Limits on Muon-Neutrino Oscillations in the Mass Range $30 < \Delta m^2 < 1000$ eV^2/c^4

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A search for inclusive muon-neutrino (ν_μ) oscillations has been performed in the Fermilab narrow-band neutrino beam using two detectors running simultaneously at two distances from the neutrino source. The data show no evidence for a distance dependence of the neutrino flux and rule out oscillations of ν_μ into any other single type of neutrino for $30 < \Delta m^2 < 1000$ eV^2/c^4 and $\sin^2(2\theta) > 0.02$–0.20.

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The possibility of massive neutrinos and neutrino oscillations is currently the subject of active experimental and theoretical interest. A recent measurement of the end point of the tritium beta-decay spectrum indicates a value for the electron-antineutrino ($\bar{\nu}_e$) mass in the range between 14 and 46 eV/c^2.[1] Neutrinos with masses in the range between 1 and 100 eV/c^2 have been proposed as the constituents of the dark matter which is needed to explain the motion of galaxies and galactic clusters.[2] In addition, massive neutrinos and mixing between neutrinos have been proposed within the frameworks of some grand unified theories.[3]

Mixing between eigenstates of neutrinos with different masses would result in oscillations of one flavor of neutrino (e.g., ν_μ) into another flavor. Within a two-neutrino mixing hypothesis, such an oscillation is described by[4]

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E_\nu), \qquad (1)$$

where $P(\nu_\mu \rightarrow \nu_\mu)$ is the probability of the appearance of ν_μ at a distance L (in kilometers) from the source of a pure ν_μ beam, E_ν is the energy (in gigaelectronvolts), θ is the mixing angle, and Δm^2 (in eV^2/c^4) is the difference between the squares of the masses of the two neutrino eigenstates. Equation (1) is also applicable for the more general case in the leading mass limit.[4]

Oscillations can be detected from an initially pure beam of ν_μ either by detecting the appearance of ν_e or ν_τ downstream of the source (exclusive searches), or by measuring a change in the ν_μ flux as a function of distance from the source (inclusive searches). Oscillations in the channels $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ have been ruled out by exclusive searches[5,6] for $\Delta m^2 > 1$–3 eV^2/c^4 and $\sin^2(2\theta) > 0.006$–0.020. Unlike exclusive searches, inclusive searches are also sensitive to mixing of ν_μ with other types of neutrinos, such as a left-handed antineutrino (whose interactions would be suppressed by the $V-A$ structure of the weak interaction), or a neutrino associated with a new charged lepton with a mass too high to be produced in current experiments. Results from an inclusive search using the Gösgen reactor as a $\bar{\nu}_e$ source have recently been published.[7] These results exclude signals in a region indicated by a previous experiment.[8]

We present the results of the first inclusive search for oscillations in a ν_μ beam. The experiment used the Fermilab narrow-band neutrino beam as a neutrino source.[9] The integrated proton flux was 3.4×10^{18} incident on the production target. Data were taken at five momentum settings for π^+ and K^+ mesons (100, 140, 165, 200, 250 GeV/c), yielding neutrinos with E_ν between 40 and 230 GeV. To minimize the systematic errors associated with neutrino flux monitoring, we simultaneously operated two similar detectors at different distances from the neutrino source [Fig. 1(a)]. This ensured that the ν_μ interaction rate measured at each location resulted from the same incident flux.

The neutrino beam was produced by decays of sign- and momentum-selected ($\Delta p/p = \pm 11\%$) pions and kaons in a 352-m-long evacuated decay pipe. Beam monitoring devices, including segmented ionization chambers used to monitor beam steering, were placed in the decay pipe. The hadron beam dump at the end of the decay pipe was followed by a muon profile monitor.[10] The two neutrino detectors were located behind an iron and earth shield, and were centered 715 and 1116 m from the midpoint of the decay pipe. For neutrinos from pion decay (ν^π) and kaon decay (ν^K) the decay kinematics produces a correlation between the energy and the radial location of the neutrino interaction in each detector with respect to the center of the beam.[9]

Each neutrino detector consisted of a target calorimeter instrumented with counters and spark chambers, followed by an iron toroidal muon spectrometer [Figs. 1(b) and 1(c)]. The target calorimeter at the downstream location (Lab E) consisted of 4444 tons[11] of 3-m$\times$3-m$\times$5-cm-thick steel plates, 56 3$\times$3-m^2 liquid scintillation counters (located after ever 10 cm of steel), and 26 3$\times$3-m^2 magnetostrictive readout spark chambers (located

