# $K^0$ Phenomena Associated with Neutrino-Induced $\mu^- e^+$ Events*

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Using the Fermilab 15-ft neon-hydrogen bubble chamber we have identified seventeen events of the type $\nu_\mu N \rightarrow \mu^- e^+ X$. The ratio of the production of these events to ordinary neutrino charged-current events is $(7.7 \pm 3.0) \times 10^{-3}$ for positron energy greater than 800 MeV and neutrino energy greater than 10 GeV. Associated with these seventeen events are 11 $V$'s, of which eight fit $K_s^0 \rightarrow \pi^+\pi^-$ and three fit $K_s^0 \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow p\pi^-$ ambiguously. The average $K^0$ multiplicity per $\mu^- e^+$ event is determined to be $1.84^{+0.63}_{-0.53}$.

We report $K^0$ phenomena associated with direct electrons produced in neutrino interactions. The observation of single direct electrons in events induced by muon neutrinos is evidence for the $\beta$ decay of a new particle.[1] Theoretical investigations have suggested particles possessing a new hadronic degree of freedom called charm which is related to strangeness.[2] These theories predict that charmed particles will be accompanied by strange particles in both production and decay. Thus it is important to investigate the association of strange particles with these $\mu^- e^+$ events in order to interpret our observation as evidence for charm.

This study utilizes film from the Fermi National Accelerator Laboratory 15-ft bubble chamber filled with a 21% atomic mixture of neon in hydrogen exposed in the two-element horn-focused neutrino beam with 300-GeV incident protons. An array of twenty-four multiwire proportional chambers (total 24 m$^2$), located behind the chamber, serves as an external muon identifier (EMI).[3]

All neutrino events were examined to determine if an electron or positron was produced in the interaction. The criteria for positron or electron identification consisted of one or more of the following: (1) an abrupt change of track curvature with no visible kink, (2) an electron pair pointing tangentially to the track, (3) an electron pair superimposed on the track with at least 10% of the track energy (trident). For those cases where the electron pair could also have originated from the primary vertex, criteria on distance ($l$) from the neutrino vertex and displacement ($d$) of the electron pair from the track were chosen ($d/l < 10^{-3}$) so that accidental coincidence of the electron pairs originating from $\gamma$ rays from the neutrino vertex was less than $10^{-5}$ per neutrino charged-current interaction. For every event except three, the positron is identified by two or more of these signatures. A detailed discussion of the event selection criteria is now in preparation.

Seventeen events with identified positrons were found in 70 000 frames which satisfied the following criteria: (a) The vertex of the interaction is within a fiducial volume (allowing at least 65 cm potential track length) of 19 m$^3$, the total visible energy ($E_{\text{vis}}$) is greater than 10 GeV, and the total longitudinal momentum ($\sum P_x$) is greater than 5 GeV/$c$. (b) The identified positron cannot be paired with any negative track to form a Dalitz pair with an invariant mass less than the pion mass (only negative tracks consistent with an electron interpretation are considered). (c) The positron energy is greater than 800 MeV. For lower energies the background due to Dalitz pairs and $\pi$-$\mu$ decay becomes important and the electron detection efficiency decreases rapidly with decreasing energy. (d) There is a leaving negative track which either goes into the EMI and is identified as a muon or misses the EMI but has energy and transverse momentum consistent with its identification as a muon.[4] However, because of the undertainty in muon identification with the single-plane EMI we cannot exclude direct production of $e^+$ without an accompanying muon at a level of ~20%.

The scanning and selection of events which conform to the above criteria do not depend in any way on the presence or absence of a $V$ associated with the event.

A discussion of the backgrounds for these dilepton events has been previously presented[1] and further detailed studies confirm the earlier conclusion that less than one of the seventeen $\mu^+e^-$ candidates may be explained by background.

