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Search for Muon Neutrino and Antineutrino Oscillations in the Mass Range $15 < \Delta m^2 < 1{,}000\ \mathrm{eV}^2/\mathrm{c}^4$

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Abstract. A search for inclusive muon-neutrino (ν_μ) and muon-antineutrino ($\bar{\nu}_\mu$) oscillations has been performed in the Fermilab narrow band neutrino beam using two detectors running simultanously at two distances from the neutrino source. The data show no evidence for either neutrino or antineutrino oscillations and rule out oscillations of ν_μ or $\bar{\nu}_\mu$ into any other single type of neutrino for $15 < \Delta m^2 < 1{,}000\ \mathrm{eV}^2/\mathrm{c}^4$ and $\sin^2(2\theta) > 0.02$–0.40.

In a previous publication [1] we presented the results of a search for inclusive oscillations of muon neutrinos ($\nu_\mu \to \nu_\mu$) in the region $30 < \Delta m^2 < 1{,}000\ \mathrm{eV}^2/\mathrm{c}^4$. In this communication we present results for the first experimental search for inclusive oscillations of muon-antineutrinos ($\bar{\nu}_\mu \to \bar{\nu}_\mu$) in a similar range of Δm^2. This mass scale is of interest because neutrinos with masses in the range between 1 and 100 $\mathrm{eV/c}^2$ 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, measurements of the endpoint of the tritium β-decay spectrum indicate a value for the mass of the electron-antineutrino [3] ($\bar{\nu}_e$) around 30 $\mathrm{eV/c}^2$. The present limits on the masses [4] of ν_μ and ν_τ are $m(\nu_\mu) < 250\ \mathrm{KeV/c}^2$ and $m(\nu_\tau) < 164\ \mathrm{MeV/c}^2$.

Exclusive search experiments [5], which look for the appearance of $\bar{\nu}_e$ or $\bar{\nu}_\tau$ in an initially pure beam of $\bar{\nu}_\mu$, have ruled out oscillations in the channels $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\bar{\nu}_\mu \to \bar{\nu}_\tau$ for $\Delta m^2 > 1$–$3\ \mathrm{eV}^2/\mathrm{c}^4$, and mixing angles $\sin^2(2\theta) > 0.006$–0.020. Similar limits [5] have been reported for the channels $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$. CPT invariance leads to $P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$, while CP invariance leads to $P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$, where α and β denote different weak eigenstates. The equality of the diagonal transition probabilities $P(\nu_\alpha \to \nu_\alpha) = P(\bar{\nu}_\alpha \to \bar{\nu}_\alpha)$ follows from CPT *or* CP symmetry alone [6]. It has been suggested that both CP and CPT may be violated in neutrino oscillations phenomena [6]. A comparison of $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ oscillations signals can serve as a test of CP and CPT. Conversely, if either CP or CPT conservations is assumed, then $\bar{\nu}_\mu$ data can be combined with ν_μ data in neutrino oscillations searches.

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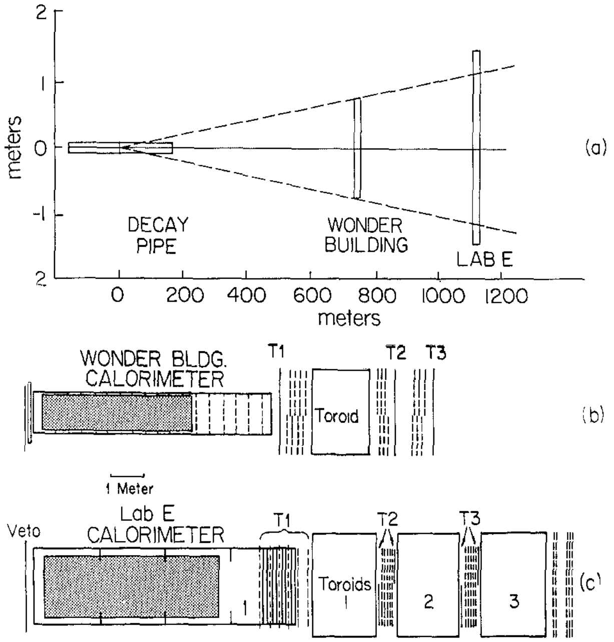

Fig. 1. A plan view **a** of the neutrino source and the two detectors. The width of the decay pipe in the figure defines the outer edge of the secondary hadron beam. The upstream **b** and downstream **c** detectors are shown with the longitudinal fiducial volumes shaded

In this communication we present new results on a search for inclusive oscillations in a $\bar{\nu}_\mu$ beam. In addition, an analysis combining the new $\bar{\nu}_\mu$ data with our previous ν_μ results is performed.

