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A Brief Report on a New Limit on the Strength of Mixing Between $\nu_\mu - \nu_e$

JAPAN-U.S.A. NEUTRINO COLLABORATION*

L. A. Ahrens, S. H. Aronson,
P. L. Connolly, B. G. Gibbard, M. J. Murtagh,
S. Murtagh, S. Terada, D. H. White (B.N.L.); J. L. Callas,
D. Cutts, J. S. Hoftun, R. E. Lanou, T. Shinkawa (Brown Univ.);
K. Amako, S. Kabe (K.E.K.); Y. Nagashima, Y. Suzuki, S. Tatsumi
(Osaka Univ.); K. Abe, E. W. Beier, D. C. Doughty, L. S. Durkin,
S. M. Heagy, M. Hurley, A. K. Mann, F. M. Newcomer,
H. H. Williams, T. York (Univ. of Pennsylvania);
D. Hedin, M. D. Marx, E. Stern (Stony Brook)

Presented by R. E. Lanou
Department of Physics
Brown University
Providence, Rhode Island
02912

Abstract

Measurements have been made of the reactions $\nu_e n \to e^- p$ and $\nu_\mu n \to \mu^- p$ in a detector located 96 meters from the A.G.S. neutrino source. A direct measurement is made of the energy dependent flux ratio for the two neutrino species. After comparison to calculated energy dependence of this same ratio, an improved new limit of $\sin^2 2\alpha < 3.4 \times 10^{-3}$ (90% CL) at large Δm^2 is obtained. Possible systematic errors are estimated to be less than 20%.

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The USA-JAPAN neutrino detector constructed for studies of neutral current reactions ($\overset{(-)}{\nu}_\mu e^- \to \overset{(-)}{\nu}_\mu e^-$ and $\overset{(-)}{\nu}_\mu p \to \overset{(-)}{\nu}_\mu p$) and normalization reactions ($\nu_\mu n \to \mu^- p$, $\bar{\nu}_\mu p \to \mu^+ n$) at the B.N.L.-A.G.S. has been used to search for neutrino oscillations. The detector[1] is a fully active one (liquid scintillator) with good angular and energy resolution --

$$\Delta\theta^e_{x,y} = \frac{16 \text{ mrad}}{\sqrt{E(\text{GeV})}} \text{ and } \frac{\Delta E_e}{E_e} = \frac{13\%}{\sqrt{E(\text{GeV})}}, \text{ respectively.}$$

The detector was placed at a mean distance of 96 meters from the effective neutrino source. The beam was a wide band, horn focussed one of most probable energy about 1GeV (see Fig. 2).

The configuration of detector elements is such that we can detect both quasi-elastic reactions:

$$\nu_e + n \to e^- + p \tag{1}$$

$$\nu_\mu + n \to \mu + p \tag{2}$$

These reactions are used to establish the ν_e and ν_μ relative composition of the beam at the detector position.

In a two component model the probability for ν_μ of energy E_ν (Mev) to have oscillated to ν_e at a distance L (meters) is

$$P(\nu_\mu \to \nu_e) = \sin^2 2\alpha \sin^2\left(1.27 \frac{L}{E_\nu} \Delta m^2\right) \tag{3}$$

where $\Delta m^2 = |m_1^2 - m_2^2|$ and $\sin^2 2\alpha$ is the mixing strength between the states of mass, m_1 and m_2.

Note that in the limit of large Δm^2,

$$P(\nu_\mu \to \nu_e) \longrightarrow \frac{1}{2} \sin^2 2\alpha \tag{4}$$

and is independent of L/E_ν.

If we define $\Phi^e_L(E_\nu)$ and $\Phi^\mu_L(E_\nu)$, respectively, as the flux of ν_e and ν_μ at L, then as a function of E_ν, $\int \Phi^e_L(E_\nu) dE_\nu / \int \Phi^\mu_L(E_\nu) dE_\nu \neq 0$ even with no oscillations due to some ν_e contamination in the ν_μ beam (typically 0.5% at A.G.S. energies) due to $\pi - \mu - e$ and kaon decays. However, an important feature at these energies is that this neutrino flux ratio is particularly characteristic but not very sensitive to either the π/K production ratio or to the absolute flux.

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The principle of the experiment then is to directly measure the energy dependence of $\Phi_L^e(E_\nu)/\Phi_L^\mu(E_\nu)$ and to test it against the neutrino oscillation hypothesis.

