composed of ten alternative layers of scintillator and lead plates. The total thickness of the electromagnetic shower counter was 13.6 radiation length. The energy resolution of the electromagnetic shower counter for electrons was $\sigma/E \simeq 0.20/\sqrt{E(GeV)}$. An electron was identified by requiring a signal with a pulse height greater than 1.5 photo-electrons in the Čerenkov counter, and a signal from the electromagnetic shower counter with a pulse height corresponding to the energy deposit more than 0.7 times its momentum. Details of the detector system, data aquisition, track fitting and particle identification were described elsewhere.[2,7]

Figure 1 shows a scatter plot of $M_{e^+e^-}$ vs P_t for well identified e^+e^- events, where $M_{e^+e^-}$ is the effective mass of the e^+e^- pair and P_t is the transverse momentum of the e^+e^- pair with respect to the target-to-e^+e^- pair vertex direction. Many events are thickly clustered in the region of the effective mass below $470MeV/c^2$. A considerable number of events are present in the region between $470MeV/c^2$ and the K_L^0 mass (M_K). There was no event above M_K. The high P_t edge of the distribution in each mass region decreases with increasing e^+e^- mass. This feature indicates that these e^+e^- events came from some K_L^0 decays having missing particles.

The number of e^+e^- events in the region $450MeV/c^2 < M_{e^+e^-} < 470MeV/c^2$ and $P_t < 20MeV/c$ is 430 with a statistical fluctuation of 21. The number of events expected in the same region from the decay $K_L^0 \to \pi e\nu$ whose pion was misidentified as an electron, $N_{e^+e^-}$, was calculated by a Monte Carlo simulation using the observed number of the $K_L^0 \to \pi^+\pi^-$ events as the normalization factor.

$$N_{e^+e^-} = N_{\pi^+\pi^-} \cdot \frac{B_{\pi e\nu}}{B_{\pi^+\pi^-}} \cdot \frac{A_{\pi(e)e\nu}}{A_{\pi^+\pi^-}} \cdot \epsilon_{\pi e\nu \to ee} \cdot C, \tag{1}$$

where $N_{\pi^+\pi^-}$ is the number of the detected $K_L^0 \to \pi^+\pi^-$ events, which is $(6.80 \pm 0.07) \times 10^7$, and $B_{\pi e\nu}$ and $B_{\pi^+\pi^-}$ are the branching ratios of the decays $K_L^0 \to \pi e\nu$ and $K_L^0 \to \pi^+\pi^-$ which are given as $(38.7 \pm 0.5)\%$ and $(2.03 \pm 0.04) \times 10^{-3}$ [8], respectively. $A_{\pi^+\pi^-}$ is the acceptance for the decay $K_L^0 \to \pi^+\pi^-$ and $A_{\pi(e)e\nu}$ is that for the decay $K_L^0 \to \pi e\nu$ whose pion is misidentified as an electron and whose kinematical variables, $M_{e^+e^-}$ and P_t, fall into the above defined region. The value of the ratio of the acceptances, $A_{\pi(e)e\nu}/A_{\pi^+\pi^-}$ is $(2.69 \pm 0.04) \times 10^{-4}$. $\epsilon_{\pi e\nu \to ee}$ is the probability of misidentifying π as e. Since the efficiency of the electromagnetic shower counter was determined as a function of particle momentum and that of the gas Čerenkov counter was determined as a function of hit position, the probability was obtained by averaging over the pion and electron spectra of the decay $K_L^0 \to \pi e\nu$, and $\epsilon_{\pi e\nu \to ee}$ was obtained to be $(1.31 \pm 0.48) \times 10^{-4}$. C is a correction term with a value 1.028, which includes the dead-time correction of $(1.3 \pm 0.3)\%$, the pion absorption rate for $K_L^0 \to \pi e\nu$ of $(2.4 \pm 1.9)\%$ and that for $K_L^0 \to \pi^+\pi^-$ of $(6.3 \pm 0.6)\%$. With these values, $N_{e^+e^-}$ was calculated to be 474 ± 34, which agrees with the number of events experimentally detected within the errors. The contribution from the decay $K_L^0 \to ee\gamma$ in this region was also estimated and the number

of events expected found to be only three.

