Search for Muon-Neutrino Oscillations $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) in a Wide-Band Neutrino Beam

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We present the results of a search for neutrino oscillations at the Brookhaven National Laboratory. The experiment searched for the appearance of ν_e ($\bar{\nu}_e$), 1 km from the source of a wide-band ν_μ ($\bar{\nu}_\mu$) beam. The experiment used a total of 3×10^{19} protons on target from the Alternating Gradient Synchrotron. The data collecting was split evenly between positive and negative horn polarities, corresponding to neutrino and antineutrino beams. No excess of ν_e or $\bar{\nu}_e$ over the expected background was detected. The 90%-confidence-level limits obtained are $\Delta m^2 \leq 0.075$ eV^2 for maximal mixing, and $\sin^2 2\theta \leq 0.003$ for large Δm^2.

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The phenomenon of neutrino oscillations is a powerful probe of neutrino masses and mixing. Assuming two-flavor dominance (for simplicity), the probability for ν_μ to oscillate to ν_e in vacuum over a distance L is then given by

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

where θ is the lepton flavor mixing angle, L is the distance between the neutrino source and detector in kilometers, E is the neutrino energy in GeV, and Δm^2 is the difference in the masses squared of the mass eigenstates in eV^2.

We report the results of experiment E-776 at Brookhaven National Laboratory (BNL) which searched for an excess of ν_e ($\bar{\nu}_e$) events in a wide-band ν_μ ($\bar{\nu}_\mu$) beam. The magnetic horn in our neutrino beam line had its current set to both positive and negative polarities during data taking to produce beams primarily composed of either muon neutrinos or antineutrinos. The detector, described in more detail elsewhere [1-3], is a large-fiducial-mass electromagnetic calorimeter and a muon spectrometer located at a distance of $L=1$ km from the proton target. The 230-ton calorimeter is comprised of 90 planes of proportional drift tubes (PDT's) interleaved with 1-in.-thick concrete absorber. Each plane of PDT's together with the absorber corresponds to 0.3 radiation length and 0.08 nuclear interaction length. The average muon energy resolution is 15% and the electron-shower energy resolution is $20\%/\sqrt{E}$. The two primary backgrounds for this experiment were ν_e ($\bar{\nu}_e$) contamination in the ν_μ ($\bar{\nu}_\mu$) beam and π^0's from ν_μ interactions, misidentified as electrons in our detector.

The expected neutrino flux for the wide-band beam used in this experiment was calculated using a Monte Carlo program [3-5]. The primary sources of ν_μ ($\bar{\nu}_\mu$) are π^+ and K^+ (π^- and K^-) for the horn at positive (negative) polarity. Dominant contributions to the ν_e ($\bar{\nu}_e$) background arise from K^+,μ^+,K_L (K^-,μ^-,K_L). The calculated energy spectra for the various neutrino flavors are shown in Fig. 1. The integrated flux ratio ν_e/ν_μ ($\bar{\nu}_e/\bar{\nu}_\mu$) for positive (negative) horn polarity is 6.8×10^{-3} (6.3×10^{-3}) with an uncertainty of 10% due to uncertainties in the kaon production models considered.

During the spring of 1986, a total of 1.43×10^{19} (1.55×10^{19}) protons on target were collected with the horn at positive (negative) polarity. The data were then processed by a pattern-recognition program [3] where clus-

