Search for $\nu_\mu \to \nu_e$ Oscillations

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We present the results of a search for neutrino oscillations conducted at Brookhaven National Laboratory. The experiment searched for the appearance of ν_e 1 km from the source of a 1.4-GeV (mean energy) narrow-band ν_μ beam. With 3×10^{19} protons on target from the Alternating Gradient Synchrotron, no excess of ν_e was detected. The 90% confidence limits obtained are $\Delta m^2 \leq 0.10$ eV^2 for maximal mixing, and $\sin^2 2\theta \leq 0.016$ for large Δm^2.

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The phenomena of neutrino oscillations can arise if neutrinos are massive, and lepton numbers are not independently conserved. The weak eigenstates can then be expressed as mixtures of the mass eigenstates. Assuming two-flavor dominance (for simplicity), the probability for ν_μ to oscillate to ν_e over a distance L is then given by

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

where θ is the lepton-flavor mixing angle, L is the distance between the neutrino source and detector in km, 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 776 at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron[1] (AGS) which searched for an excess of ν_e events in a narrow-band ν_μ beam of mean energy 1.4 GeV. The detector is a fine-grained electromagnetic calorimeter located at a distance of $L=1$ km from the proton target. The two primary backgrounds for this experiment come from ν_e contamination in the ν_μ beam, and from π^0's misidentified as electrons in our detector.

The neutrino flux for the narrow-band beam used in this experiment was calculated using a Monte Carlo program.[2] Target production was simulated using NUCEVT (Ref. 3) in conjunction with a model by Grote, Hagedorn, and Ranft.[4] The source of the ν_μ's is primarily from $\pi^+_{\mu 2}$ and $K^+_{\mu 2}$ decays. Dominant contributions to the ν_e background arise from $K^+ \to \pi^0 e^+ \nu_e$ (45%), $\pi^+ \to \nu_\mu \mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ (34%), and $K_L \to \pi^- e^+ \nu_e$ (17%). The energy spectra for the various neutrino flavors are shown in Fig. 1. The integrated ν_e/ν_μ ratio is about 6.5×10^{-3}, with an error of 10% due to production uncertainties in the models considered.

The detector (described in more detail elsewhere[5,6]) is composed of two sections: a finely segmented electromagnetic calorimeter, followed by the muon spectrometer, which consists of a system of tracking chambers and a toroidal magnet with an 18-kG field for muon momentum and charge measurements. The electromagnetic calorimeter is composed of 90 planes of proportional drift tubes (PDT's) interleaved with 1-in.-thick ($\frac{1}{4}$ radiation length) concrete absorbers, comprising a total mass of 230 metric tons. Consecutive planes are placed orthogonally. Every tenth plane of concrete is replaced by a plane of scintillator used for timing. Each PDT plane contained 64 18-ft×3.25-in.×1.5-in. aluminum drift tubes. The PDT signals were amplified and read out by a 6-bit flash analog-to-digital converter (ADC) running with 22.4-ns clock in conjunction with a 256-bin memory, providing us with detailed pulse information for a time span of 5.7 μs. The pulse information is essential for the identification of event types in the detector. Electromagnetic showers are characterized by multiple peaks and large pulses which result from several tracks crossing each PDT as the shower cascades. In contrast, muons are characterized by a single minimum-ionizing peak in each PDT. The energy resolution of the

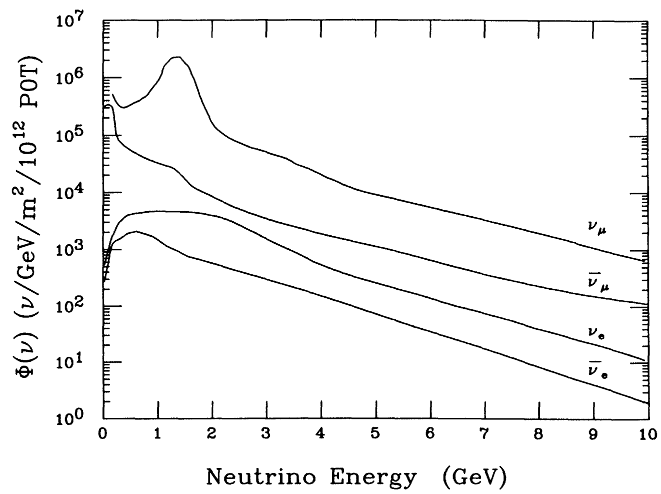

FIG. 1. Calculated spectra for ν_μ, ν_e, $\bar{\nu}_\mu$, and $\bar{\nu}_e$.

detector for electromagnetic showers, measured in a test beam, is $20\%/\sqrt{E}$. The angular resolution is about 2°.

