VOLUME 36, NUMBER 13 PHYSICAL REVIEW LETTERS 29 MARCH 1976

Observation of $\mu^- e^+ K_s^0$ Events Produced by a Neutrino Beam

J. von Krogh, W. Fry, U. Camerini, D. Cline, R. J. Loveless, J. Mapp,
R. H. March, and D. D. Reeder
*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706**

and

A. Barbaro-Galtieri, P. Bosetti,† G. Lynch, J. Marriner, F. Solmitz, and M. L. Stevenson
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

D. Haidt, G. Harigel, and H. Wachsmuth
CERN, 1211 Geneva 23, Switzerland

and

R. Cence, F. Harris, S. I. Parker, M. Peters, V. Peterson, and V. Stenger
Department of Physics, University of Hawaii, Honolulu, Hawaii 96822

(Received 15 January 1976)

Four events have been observed with an e^+ and a K_s^0 decay in the final state induced by a neutrino beam incident on the Fermilab 15-ft neon bubble chamber. Conventional backgrounds are unable to account for these events. Two of the events have in addition a μ^- in the final state clearly identified by the external muon identifier. The other two have μ^- candidates.

The 15-ft Fermi National Accelerator Laboratory (FNAL) bubble chamber filled with a mixture of neon and hydrogen, coupled with the external muon identifier (EMI), is a tool for searching for new phenomena in the interactions of neutrinos from the FNAL accelerator. The EMI consists of 24 1-m^2 proportional chambers located behind the bubble chamber and a wall of absorber.[1] This combination of muon detection, short mean free path for hadron identification, and short radiation length for electron identification along with high spatial resolution permits a detailed study of phenomena involving more than one lepton coupled with strange particles.

The bubble chamber was exposed to a wide-band neutrino beam focused by two horns using 300-GeV incident protons. It was filled with a light Ne/H$_2$ mixture (~ 20% Ne by volume). The running conditions resulted in approximately one neutrino interaction in every ten frames.

The film was scanned by professional scanners for all interactions induced by neutrals. For a partial sample, every event found by the scanners was then checked by physicists. The results presented in this paper are based on this partial sample. A physicist studied every track to see if there were any electrons, positrons, or electron pairs (Dalitz) from the main vertex. The criteria used for electron detection were energy loss due to bremsstrahlung, conversion of the resulting photon in the chamber, direct pair production on the electron track, or any combination of these phenomena. Events with $e^\pm$ compatible with being part of a Dalitz pair were excluded from the sample. In a separate study of converted γ rays, the electron detection efficiency was empirically determined to be about 20–30%.

The results of this search on a sample of about 1500 events were four events with an e^+ and six events with an e^- in the final state. The six events with e^- are interpreted as ν_e interactions because in each case the electron is the highest momentum track in the event and none of the events has a track that could be identified as a muon by the EMI. The four e^+ events have been labeled 1, 2, 3, 4.[2]

The detailed characteristics of event 3 will be given. It was chosen because the final state appears to be simple and the particles well identified. It illustrates the good analyzing power of the neon-filled 15-ft chamber coupled with the EMI. This event is shown in Fig. 1. There are only two charged particles from the main vertex. In addition, a K_s^0 points to the neutrino vertex. The e^+ is identified by a combination of energy loss due to radiation, with two γ's from bremsstrahlung which convert, and the annihilation of the positron with a subsequent conversion of the annihilation γ into an electron pair.

The μ^- is identified by its lack of scattering in

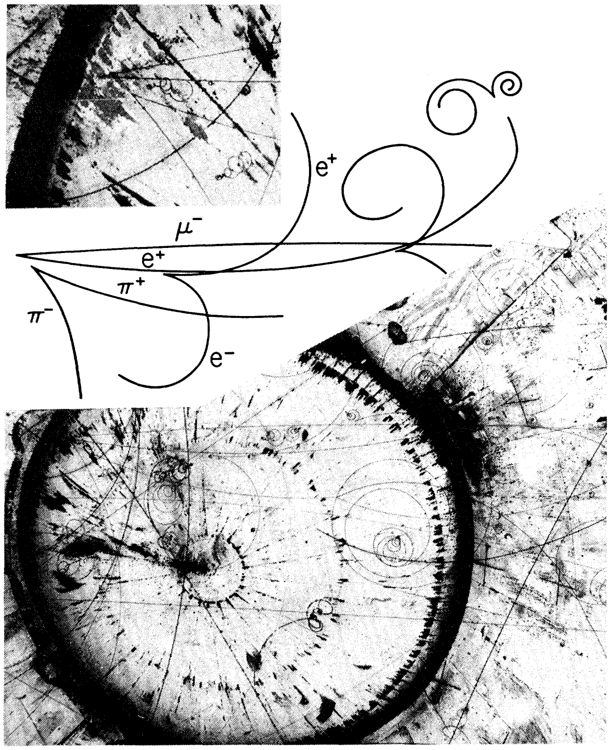

FIG. 1. The two photographs and drawing illustrate event 3. The top photograph is an enlargement of the vertex to illustrate the absence of a low-energy electron.