No e^+e^- event is expected from the decay $K_L^0 \to \pi e\nu$ in the region $M_{e^+e^-} > 470 MeV/c^2$, since the misassignment of the pion as an electron reduces $M_{e^+e^-}$. The decay $K_L^0 \to ee\gamma$ which has the branching ratio of $(9.1 \pm 0.5) \times 10^{-6}$, [9] can yield events with $M_{e^+e^-} > 470 MeV/c^2$. The number of the e^+e^- events expected from the decay $K_L^0 \to ee\gamma$ in this mass region was estimated by a Monte Carlo simulation[10]. The relative acceptance $A_{ee\gamma}/A_{\pi^+\pi^-}$ was $(1.85 \pm 0.33) \times 10^{-5}$ in the region $M_{e^+e^-} > 470 MeV/c^2$ and $(3.50 \pm 0.70) \times 10^{-6}$ in $M_{e^+e^-} > 480 MeV/c^2$. The particle-identification efficiency was obtained to be 0.746 ± 0.005 averaging over the momentum spectra of the electrons from the decay $K_L^0 \to ee\gamma$. The number of events expected from the decay $K_L^0 \to ee\gamma$ in the region $M_{e^+e^-} > 470 MeV/c^2$ is 4.4 ± 0.9 and that in $M_{e^+e^-} > 480 MeV/c^2$ is 0.8 ± 0.2. Since there are 18 and 6 events in the experimental data in the respective regions, the decay $K_L^0 \to ee\gamma$ alone can not satisfactorily explain the data.

The $K_L^0 \to e^+e^-e^+e^-$ decay rate was theoretically calculated[4,5] using the Kroll-Wada formula for the double internal conversion through the $\gamma^*\gamma^*$ intermediate state. The validity of the formula was confirmed by an experiment[12] for a similar decay $\pi^0 \to e^+e^-e^+e^-$. The $K_L^0 \to e^+e^-e^+e^-$ decay rate is written as follows:

$$\Gamma_{total} = \Gamma_1 + \Gamma_2 + \Gamma_{12}, \tag{2}$$

where Γ_1 is given by

$$2\Gamma_{\gamma\gamma}^{-1} \frac{d^2\Gamma_1}{dx_1 dx_2} = \left(\frac{2\alpha}{3\pi}\right)^2 \frac{(1-(x_1+x_2)^2)^{3/2}(1-(x_1-x_2)^2)^{3/2}}{x_1 x_2} \times \left[\left(1 - \frac{4m_e^2}{x_1^2 M_K^2}\right)^{1/2} \left(1 + \frac{2m_e^2}{x_1^2 M_K^2}\right)\right] \left[\ x_1 \leftrightarrow x_2\ \right], \tag{3}$$

and $\Gamma_{\gamma\gamma}$ is the width of the decay $K_L^0 \to \gamma\gamma$, α is the fine structure constant and x_i is the i-th virtual photon mass divided by M_K. The energy sharing between the e^+ and e^- in a pair and the correlation between the two planes made by two e^+e^- pairs follow the distribution:

$$\begin{aligned} g(x_1, x_2, y_1, y_2, \phi) &= \left[1 + (y_1^2 + \frac{4m_e^2}{x_1^2 M_K^2})(y_2^2 + \frac{4m_e^2}{x_2^2 M_K^2})\right] \sin^2\phi \\ &+ \left[(y_1^2 + \frac{4m_e^2}{x_1^2 M_K^2}) + (y_2^2 + \frac{4m_e^2}{x_2^2 M_K^2})\right] \cos^2\phi, \end{aligned} \tag{4}$$

where y_i is given by $\sqrt{1 - 4m_e^2/x_i^2/M_K^2}\cos\theta_i$, and θ_i is the angle between the momentum direction of the i-th virtual gamma and that of the electron in the virtual gamma rest frame, and ϕ is the correlation angle between the planes which were determined by the e^+e^- pairs. The contribution of Γ_2, which is defined below, is important at large x as mentioned by Miyazaki and Takasugi.[5]