Data were taken at two horn-current settings. Two-thirds of the data were taken with a mean neutrino energy of 1.3 GeV, corresponding to a horn current of 240 kA. The final third of the data was taken with a mean neutrino energy of 1.5 GeV corresponding to a horn current of 280 kA. Events were recorded with three triggers. The beam trigger was generated from the AGS clock; the contents of the detector were written to tape for each beam trigger. A "free trigger" opened a gate between beam pulses to measure the cosmic-ray background. Finally, a trigger was set up to record straight-through cosmic rays, which were used to monitor detector performance. A total of 2.6×10^6 beam triggers was taken, corresponding to 3×10^{19} protons on target. Data recorded with the beam trigger were passed through three filter programs which rejected most cosmic rays and triggers with no observable interactions in the detector. After the filtering, 12.8×10^3 events remained in the sample.

A detector Monte Carlo program was written to calculate acceptances. This Monte Carlo program includes a detailed description of all relevant neutrino interactions: quasielastic and elastic interactions, single-pion production,[7] multipion production,[8] and coherent π^0 production.[9] Electromagnetic showers are modeled using EGS4 (Ref. 10) while nuclear scattering and other hadronic processes are modeled using NUCRIN.[11] The combined sample consisting of the 12.8×10^3 data events, in addition to approximately 10000 ν_e and ν_μ Monte Carlo events, was scanned by physicists for tracks (muon candidates) and for clusters of hits (shower candidates). Analysis of the charged-current ν_μ and ν_e event candidates followed.

The objectives of the ν_μ analysis were to study the narrow-band beam energy spectrum and the measure the flux of ν_μ for normalization of the ν_e data. The following cuts were applied to obtain a sample of quasielastic event candidates, which permit the accurate reconstruction of the neutrino energy using the lepton energy and angle: (1) The track was required to have matched partners in both the x and y views. (2) The track vertex was required to be within the fiducial volume, the boundaries of which were 5 planes from the front of the detector, 15 planes from the back, and 4 wires from the sides. (3) The longest track was required to be either contained in the detector, or to pass through the muon spectrometer, allowing us to measure the muon energy/momentum. (4) The track was required to have an initial momentum, greater than 500 MeV/c (~35 planes=3 interaction lengths) assuming the track was a muon. (5) A timing cut required that the pulses on the PDT's were completely contained within the time window of the flash ADC's. (6) The angle of the muon with respect to the incoming neutrino direction was required to be less than 40°. (7) To select a quasielastic rich sample, the number of hits not associated with the primary track was required to be less than or equal to 6. Despite these cuts, Monte Carlo studies indicate that the contamination from both single-pion production and multipion events (where the pions are not visible) is 41%. Assuming the event is quasielastic, and using the muon energy and angle, we reconstruct a neutrino energy. Figure 2 shows the energy spectrum of the data superimposed with the Monte Carlo prediction. After a cosmic-ray background subtraction of 17 events, obtained from a similar analysis of the free triggers, the data correspond to 879 events with an acceptance of 10%. The acceptance is due in large part to the fiducial and containment cuts.

To search for ν_e events, we began with 1496 shower candidates (clusters) selected in the scan. Cuts identical to those in the muon analysis were made with the following exceptions: (1) The cluster was required to be contained in the electron calorimeter since the toroidal spectrometer is not used in the measurement of electromagnetic showers. (2) The length of the cluster was required to be greater than 15 planes to ensure that the cluster span at least one scintillation plane, for timing purposes. (3) The energy of the cluster, as measured by pulse area, was required to be greater than 600 MeV, below which the efficiency falls off rapidly. (4) The cluster was required to be attached to any vertex (i.e., within two planes) defined by the allowed 6 extra hits. Single showers with no extra hits were assumed to be attached to the vertex. After these cuts were applied, 55 events remained; no free trigger events survived at this stage. The final two cuts include an electromagnetic shower cut and an electron pattern cut, which will be described in

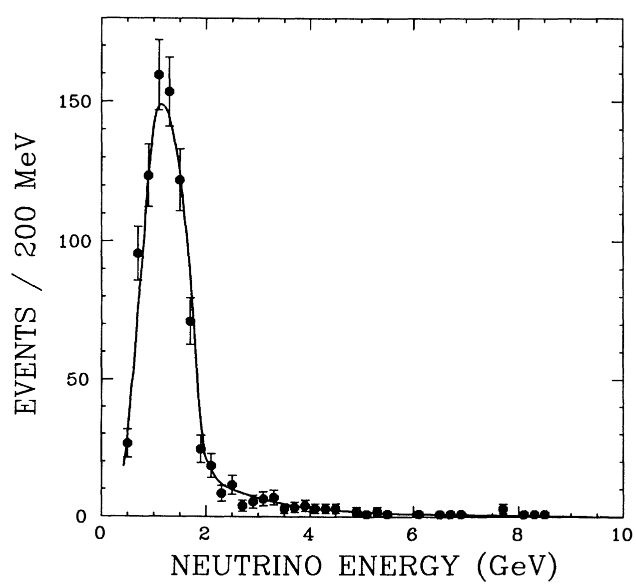

FIG. 2. The measured ν_μ energy spectrum. The solid line is the prediction of the Monte Carlo calculation of the spectrum normalized to the data. The contribution from nonquasielastic sources is not subtracted.

detail.