Although inclusive searches cannot achieve the sensitivity of the best exclusive searches, they can study the mixing of ν_μ and $\bar{\nu}_\mu$ with other types of neutrinos, such as neutrinos with the wrong helicity whose interactions would be suppressed by the V−A structure of the weak interaction, or neutrinos associated with a new lepton of high mass.

Within a two-neutrino mixing hypothesis, or in the more general leading mass limit [7], inclusive oscillations are described by

$$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \sin^2(2\theta) \cdot \sin^2(1.27 \Delta m^2 L/E_{\bar{\nu}}) \qquad (1)$$

where $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ is the probability of the appearance of $\bar{\nu}_\mu$ at a distance L (in km) from the source of a pure $\bar{\nu}_\mu$ beam, θ is the mixing angle, $E_{\bar{\nu}}$ is the energy (in GeV), and Δm^2 (in eV^2/c^4) is the difference in the squares of the masses of the two neutrino eigenstates.

The experiment and analysis procedure have been discussed previously [1]. The Fermilab narrow band neutrino beam was used to obtain data at five momentum settings ($\Delta p/p = \pm 11\%$) for π^+ and K^+ mesons (100, 140, 165, 200, and 250 GeV/c) yielding neutrinos with E_ν between 40 and 230 GeV, and at a single setting for antineutrinos (165 GeV/c) yielding both low energy $\bar{\nu}_\mu$ (from π^- decays) and high energy $\bar{\nu}_\mu$ (from K^- decays). Systematic errors associated with neutrino flux monitoring were minimized by simultanously operating two similar detectors at different distances from the neutrino source, which was a 352 m long evacuated decay pipe (Fig. 1 a). 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 444 tons of 3 m × 3 m × 5 cm-thick steel plates. The target calorimeter at the upstream location (in the Wonder Building) consisted of 105 tons of 1.5 m × 1.5 m × 5 cm-thick steel plates. The two detectors were situated behind an iron and earth shield, and were centered 715 m and 1,116 m from the midpoint of the decay pipe.

The event trigger in each detector was designed to select charged current neutrino interactions for which the outgoing muon could be momentum analyzed in the toroidal spectrometer. Only events that occurred when the beam was properly steered and both detectors were operating were used in the analysis. This initial sample consisted of 96,961 neutrino and 15,621 antineutrino events in Lab E, and 85,047 neutrino and 11,480 antineutrino events in the Wonder Building. The events were then required to pass a series of cuts which were applied twice to each event. First, cuts were imposed in the detector in which the interaction occurred. Then the event was 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 analysis cuts for the second detector were then applied. This procedure assured identical geometrical acceptance for events in both detectors under the above assumption. The final data sample consisted of 33,400 neutrino and 4,600 antineutrino events in Lab E, and 33,700 neutrino and 4,960 antineutrino events in the Wonder Building. Relative normalization factors were then applied for each secondary beam setting to account for deadtimes, and other minor differences between the two detectors.

The search for neutrino oscillations is performed by comparing the event rates in the two detectors as a function of the neutrino energy. For each secondary beam setting, the events from each detector are divided into three energy bins. First, the higher energy events originating from kaon decay neutrinos (ν_k) are separated from the corresponding pion decay neutrinos (ν_π) using the measured neutrino energy in conjunction with the transverse location of the