$$\Gamma_2(p_+, p_-, p'_+, p'_-) = \Gamma_1(p_+, p'_-, p'_+, p_-), \tag{5}$$

where p_+, p_-, p'_+ and p'_- represent the four momenta of the positrons and electrons. Therefore, Γ_2 can be obtained by using the alternative combination of the electron-positron pairs in Γ_1. We generated $K_L^0 \to e^+e^-e^+e^-$ events in a Monte Carlo calculation using only the equation for Γ_1. The contribution from Γ_2 was automatically taken into account by taking all e^+e^- combinations in the calculation. The decay spectra of Γ_1 and Γ_2 as functions of x are shown in Figure 2(a), which reproduced well those given by Miyazaki and Takasugi.[5] The cross term Γ_{12} was estimated to be negligibly small, and its contribution was neglected in the calculation. The acceptance ratio $A_{eeee}/A_{\pi^+\pi^-}$ obtained from a Monte Carlo simulation using thus generated $K_L^0 \to e^+e^-e^+e^-$ events was $(8.54 \pm 0.21) \times 10^{-3}$ in the region $M_{e^+e^-} > 470 MeV/c^2$ and $(2.85 \pm 0.12) \times 10^{-3}$ in $M_{e^+e^-} > 480 MeV/c^2$. The average particle identification efficiency for e^+e^- detection was 0.743 ± 0.006. The acceptance for the e^+e^- pair from the decay $K_L^0 \to e^+e^-e^+e^-$ as a function of x is shown in Figure 2(b). Figure 3 shows a $M_{e^+e^-}$ vs P_t plot obtained from a Monte Carlo simulation for the decays $K_L^0 \to \pi e\nu$, $K_L^0 \to ee\gamma$ and $K_L^0 \to e^+e^-e^+e^-$. The number of K_L^0 decays generated was 10 times that of our experiment. The shape of the event distribution in Figure 1 was reproduced well by the simulation.

The external conversions of γ's from the decays $K_L^0 \to \gamma\gamma$ and $K_L^0 \to ee\gamma$ would be possible sources for high mass e^+e^- events. But an electro-magnetic shower calculation showed that 0.45 and 0.2 events from the decay $K_L^0 \to \gamma\gamma$ were expected in the regions above $470 MeV/c^2$ and $480 MeV/c^2$, respectively, and 0.19 and 0.06 events from the decay $K_L^0 \to ee\gamma$ were expected in the same regions. The smallness of the contribution is due to the fact that there was very little material in the upstream part of the detector. Another possible source for high mass e^+e^- events would be double misidentification of a pair of hadrons which were produced by the interaction of a neutral particle in

the beam with the residual gas in the decay chamber. We estimated the background contamination from this source using the $\mu^+\mu^-$ events in the region $M_{\mu\mu} > 510 MeV/c^2$, and the number of e^+e^- events expected in the region $M_{e^+e^-} > 470 MeV/c^2$ was found to be less than 0.01.

After subtracting the expected number of events from the decay $K_L^0 \to ee\gamma$ and those from the external conversions, the branching ratio of the decay $K_L^0 \to e^+e^-e^+e^-$ was estimated to be $(6\pm2\pm1)\times10^{-8}$ in the region $M_{e^+e^-} > 470 MeV/c^2$ and $(7\pm3\pm2)\times10^{-8}$ in $M_{e^+e^-} > 480 MeV/c^2$. The first error is statistical and the second one is systematic. The systematic error was estimated by the quadratic sum of the following errors. There are 3 and 5 % uncertainties in the acceptance calculation and 8 and 7 % uncertainties in the background subtraction in the regions $M_{e^+e^-} > 470 MeV/c^2$ and $M_{e^+e^-} > 480 MeV/c^2$, respectively, and 1% uncertainty in particle identification. The one event of the highest $M_{e^+e^-}$ is in the fiducial region for the decay $K_L^0 \to ee$. Since the branching ratio for the decay $K_L^0 \to ee$ is expected to be $(3-5)\times10^{-12}$ [13] by the Standard Model, we could not ignore the possibility that this was a genuine $K_L^0 \to ee$ event, and we included one event in the systematic error. Both values are consistent with each other, and we take the first higher statistical value as our estimate.

The present value of the branching ratio of the decay $K_L^0 \to e^+e^-e^+e^-$ is consistent with the previous value of $(4\pm3)\times10^{-8}$ given by Barr et al.[6] and the recently reported preliminary result of $(5\pm2\pm3)\times10^{-8}$ using 6 events by Morse et al.[14]

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10) *In the simulation, events were generated using the equation (4) and (5) in the reference*[11], *in which $\alpha_{K^*} = -0.28^{+0.082}_{-0.079}$ was quoted from the experiments*[9]. The error in this α_{K^*} was a primary source of ambiguity in the background subtraction.