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 as the shower develops. We define electromagnetic showers by requiring the following: (1) There must be at least one skipped plane in the cluster. (2) The number of hits in the cluster must be within 2σ of the expected number for the observed shower energy. (3) The length of the shower must be within 2σ of the expected length. (4) Using the full shower length, the energy contained within ± 1 wire of the shower axis must be greater than 80% of the total shower energy. (5) Using the first 70% of the shower length, the energy contained within ± 1 wire of the shower axis must be greater than 85% of the total shower energy. From test data studies, we find that the efficiency for this set of criteria for electromagnetic shower identification is about 45% at 600 MeV and rises to 95% above 1 GeV. After applying these cuts, 38 events remained in the electron sample.

A major source of background is from π^0's which are misidentified as electrons in our detector. The shower profile for a π^0 is different than that of an electron of the same energy; in general, π^0's are wider and exhibit greater asymmetry than electrons. We parametrize the electron shower profile using a standard shower development function.[12] The function is fitted to the showers and a "goodness-of-fit" variable is defined. We establish an optimum criteria on this variable which rejects about 80% of 1-GeV π^0's while retaining 80% of 1-GeV electrons. This corresponds to a final sample of 17 "e" events. The remaining 21 events comprise the "π^0" sample.

Using the ν_μ Monte Carlo program, coupled with the above criteria, we calculate the probability that a π^0 is misidentified as an e, divided by the probability that a π^0 is correctly identified as a π^0, as a function of energy. We then calculate the π^0 background from ordinary ν_μ reactions as follows: $N_e = N_{\pi^0} P(\pi^0 \rightarrow \text{"}e\text{"})/P(\pi^0 \rightarrow \text{"}\pi^0\text{"})$, where N_e is the number of π^0's misidentified as e's in the data, N_{π^0} is the number of π^0's identified as π^0's in the data, $P(\pi^0 \rightarrow \text{"}e\text{"})$ is the probability that a π^0 is misidentified as an e, and $P(\pi^0 \rightarrow \text{"}\pi^0\text{"})$ is the probability that a π^0 is identified as a π^0. We then convolute the π^0 distribution for the data with the ratio of probabilities to obtain the background distribution of π^0's misidentified as electrons. This corresponds to a background of 9.6 events from ν_μ [Fig. 3(a)]. A systematic error of 40% comes from the uncertainty inherent in our knowledge of the probability ratio $P(\pi^0 \rightarrow \text{"}e\text{"})/P(\pi^0 \rightarrow \text{"}\pi^0\text{"})$, and from the variation in the relative number of π^0's as the goodness-of-fit criteria is changed.

An independent check of the calculation of $P(\pi^0 \rightarrow \text{"}e\text{"})/P(\pi^0 \rightarrow \text{"}\pi^0\text{"})$ was made in the following way. Charged-current muon-neutrino events with an electromagnetic shower were selected from the data sample.

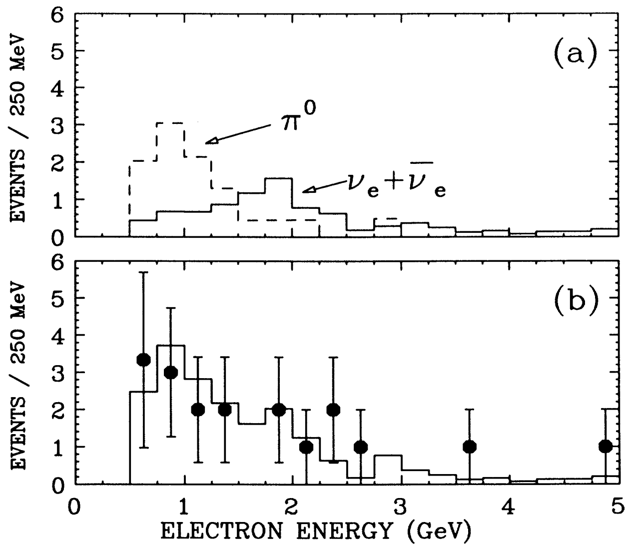

FIG. 3. (a) The contributions to the background from ν_μ-induced π^0 events (dotted line) and from beam ν_e plus $\bar{\nu}_e$ (solid line). (b) The electron energy spectrum for ν_e events. The solid line is the sum of the backgrounds.