In order to evaluate the ratio

$$\frac{\mu^-e^+}{\mu^-}=\frac{\text{rate of } \mu^-e^+ \text{ events}}{\text{rate of charged-current events}}$$

it is necessary to know (1) the observational efficiency $\epsilon_1$ and (2) the electron identification efficiency $\epsilon_2$. We define the observational efficiency $\epsilon_1$ to be the probability that a physicist and/or a scanner would have found an electron which meets all of the selection criteria. We estimate this to be $\epsilon_1 = 0.7 \pm 0.2$ from a double scan for Dalitz pairs by different laboratories. The efficiency $\epsilon_2$ is the probability that an electron will, on the average, undergo one or more electromagnetic processes which will permit its recognition. It is dependent upon the radiation length in the liquid and the position of the event. This efficiency

TABLE I. Characteristics of $\mu^-e^+$ events. $X_{vis}$, $Y_{vis}$, and $W_{vis}^2$ are defined in Ref. 1 and are in terms of visible energy. Events 6, 7, 8, and 10 of Ref. 6 have been excluded by positron selection criteria. Event 9 of Ref. 6 has no $\mu^-$; it is a $\overline{\nu}_e$ candidate. $c_\mu$ is the EMI confidence level that the track in question is a muon (see Ref. 3). Less than 16% of the hadrons above 2 GeV/$c$ have a $c_\mu$ greater than 0.10.

| Roll | Frame | $E_{vis}$ (GeV) | $x_{vis}$ | $y_{vis}$ | $W^2_{vis}$ (GeV$^2$) | $E(e^+)$ (GeV) | $\frac{P_e \cdot P_\nu \times P_\mu}{\lvert p_\nu \times p_\mu \rvert}$ | $p(\mu)$ (GeV/c) | $c_\mu$ | V | $\tau_K$ (lifetimes) | $p(v)$ (GeV/c) | $M_{Ke}$ (GeV) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 53 | 4421 | 60.5 | .01 | .71 | 80.2 | 4.0 | −.14 | 17.9 | .92 | | | | |
| 53 | 6653 | 20.5 | .10 | .31 | 11.6 | 1.3 | −.38 | 14.1 | .15 | | | | |
| 54 | 2690 | 69.8 | .24 | .05 | 5.9 | 2.0 | +.08 | 66.3 | .63 | | | | |
| 55 | 1338 | 40.9 | .25 | .19 | 11.6 | .8 | −.42 | 33.3 | .22 | $K_s$-$\Lambda$ | 4.0 | 1.6 | .9 |
| 56 | 4224 | 99.0 | .002 | .41 | 77.4 | 2.6 | −.03 | 58.1 | .72 | $K_s$ | .1 | 4.7 | .7 |
| 56 | 6973 | 30.1 | .37 | .13 | 5.6 | 1.4 | +.47 | 26.2 | .06 | $K_s$-$\Lambda$ | 2.4 | 1.6 | 1.2 |
| 57 | 1282 | 36.7 | .004 | .58 | 40.7 | 1.8 | +.02 | 15.4 | .13 | $K_s$ | .3 | 6.6 | .8 |
| 58 | 1338 | 27.0 | .90 | .15 | 1.7 | 2.3 | +.33 | 22.9 | .57 | $K_s$ | .3 | 1.8 | 1.1 |
| 58 | 5816 | 12.4 | .10 | .71 | 15.7 | 1.3 | +.06 | 3.6 | x | $K_s$ | 3.4 | 3.2 | .9 |
| 75 | 3874 | 98.2 | .06 | .91 | 158.1 | 5.2 | −.03 | 9.3 | .07 | $K_s$ | .1 | 38.6 | 2.0 |
| 76 | 4547 | 44.9 | .03 | .32 | 26.7 | 1.7 | −.34 | 30.7 | .19 | $K_s$-$\Lambda$ | 5.6 | 2.6 | 1.2 |
| 79 | 6445 | 167.6 | .37 | .61 | 120.0 | 7.8 | −.54 | 66.3 | .22 | | | | |
| 78 | 5450 | 17.5 | .48 | .95 | 17.1 | 4.1 | +.05 | .8 | a | | | | |
| 79 | 6323 | 145.3 | .02 | .23 | 63.2 | 3.5 | +.14 | 111.3 | b | $K_s$ | .5 | 11.3 | 1.2 |
| 79 | 7083 | 13.3 | .05 | .36 | 9.4 | 1.3 | −.58 | 8.5 | .05 | | | | |
| 80 | 1059 | 23.5 | .31 | .94 | 29.1 | 4.3 | −.01 | 1.5 | .81 | $K_s$ | 1.9 | 14.2 | 1.2 |
| 80 | 4472 | 28.7 | .22 | .67 | 29.0 | 5.6 | +.19 | 9.6 | x | $K_s$ | 1.2 | 5.7 | .7 |