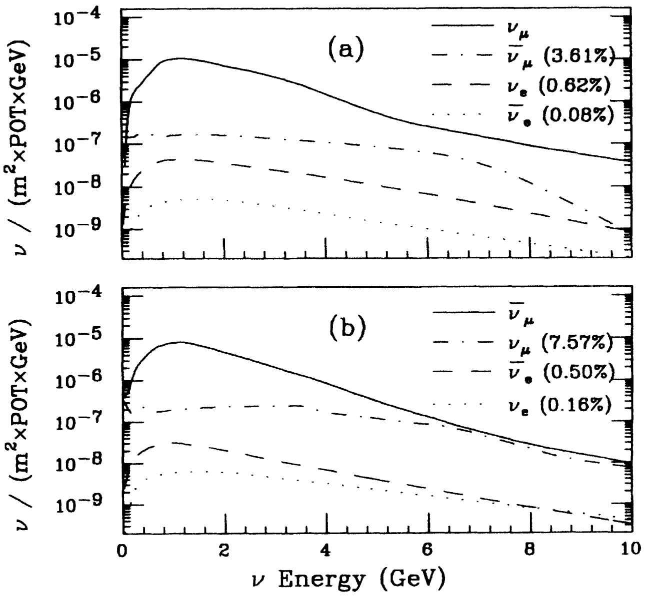

FIG. 1. Calculated spectra for ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$ per proton on target (POT) per m^2 for (a) the horn at positive polarity and (b) the horn at negative polarity.

ters of hits (proportional drift chamber pulses) were identified as muon and shower candidates. Analysis of the charged-current ν_μ and ν_e event candidates followed.

A detector Monte Carlo program was written to calculate acceptances, to develop pattern-recognition software, and to study cuts. This Monte Carlo program included a detailed description of all relevant neutrino interactions: quasielastic and elastic interactions, single-pion, multipion, and coherent π^0 production [3]. Monte Carlo ν_μ, $\bar{\nu}_\mu$, ν_e, and $\bar{\nu}_e$ events were processed through the same analysis as the data.

The objectives of the ν_μ analysis were to study the wide-band-beam energy spectrum and to measure the flux of ν_μ for normalization of the ν_e data. Selecting quasielastic events allowed reconstruction of neutrino energy using the muon energy and angle. In order to obtain the final muon-neutrino energy spectrum we applied the following cuts to enrich the quasielastic event sample: (1) The event vertex was required to be within the fiducial volume; (2) the primary track was required to be contained in the detector or to pass through the muon spectrometer, allowing us to measure the muon energy/momentum; (3) the primary track was required to be longer than 3 interaction lengths (35 planes), to reject hadrons; (4) the angle of the primary track with respect to the incoming neutrino direction was required to be within $\cos\theta \leq 0.8$; and (5) the number of hits not associated with the primary track in each view was required to be less than or equal to 5. This final cut rejected multipion events. The cosmic-ray contamination was calculated using background triggers and was found to be negligible. We were left with the final sample of 6676 (3065) events for positive (negative) horn polarity. The spectra for the Monte Carlo simulation and the data agree for both sets (Fig. 2) requiring no renormalization. For both spectra, 90% of the data are above 1 GeV with a peak at about 1.4 GeV. Monte Carlo studies indicate that the contamination from multipion events, where the pions are not detectable, is 11% (8%) in the positive (negative) polarity data. Single-pion events are a more significant fraction of the sample; however, the systematic shift in reconstruction of the neutrino energy is typically 300 MeV and contributes to a broadening of the spectrum. The acceptances for quasielastic events with the vertex inside the fiducial volume are 29% for ν_μ and 40% for $\bar{\nu}_\mu$. These acceptances are primarily due to the containment, length, and angle cuts.

To search for ν_e events, cuts identical to those in the muon analysis were made with the following exceptions: (1) The primary cluster was required to be contained in the electron calorimeter since the toroidal spectrometer was not used in the measurement of electromagnetic showers, and (2) the length of the cluster was required to be greater than 15 planes. After these cuts were applied, 2303 (733) events remained in the positive (negative) horn polarity sample. Electromagnetic-shower selection and a categorization of these showers into a sample of electron showers and π^0 showers followed.

