Comparison of narrow-band and wide-band neutrino beams in the search for $\nu_\mu \to \nu_e$ oscillations

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Motivated by the apparent advantages of a narrow-band neutrino beam for neutrino-oscillation experiments, a search for $\nu_\mu \to \nu_e$ was made with a magnetic horn-focused 3-GeV narrow-band neutrino beam. The detector and its distance from the neutrino source were the same as in a previous search for $\nu_\mu \to \nu_e$ with a horn-focused wide-band neutrino beam of mean energy 1.2 GeV. A direct comparison of the results of the two searches is made, and a brief survey of events induced by a 1.3-GeV narrow-band neutrino beam is noted.

INTRODUCTION

The possibility that neutrinos might oscillate in type has been explored in a number of experiments with neutrinos from reactors and accelerators[1] without a compelling positive result. Theoretically[2] the probability of appearance of an electron-type neutrino ν_e at a distance L (meter) from the source of a muon-type neutrino ν_μ beam of energy E_ν (MeV) is given by

$$P(\nu_\mu \to \nu_e) = \sin^2 2\alpha \sin^2(1.27\Delta m^2 L/E_\nu) , \quad (1)$$

where $\Delta m^2 = |m_1{}^2 - m_2{}^2|$ (eV^2) is the difference of the squared masses of the eigenstate neutrinos ν_1 and ν_2, and α is the angle of mixing between them, i.e.,

$$\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} . \quad (2)$$

Clearly, assuming only the two neutrino types ν_μ and ν_e, the probability that the initial ν_μ beam remains undiminished is

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_e) . \quad (3)$$

Accordingly, neutrino-oscillation experiments are of two kinds: appearance experiments to measure $P(\nu_\mu \to \nu_e)$ directly and disappearance experiments to measure $1 - P(\nu_\mu \to \nu_e)$. Both kinds have been done with high-energy neutrinos (≥ 1 GeV) from accelerators, but only the latter kind has been carried out with the low-energy neutrinos (< 10 MeV) from reactors.[3]

Reactor experiments make L/E_ν several times larger than the same quantity in most accelerator experiments so they have been roughly an order of magnitude more sensitive to small values of Δm^2. The overall limitations of the disappearance method, on the other hand, have confined the results of reactor experiments to the region of relatively large values (≥ 0.1) of $\sin^2 2\alpha$.

To search for the smallest value of the product (Ref. 4) $\Delta m^2 \sin 2\alpha$ with neutrinos from a terrestrial source, it is desirable to do appearance experiments with L/E_ν as large as possible, and with the background that simulates "appearance" events minimized. In general, L is constrained by the L^{-2} falloff of the initial neutrino beam, and by the size of detectors that can be realized. In principle, it appears possible to limit the energy spread and perhaps lower the average energy of the neutrino beam from an intermediate-energy accelerator such as the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory by construction of a narrow-band neutrino beam (NBB). Perhaps more important in searching for $\nu_\mu \rightarrow \nu_e$ would be the advantage of the narrow-band beam which arises from the expectation that any excess of observed ν_e-induced events due to oscillations should reflect the energy structure of the narrow-band beam and not the relatively uniform energy distribution of ν_e events resulting from ν_e in the incident beam (from K_{e3} and muon decays). This would serve therefore as an additional signature of a positive "appearance" signal. These apparent advantages motivated a search for $\nu_\mu \rightarrow \nu_e$ with a horn-focused 3-GeV narrow-band neutrino beam, and also a brief survey of events induced by a 1.3-GeV narrow-band neutrino beam. The results of both searches, which used an existing neutrino detector at the AGS, are reported here.

