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N.J. Baker, P.L. Connolly, S.A. Kahn, H.G. Kirk,
M.J. Murtagh, R.B. Palmer, N.P. Samios and M. Tanaka
Brookhaven National Laboratory, Upton, NY 11973
and
C. Baltay, M. Bregman, D. Caroumbalis, L.D. Chen,
H. French, M. Hibbs, R. Hylton, J.T. Liu,
J. Okamitsu, G. Ormazabal, R.D. Schaffer, J. Spitzer
Columbia University, New York, NY 10027

presented by N.J. Baker

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ABSTRACT

We have searched for neutrino oscillations in a wideband neutrino beam at Fermilab using the 15-foot bubble chamber. We find no evidence for neutrino oscillations and set upper limits on the mixing angles and neutrino mass differences in the transitions: $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\tau$, and $\nu_e \nrightarrow \nu_e$.

Recently various authors have suggested[1] the possibility of neutrino oscillations; i.e. a time dependent mixing of neutrino eigenstates of the weak interaction. These oscillations can only occur if the neutrino mass eigenstates are not degenerate and the mixing angles (which characterize the contribution of the mass eigenstates to the weak interaction eigenstates) are non-zero. If we consider two neutrino eigenstates of the weak interaction $|\nu_\alpha\rangle$ and $|\nu_\beta\rangle$, these are quantum mechanical mixtures of the neutrino mass eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$ (with masses m_1 and m_2, respectively).

$$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\beta\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle.$$

The probability, P, of the appearance of a neutrino of type ν_β, at a distance, L, from the source, when initially a neutrino of type ν_α was created, is given by

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\ \sin^2(1.27\ \delta_m^2\ L/E)$$

where $\delta_m^2 = m_1^2 - m_2^2$ (eV^2), E is the neutrino energy (GeV). L is in km.

Experimentally we identify neutrinos via their charged current interaction

$$\nu_\alpha + Ne \to \alpha^- + \text{hadrons}.$$

To relate the number of observed interactions (N_α), due to neutrinos ν_α, and the oscillation probability $P(\nu_\alpha \to \nu_\beta)$, we have to integrate over the neutrino energy spectrum and the length of the decay region, in which the neutrinos are created. For small oscillation probabilities,

$$R_{\alpha \to \beta} = \frac{N_\beta}{N_\alpha} = \frac{\int\int P(\nu_\alpha \to \nu_\beta)\phi_\alpha \sigma_\beta \, dEdL}{\int\int \phi_\alpha \sigma_\alpha \, dEdL}$$

where ϕ_α is the initial flux of neutrinos ν_α, and $\sigma_{\alpha(\beta)}$ is the total charged current cross-section for neutrinos of type $\nu_{\alpha(\beta)}$.

In this experiment we have examined the oscillations $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ using methods which are independent of any flux calculation, thus avoiding the systematic uncertainties which arise from neutrino flux calculations. (For comparison, the limits we obtain by the flux subtraction method are given in Table Ib.) For $\nu_\mu \to \nu_e$ oscillations we select only events with $5 < E_\nu < 10$ GeV, and attribute all of the observed ν_e events to $\nu_\mu \to \nu_e$ oscillations. For $\nu_\mu \to \nu_\tau$ oscillations this approach is of no value since the ν_τ charged current cross-section falls rapidly below 10 GeV. Instead we employ a method which utilizes the particular kinematics of the interaction, $\nu_\tau + Ne \to \tau^- X$; $\tau^- \to e^- \bar{\nu}_e \nu_\tau$. These interactions appear similar to ν_e interactions but have a large momentum imbalance, P_{out}[(2)], due to the missing neutrinos in the final state.

The data was obtained from a 134,000 picture exposure of the FNAL 15-foot bubble chamber filled with a heavy Ne/H_2 mixture. The neutrinos are produced in a 400 m long decay region. Muons and hadrons are absorbed in the 1000 m of shielding. The chamber is located downstream of the shielding, giving an average neutrino path length, L, of 1.2 ± 0.2 km. The energy spectrum in the wide-band beam ranges from a few GeV up to a few hundred GeV and peaks at ~ 30 GeV. The bubble chamber is 4 m in diameter and is in a 30 kG magnetic field. In the heavy neon (64 atomic % neon with 36% hydrogen) mixture, the hadronic interaction length is 125 cm, the radiation length 40 cm. Hadrons will typically interact, muons will leave the chamber without interacting, and electrons can be reliably identified by their radiation.