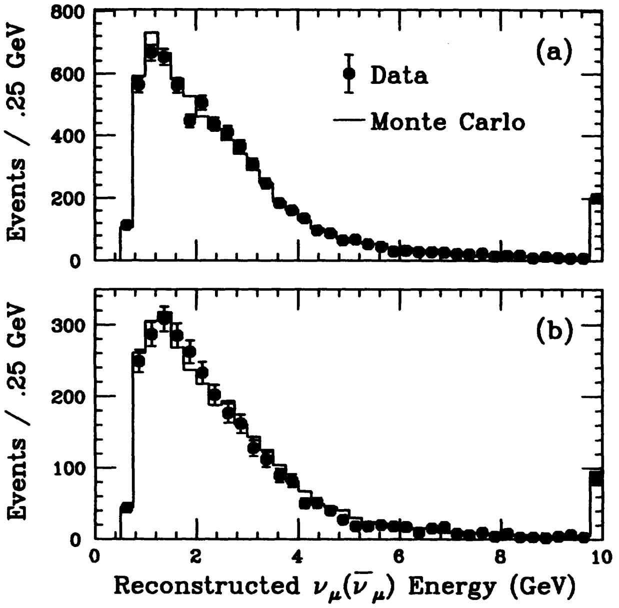

FIG. 2. The measured ν_μ energy spectrum for (a) the horn at positive polarity and (b) the horn at negative polarity. The solid line is the Monte Carlo prediction of the spectrum. The highest energy bin is an overflow bin.

Electromagnetic showers are characterized in our detector by a dense, well-collimated core, with a discontinuous hit pattern due to the exchange of energy between photons and electrons. Shower energy was measured using the pulse area found in the PDT's. Calibration was done using test electron data. Using the test-beam data as well as the Monte Carlo data, we defined the following criteria for identification of electromagnetic showers: (1) The length of the cluster must be within 2σ of the expected length based on its total energy; (2) the cluster has to have a certain amount of randomness in the hit pattern which is not present in most muon or charged-pion tracks; and (3) treating the primary cluster as a massive object with the pulse area corresponding to mass, the "moment of inertia" tensor is calculated. A cut on the eigenvalues selects well-collimated showers and rejects large hadronic clusters formed by the overlap of many pions from a multipion event. Finally, we introduce a cut which reduces the contamination to the electromagnetic shower sample from secondary hardonic interactions or overlapping tracks by utilizing the fact that electromagnetic showers deposit the bulk of their energy in a discontinuous manner near the longitudinal axis. We require, specifically, that there must be at least one skipped plane in the cluster and that over 80% of the energy is deposited within one PDT wire from the longitudinal axis of the cluster.

At energies above 1 GeV, where the experiment is sensitive to the oscillation signal, these cuts are 99% efficient in rejecting test-beam charged pions, while retaining 85% of test-beam electrons. After applying these cuts, 220

(76) events remained in the electromagnetic-shower sample for data taken with the horn running at positive (negative) polarity.

The shower sample consists of electron events and a significant contribution of events with a π^0 in the final state. Separation of π^0's from the electron showers of the same energy is possible due to differences in their respective shower profiles; in general, π^0-induced showers are wider and exhibit greater asymmetry than electron showers. A standard shower development function, used in parametrizing the electron-shower profile (lateral and transverse shower development) [6], is fitted to showers and a "goodness-of-fit" variable is defined. We establish a criteria on this variable which (as a function of energy) separates the shower sample into electron-induced showers and π^0-induced showers. Monte Carlo calculations indicate that this method correctly identifies about 70% of the π^0-induced showers above 1 GeV; the remaining 30% are primarily asymmetrically decaying π^0's. Studies using 1- and 2-GeV test data show that 80% of electrons are correctly identified. At this point 136 (47) events remain in the electron sample for positive (negative) horn polarity data.

To calculate the π^0 background we use the events identified as π^0's in the data ($N_{\pi^0\to``\pi^0"}$) and the expression $N_{\pi^0\to``e"}=N_{\pi^0\to``\pi^0"}R(E)$, where

$$R(E)=P(\pi^0\to``e")/P(\pi^0\to``\pi^0") . \qquad (2)$$

The ratio $R(E)$, calculated as a function of energy using Monte Carlo events, is the probability that a π^0 is misidentified as an electron, divided by the probability that a π^0 is correctly identified as a π^0. The value $N_{\pi^0\to``e"}$ is the calculated number of π^0's misidentified as electrons. The π^0 background given by this method is 94 (41) events total with 28 (7) events above 1 GeV for the positive (negative) polarity sample. Figures 3(a) and 3(c) show the energy spectra for the π^0 background.