The procedure of the experiment is briefly as follows:

a) First, we isolate reactions (1) (418 events) and (2) (1370 events) in the region $0.9 < E_e < 5$GeV.

b) On an event by event basis the energy, E_ν, is solved for using θ_e and E_e for reaction (1) and θ_p and E_p for reaction (2).

c) The acceptances (a^{ep} and $a^{\mu p}$) for reactions (1) and (2), respectively, are calculated by Monte Carlo. For a^{ep} the momentum transfer range is $0 < Q^2 < 0.4$ $(GeV/c)^2$ and for $a^{\mu p}$, $0.4 < Q^2 < 1.1$ $(GeV/c)^2$. The standard (V-A) form for the quasi-elastic cross section is assumed and the experimentally[2] determined value of the axial-vector mass is used. A contribution of 14% systematic error to $[\sigma^e(Q.E.) \times a^{ep}]/[\sigma^\mu(Q.E.) \times a^{\mu p}]$ is established from variation of these parameters.

d) Corrections for backgrounds of 28% and 18% to reactions (1) and (2), respectively, are made. Figure 1 illustrates the nature of the bin-by-bin subtraction made for the $\nu_e + n \rightarrow e^- + p$ channel.

e) An indirect check upon the Q^2 dependences of a^{ep} and $a^{\mu p}$ is made and, as can be seen in Figure 3, is a good representation of the data.

f) Utilizing the data resulting from the steps (a) through (e), the experimental flux ratio, $[\Phi_L^e(E_\nu)/\Phi_L^\mu(E_\nu)]_{OBS.} = R_{OBS.}$ is determined in seven energy bins. These are shown as the points in Figure 4a.

g) A detailed Monte Carlo beam program[3] is then used to calculate the flux ratio, $R_{CALC.} = [\Phi_L^e(E_\nu)/\Phi_L^\mu(E_\nu)]_{CALC.}$, to be expected in the absence of neutrino oscillations. The result of this calculation is illustrated as the solid curve in Figure 4a. The comparison of calculation and measured spectrum for the separate channels (1) and (2) is shown in Figure 2. The agreement in the relevant energy ranges is seen to be quite satisfactory.

This satisfactory agreement can be used to set a limit on the oscillation mixing strength by forming the difference, $[R_{CALC} - R_{OBS}]$. The result of this subtraction is shown in Figure 4b. We conclude that there is no evidence for $\nu_\mu \rightarrow \nu_e$ oscillations in this kinematic range. The excluded area is shown in Figure 5. These mixing limits extend the excluded region beyond that of the previous[4] best search for $\nu_\mu \rightarrow \nu_e$ oscillations.

In the limits of large and small mass differences we can give results for the complementary variable both with and without flux subtraction. These are at 90% C.L.,

- No flux subtraction and data in the range 0.9 - 1.5 Gev:

$$\sin^2 2\alpha \lesssim 1.0 \times 10^{-2} \text{ at large } \Delta m^2$$

$$\Delta m^2 \sin 2\alpha \lesssim 0.67 \text{eV}^2 \text{ at small } \Delta m^2$$

- Flux subtracted and data in the range 0.9 - 2.1GeV:

$$\sin^2 2\alpha \lesssim 3.4 \times 10^{-3} \text{ at large } \Delta m^2$$

$$\Delta m^2 \sin 2\alpha \lesssim 0.43 \text{eV}^2 \text{ at small } \Delta m^2$$

Two additional comments should be made. First, the total systematic error is estimated to be about 20% with equal contributions from uncertainties in the acceptance and flux calculations. A more detailed discussion of these effects is in reference 5. Secondly, it should be noted that since R is independent of L/E_ν, at large Δm^2, any oscillation affect can be no greater at high E points (Figure 4b) than it is at 1GeV; consequently, these higher energy points serve as a direct test (within errors) of the flux calculation particularly as it relates to the π/K production ratio.

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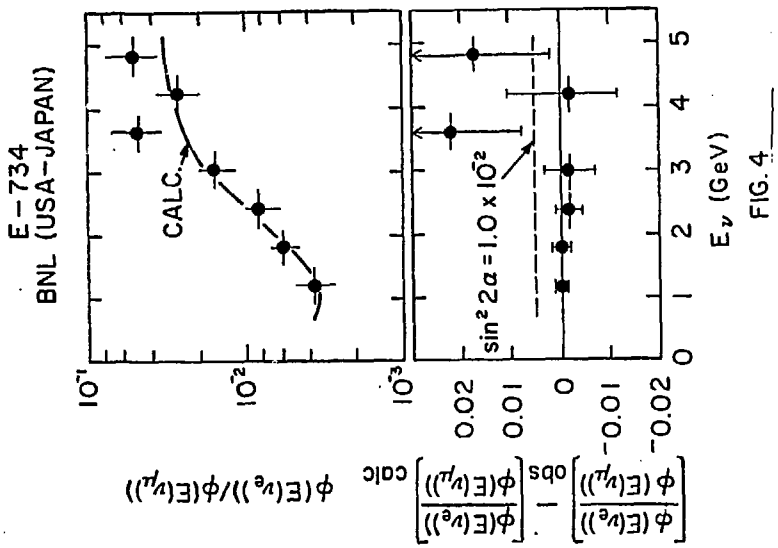