NEUTRINO BEAM

Protons were accelerated in the Brookhaven AGS to 28.3 GeV every 1.4 sec and impinged on a tungsten target. A proton burst had a typical intensity of 7×10^{12} protons on target (POT) and consisted of 12 bunches each about 25 nsec long, 224 nsec apart. The secondary particles were focused by the magnetic two-horn system used in a previous AGS experiment,[5] which was optimized to focus positive pions of 10 GeV/c ($\pm 10\%$) into a narrow-band beam using a collimation system integral to the horn structure. The pions were allowed to decay in a 60-m-long decay region. The energy of the neutrino beam from pion decay was 4 GeV in the forward direction, falling to about 1.5 GeV at the angular limits of the detector; the mean energy was 3 GeV. The flux from K-meson decay was small, contributing primarily between 4 and 10 GeV. During operation of the beam, events due to a wide-band background of neutrinos in the vicinity of 1 GeV were observed. The presence of this background did not significantly affect the analysis of the experiment because only events with visible energy greater than 2 GeV were accepted, and above 2 GeV the ν_e/ν_μ ratio for the wide-band background was essentially similar to the ν_e/ν_μ ratio in the narrow-band beam.

DETECTOR

The detector has been described in detail elsewhere.[6] It was designed to measure $(\nu_\mu e)$ and $(\nu_\mu p)$ elastic scattering, and consisted primarily of a liquid-scintillator calorimeter with more than 80% of the volume active. The magnitude of the energy and the time at which it was deposited in each scintillator were recorded. Interspersed between calorimeter elements were proportional drift tubes to track particles in the detector and measure energy loss. The total mass was 170 tons with cross-sectional area 4 m$\times$4 m perpendicular to the neutrino beam. A lead–liquid-scintillator shower detector followed the main detector and contained showers from events originating near the end of the main detector. A magnetic spectrometer was placed downstream of the shower detector to measure muons from a fraction of $\nu_\mu n \rightarrow \mu^- p$ events for beam diagnostic purposes. The detector was located approximately 110 m from the pion production target, and so was sensitive primarily to oscillations of wavelength comparable to 110 m.

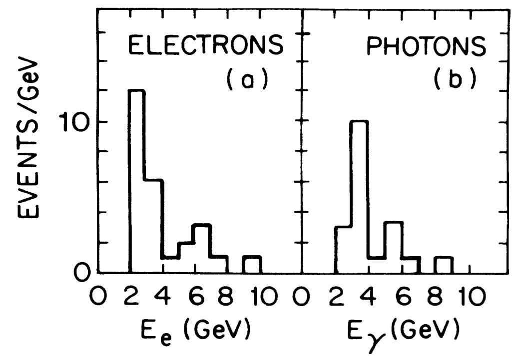

FIG. 1. Energy spectra of (a) the electrons and (b) the photons from the 3-GeV NBB experiment after all corrections.

QUASIELASTIC EVENTS: $\nu_e n \rightarrow e^- p$

The detector was operated in a triggerless mode by recording all signals for 10 μsec starting just before a beam burst. A total of 1.26×10^6 bursts was recorded, corresponding to 9×10^{18} POT. The calorimeter hits for each burst were correlated in time and a time cluster was retained if it extended spatially for more than 5 consecutive modules. Twelve percent of the bursts had such a cluster and were analyzed for events containing electrons or muons. Electromagnetic-shower candidates were identified in the same way as in an earlier $(\nu_\mu e)$ scattering experiment.[7] The filter algorithm selected events in which fluctuating energy deposition occurred within an angle of 20° of the neutrino direction. This cut restricted the selected events to relatively low Q^2 [$Q^2 < 0.4$ (GeV/c)^2].

A total of 3000 bursts contained shower candidates. These were scanned by physicists to reject time clusters which did not contain a single isolated electromagnetic shower with at most one additional identifiable track at the vertex. Approximately 75% of the events passing the filter were identified as muon or hadron tracks passing through cracks in the detector or obvious multitrack events which provided the fluctuating energy signature required by the filter. Another 20% of the events had clear related activity such as additional photon or neutron interactions. Events with π-μ-e decay signatures at the vertex (7 events) or with kinematics inconsistent with quasielastic scattering (2 events) were also removed from the sample.

After this selection, 63 events remained in the fiducial volume within 15° of the nominal beam direction and with at most one additional track at the vertex. The remaining dominant background was from the conversion of photons from neutral-current single π^0 production. Such events simulate the $e^- p$ final state only if there are no extra tracks or energy distributions in the detector. In addition, only a relatively small fraction of the total energy of such events is visible, so that in general the event energy will appear much lower than the nominal 3-GeV beam energy.