The largest source of systematic error in the π^0 background calculation is due to the effect of the uncertainty in the rate of π^0 production on the ratio $R(E)$. Over 85% of the π^0 sample are events with most or all detectable energy deposited by the π^0 electromagnetic (EM) shower. Thus in spite of the aforementioned uncertainty, this method depends on the well-established understanding of EM showers and not on the details of production. To estimate the systematic error inherent in this method, we study how various changes in the analysis affect $R(E)$. First, the cross sections for coherent π^0, neutral-current multipion, and charged-current multipion production are varied separately by a factor of 4.0. Second, the shower cuts are modified, allowing the total number of events in the shower sample to change. Third, $R(E)$ is calculated using the positive polarity Monte Carlo sample and compared to that from the negative polarity sample. We estimate the systematic uncertainty on $R(E)$ to be 20%. Varying this error from 10% to 40% has a negligible effect on the final limits. The final overall uncertainty in the π^0 background including statistical errors arising from the number of events in our identified π^0 sample is 36% (42%) below 1 GeV and 27% (39%) above 1 GeV.

To estimate the ν_e background we employed the beam Monte Carlo calculation described previously. With the

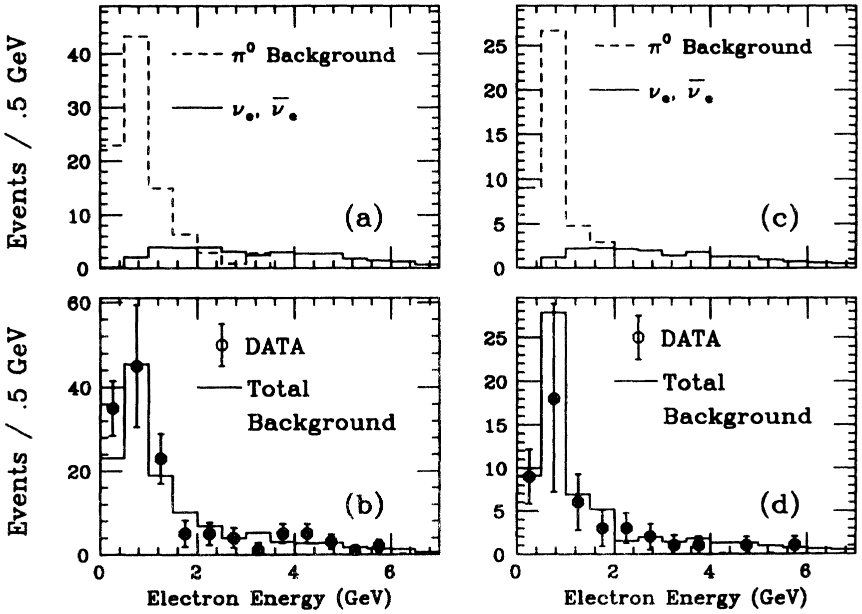

FIG. 3. (a) The contributions to the background from ν_μ-induced π^0 events (dashed line) and from beam ν_e plus $\bar{\nu}_e$ (solid line). (b) The electron energy spectrum for ν_e events. The solid line is the sum of the backgrounds. (a) and (b) are for the horn at positive polarity and (c) and (d) are for the horn at negative polarity. The error bars include the statistical errors from the π^0 calculation.

use of the detector Monte Carlo program to obtain acceptances, the background in the positive (negative) horn polarity sample is predicted to be 32.0 (7.7) from ν_e and 3.5 (12.2) from $\bar{\nu}_e$. The ratio of acceptances for quasielastic ν_e ($\bar{\nu}_e$) events to that of ν_μ ($\bar{\nu}_\mu$) quasielastic events is 0.8 (0.8). Since the ν_μ and $\bar{\nu}_\mu$ fluxes are measured, the systematic errors associated with the overall normalization of the beam spectra do not enter. The systematic error in the ν_e beam background is 11% which includes the effects of the 10% beam systematic error mentioned previously, a statistical error of about 1% in the calculation of the ν_e background, and a 3% systematic error in the calculation of the acceptance. Neutrino-electron elastic scattering contributes an additional 1.2 (0.6) events to the electron background for positive (negative) horn polarity.