The muon was deleted in the software and the sample was analyzed using the same criteria utilized in the electron analysis. The 12 electromagnetic events in the data sample were identified as 3 μe events and 9 $\mu\pi^0$ events. The 3 events identified as μe events are clearly misidentified $\mu\pi^0$ events since there are no real μe events at these neutrino energies. Since this is a known sample of ν_μ events, the desired ratio of efficiencies can be obtained directly. This method gives a background of 7 events, in good agreement with the previous calculation.

To estimate the ν_e background, the beam Monte Carlo calculation, described previously, is employed. Using the detector Monte Carlo program to obtain the acceptance, the ν_e background is 8.2 events, and the $\bar{\nu}_e$ background is 0.52 event [Fig. 3(a)]. Our acceptance for ν_e events is 10%; and as in the case of the ν_μ's, the acceptance is due in large part to the fiducial and containment cuts. The Monte Carlo calculation is normalized such that the predicted number of ν_μ events agree with the data. In this manner any systematic errors affecting the absolute number of ν_μ or ν_e events cancel. This normalization introduces a statistical error of 4% in the calculation of the ν_e background, as well as a 5% systematic error in the calculation of the acceptance. This leads to a systematic error of 12% including the uncertainties in the beam calculation as mentioned previously. The final electron data sample of 17 electron events is consistent with the background prediction of $18.4 \pm 4.3(\text{stat.}) \pm 3.9(\text{syst.})$ events [$9.6 \pm 3.8(\text{syst.})$ from π^0's and $8.8 \pm 1.1(\text{syst.})$ from ν_e and $\bar{\nu}_e$]. The distribution of the data in the final sample is in agreement with the expected background distributions [Fig. 3(b)]. We then calculate the oscillation limits at the 90% confidence level as follows. For each pair of

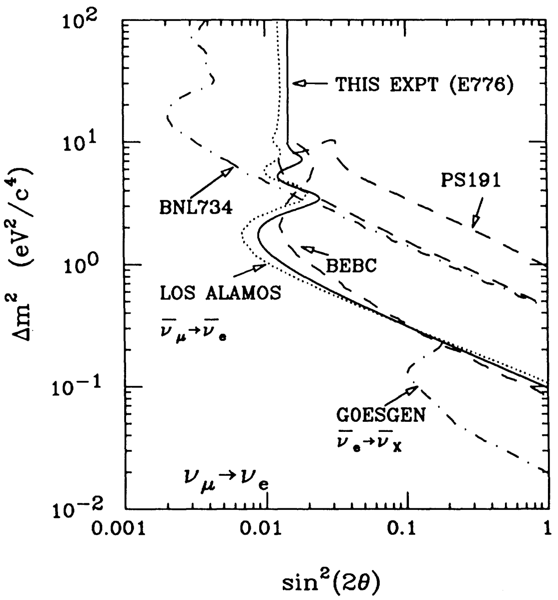

FIG. 4. Limits on ν_e appearance from this experiment (E776). Also shown are the E734 and BEBC results. A limit on $\bar{\nu}_\mu \to \bar{\nu}_e$ from Los Alamos, and on $\bar{\nu}_e \to \bar{\nu}_X$ from Goesgen are also shown. The PS191 result reports an excess of ν_e.

values $(\Delta m^2, \sin^2 2\theta)$, we calculate the number of ν_e events that would be observed above the background if the $\nu_\mu \to \nu_e$ oscillations occurred at those values. If the excess number of ν_e events is not consistent with zero at the 90% confidence level (taking into consideration both statistical and systematic errors), then those values of Δm^2 and $\sin^2 2\theta$ are in the excluded region. We therefore find, at the 90% confidence level, $\Delta m^2 \leq 0.10$ eV^2 for maximal mixing and $\sin^2 2\theta \leq 0.016$ at large Δm^2. Figure 4 shows the region excluded by this experiment at the 90% confidence level. As shown in the figure, significant past results for $\nu_\mu \to \nu_e$ were reported by both BNL experiment 734 (Ref. 13) and the BEBC Collaboration at the CERN Proton Synchrotron (PS).[14] One experiment, PS191 at CERN, reports an excess of ν_e.[15] Limits for the process $\bar{\nu}_\mu \to \bar{\nu}_e$ were set by an experiment at Los Alamos.[16] An experiment at the Goesgen nuclear reactor[17] has produced results for the process $\bar{\nu}_e \to \bar{\nu}_X$.

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