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Search for the decay $K_L \to \pi^0 \nu\bar{\nu}$

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Data collected in Fermilab experiment E731 was used to perform the first search for the decay $K_L \to \pi^0 \nu\bar{\nu}$. This decay is dominated by short distance effects and is almost entirely direct *CP* violating within the standard model. Cuts were developed to reject the background processes $\Lambda \to n\pi^0$ and $K_L \to \pi^+ e^- \gamma\nu$. No candidate events were seen. We find BR $(K_L \to \pi^0 \nu\bar{\nu}) < 2.2. \times 10^{-4}$ at the 90% confidence level.

The decay $K_L \to \pi^0 \nu\bar{\nu}$ is uniquely well suited to the study of direct *CP* violation within the standard model. It is one of four related processes in which a kaon decays to a pion and a light lepton pair. These are (i) $K^+ \to \pi^+ e^+ e^-$ ($K^+_{\pi ee}$); (ii) $K^+ \to \pi^+ \nu\bar{\nu}$ ($K^+_{\pi\nu\nu}$); (iii) $K^0 \to \pi^0 e^+ e^-$ ($K^0_{\pi ee}$); and (iv) $K^0 \to \pi^0 \nu\bar{\nu}$ ($K^0_{\pi\nu\nu}$).

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The first of these, $K^+_{\pi ee}$, has been observed [1] with a branching ratio measured to be 2.75×10^{-7}. Unlike the other three, this process is dominated by long distance effects.

The branching ratio limit [2] for the second process, $K^+_{\pi\nu\nu}$, is $< 3.4 \times 10^{-8}$ at the 90% confidence level. This decay mode is dominated by short distance effects [3] described by one-loop diagrams involving virtual charm or top quarks. The top quark term is proportional to the magnitude of the as yet undetermined V_{td} element of the CKM matrix. The standard model predicts that the branching fraction for this decay will be around 10^{-10}.

For the third process, $K^0_{\pi ee}$, the branching ratio [4] is $< 3.5 \times 10^{-9}$ for K_L and the limit [5] is $< 4.5 \times$

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10^{-5} for K_S, at the 90% confidence level. The K_L decay mode has both direct and indirect *CP* violating contributions [6]. The interesting direct piece is primarily a short-distance effect which can be fairly reliably calculated. However, this term can be extracted from a measurement of $K_L \to \pi^0 e^+ e^-$ only after the indirect piece has been determined from a measurement of $\Gamma(K_S \to \pi^0 e^+ e^-)$. It will be necessary to subtract the *CP*-conserving amplitude arising from the $\pi^0 \gamma^* \gamma^*$ intermediate state [7] and measurements [8] of $K_L \to \pi^0 \gamma\gamma$ has been made. Experimentally a substantial background [9] from radiative Dalitz decays, $K_L \to e^+ e^- \gamma\gamma$, also needs to be subtracted.

In this paper, we report the results of a search for the fourth mode, $K^0 \to \pi^0 \nu\bar{\nu}$. This process has been considered theoretically [10], but because of the formidable experimental difficulties, no search for this mode has previously been performed. The major attraction of this mode is its potential for the study of direct *CP* violation in the standard model. There is no significant long-distance contribution to $K_L \to \pi^0 \nu\bar{\nu}$ and, based on existing upper limits for the $K^+_{\pi\nu\nu}$ mode, the amplitude from indirect *CP* violation is negligible compared to direct *CP* violating effects. The dominant, direct *CP* violating, contribution to the decay is proportional to the imaginary part of V_{td}. In the Wolfenstein [11] parametrization of the CKM matrix, $V_{td} = A\lambda^3(1-\rho-i\eta)$ and the standard model predicts

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = 1.5 \times 10^{-10} (M_t / 100\ \mathrm{GeV})^2 A^4 \eta^2 ,$$

where M_t is the mass of the top quark. In the standard model, the magnitude of η can be related to the known value of ϵ: it is estimated [12] that η lies somewhere between about 0.1 and 0,6. Based on the value [12] $A = 0.85 \pm 0.09$, and the mass of the top quark determined indirectly from LEP data [13] to be 157 ± 40 GeV/c^2, the branching fraction for $K_L \to \pi^0 \nu\bar{\nu}$ could be as large as 2×10^{-10}.