the chamber and its penetration into the EMI at a point less than 1 cm from the extrapolated position. The expected error, due mostly to Coulomb scattering, is about 8 mm. In all, the track had passed through almost five interaction lengths. An enlargement of the vertex region of event 3 is also shown in Fig. 1. Note that no additional tracks emerge from the vertex. An upper limit of 5 MeV can be safely placed on the energy of any additional electron track at the vertex. The 6-MeV δ ray on the positron track illustrates how conservative this upper limit is. The other events, 1, 2, and 4, all show a similar clean vertex and a unique e^+ identification. Events 1 and 3 have a μ^- identified by the EMI while the other two events have negative tracks that can be plausibly identified as a μ^-, but are not uniquely identified as such, because they physically miss the EMI chambers.

Since the positron is the most important particle in the selection of these events, backgrounds which involve positrons must be evaluated. The most important of these backgrounds are the following:

(1) An asymmetric Dalitz pair $\pi^0 \to \gamma + e^+ + e^-$ with the e^- having an energy less than 5 MeV. From the theoretical energy distribution between the e^- and e^+, and the number of observed Dalitz pairs in the sample, this contribution has been estimated as less than 0.2 event.

(2) $K^+ \to e^+ + \pi^0 + \nu$. The estimated number of events is less than 0.1, assuming a 2-GeV K^+ decay length of 50 cm and the ability to detect kinks with projected angles of greater than 6° on film.

(3) $K_L^0 \to e^+ + \pi^- + \nu$. If this happens close to the vertex (within 1 cm), the tracks are taken as coming from the main vertex; 5×10^{-3} event expected.

(4) $K^+ \to e^+ + \nu$ and $\pi^+ \to e^+ + \nu$. The contribution from these processes is 5×10^{-4} event.

(5) Incoming neutral hadrons simulating ν interactions where a kaon is produced and decays in flight into an electron. This background was evaluated empirically in the same experiment, giving rise to an expected background of 2×10^{-3} event.

(6) $\bar{\nu}_e + N \to e^+ +$hadrons. Note that for the $\bar{\nu}_e$ hypothesis, the four e^+ events would have the following values of $y_{\text{vis}} = (E_{\text{vis}} - E_{e+})/E_{\text{vis}}$: $y_{\text{vis}} = 0.88$, 0.92, 0.94, 0.81, respectively. This has to be contrasted with the fact that for $\bar{\nu}_e$ interactions, one expects a y distribution falling like $(1-y)^2$, with a mean value of 0.25. From the estimated $\bar{\nu}_e$ flux for this experiment[3] $(\varphi_{\bar{\nu}_e}/\varphi_{\nu_\mu} \simeq 10^{-3})$ we expect to observe 4×10^{-3} event with $y > 0.7$.

As a check we computed the number of ν_e interactions ($\nu_e N \to e^- +$hadrons) expected to be observed in the considered film sample. This number is 4.8 events, to be compared with 6 ν_e events found. (For these events the EMI confirmed that there is no muon in the final state.) This gives credence to the correctness of the $\bar{\nu}_e$ flux used for background (6).

This leads to a total expected background of 3.1×10^{-1} event. The probability that the 4 events are due to background is 2.8×10^{-4}. We conclude that these positron events are not due to background and represent the first observation of the reaction

$$\nu_\mu + N \to \mu^- + e^+ + \nu_e + K_s^0 + X.$$

The topological and inferred particles (denoted

TABLE I. Kinematic quantities of the four positron events. Definitions: $y_{\text{vis}}(\nu_\mu)=(E_{\text{vis}}-E_{\mu^-})/E_{\text{vis}}$; $y_{\text{vis}}(\bar{\nu}_e)=(E_{\text{vis}}-E_{e^+})/E_{\text{vis}}$; $Q_{\text{vis}}^2=4E_{\text{vis}}E_\mu \times \sin^2(\theta_{\nu\mu}/2)$; $x_{\text{vis}}=Q_{\text{vis}}^2/[2M(E_{\text{vis}}-E_\mu)]$; $W_{\text{vis}}^2=M^2+2M(E_{\text{vis}}-E_\mu)-Q_{\text{vis}}^2$.

