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## Limits on Neutrino Oscillations from Muon-decay Neutrinos

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Abstract: No evidence for neutrino oscillations is seen in our experi-  
ment which observed neutrinos from muon-decays at rest.  
Upper limits on oscillation parameters are presented for  
neutrino mixing of the kind  $\nu_e \leftrightarrow \nu_\mu$  and also of the kind  
 $\nu_e \leftrightarrow \nu_i$ ,  $i \neq \mu$ .

In a recent Letter<sup>1</sup>, we pointed out that our neutrino experiment on  
the nature of muon conservation also provides an upper limit on neutrino  
oscillations. Here we present a more detailed analysis of this result.

Neutrino oscillations, first proposed by B. Pontecorvo<sup>2</sup> and by Z.  
Mako, et al<sup>3</sup>, are of considerable interest in the light of gauge  
theories with broken lepton flavor symmetry. Experimental upper limits  
on neutrino oscillations have been reported by E. Bellotti et al.,<sup>4</sup> and  
by J. Blietschau et al.<sup>5</sup>; F. Reines et al. have reported evidence for  
neutrino instability.<sup>6</sup>

In our analysis we make use of our previously published evidence<sup>1</sup>  
that muon conservation is an additive law. We also make the simplifying  
assumption that oscillations occur between only two neutrino states.  
Neutrino mixing is then described by a 2 x 2 matrix and the oscillations  
depend on two parameters, the mixing angle  $\theta$ , and the mass difference  
 $\Delta = (m_1^2 - m_2^2)$  between neutrino mass eigenstates. The oscillation

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probability for neutrinos of momentum  $p$  at a distance  $D$  from the source is given by

$$P(\nu_a \rightarrow \nu_b) = 0.5 \sin^2 2\theta \left(1 - \cos \frac{D\Delta}{2p}\right). \quad (1)$$

In the experiment we utilized a six-ton water Cerenkov counter to observe  $\nu_e$  and  $\bar{\nu}_e$  from the decay chain  $\pi^+ \rightarrow \mu^+ \nu_\mu$  (at rest) and  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$  (at rest) by the charged current reactions  $\bar{\nu}_e p \rightarrow n e^+$  (in  $H_2O$ ) and  $\nu_e d \rightarrow p p e^-$  or  $\bar{\nu}_e d \rightarrow n n e^+$  (in  $D_2O$ ). The neutrino source was the Clinton P. Anderson Meson Physics Facility (LAMPF) beam stop at a mean distance of 9 m from the detector. For details, see Ref. 1. The results<sup>7</sup> are

$$R = \bar{\nu}_e/\mu^+ \text{ decay} = 0.00 \pm 0.06 \quad (2)$$

and

$$R' = \nu_e/\mu^+ \text{ decay} = 1.09 \pm \begin{matrix} 0.37 \\ 0.41 \end{matrix} \quad (3)$$

where we have added (in quadrature) a  $\pm 10\%$  uncertainty in neutrino flux and a  $+25\%/-10\%$  uncertainty<sup>8</sup> in the neutrino deuteron cross-section calculation of J.S. O'Connell<sup>9</sup> to our experimental error in  $R'$ .

Our null result (2) for  $R$  is a direct upper limit on  $\nu_e \leftrightarrow \nu_\mu$  oscillations producing  $\bar{\nu}_e$  from the  $\bar{\nu}_\mu$  in the muon decay. To evaluate this limit we weight the muon-decay  $\bar{\nu}_\mu$  spectrum by the  $E^2$  dependence of the cross section and by the oscillation probability (1) averaged over the finite detector size (1.8 m) to obtain a predicted spectrum shape and normalization for any combination of the oscillation parameters  $\Delta$  and  $\theta$ . After folding in the experimental resolution we fit these spectra to our observed spectrum of  $H_2O$  events (Ref. 1, Fig. 2) above our energy cutoff of 25 MeV, to obtain the 68% and 90% confidence level upper limits on  $\Delta$ , as a function of the mixing parameter,  $\sin^2 2\theta$ , shown in Fig. 1.

Our heavy water measurement (3) does not distinguish electron neutrinos and electron antineutrinos. Since two muon neutrinos are produced for every electron neutrino in the  $\pi$ - $\mu$ - $e$  decay sequence,

$\nu_\mu \leftrightarrow \nu_e$  oscillations would increase  $R'$ . However, our water measurement (2), which yielded Fig. 1, is a far more sensitive test for oscillations of this kind and limits their contribution to  $R'$  to a negligible level.