The experimental signature for $K_L \to \pi^0 \nu\bar{\nu}$ is an observed single π^0 with unbalanced transverse momentum. Two decay modes of the neutral pion, $\pi^0 \to \gamma\gamma$ and $\pi^0 \to e^+ e^- \gamma$, could be used for detection, each with its own experimental difficulties. If the $\gamma\gamma$ final state is used, the transverse position of the decay vertex within the neutral beam cannot be accurately determined, and a very hermetic photon veto system is required in order to reject background from $K_L \to 2\pi^0$ decays. Using the $e^+ e^- \gamma$ final state (Dalitz decays) permits the determination of the decay vertex so that the invariant mass and transverse momentum of the $e^+ e^- \gamma$ system can be calculated, allowing considerable background rejection. We have therefore elected for this first search to require a Dalitz decay, even though the Dalitz decay branching fraction is only about $\frac{1}{80}$ of that for $\pi^0 \to \gamma\gamma$. With this technique, we found that the most important backgrounds in this experiment were due to the decays $\Lambda \to n\pi^0 (\pi^0 \to e^+ e^- \gamma)$ and $K_L \to \pi^+ e^- \gamma\nu$ (and its charge conjugate) when the pion is misidentified as an electron. It was necessary to develop cuts to identify and reject events from each of these processes.

Here we describe briefly the features of the experimental apparatus relevant to this search. Two neutral K_L beams (each $\frac{1}{2} \times \frac{1}{2}$ mrad^2) were created at 4.8 mrad by 800 GeV protons striking a Be target. One of the two neutral beams hit a regenerator in order to produce a K_S flux, but only decays from the other (vacuum) beam were used in this search. The trajectories and momenta of charged particles were reconstructed using four drift chambers and an analyzing magnet which imparted a horizontal transverse momentum (P_t) kick of about 200 MeV/c. Each drift chamber consisted of two X planes and two Y planes; each plane had a resolution of approximately 100 μm. A roughly circular array of 804 lead glass blocks was used to measure the energies and positions of electrons and photons. Each block measured 5.82 cm by 5.82 by 60 cm long, this depth being equal to about 19 radiation lengths. We obtained photon energy and position resolutions of $\sigma/E \cong 2.5\% + 5\%/\sqrt{E}$ and ~ 3 mm, respectively. In the lead glass array, there were two 11.6 cm by 11.6 cm beam holes whose centers were 11.6 cm above and below the center of the array, through which the neutral beams passed. These two beam holes were viewed by a beam hole calorimeter which was about 30 radiation lengths (1.3 interaction lengths) long. There were altogether twelve planes of photon veto counters at different positions in the spectrometer which were used to detect decay products outside the chamber and calorimeter acceptances. In this search we used K_L decays occurring in a region 31 m long. Further characteristics of the E731 detector have been described elsewhere [14].

The trigger used to collect the events analyzed here required two or more charged particles, one each on the left and right sides of the second drift chamber (1.63 m wide × 1.42 m high located about 3 meters upstream of the analyzing magnet). It also required charged particle hits in opposite quadrants of a scintillator hodoscope just in front of the lead glass calorimeter, with some overlap between quadrants near the center of the detector. These requirements were only rarely satisfied by π^0 Dalitz decays since the electron–positron pair usually has a very small opening angle [15].

In the analysis, a signal event candidate is required to have two charged tracks and one photon, where a photon is defined as an energy cluster in the lead glass not matched to either track. Both tracks were identified as electrons by the requirement that $0.925 < E/p < 1.075$, where E is the total energy of the calorimeter cluster matched to the track, and p is the track momentum measured in the drift chamber system. All three clusters' shapes were required to be consistent with the shape expected for electromagnetic showers. The E/p and shape cuts together gave a π/e rejection of about 100 for track momentum in the range of 2–20 GeV/c. Radiative K_{e3}($K_L \to \pi e \gamma \nu$) background events in which the pion was misidentified as electron were reconstructed by assuming that one of the two tracks was a pion. The neutrino is not observed, but using mass and P_t constraints, its momentum (and therefore that of the decaying kaon) can be calculated up to a two-fold ambiguity in the longitudinal component. The cosine of the angle between the electron and photon in the kaon center-of-mass frame is then calculated based on the assumption that the smaller oft he two kaon energy solutions is correct. The resulting distribution of cosines, shown in fig. 1, is not sensitive to this assumption. The distribution peaks sharply near +1 since the photons in $\pi e \gamma \nu$ background events are produced by internal or external bremsstrahlung, and so tend to be collinear with the electron. Events were rejected if $\cos\theta_{e\gamma} > 0.95$ for either possible assignment of one track as an electron and the other as a pion.