FIG. 4

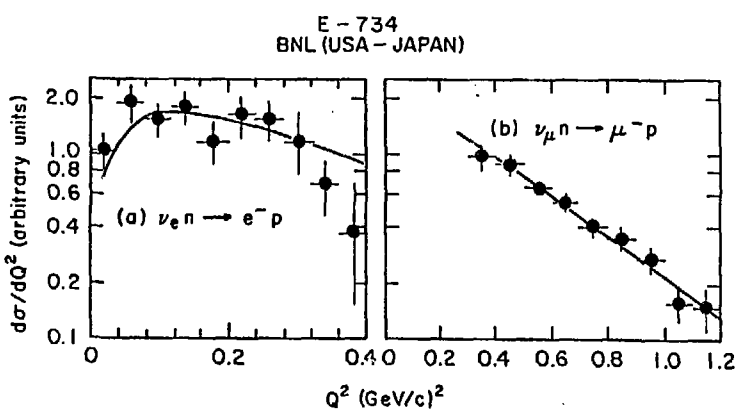

FIG. 3

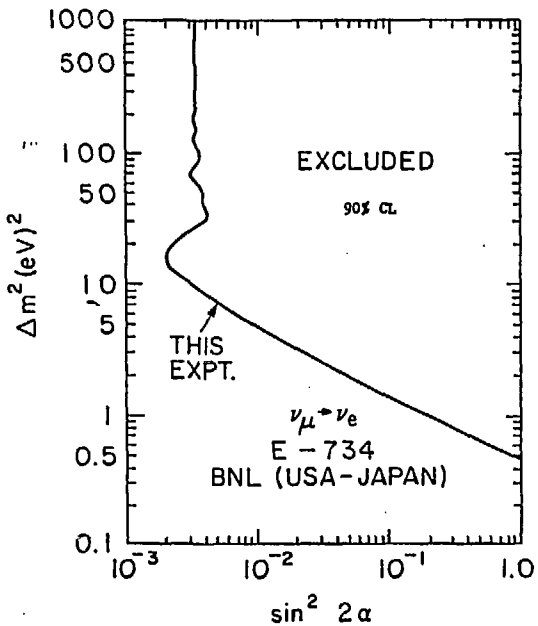

FIG.5

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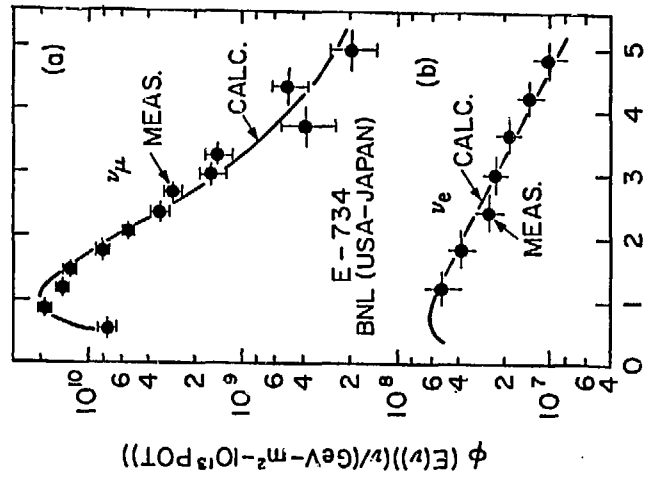

FIG. 2

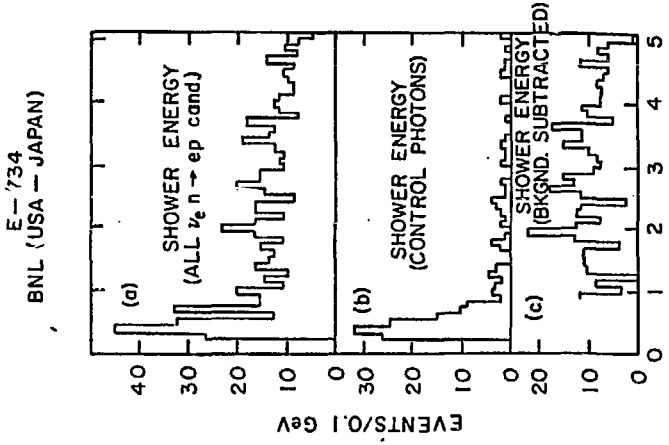

FIG. 1