In the absence of  $\nu_e \leftrightarrow \nu_\mu$  oscillations,  $\nu_e$  can still disappear by oscillations of the kind  $\nu_e \leftrightarrow \nu_i$ ,  $i \neq \mu$ , (e.g.,  $\nu_e \leftrightarrow \nu_\tau$ ), thus decreasing  $R'$ . Therefore, our observation (3) of  $R'$  at full strength puts a limit, albeit much weaker because of the big error bars, on such oscillations. For any combination of  $\Delta$  and  $\theta$ , we fit the expected spectrum of the original  $\nu_e$  events, less those that have changed into  $\nu_i$ , to our observed spectrum (Ref. 1, Fig. 1) of  $D_2O$  events (above 25 MeV) with the folding procedure described above. We obtain the 68% and 90% confidence level upper limits on  $\Delta$ , as a function of  $\sin^2 2\theta$ , shown in Fig. 2.

We note that the curves of Fig. 1 and Fig. 2 are not asymptotic. The limits oscillate with  $\Delta$ , dramatically in the case of  $\nu_e \leftrightarrow \nu_i$  ( $i \neq \mu$ ). Fig. 3 and Fig. 4 show the large  $\Delta$  behavior of the limits for both cases.

We conclude that our experiment does not show evidence for neutrino oscillations at the levels of sensitivity indicated in the figures.

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### Figure Captions

- Fig. 1 Upper limit on  $\nu_e \leftrightarrow \nu_\mu$  from H<sub>2</sub>O data.
- Fig. 2 Upper limit on  $\nu_e \leftrightarrow \nu_i$  ( $i \neq \mu$ ) from D<sub>2</sub>O data.
- Fig. 3 Large  $\Delta$  behavior of  $\nu_e \leftrightarrow \nu_\mu$  limit. The allowed region is to the left of the curves.
- Fig. 4 Large  $\Delta$  behavior of  $\nu_e \leftrightarrow \nu_i$  ( $i \neq \mu$ ) limit. The allowed region is to the left of the curves.