The energy of the photon was required to be greater than 5 GeV in order to reject the usually softer photons which were accidentally coincident with K_{e3} events. To reject events with radiative external conversion and backgrounds resulting from accidental activity, we required $12 < M_{ee} < 48$ MeV/c^2, $M_{\pi e \gamma} < 500$ MeV/c^2, and $P_t^{ee} < 17$ MeV/c where M_{ee} and $M_{\pi e \gamma}$ are the invariant masses of the assumed ee pair and $\pi e \gamma$ system, and P_t^{ee} is the transverse momentum of the ee pair relative to the kaon flight direction. Although the M_{ee} value for a real π^0 Dalitz decay could be higher than 48 MeV/c^2, the cut was set to further reject the remaining K_{e3} background with the misidentified pion as electron. This misidentification shifted the reconstructed M_{ee} invariant mass down by the pion mass value, however due to the characteristics [15] of the M_{ee} distribution of π^0 Dalitz decay, the signal sensitivity suffers only a small loss. These cuts reduced the acceptance by about 8% in a Monte Carlo signal simulation while reducing the number of events of the data sample by a factor of 18.

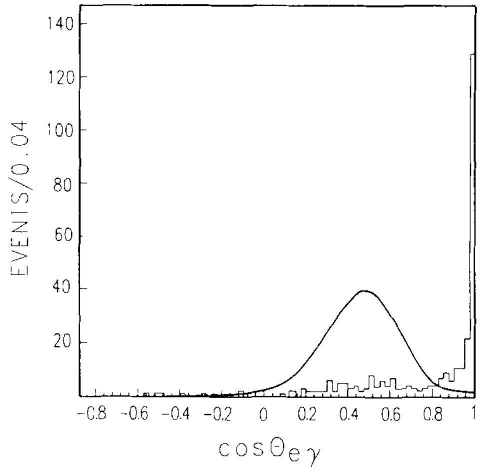

Fig. 1. The histogram is the distribution of $\cos\theta_{e\gamma}$ for events surviving all other cuts. The peak at +1 is from radiative K_{e3} decays. This background is removed by discarding events with $\cos\theta_{e\gamma} > 0.95$. The curve shows the distribution predicted by a Monte Carlo simulation of $K_L \to \pi^0 \nu\bar{\nu}$ with $\pi^0 \to e^+e^-\gamma$.

To normalize the total exposure of the experiment, we reconstructed $K_L \to e^+e^-\gamma$ events from the same data sample. Fig. 2 shows the invariant $e^+e^-\gamma$ mass distribution. Forty-nine events are seen. Based on the measured branching ratio for this mode [16] and the Monte Carlo calculated acceptance of 4.75×10^{-3}, the total number of kaon decays to which the detector was exposed is about 1.08×10^9. This agrees to within 5% with the result of an independent flux calculation based on a sample of about 3.3×10^5 $K_L \to \pi^+\pi^-$ events collected simultaneously.

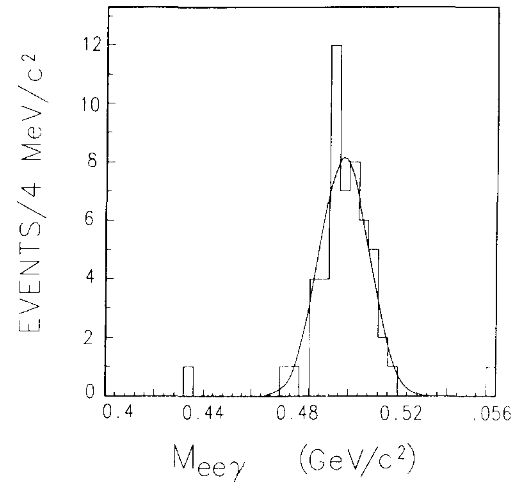

Fig. 2. Distribution of the reconstructed kaon mass for $K_L \to e^+e^-\gamma$ candidates. There are 49 events lying between 480 and 520 MeV/c^2. The width of the gaussian fit is 9.5 MeV/c^2.