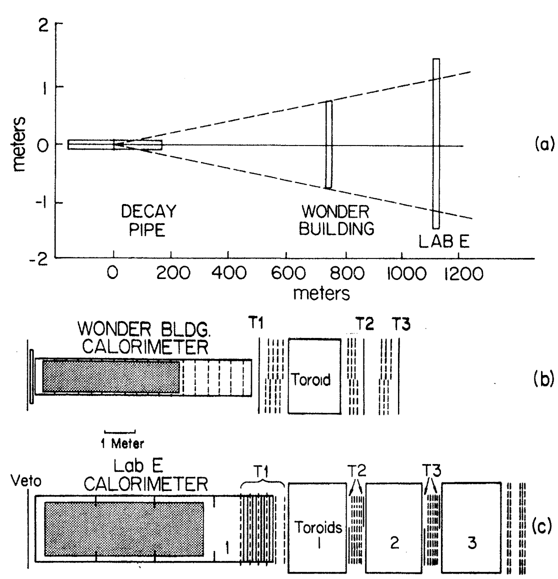

FIG. 1. (a) A plan view of the neutrino source and the two detectors. The width of the decay pipe in the figure defines the outer edge of the secondary hadron beam. The (b) upstream and (c) downstream detectors are shown with the longitudinal fiducial volumes shaded.

after every 20 cm of steel). The upstream target calorimeter (in the Wonder Building) consisted of 108 tons of 1.5-m$\times$1.5-m$\times$5-cm-thick steel plates, 56 1.5$\times$1.5-m^2 acrylic scintillation counters (located after every 10 cm of steel), and 17 1.5$\times$3-m^2 spark chambers (located after every 30 cm of steel). Minimum-ionizing muons were used to calibrate the counters in each detector. The Lab E target calorimeter had been previously calibrated with a known momentum hadron beam. An rms hadron energy resolution of about $0.9/\sqrt{E}$ (GeV) pertained to both calorimeters.

The detectors at the two locations were used to observe the interaction of neutrinos on iron, $\nu_\mu + N \rightarrow \mu^- +$ hadrons. The Lab E muon spectrometer consisted of three 1.6-m-long toroidal magnets with 1.8 m outer radius and a 12.7-cm-radius hole for the coils. Each toroid was followed by five 3$\times$3-m^2 chambers. The total transverse momentum kick of the toroids was 2.4 GeV/c (directed inward for μ^-) and the rms momentum resolution was 11%. The Wonder Building spectrometer consisted of a single 2.4-m-long iron toroidal magnet, 1.5 m in outer radius with a 12.7-cm-radius hole. The magnet was preceded by four 3$\times$3-m^2 planes of spark chambers and followed by six 3$\times$3-m^2 planes of spark chambers. The total p_t kick was 1.2 GeV/c and the rms momentum resolution was 16%. The measured neutrino energy was determined by adding the measured hadron and muon energies.

The charged-current trigger in each detector was designed to select neutrino interactions which could be momentum analyzed. It required that there be at least one minimum-ionizing signal in the target in coincidence with signals from trigger counters T1 and T2, and with no signal in the front veto counter.

The data analysis uses only those events that occurred when both detectors were operating. Information from the hadron beam monitors in the decay pipe is used to ensure that the beam center remained constant to within 2.5 cm at the Lab E detector. The events are also required to pass a series of cuts which are applied twice to each event. First, cuts are applied in the detector in which the event is found. Then the event is translated along a straight-line neutrino trajectory to the other detector, under the assumption that the neutrino originated from the center of the decay pipe. The longitudinal vertex of this translated event is set at the same distance from the end of the calorimeter as the interaction vertex in the original detector. The analysis cuts for the second detector are applied to the translated event at this new vertex. This procedure assures the same geometrical acceptance for events in both detectors.

Each event in the Wonder Building detector is required to have a transverse vertex within a 1.3-m × 1.3-m square in order to contain the hadron shower. In addition, ν^{π} (ν^{K}) events must have a vertex whose radius is within 57 cm (64 cm) of the beam center. These fiducial dimensions are scaled to the Lab E detector by a factor of 1.56, which is the ratio of the two detectors' distances to the center of the decay pipe. Longitudinal shower containment is ensured by requiring the interactions to occur within a restricted fiducial volume.