Event	1	2	3	4
E_{vis}	34 GeV	11 GeV	26 (34) GeV	28 GeV
$E(\mu^-)$	14	3	22	9
$E(e^+)$	2.0	1.1	2.2	5.3
$E(K^0)$	6	3	2	6
E(other hadrons)	12	4	None (8)	8
y_{vis} (ν_μ)	0.6	0.7	0.2 (0.4)	0.6
y_{vis} $(\bar{\nu}_e)$	0.88	0.92	0.94	0.81
x_{vis} (ν_μ)	0.003	0.09	0.9 (0.4)	0.2
W_{vis}	6 GeV	4 GeV	1.3 (4) GeV	5 GeV
Q_{vis}^2	0.1	1.4	6 (9)	7
$p(\mu^-)/p(e^+)$	7	3	10	2

by parentheses) in the four events are

$$\nu_\mu+N\to\mu^-+e^++(\nu_e)+K_s^{\,0}+2\pi^-+3\pi^+ +\pi^0+4p+n+(\text{neutrals?}), \quad (1)$$

$$\nu_\mu+N\to(\mu)^-+e^++(\nu_e)+K_s^{\,0}+2\pi^-+\pi^+ +\pi^0+p+(\text{neutrals?}), \quad (2)$$

$$\nu_\mu+N\to\mu^-+e^++(\nu_e)+K_s^{\,0}+(\text{neutrals?}), \quad (3)$$

$$\nu_\mu+N\to(\mu)^-+e^++(\nu_e)+K_s^{\,0}+\pi^-+\pi^+ +\pi^0+p+(\text{neutrals?}), \quad (4)$$

where N stands for nucleus. Some of the charged π's could be K's.

The kinematic quantities which help to describe the four positron events are given in Table I.

The quantities are obtained from the observed hadronic and leptonic energies. As an illustration an attempt has been made to correct event 3 for missing neutral energy by reducing the value of x_{vis} from 0.9 to 0.4, a value that is closer to the mean for deep inelastic neutrino interactions. These values are given in parentheses in Table I.

The important features of the events can be summarized as follows: (1) All events have oppositely charged leptons μ^-e^+; no events with μ^-e^- or e^-e^+ (other than Dalitz pairs) have been observed. (2) As illustrated by event 3, there is no additional charged lepton at the vertex with an energy greater than a few MeV. This implies a missing neutral lepton (probably a neutrino). (3) Every event is accompanied by a $K_s^{\,0}$ which decayed by the $\pi^-\pi^+$ mode. The observation of a strange particle was not a factor in the selection of the events. (No Λ has been observed which is associated with a μe event.) (4) The positron is of lower energy than the muon in every case. (5) The visible total energy is compatible with the flux distribution of this neutrino beam; none are above 40 GeV. (6) The background is small. (7) These four events give a preliminary evaluation of the ratio (μ^-e^+)/(total ν interaction) of about 1%.

Even though the number of events is small, we would like to make a few remarks with regard to their interpretation.

The value of the ratio $\langle P_{\mu^-}\rangle/\langle P_{e^+}\rangle \cong 4.6$ falls outside the bounds derived by Pais and Treiman for the production of a heavy neutral lepton.[4] This by no means excludes the heavy-lepton hypothesis for all the events, but makes it less likely. Also, the fact that we do not observe any (e^+e^-) events which are incompatible with Dalitz pairs further strengthens this argument. We therefore think that the phenomenon observed is the production at the hadronic vertex of a new particle which subsequently decays leptonically.

The absence of a kink in the positron track within 2 cm of the vertex along with the measured momenta of the e^+ and $K_s^{\,0}$ makes it possible to set a rough estimate of the upper limit on the new particle's lifetime. This value is 2×10^{-11} sec.

Table II lists some properties of the $K_s^{\,0}$ and e^+

TABLE II. Kinematic quantities for the $K_s^{\,0}$ and e^+.

Event	$p_{\perp K^0}$ (GeV/c)	$p_{\perp e^+}$ (GeV/c)	M_{Ke} (GeV)
1	0.8	0.4	1.3
2	0.7	0.7	0.9
3	0.4	0.4	1.1
4	0.3	0.7	0.7

as obtained from the visible momenta of the particles excluding the muon. Specifically the transverse momentum of the $K_s{}^0$ and the e^+ relative to the direction of the visible hadron momentum has been calculated.

The transverse momenta of the e^+ are consistent with a three-body decay involving a neutrino from a particle of mass about 2 GeV. Assuming that both the $K_s{}^0$ and e^+ come from a three-body decay process, their mean invariant mass can be used to compute the mass of the parent particle by using the relation $M = 1.5\langle M_{Ke}\rangle$. The value found is 1.5 GeV. If more complicated decays are responsible then this represents a lower limit on the mass of the particle.