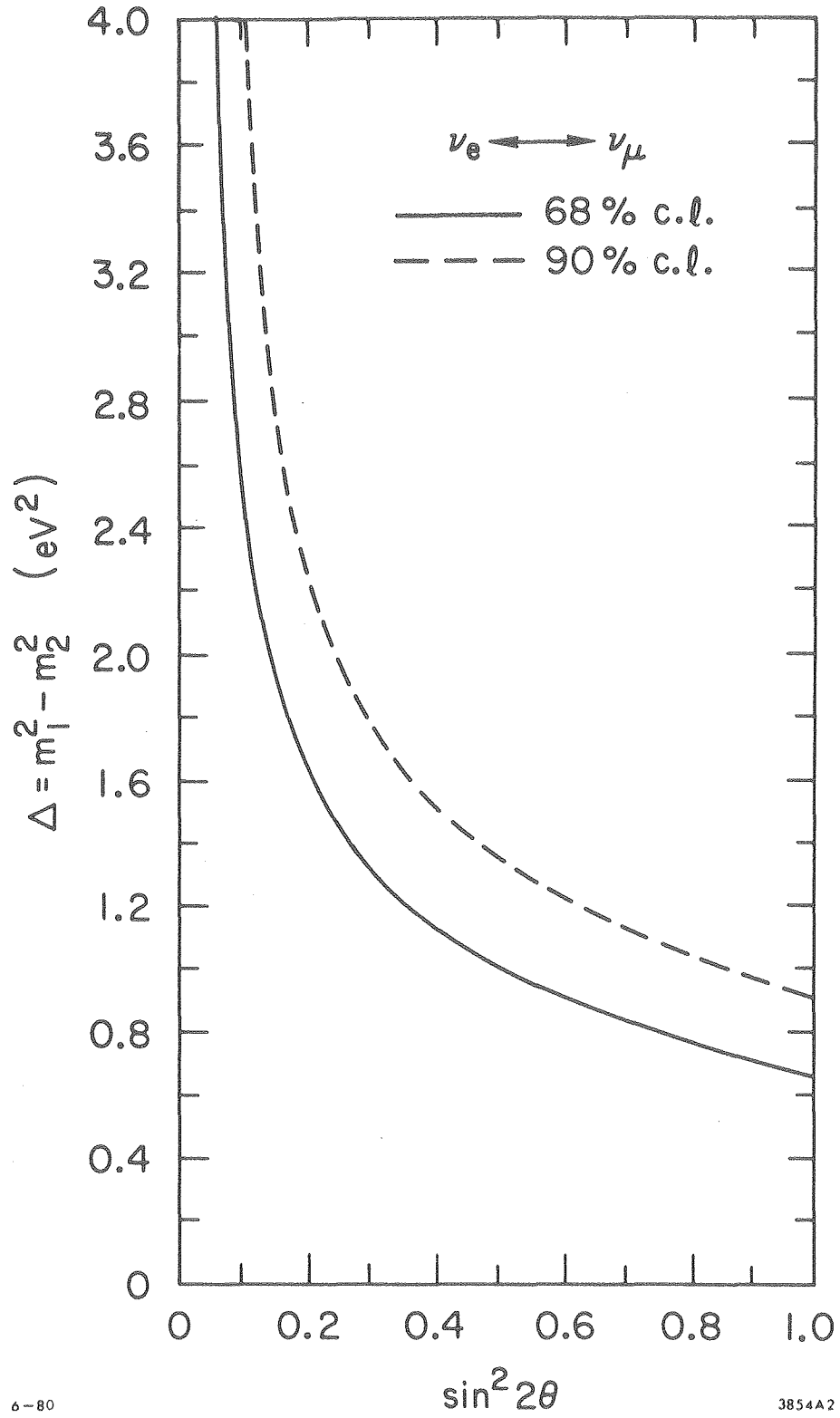


Fig. 1