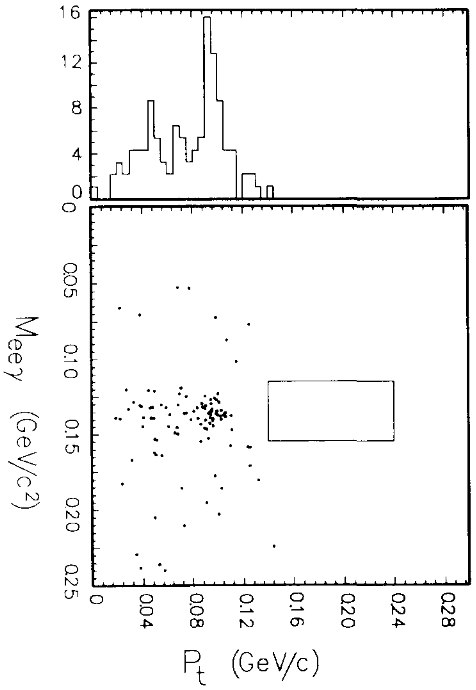

Fig. 3. Reconstructed $e^+e^-\gamma$ invariant mass versus the transverse momentum for events surviving all cuts. The box represents the $\pi^0\nu\bar{\nu}$ search region as described in the text. The vertical axis projection clearly shows the residual $\Lambda \to n\pi^0$ events. The remaining backgrounds are due to radiative K_{e3} decays, and K_{e3}'s in accidental coincidence with photons, both with misidentified pions.

Even though the beam production target was about 100 meters upstream of the decay volume, some very high energy (250–350 GeV) Λ hyperons produced at the target lived long enough to enter the fiducial volume. The neutron from the decay $\Lambda \to n\pi^0(\pi^0 \to e^+e^-\gamma)$ usually went into the beam holes. To reduce background from this source, we rejected any event in which more than 10 GeV was deposited in the beam hole calorimeter. Because sufficient accidental activity in the beam hole calorimeter would cause good events to be discarded, this cut reduced the effective flux by about 5%. The P_t spectrum of reconstructed π^0's from $\Lambda \to n\pi^0$ peaks just below 100 MeV/c, near the kinematic limit of 104 MeV/c for this decay. Fig. 3 shows the distribution of reconstructed $e^+e^-\gamma$ invariant mass versus P_t after all cuts. The empty box in the figure contains the region within which we search for $K_L \to \pi^0\nu\bar{\nu}$ events. The events below the box are the remaining $\Lambda \to n\pi^0(\pi^0 \to e^+e^-\gamma)$ background. Events outside the sensitivity box but away from the π^0 peak are from the small fraction of radiative K_{e3} decays surviving all cuts.

The search region is defined by the cuts $115 < M_{ee\gamma} < 155$ MeV/c^2 and $140 < P_t^{ee\gamma} < 240$ MeV/c. The high limit of $P_t^{ee\gamma}$ is the largest possible P_t of the π^0 from $K_L \to \pi^0\nu\bar{\nu}$ could have attained with resolution effect (231 MeV/c is the kinematical limit with no resolution effect). Fig. 4 shows the distribution of reconstructed $e^+e^-\gamma$ invariant mass versus P_t from Monte Carlo simulated data of $K_L \to \pi^0\nu\bar{\nu}(\pi^0 \to e^+e^-\gamma)$ after all other cuts. Assuming a matrix element with a pure vector form factor, about 40% of $K_L \to \pi^0\nu\bar{\nu}(\pi^0 \to e^+e^-\gamma)$ events lie within the defined search region (the box shown in fig. 4). Including this factor, the Monte Carlo calculated acceptance for $K_L \to \pi^0\nu\bar{\nu}(\pi^0 \to e^+e^-\gamma)$ is 8.2×10^{-4} for kaon energies between 20 and 220 GeV and decay vertices between 106 and 137 meters downstream of the target. We see no events within the search region, and therefore conclude with 90% confidence that the branching fraction for the decay $K_L \to \pi^0\nu\bar{\nu}$ is less than 2.2×10^{-4}.

Searches with far greater sensitivity will be required in order to observe this process at the level predicted by the standard model.

This work partially fulfilled the requirements of a

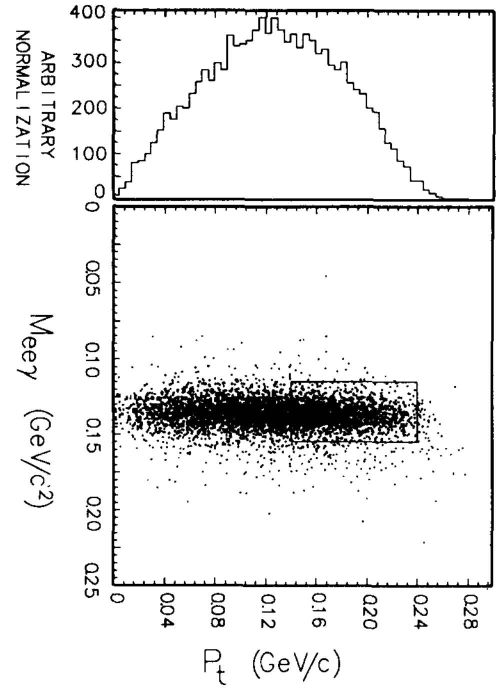

Fig. 4. Monte Carlo simulated distribution of reconstructed $e^+e^-\gamma$ invariant mass versus the transverse momentum for events surviving all cuts. The box represents the $\pi^0\nu\bar{\nu}$ search region as described in the text.