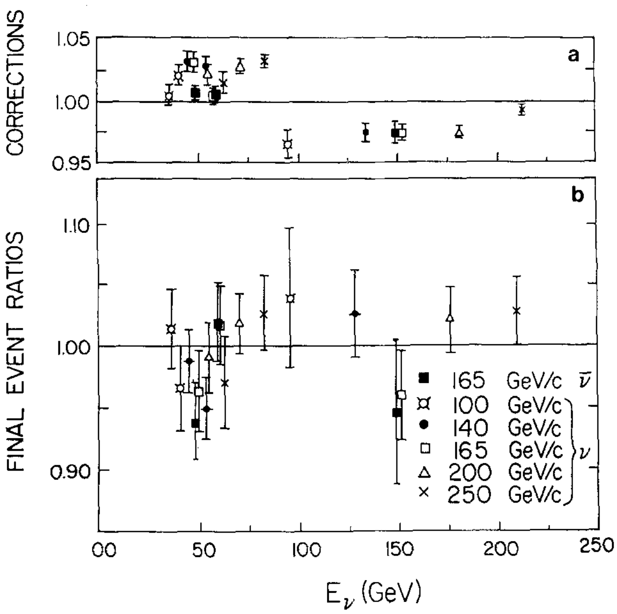

Fig. 2. **a** Corrections for the event ratios (Lab E/Wonder Building) due to finite size and angular divergence of the beam. The measured event ratios are divided by these corrections. **b** Final event ratios (including corrections from a). The symbols indicate the different ν_μ and $\bar{\nu}_\mu$ secondary momentum settings

event. The ν_π events are separated into two energy bins using the measured radial vertex location. The mean neutrino energy for a bin is determined from the narrow band momentum 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 from the vertex distributions of the neutrino events. This procedure assures that the assignment of the neutrino energy in each detector is independent of the resolution and relative calibration of the two detectors. Event ratios (number of events in Lab E divided by the number in the Wonder Building) are then calculated for each of the three energy bins for each momentum setting of the narrow band beam.

If all the neutrinos originated from the center of the decay pipe, the analysis procedure would result in event ratios of 1.0 for the case of no oscillations. There are small corrections, of order 0.5% to 3.5% (see Fig. 2a), which account for effects such as the finite size of the neutrino source, the exponential decay of the particles along the decay pipe, beam angular divergence, and solid angle [1]. The corrected event ratios for all ν_μ and $\bar{\nu}_\mu$ settings are shown in Fig. 2b.

Tests of neutrino oscillation hypotheses are performed by comparing the Lab E/Wonder Building ratios to the ratios expected from the assumed neutrino oscillations parameters. The expected ratios are obtained from a Monte Carlo simulation of the ex-

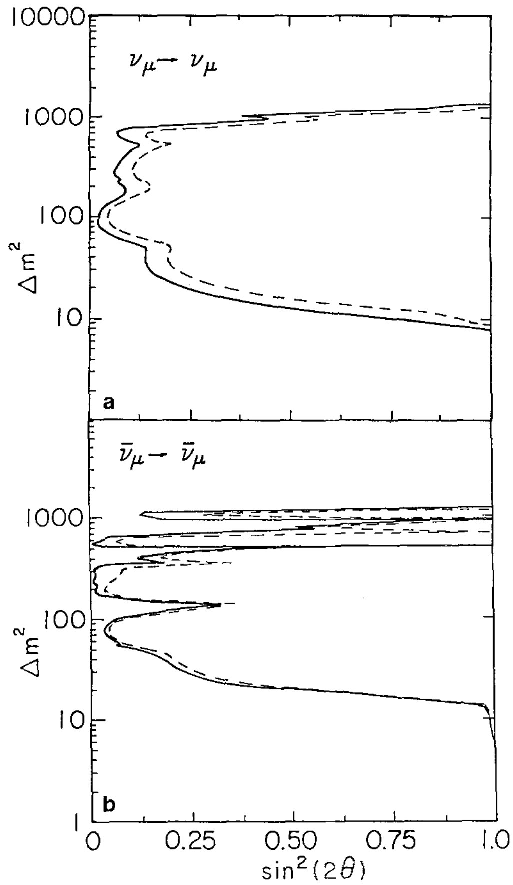

Fig. 3a and b. Ninety percent C.L. limits on possible neutrino oscillations as a function of Δm^2 and $\sin^2(2\theta)$, calculated using the likelihood ratio test (solid line). The region to the right of the curve is excluded. These limits are calculated including systematic errors. The limits obtained from the Pearson χ^2 test are also shown (dashed line). **a** $\nu_\mu \to \nu_\mu$, **b** $\bar{\nu}_\mu \to \bar{\nu}_\mu$

periment, including the beam, the geometry of the decay pipe and detectors, and the experimental resolutions. A χ^2 is calculated as a function of Δm^2 and $\sin^2(2\theta)$. The uncertainties in the beam angular divergence, and the relative normalization uncertainty of $\pm 1.5\%$ for each beam momentum setting are included in the calculation.