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Figure Captions

Fig. 1 $M_{e^+e^-}$ vs P_t plot;

Fig. 2 (a) Monte Carlo generated distributions of Γ_1 and Γ_2 for the decay $K_L^0 \to e^+e^-e^+e^-$ as a function of x. The Γ_2 distribution is obtained by exchanging the combination of the e^+e^- pair generated according to the Γ_1 distribution. (b) The x dependence of the acceptance in the region of high e^+e^- mass.

Fig. 3 Monte Carlo generated $M_{e^+e^-}$ vs P_t plot with ten times sensitivity of this experiment. The dot indicates an event from the decay $K_L^0 \to \pi e \nu$, the cross from the decay $K_L^0 \to ee\gamma$ and the open circle from the decay $K_L^0 \to e^+e^-e^+e^-$.

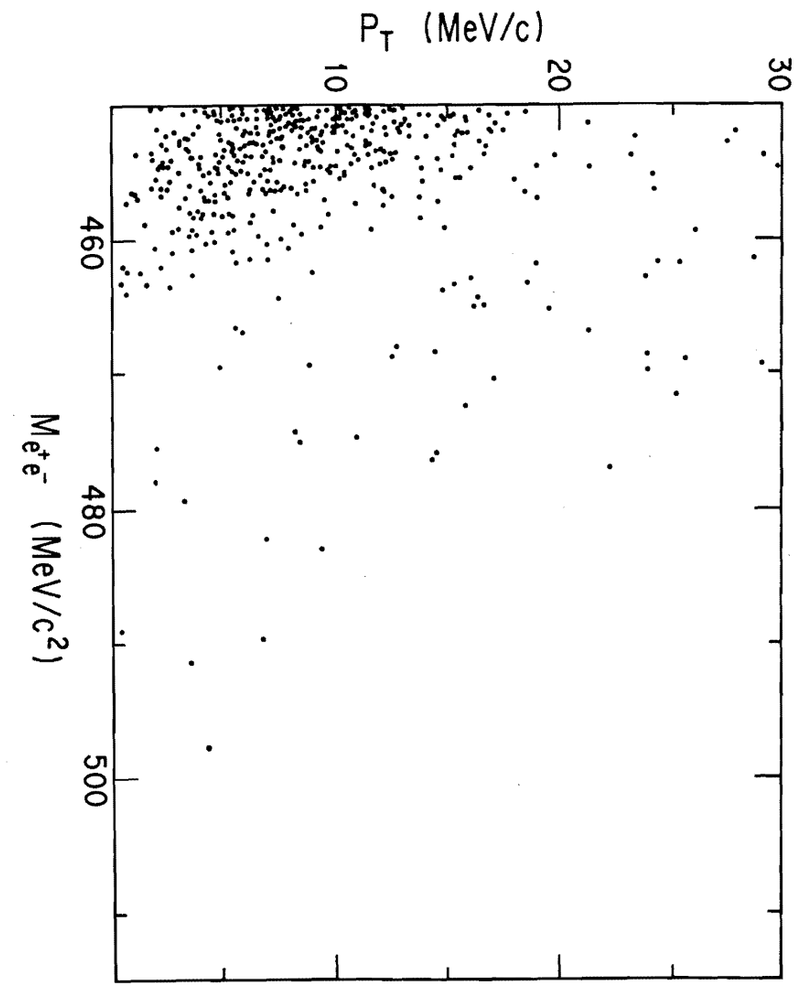

Figure 1

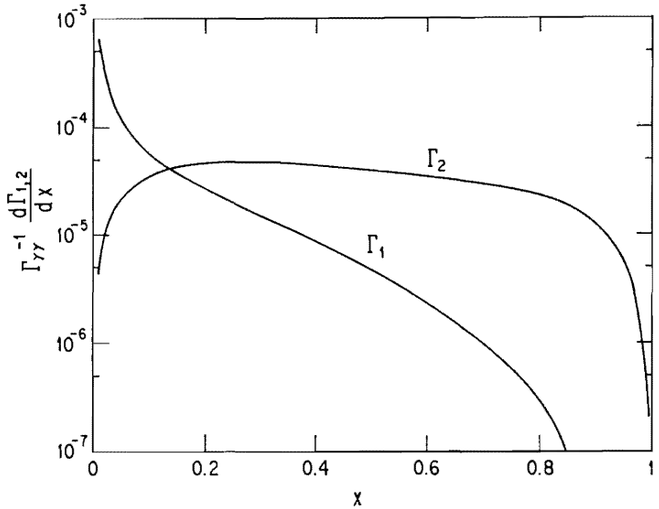

Figure 2(a)