Accordingly, the signal of $\nu_e n \to e^- p$ events was restricted to those events with visible energy greater than 2 GeV. Of events with visible energy greater than 2 GeV and $\theta_{sh} < 15°$, 22 out of 42 events were identified as electrons by applying a criterion on ionization to the early part of the track.[7]

The efficiency of electron selection was (0.78 ± 0.06) for electrons and the selection criteria rejected (0.81 ± 0.05) of the photons in the sample. The corrected number of electrons in the sample was then 24 events. The energy distributions of the selected electron and photon samples are shown in Figs. 1(a) and 1(b), respectively. Additional corrections were made for scanning efficency (0.97 ± 0.02), unobserved π^+ decays at the vertex (1 event), and the average acceptance for electrons (0.61 ± 0.04), to give the final number of quasielastic $\nu_e n \to e^- p$ events with $E_\nu > 2$ GeV:

$$N_{obs}(\nu_e n \to e^- p) = 39\pm14 \ . \tag{4}$$

QUASIELASTIC EVENTS: $\nu_\mu n \to \mu^- p$

The number of $\nu_\mu n \to \mu^- p$ events induced in the detector by the principal (ν_μ) component of the incident neutrino beam was obtained from event samples selected in the same manner as described in detail earlier.[7,8] Briefly, events with a single long track with $\theta_\mu < 15°$ relative to the neutrino-beam direction were accepted, and corrections were made for backgrounds from all single-pion channels (0.20 ± 0.02), for track-reconstruction efficiency (0.92 ± 0.03), and for the fraction of events with neutrino energy greater than 2 GeV (0.65 ± 0.06). This yielded the final, total $\nu_\mu n \to \mu^- p$ event sample with $E_\nu > 2$ GeV:

$$N_{obs}(\nu_\mu n \to \mu^- p) = 3071\pm196 \ . \tag{5}$$

The actual shape of the ν_μ energy spectrum was determined in two separate ways. One sample consisted of events in which both final-state particles μ^- and p were observed so that each event could be fully reconstructed. The ν_μ spectrum obtained from that sample is shown in Fig. 2. The other sample consisted of events with single muons with small θ_μ which could be measured in the downstream magnetic spectrometer. The number of $\nu_\mu n \to \mu^- p$ events determined in each case was consistent within $\pm15\%$.

COMPARISON OF CALCULATED AND MEASURED VALUES OF $\phi(\nu_e)/\phi(\nu_\mu)$

The ν_e and ν_μ spectra from the narrow-band horn system were calculated with the Monte Carlo beam program NUBEAM which has been tested extensively on the wide-band neutrino beams at the AGS.[9] For the measurement described here only the ratio of the electron and muon fluxes above 2 GeV is required, and this ratio is essentially determined by the K/π production spectra. It is relatively insensitive to changes in horn current, targeting, and the relative contribution from the wide-band background present at low energy in the beam. The calculated ratio of fluxes $\phi(\nu_e)/\phi(\nu_\mu)$ above 2 GeV was

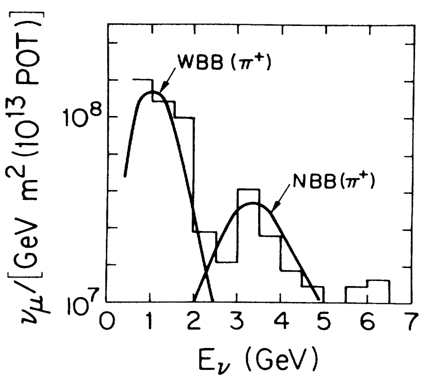

FIG. 2. The histogram is the spectrum of ν_μ determined from measurements of 2-prong $\nu_\mu n \to \mu^- p$ events. The curves indicate the location and shape of the WBB and NBB components arising from π^+ decay. The magnitude of the NBB flux is approximately as expected from a Monte Carlo NBB calculation. In a perfect NBB the WBB component would be negligibly small. Neutrinos above 5 GeV arise primarily from K^+ decay. The accuracy of the absolute values on the flux axis is roughly $\pm30\%$.

$$\phi(\nu_e, E_\nu > 2\ \text{GeV})/\phi(\nu_\mu, E_\nu > 2\ \text{GeV}) = (9\pm2)\times10^{-3} \ . \tag{6}$$

From this ratio the number of $\nu_e n \to e^- p$ events expected from the presence of ν_e in the initial beam was

$$N_{calc}(\nu_e n \to e^- p) = (3071\pm196)\times(9\pm2)\times10^{-3} = 28\pm7 \tag{7}$$

to be compared with the value $N_{obs}(\nu_e n \to e^- p) = 39\pm14$ in Eq. (4).