All the pictures were scanned for events with an $e^\pm$ in the final state. The $e^\pm$ was required to be identified by two signatures, a signature being radiation followed by a visible conversion into an e^+e^- pair, or a spiral at the end of the track due to ionization energy loss. 794 electron events were found, in which the electron momentum was greater than 300 MeV/c. 595 events remain after a fiducial volume cut and a further electron momentum cut requiring the electron momentum to be greater than 1 GeV/c. After correcting for backgrounds (12 ± 6 ν_μ events with a Compton electron over 1 GeV/c) and for efficiencies (electron identification, 95%; scanning, 72%; and 10% loss for confused events), the number of electron events is 942 ± 85.

All neutrally induced interactions on an unbiased subset of the pictures (~3.5%) were completely measured. ν_μ charged current candidates were defined to be those events containing a leaving negative particle. The raw event rate corresponded to 106000 candidate ν_μ events. After applying the fiducial volume cut; requiring the muon momentum to be greater than 1 GeV/c; subtracting neutral current and neutron star background (10%) and correcting for scanning efficiency (93%), 68500 ± 4000 ν_μ charged current interactions remain. All the events were completely measured and the visible neutrino energy corrected for missing neutral particles and mismeasured/failing tracks.

Our limits on $\nu_\mu \to \nu_e$ oscillation are set using the data in the energy interval $5 < E_\nu < 10$ GeV. In this region we observe 34 electron events. Correcting for Compton electron background removes (1±1) events. The electron identification and scanning efficiencies are applied as before, but not the 10% correction due to confused events, since the electron events with $E_\nu < 10$ GeV are of much simpler topology. This yields 48 ± 9 ν_e interactions. The corresponding number of ν_μ interactions is 4950 ± 1000[3], after all corrections. This gives

$$R_{\mu \to e} = \frac{48 \pm 9}{4950 \pm 1000} \leq 1.3 \times 10^{-2} \text{ at } 90\% \text{ C.L.}$$

After integrating over the observed neutrino energy spectrum and the decay space, we obtain at 90% C.L.

$$\delta_m^2 \leq 0.6 \text{ eV}^2 \text{ for } \sin^2(2\theta) = 1$$

and

$$\sin^2(2\theta) \leq 2.7 \times 10^{-2} \text{ for } \delta_m^2 > 100 \text{ eV}^2.$$

This result is shown as curve (1) on Fig. 1.

For limits on $\nu_\mu \to \nu_\tau$ oscillation, we use the electron sample after fiducial volume and electron momentum ($P_{e^-} > 1$ GeV) cuts and further require P_{out} to be greater than 1.0 GeV/c. 41 out of 595 electron events remain. A Monte Carlo calculation[4] indicates that 35% of ν_τ interactions, in which τ^- decays into e^-, would have $P_{out} > 1$ GeV/c. The electron identification and scanning efficiencies, the correction for confused events, and the $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ branching ratio of 17%[5], were applied to give 1120 ± 210 ν_τ interactions. This number of ν_τ interactions has to be compared to the 68500 ± 4000 ν_μ interactions to give

$$R_{\mu \to \tau} = \frac{1120 \pm 210}{68500 \pm 4000} \leq 2 \times 10^{-2} \text{ at } 90\% \text{ C.L.}$$

Again we integrate over the observed neutrino energy spectrum and the decay space, using the ν_τ charged current total cross section to obtain at 90% C.L.

$$\delta_m^2 \leq 3.0 \text{ eV}^2 \text{ for } \sin^2(2\theta) = 1$$

and

$$\sin^2(2\theta) \leq 6 \times 10^{-2} \text{ for } \delta_m^2 > 100 \text{ eV}^2.$$

This result is shown as curve (2) on Fig. 1. The results are summarized in Table I. This research supported in part by the U.S. Department of Energy under Contract No. DE-AC02-76CH00016 and by the National Science Foundation.

TABLE IA

Summary of Limits on the Neutrino Oscillation Parameters, Obtained by the Flux Independent Methods (90% C.L.)