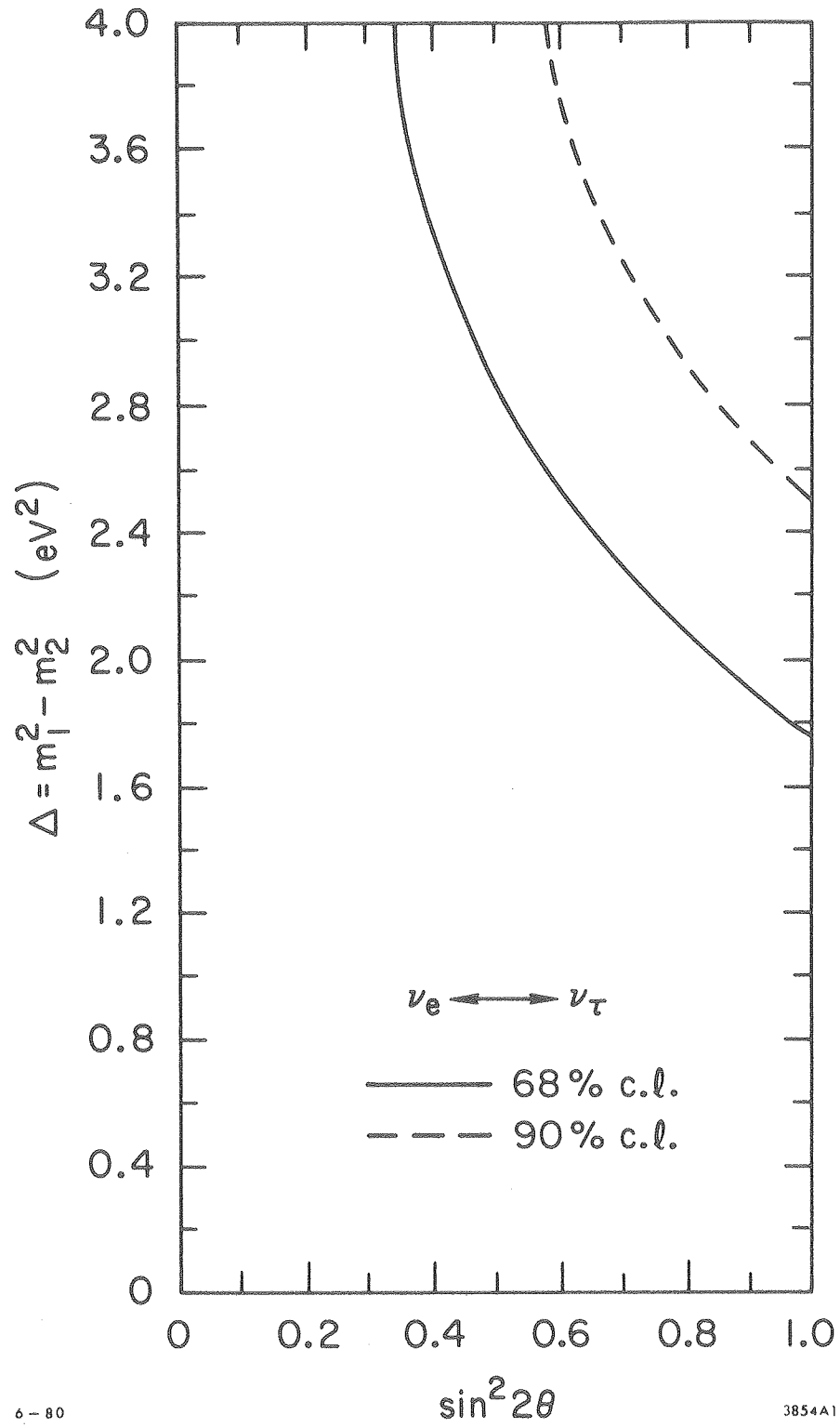


Fig. 2



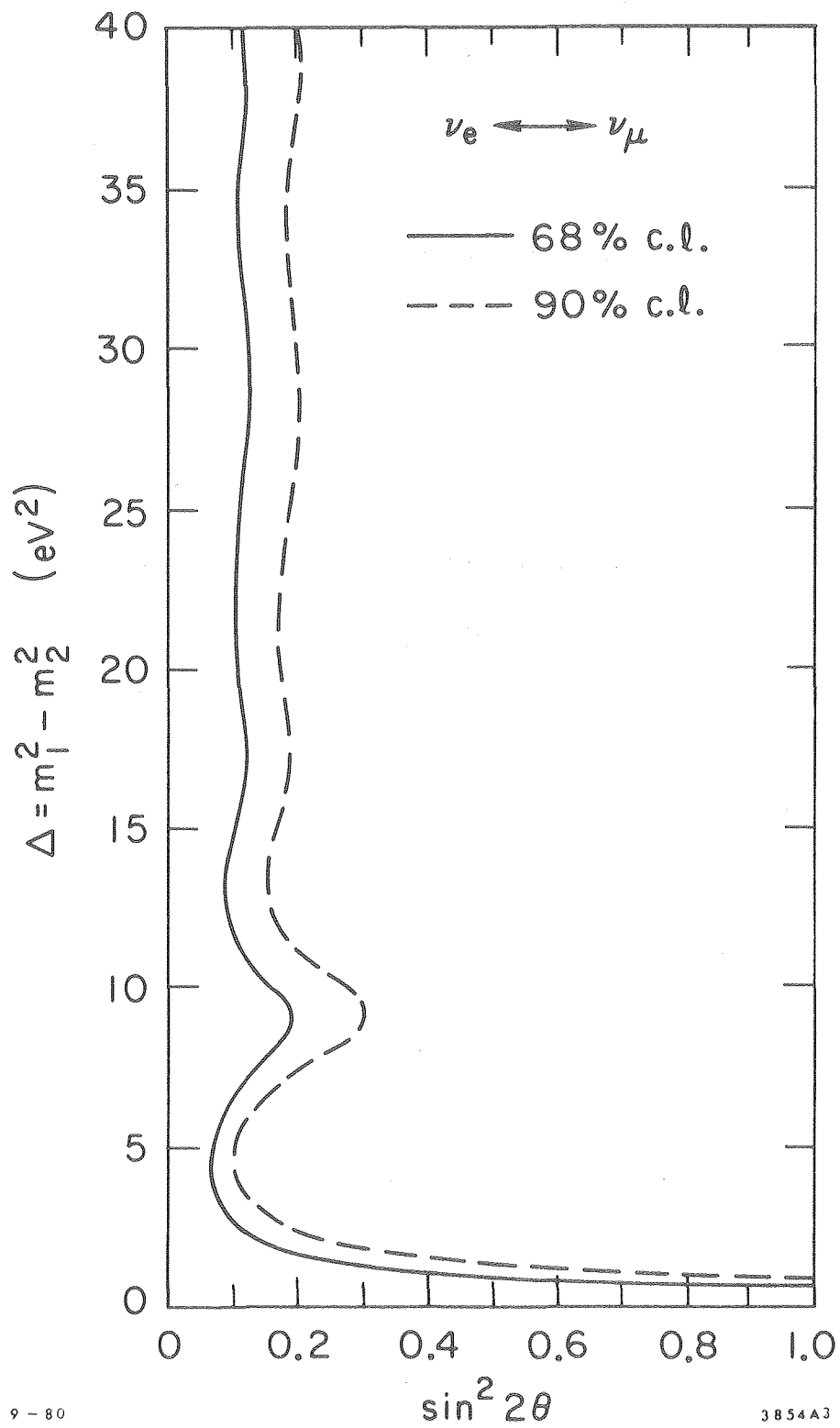