LIMITS ON $\sin^2 2\alpha$ AND Δm^2

There is no significant excess of $\nu_e n \to e^- p$ events beyond that expected from the quasielastic reactions of ν_e initially present in the neutrino beam, and consequently no evidence for $\nu_\mu \to \nu_e$ oscillations. In the limit of Δm^2 large, such that $\sin^2(1.27\Delta m^2 L/E_\nu) \to \frac{1}{2}$:

$$\sin^2 2\alpha = 2P(\nu_\mu \to \nu_e) = 2\Delta N(\nu_e n \to e^- p)/N(\nu_\mu n \to \mu^- p) \tag{8}$$

and we obtain

$$\sin^2 2\alpha \le 1.0\times10^{-2}, \quad 90\%\ \text{C.L.} \ , \tag{9}$$

independent of L/E. Similarly, in the limit Δm^2 small, such that $\sin^2(1.27\Delta m^2 L/E) \to (1.27\Delta m^2 L/E)^2$, one finds

$$\Delta m^2 \sin 2\alpha \le 2.4\ \text{eV}^2, \quad 90\%\ \text{C.L.} \tag{10}$$

COMPARISON OF 3-GeV NBB RESULTS WITH WIDE-BAND-BEAM RESULTS

The limits on $\sin^2 2\alpha$ and $\Delta m^2 \sin 2\alpha$ found here are less stringent than those obtained by essentially the same collaboration using the same detector in a wide-band beam (WBB) at the same distance from the AGS target[10] by factors of 3 and 5.6, respectively. (Part of the latter factor is due to the difference in average energy of the two neutrino beams, 3 GeV in the NBB and 1.2 GeV in the WBB, which leads to a net factor of 2.2 in the comparison.) Comparison of the appropriate calculated flux ratios,

$$\phi(\nu_e, E_\nu > 2 \text{ GeV})/\phi(\nu_\mu, E_\nu > 2 \text{ GeV}) = (9\pm2)\times10^{-3}$$

in the NBB, and

$$\phi(\nu_e, E_\nu = 1.2 \text{ GeV})/\phi(\nu_\mu, E_\nu = 1.2 \text{ GeV}) \simeq (4\pm1)\times10^{-3}$$

in the WBB,[9,10] yields a similar factor. The ratio of POT in the two experiments was approximately unity: 9×10^{18} POT in the NBB and 8.8×10^{18} POT in the WBB. It is clear that the wide-band-beam experiment was superior in all respects to the narrow-band-beam experiment, particularly in its more economical use of POT.

COMMENTS ON DATA FROM A 1.3-GeV NARROW-BAND BEAM

The oscillation experiment with the 3-GeV NBB was in part intended as a test of the value of a narrow-band beam in a neutrino-oscillation experiment, and in part as the prototype of a narrow-band-beam experient at lower neutrino energy and longer distance. The calculated value of

$$\phi(\nu_e, E_\nu \simeq 1.3 \text{ GeV})/\phi(\nu_\mu, E_\nu \simeq 1.3 \text{ GeV}) \simeq 3\times10^{-3}$$

for a 1.3-GeV NBB is to be compared with the calculated value of 4×10^{-3} for the WBB at $E_\nu \simeq 1.2$ GeV.