The ratios for both neutrino and antineutrino data are consistent with unity and therefore consistent with the hypothesis of no oscillations. The values of χ^2 for the no oscillations hypothesis are 11.0, 4.7, and 15.7 for the neutrino (15 D.F.), antineutrino (3 D.F.) and combined $\nu_\mu, \bar{\nu}_\mu$ (18 D.F.) data sets, respectively. The 90%-Confidence-Level (C.L.) limits are determined using both the likelihood ratio test [8], and the Pearson χ^2 test [8]. The likelihood ratio technique tests a particular Δm^2 and $\sin^2(2\theta)$ hypothesis against all other two-component hypotheses. The Pearson χ^2 test is equivalent to testing a particular two-component mixing hypothesis against all other hypotheses (e.g. three-component

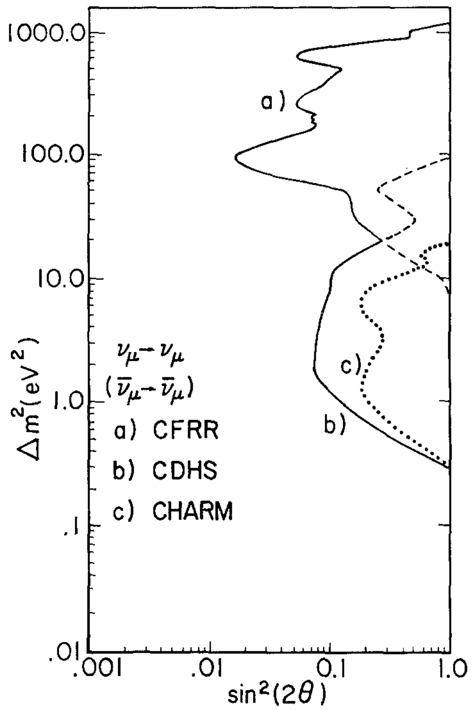

Fig. 4. 90% C.L. Limits on neutrino oscillations from this experiment, CDHS [13], and CHARM [14]. Both ν_μ and $\bar\nu_\mu$ data are used in all analyses

mixing, four-component mixing etc.). Most experiments quote results using the likelihood ratio test. Figures 3a and 3b show the 90% C.L. limits for inclusive ν_μ and $\bar\nu_\mu$ oscillations, respectively. The solid lines are obtained using the likelihood ratio test [9, 10], and the dashed lines indicate the limits obtained from the Pearson χ^2 test [11]. The regions to the right of the curves are excluded.

If either CP or CPT is assumed, then the parameters for inclusive ν_μ and $\bar\nu_\mu$ oscillations should be the same [6, 7]. A likelihood ratio analysis of the combined ν_μ and $\bar\nu_\mu$ data sets [12] results in the 90% C.L. limits which are shown in Fig. 4. Also shown are results of lower energy experiments [13, 14] which searched for ν_μ or $\bar\nu_\mu$ oscillations at lower values of Δm^2. In those experiments, no separation of neutrino and antineutrino data was possible, and those results should therefore be compared to our combined $\nu_\mu, \bar\nu_\mu$ limits.

In conclusion, this measurement excludes the oscillations of muon neutrinos and muon antineutrinos into any other single type of neutrino for the regions shown in Fig. 3 and 4.

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10. For the $3\bar\nu_\mu$ data points, oscillations are excluded for $(\chi^2 - \chi^2_{min}) > 5.2$. The minimum χ^2 for the $\bar\nu_\mu$ data χ^2_{min}, is 0.23 for $\Delta m^2 = 132\,eV^2/c^4$ and $\sin^2(2\theta) = 0.16$
11. The Pearson χ^2 test excludes oscillations hypotheses with $\chi^2 > 22.3$, and 6.25 for the $15\,\nu_\mu$ and $3\,\bar\nu_\mu$ data points, respectively
12. For the $18\,\nu_\mu$ and $\bar\nu_\mu$ points, oscillations are excluded for $(\chi^2 - \chi^2_{min}) > 4.3$. The minimum χ^2 for the combined $\nu_\mu, \bar\nu_\mu$ data χ^2_{min}, is 12.5, for $1{,}252\,eV^2/c^4$ and $\sin^2(2\theta) = 0.61$
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