[a] Muon geometrically misses EMI.

[b] Multiple hits in EMI make identification impossible.

$\epsilon_2$ has been evaluated by utilizing electron pairs and weighting their spatial distribution to correspond to the neutrino interaction spatial distribution. We found no significant energy dependence of the detection efficiency for electron energies less than 5 GeV and greater than 800 MeV. The value was determined to be $\epsilon_2 = 0.52 \pm 0.04$. The overall efficiency $\epsilon = \epsilon_1 \times \epsilon_2 = 0.36 \pm 0.10$.

The efficiency for muon identification decreases as the muon momentum decreases so that for this calculation we require a muon momentum greater than 2 GeV/$c$. Using the fifteen events surviving this cut and a corresponding sample of $5400 \pm 250$ charged-current events, we calculate the ratio

$$\mu^- e^+/\mu^- = (7.7 \pm 3.0) \times 10^{-3}$$

subject to the previous acceptance criteria.

The total $\mu^- e^+$ rate is likely to be appreciably higher because of the rejection of low-energy electrons.[5] The characteristics of these $\mu^- e^+$ events are presented in Table I. The momentum distributions for positrons and neutral strange particles are shown in Fig. 1. The electron momentum transverse to the muon-neutrino plane is small $[\langle p_\perp^2 \rangle = 0.09\ (\mathrm{GeV}/c)^2]$ and consistent with hadron values in our charged-current sample. We note that a large fraction of the events have $x$ values less than 0.1 consistent with the production of these particles off the quark-antiquark sea.

The most striking feature of these $\mu^- e^+$ events is the large number of $K_s^0$'s which accompany them as noted in Table I. We find eleven $K_s^0$ or $\Lambda^0$ decays in seventeen $\mu^- e^+$ events. Of these eigth are $K_s^0 \to \pi^+\pi^-$ decays, three fit both $K_s^0$ and $\Lambda^0$ decays, and none fits $\Lambda$ decay unambiguously. On the basis of the distribution of the transverse momentum of the negative track we divide the three ambiguous decays into 1.5 $K_s^0$ and 1.5 $\Lambda^0$ decays. The correction factor for the $K^0$ branching ratio and the loss at short distances is 3.3. Therefore the $K^0$ multiplicity, $n_K$, in the seventeen $\mu^- e^+$ events is $9.5 \times 3.3/17 = 1.84^{+0.63}_{-0.53}$. Figure 2 shows the multiplicity likelihood distribution for our experimental data using Poisson statistics.

The only strange particles which are efficiently detected in this experiment are $K_s^0$ and $\Lambda^0$ in their charged decay modes.[7] The detection efficiency for $K^\pm$ is small and the number of observed $K^\pm$ candidates is too small to permit comparison with the $K^0$ multiplicity.