Fig. 3

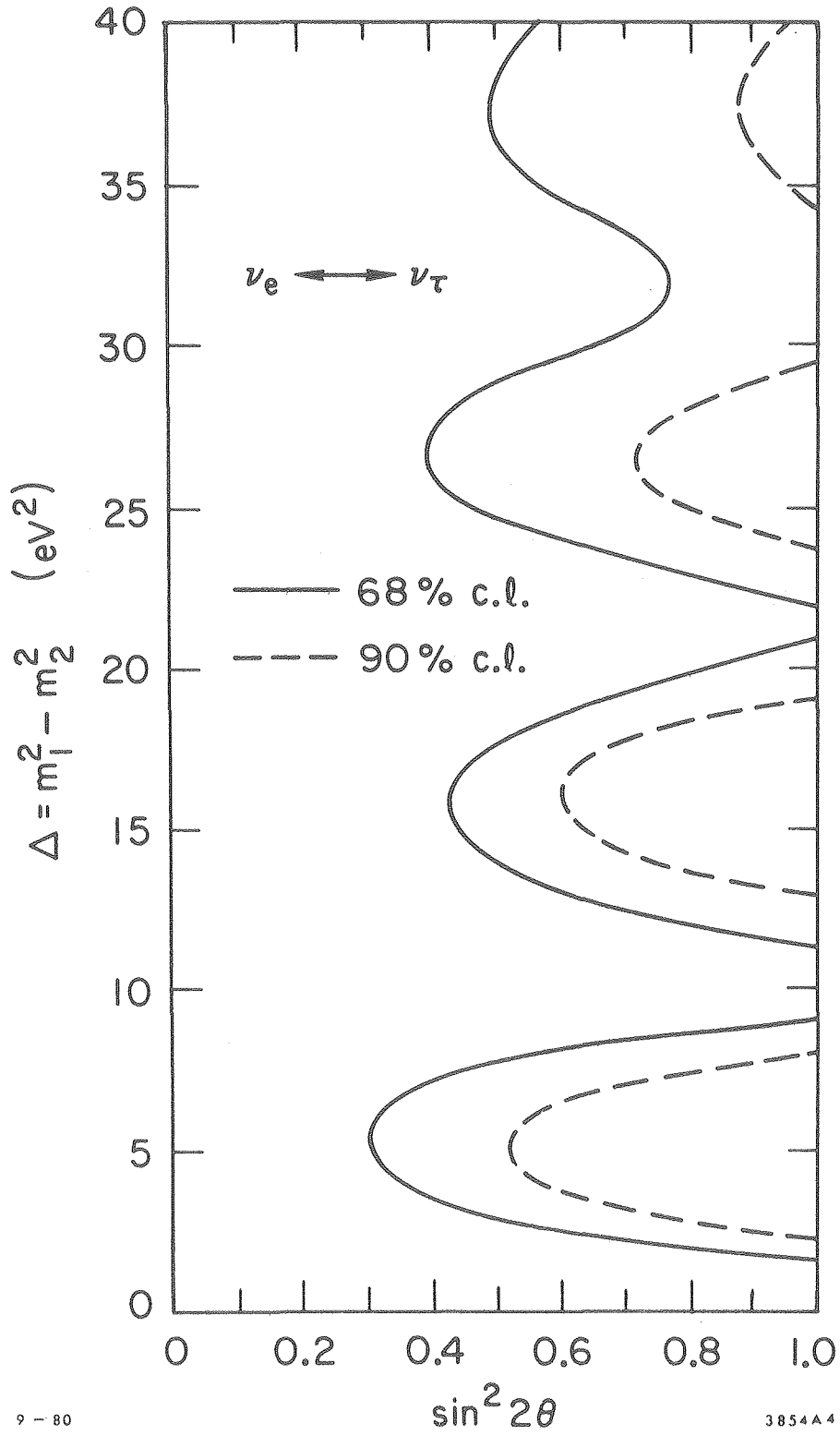


Fig. 4