Several cuts are applied in both detectors to select an event sample with high efficiency for reconstruction of the muon track. The muon track must have an angle of less than 200 mrad with respect to the detector's longitudinal axis, while its straight-line extrapolation from the target must pass through the magnet steel and intersect counter T2 (Fig. 1). The reconstructed muon momentum must exceed 7.5 GeV/c to guarantee that the particle reaches the downstream toroid chambers. The final data sample consists of 32 400 Lab E events and 33 700 Wonder Building events.

The oscillation results are obtained by comparing the number of events in the two detectors as a function of neutrino energy. The mean neutrino energy used for this comparison is obtained from the dichromatic beam properties and the radial vertex position (r_{ν}),[10] thus making the oscillation study largely independent of detector resolution. The measured neutrino energy of each event is used only to separate ν^{π} from ν^{K} events.

For each secondary beam energy setting, the events from each detector are divided into three energy bins. First the ν^{K} events are separated from the ν^{π} events by use of the measured neutrino energy in conjunction with the transverse location of the event. Then the ν^{π} events are divided into two bins of $r_{\nu} < r_0$ (high-energy bin) and $r_{\nu} > r_0$ (low-energy bin), where $r_0 = 50$ cm for Lab E and $r_0 = (50/1.56)$ cm for the Wonder Building. The mean neutrino energy for a bin is determined from the narrow-band beam setting and a Monte Carlo simulation of the neutrino flux intercepted by the bin. The transverse center of the neutrino beam in each detector is determined for each energy setting (to within ± 1 cm) from the vertex distribution of high-energy ν^{π} events. Event ratios (number of events in Lab E divided by number in the Wonder Building) are calculated for each of these three bins. These ratios have been corrected for the difference in live times for the two detectors (1–15%), the difference in dead times for the veto counters in each apparatus (1–3%), and for the relative reconstruction efficiencies of the two detectors (1–3%) which were determined by visual scanning of computer displayed events.

If all neutrinos originated from the center of the decay pipe, the analysis procedure would result in event ratios of unity for the case of no oscillations. The finite size of the neutrino source yields corrections to these ratios (0.5% to 3.4%) because of the angular divergence of the secondary pion beam, solid angle effects, and the exponential decay distribution of particles along the decay pipe. These corrections were obtained from a Monte Carlo simulation of the neutrino beam. This simulation was checked by comparisons with measured secondary flux distributions from the hadron beam and muon profile monitors. The Monte Carlo simulation agreed with the measurements for the central 85% of the distributions, but failed to reproduce the wide-angle tails. The changes to the corrections (0.5% to 3.0%) caused by these tails were included as systematic errors in the final analysis. Additional corrections (< 1%) were made for the neutrinos from decays before the momentum and sign selection (wideband background). The total corrections are shown in Fig. 2(a). Backgrounds from sources other than neutrinos (e.g., cosmic rays) were determined to be negligible.

The corrected event ratios are shown in Fig. 2(b). A comparison of the corrected data with the hypothesis of no oscillations yields a χ^2 of 11.5 for 15 degrees of freedom, and the data are therefore consistent with no oscillations. To compare oscillation hypotheses to the data, the effects of the finite length of the decay pipe, and the energy spread in each bin must be incorporated into Eq. (1) by using the Monte Carlo simulation of the beam. A χ^2 is calculated as a function of Δm^2 and $\sin^2(2\theta)$. The 90%-confidence-level limits [Fig. 2(c)] were determined by using the likelihood ratio technique.[12] We have included the uncertainties in the hadron beam angular divergence and a relative normalization uncertainty of 1.5% for each hadron beam momentum setting in these calculations.[13] The likelihood ratio technique (solid line) tests a particular Δm^2 and $\sin^2(2\theta)$ hypothesis against all other two-component hypotheses. We also show limits (dotted line) obtained using Pearson's χ^2 test,[12] which is equivalent to testing a particular two-component mixing hypothesis against all other hypotheses (e.g., three-component mixing, four-component mixing, etc.). Other inclusive oscilla-