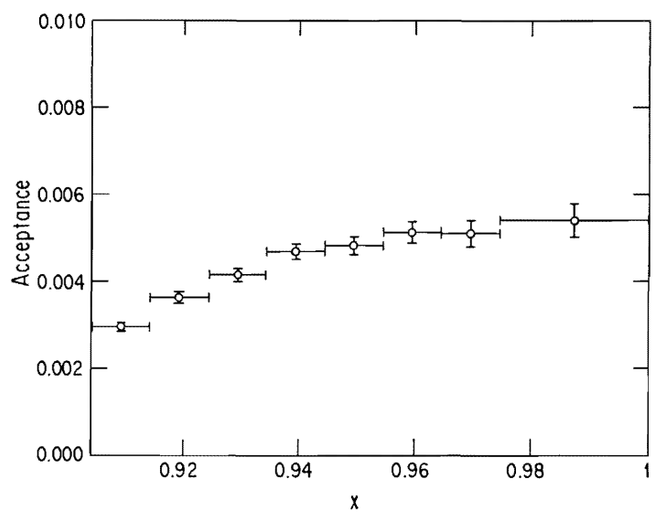

Figure 2(b)
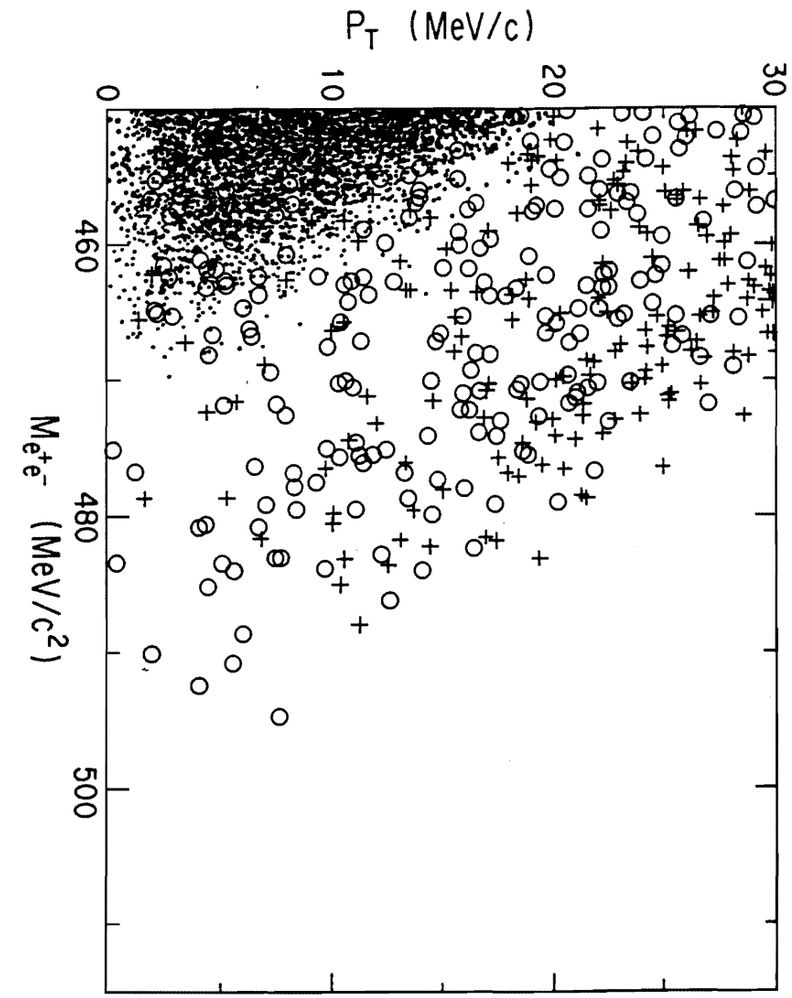
Figure 3