The $K^0$ multiplicity in $\mu^- e^+$ events is large compared to the value $n_K = 0.14 \pm 0.02$ found using $V$'s from our sample of charged-current events corrected as above (the observed fraction of charged events with fitted $K_s^0$'s or $\Lambda$'s is $0.075 \pm 0.006$). The $K^0$ multiplicity in other charged-current events with identified electrons (Dalitz pairs, electron neutrinos) is consistent with normal

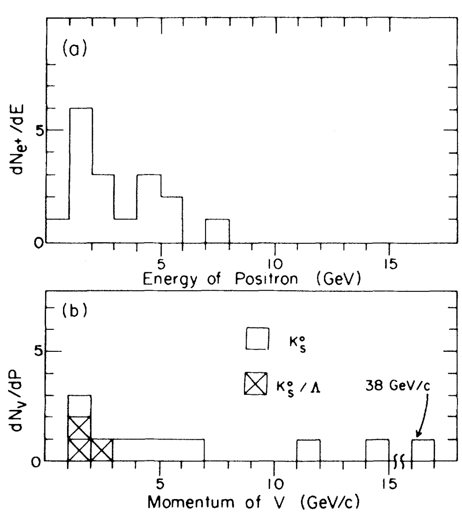


FIG. 1. Momentum distribution for positron and neutral strange particles.

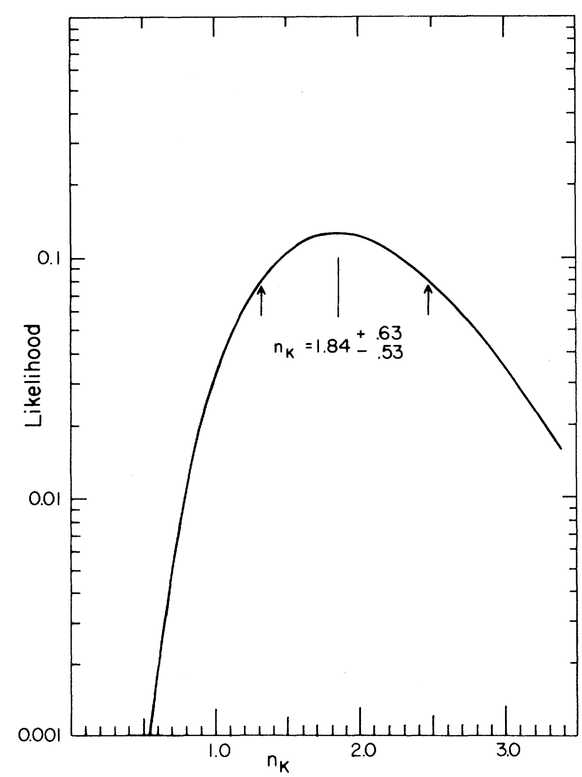


FIG. 2. Multiplicity likelihood distribtuion for observed $K^0$.

charged-current events without electrons. We note that the observed $K_s^0/\Lambda$ ratio in our charged-current events is $1.2 \pm 0.1$.

The theoretical expectation of $K^0$ multiplicity for the production and decay of charmed particles is approximately 0.8.[8] Preliminary results from the experiment of Baltay *et al.*[9] indicate a significantly smaller value for $n_K$ than our value of 1.8.

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[4]Specifically the requirements were that the candidate have a confidence level as a muon ($c_\mu$ in Ref. 2) greater than 0.05, or have a transverse momentum with respect to the $\nu$ direction opposite to that of other tracks and that it have the largest transverse momentum among negative leaving tracks.

[5]V. Barger and R. J. N. Phillips, Phys. Rev. Lett. 36, 1226 (1976). From the spectrum of positron energies presented in this paper we estimate that only about one-half of the $\mu e$ events will have $E_e > 800$ MeV and hence be detected. Thus a more realistic estimate of the true rate would be $\mu^- e^+/\mu^- \simeq 1.6 \times 10^{-2}$.

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[7]$V$'s were identified by kinematic fitting with the appropriate hypothesis $K_s^0 \to \pi^+\pi^-$ or $\Lambda \to p\pi$ originating from the primary vertex.

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