A brief run utilizing the same detector at the same distance, and 0.43×10^{18} POT in a narrow-band beam[11] with mean neutrino energy 1.3 GeV, yielded 6 electromagnetic showers (without any cut on energy) after all 535 shower candidates which had passed the preliminary filter were scanned by physicists. The energy spectra of these events are shown in Fig. 3. The raw yield of all ν_e-induced events was (1.4±0.6) per 10^{17} POT, while between 0.5 and 1.5 GeV the yield of $\nu_e n \to e^- p$ events was (0.23±0.23) per 10^{17} POT. This is to be compared with the yield above 2 GeV of $\nu_e n \to e^- p$ events in the 3-GeV NBB experiment of (0.24±0.05) per 10^{17} POT. The comparison indicates that in the energy region in which the ν_μ in the initial beam are concentrated the relative background of $\nu_e n \to e^- p$ events from ν_e in the initial beam is, within the large statistical errors, the same for the 3- and 1.3-GeV NB beams. A similar conclusion holds for the photon background from neutral-current single π^0 production $\nu_\mu n \to \nu_\mu n \pi^0$.

SUMMARY AND CONCLUSION

The appearance neutrino-oscillation experiment $\nu_\mu \to \nu_e$ described here, which utilized a 3-GeV NBB, was inferior

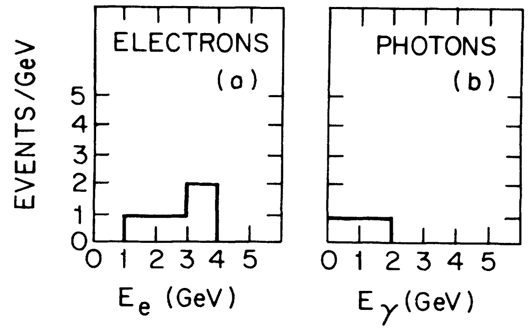

FIG. 3. Observed energy spectra of (a) the electrons and (b) the photons from a short exposure of the detector to a 1.3-GeV NBB.

in the limits obtained on $\sin^2 2\alpha$ and $\Delta m^2 \sin 2\alpha$ to a WBB neutrino-oscillation experiment with the same detector at the same distance from the neutrino source.[10] A short run with the neutrino energy of a NBB approximately equal to that of the WBB (≈ 1 GeV) also showed no significant improvement in the NBB either in the number of $\nu_e n \to e^- p$ events from ν_e in the initial beam relative to the number of $\nu_\mu n \to \mu^- p$ events, or in the photon background relative to the number $\nu_\mu n \to \mu^- p$ events.

We conclude that the apparent promise of the horn-focused NBB for appearance oscillation experiments is largely vitiated by the loss of neutrino intensity and by the failure to reduce significantly the backgrounds from ν_e in the initial beam and from neutral-current single π^0 production. Together, these disadvantages lead to increased statistical and systematic errors on the ratio $N(\nu_e$-induced events$)/N(\nu_\mu$-induced events), and therefore to a loss of sensitivity to possible oscillation generated ν_e-induced events.

It appears that a superior way to improve on present limits from an appearance neutrino-oscillation experiment at an accelerator is to employ a WBB and a detector at the longest possible distance from the neutrino source. A step in this direction was taken in a recent experiment[12] with $L/E \simeq 0.4$ using a wide-band beam of average energy 2 GeV at the Proton Synchrotron in CERN. This experiment yielded a poorer limit on $\sin^2\alpha$ but a better limit on $\Delta m^2 \sin 2\alpha$ relative to the limits found in Ref. 10. A natural extension of this approach would be a WBB experiment at an average neutrino energy of approximately 2 GeV at a distance of 5–10 km from the neutrino source, with a multikiloton detector capable of distinguishing electrons from photons and muons as in the experiment in Ref. 12. Such an experiment, employing an imaging water Cherenkov detector, for example, would be possible at the AGS, and could lead to 90%-C.L. limits on $\sin^2 2\alpha$ and $\Delta m^2 \sin 2\alpha$ of approximately 3×10^{-3} and 10^{-2} eV^2, respectively.

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[4]The weight of present experimental evidence suggests that $\sin^2(1.27\Delta m^2 L/E_\nu)$ is small enough to validate the approximation of

$$\Delta m^2 \sin 2\alpha = (E_\nu/1.27L)\sqrt{P(\nu_\mu \rightarrow \nu_e)} \ .$$

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