In Fig. 3 we show the final spectra for the positive and negative polarity electron samples with the expected background superimposed. Since the data are consistent with the expected background, we conclude that there is no excess of electron-neutrino events. The final positive polarity sample contains 136 events with an expected background of $131 \pm 12(\text{stat}) \pm 20(\text{background stat}) \pm 19(\text{syst})$. Above 1 GeV where the experiment is most sensitive to the oscillation signal there are 56 electron events in the data, with an expected background of $62 \pm 8(\text{stat}) \pm 5(\text{background stat}) \pm 7(\text{syst})$. The final negative polarity sample contains 47 events consistent with the expected background of $62 \pm 8(\text{stat}) \pm 13(\text{background stat}) \pm 9(\text{syst})$. Above 1 GeV there are 19 electron events in the data with an expected background of $25 \pm 5(\text{stat}) \pm 3(\text{background stat}) \pm 3(\text{syst})$.

To calculate the oscillation limits we employ a maximum-likelihood function assuming Poisson statistics. The limits are not sensitive to data below 1 GeV; however, we include them in the fit for completeness, covering the whole energy spectrum from 0 to 10 GeV in 0.5-GeV bins. To incorporate the systematic errors we allow the components of the predicted backgrounds to fluctuate with a Gaussian weight, where the standard deviations correspond to the systematic uncertainty [3]. The uncertainty in the π^0 background includes the statistical errors in the π^0 data sample as described above. The likelihood function is maximized with respect to the background for every set of oscillation parameters with the limit boundary given by the likelihood function's deviation from the maximum. This calculation is performed separately for the positive and negative polarity data samples. The final region excluded by this experiment is a combination of the two limits. Other fitting procedures, such as the Pearson test, and the likelihood ratios used by the BEBC Collaboration [7] and the CCFR Collaboration [8] give similar results. Our limits are shown in Fig. 4 together with limits from BEBC [7], Los Alamos [9], E734 [10], Gösgen [11], and our previous limits from the narrow-band-beam running [2]. We thus find that at the 90% confidence level the limits obtained are $\Delta m^2 \leq 0.075$ eV^2 for maximal mixing, and $\sin^2 2\theta \leq 0.003$ for large Δm^2.

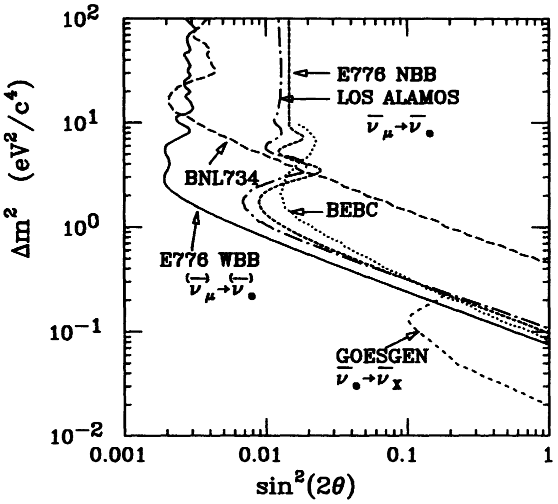

FIG. 4. Limits on ν_e appearance from this experiment (E-776 wide-band beam) combining the results of data taken with the horn running at both polarities. Also shown are the E-734 [10], BEBC [7], Los Alamos [9], and previous E-776 narrow-band beam [2] results as well as the limit on $\bar{\nu}_e \to \bar{\nu}_x$ from the Gösgen reactor experiment [11].

The excluded area for this experiment using the wide-band neutrino beam meets or exceeds each of the other experimentally excluded regions, primarily due to the unique combination of a long base line (1 km) and a high-statistics data sample.

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