Oscillation Channel	$(L/E)_{ave}$ (km/GeV)	δ_m^2(at $\sin^2(2\theta)$=1) (eV^2)	$\sin^2(2\theta)$(at δ_m^2>100eV^2)
$\nu_\mu \to \nu_e$	0.16	≤ 0.6	$\leq 2.7 \times 10^{-2}$
$\nu_\mu \to \nu_\tau$	0.04	≤ 3.0	$\leq 6 \times 10^{-2}$

TABLE IB

Summary of Limits on the Neutrino Oscillation Parameters, Obtained by the Flux Subtraction Method (90% C.L.)

Oscillation Channel	$(L/E)_{ave}$ (km/GeV)	δ_m^2(at $\sin^2(2\theta)$=1) (eV^2)	$\sin^2(2\theta)$(at δ_m^3>100eV^2)
$\nu_\mu \to \nu_e$	0.065	≤ 0.8	$\leq 6 \times 10^{-3}$
$\nu_\mu \to \nu_\tau$	0.04	≤ 3.0	$\leq 6 \times 10^{-2}$
$\nu_e \not\to \nu_e$	0.06	≤ 8.0	≤ 0.6

REFERENCES

1. B. Pontecorvo, JETP Sov. Fiz. 53, 1717 (1967); V. Gribov and B. Pontecorvo, Phys. Lett. 28B, 493 (1969); also see, S.M. Bilenky and B. Pontecorvo, Phys. Reports 41, 225 (1978).

2. $P_{out} = (\hat{P}_\nu \times \hat{P}_e) \cdot \vec{P}_{had}$; where $\hat{P}_\nu$ and $\hat{P}_e$ are unit vectors in the beam and electron directions, respectively, and $\vec{P}_{had}$ is the total hadron momentum vector.

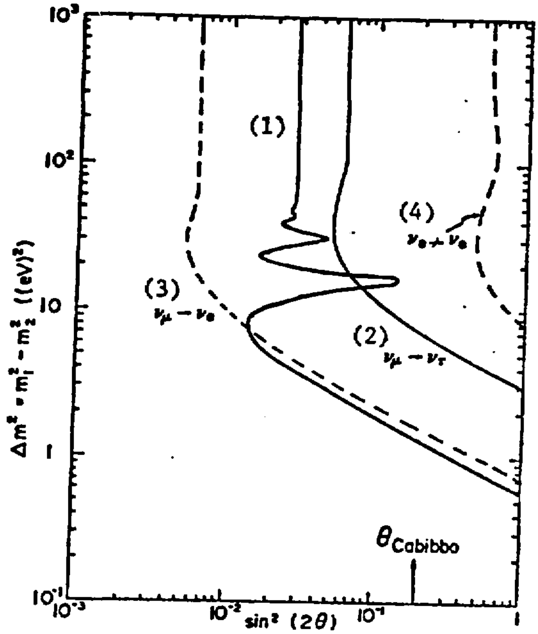
3. The neutral current and neutron star background is estimated to be 18.5% in this energy interval.

4. This calculation was computed specifically for this experiment, based on the work of C.H. Albright, R. Shrock and J. Smith, Phys. Rev. D20, 2177 (1979).

5. G. Feldman, M. Perl, Phys. Reports 33C, 268 (1977).

FIGURE CAPTIONS

Fig. 1. Limits on the neutrino oscillation parameters $\sin^2(2\theta)$ vs. δ_m^2. Solid curves (1) and (2) display the 90% C.L. for the transitions $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$, respectively, obtained by the flux independent methods. Dashed curves (3) and (4) display the 90% C.L. for the transitions $\nu_\mu \to \nu_e$ and $\nu_e \nrightarrow \nu_e$, respectively, obtained by the flux subtraction method. The limit on $\nu_\mu \to \nu_\tau$ obtained by the flux subtraction method is identical to curve (2). For each transition the region to the right of the respective curve is excluded by this experiment. Also shown is the Cabibbo angle, θ_c.



10^3
10^2
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2(2\theta)$
$\Delta m^2 = m_1^2 - m_2^2$ ((eV)^2)
(1)
(2)
$\nu_\mu - \nu_\tau$
(3)
$\nu_\mu - \nu_e$
(4)
$\nu_e \nrightarrow \nu_e$
$\theta_{Cabibbo}$

Fig. 1