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References

[1] C. Alliegro et al., Phys. Rev. Lett. 68 (1992) 278.
[2] M.S. Atiya et al., Phys. Rev. Lett. 64 (1990) 21.
[3] T. Inami and C.S. Lim, Prog. Theor. Phys. 65 (1981) 297;
J. Ellis, J.S. Hagelin and S. Rudaz, Phys. Lett. B 192 (1987) 201;
H. Harari and Y. Nir, Phys. Lett. B. 195 (1987) 586;
J. Ellis, J.S. Hagelin, S. Rudaz and D.-D. Wu, Nucl. Phys. B 304 (1988) 205;
J. Ellis and J.S. Hagelin, Nucl. Phys. B 217 (1983) 189;
J.S. Hagelin and L.S. Littenberg, Prog. Part. Nucl. Phys. 23 (1989) 1;
C.O. Dib, I. Dunietz and F.J. Gilman, report No. SLAC-PUB-4840 (1989), unpublished.
[4] K.E. Ohl et. al., Phys. Rev. Lett. 64 (1990) 2755;
A. Barker et al., Phys. Rev. D 41 (1990) 3546.
[5] L.K. Gibbons et al., Phys. Rev. Lett. 61 (1988) 2661.
[6] J.F. Donoghue, B.R. Holstein and G. Valencia, Phys. Rev. D 35 (1987) 2769;
L.M. Sehgal Phys. Rev. D 38 (1988) 808;
G. Ecker, A. Pich and E. De Rafael, Nucl. Phys. B 303 (1988) 665;
C.O. Dib, I. Dunietz and F. Gilman, Phys. Rev. D 39 (1989) 2639;
J. Flynn and L. Randall, Phys. Lett. B 216 (1989) 221;
G. Ecker, A Pich and E. De Rafael, Nucl. Phys. B 291 (1987) 692;
P. Ko, Phys. Rev. D 44 (1991) 139.
[7] G. Ecker, A. Pich and E. De Rafael, Phys. Lett. B 189 (1987) 363;
P. Ko and J.L. Rosner, Phys. Rev. D 40 (1989) 3775;
T. Morozumi and H. Iwasaki, in: Proc. Second Meeting on Physics at TeV scale, eds. K. Hidaka and K. Hikasa (KEK, Tsukuba, 1988);
L.M. Sehgal, Phys. Rev. D 41 (1990) 161;
P. Ko, Phys. Rev. D 41 (1990) 1531;
G. Ecker, A. Pich and E. De Rafael, report Nos. UWThPh-1989-65, FTUV/89-44, unpublished.
[8] G.D. Barr et al., Phys. Lett. B 242 (1990) 523;
V. Papadimitriou et al., Phys. Rev. D 44 (1991) R573.
[9] H.B. Greenlee, Phys. Rev. D 42 (1990) 3724.
[10] M.K. Gaillard and B.W. Lee, Phys. Rev. D 10 (1974) 897;
J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nucl. Phys. B 109 (1976) 213;
L.S. Littenberg, Phys. Rev. D 39 (1989) 3322;
G. Belanger and C.Q. Geng, Phys. Rev. D 43 (1991) 140.
[11] L. Wolfenstein, Phys. Rev. Lett. 51 (1983) 1945.
[12] G. Harris and J. Rosner, Phys. Rev. Lett. D 45 (1992) 946.
[13] Result reported by J. Nash at XXVIIth Rencontres De Moriond (Les Arcs, Savoie-France, March 1992), unpublished.
[14] J.R. Patterson et al., Phys. Rev. Lett. 64 (1990) 1491;
V. Papadimitriou, Ph. D. thesis (University of Chicago, 1990);
J.R. Patterson, Ph.D. thesis (University of Chicago, 1991).
[15] R.H. Dalitz, Proc. Phys. Soc. A 64 (1951) 667;
N.M. Kroll and W. Wada, Phys. Rev. 98 (1955) 1355.
[16] G.D. Barr et al., Phys. Lett. B 240 (1990) 283;
K.E. Ohl et al., Phys. Rev. Lett. 65 (1990) 1407.