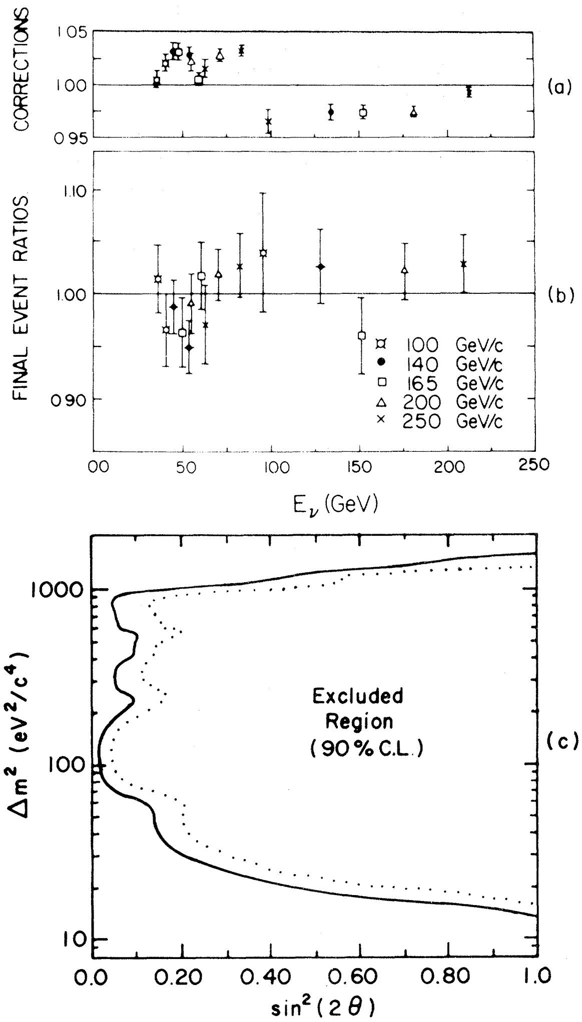

FIG. 2. (a) Corrections for the event ratios [(Lab E)/(Wonder Building)] due to the finite size and angular divergence of the beam. (b) Final event ratios [including corrections from (a)]. The symbols indicate the different secondary momentum settings. (c) 90%-confidence-level limits on possible neutrino oscillations as a function of Δm^2 and $\sin^2(2\theta)$, calculated using the likelihood ratio test (solid line). The region to the right of the curve is excluded. These limits are calculated including systematic errors. The limits obtained from Pearson's χ^2 test are also shown (dotted line).

tion experiments[7,14] have used the likelihood ratio test to calculate confidence limits and thus our likelihood-ratio limit should be used when comparing to their results.

In conclusion, this measurement excludes the oscillation of muon neutrinos into any other single type of neutrino for the area shown in Fig. 2(c), testing the region $30 < \Delta m^2 < 1000$ eV^2/c^4 for small values of $\sin^2(2\theta)$. This is a unique experiment in that a search for inclusive oscillations in this Δm^2 region can only be performed by a long-baseline experiment at high energies. (The only other search using a ν_μ beam has been performed at lower energies, excluding oscillations for smaller values of Δm^2.[14]) For a two-component mixing hypothesis, with one neutrino mass being much larger than the other, our result excludes $5 < m_\nu < 30$ eV/c^2 for $\sin^2(2\theta)$ larger than values in the range 0.02–0.20. Therefore for these mixing angles, the data exclude the mass range proposed by many cosmological models.

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[11]To obtain equal fiducial lengths for the two detectors, only 444 tons (56 counters) of the 650-ton (82 counters) Lab E detector were used. These 56 counters are shown

in Fig. 1.

[12]W. T. Eadie *et al.*, *Statistical Methods in Experimental Physics* (North-Holland, New York, 1971), p. 230. We used a Monte Carlo simulation of our experiment to determine that oscillations are excluded for $\chi^2 - \chi^2_{\rm min} > 4.6$. The minimum χ^2 for our data, $\chi^2_{\rm min}$, is 8.7. Pearson's χ^2 test excludes oscillations at the 90% confidence level for $\chi^2 > 22.3$ since there are 15 degrees of freedom.

[13]The systematic error on the event ratios is due to uncertainties in the relative live times (1.0%), relative target masses (0.3%), veto dead time (0.3%), reconstruction efficiencies (0.6%), beam steering (0.3%), and neutrino wideband background (0.1%–0.3%).

[14]F. Dydak *et al.*, Phys. Lett. **134B**, 281 (1984), who rule out inclusive ν_μ oscillations for $0.6 < \Delta m^2 < 10.5$ eV$^2/c^4$ when $\sin^2(2\theta) > 0.05$–0.10, have compared their results to preliminary results from our experiment. These preliminary limits are superceded by those shown in Fig. 2(c).