This muon-positron-kaon discovery reported here is very likely related to the earlier observation of di-muon events at FNAL.[5] In a different experiment performed by Cazzoli *et al.* utilizing the neutrino beam at Brookhaven National Laboratory, one event was reported[6] which has been interpreted as a possible nonleptonic decay of a charmed baryon. In addition, the groups utilizing the gargamelle bubble chamber at CERN without an EMI have reported three events which could be related to those reported here.[7]

In summary, we consider the four events to be evidence for the β decay of a new particle with a new quantum number. The fact that a K^0 decay is associated with each of the four events forces one to believe that the production or decay is somehow related to strangeness. One is tempted to associate these events with current ideas related to charm.[8-10] However, the observation that every event contains a $K_s{}^0$ $(\pi^+\pi^-)$ is not what one would expect from these ideas. It is interesting to speculate that our results are consistent with multiple-K processes arising from the production and the decay of a particle of strangeness 3 or higher.

We gratefully acknowledge the cooperation of the Fermilab staff and the 15-ft bubble chamber operators. We also thank the scanning personnel at our respective institutions for their diligent efforts.

---

*Work supported in part by the U. S. Energy Research and Development Administration under Contract No. ERDA (11-1)-881-494.

†Also at III. Physikalische Institut, Technische Hochschule Aachen, Aachen, Germany.

[1] S. I. Parker *et al.*, Bull. Am. Phys. Soc. 20, 593 (1975); F. Harris *et al.*, Bull. Am. Phys. Soc. 20, 593 (1975); J. Marriner *et al.*, Bull. Am. Phys. Soc. 20, 593 (1975).

[2] Preliminary results were reported in Proceedings of the Conference on Quarks and the New Particles, Irvine, California, 5 December 1975 (to be published).

[3] R. Stefanski, Fermilab, private communication.

[4] A. Pais and S. B. Treiman, Phys. Rev. Lett. 35, 1206 (1975).

[5] A. Benvenuti, D. Cline, W. T. Ford, R. Imlay, T. Ling, A. Mann, R. Orr, D. D. Reeder, C. Rubbia, R. Stefanski, L. Sulak, and P. Wanderer, Phys. Rev. Lett. 34, 419 (1975), and 35, 1199, 1203, 1249 (1975).

[6] E. Cazzoli *et al.*, Phys. Rev. Lett. 34, 1125 (1975).

[7] H. Deden *et al.*, Phys. Lett. 58B, 361 (1975); more recent results will be published; J. Blietschau *et al.*, Phys. Lett. 60B, 207 (1976).

[8] B. J. Bjørken and S. L. Glashow, Phys. Lett. 11, 255 (1964).

[9] S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[10] M. K. Gaillard, B. W. Lee, and J. L. Rosner, Rev. Mod. Phys. 47, 277 (1975).

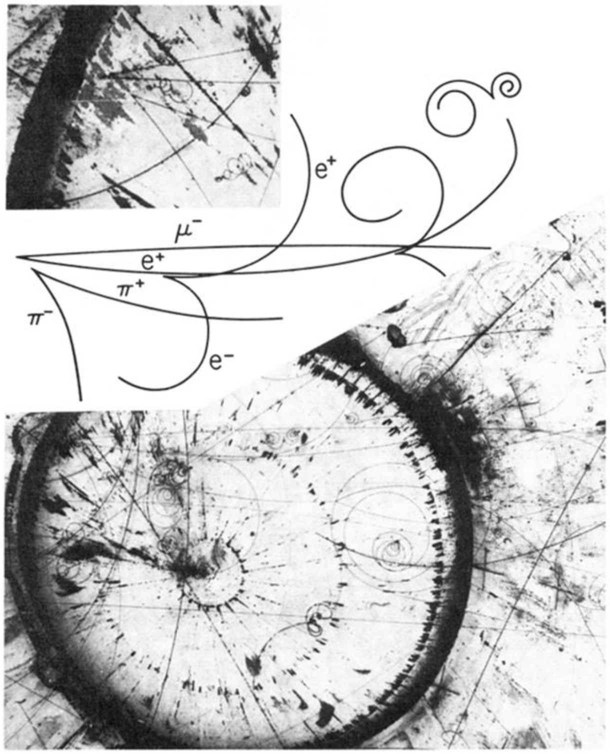

FIG. 1. The two photographs and drawing illustrate event 3. The top photograph is an enlargement of the vertex to illustrate the absence of a low-energy electron.