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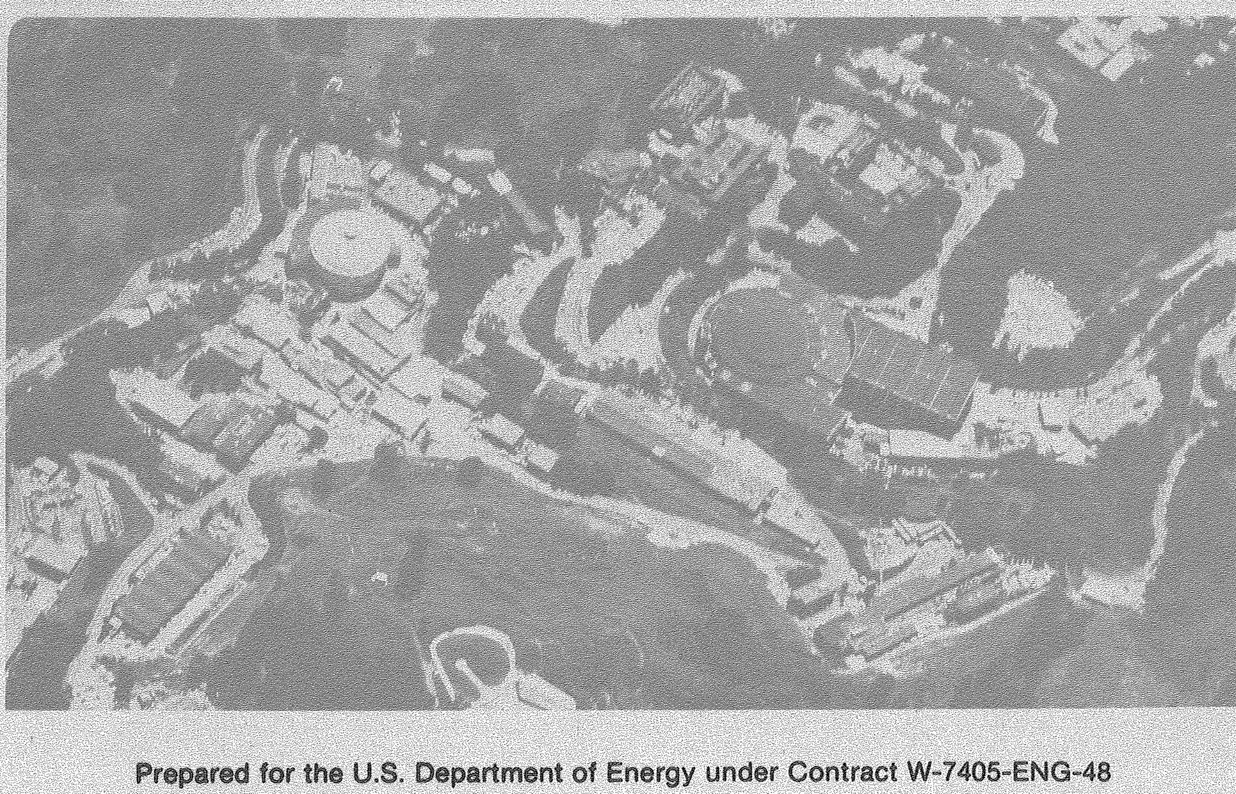

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Limits on Neutrino Oscillations from Muon-decay Neutrinos

P. Némethy, R.L. Burman, D.R.F. Cochran, J. Duclos, J.S. Frank, C.K. Hargrove, V.W. Hughes, H. Kaspar, U. Moser, R.P. Redwine and S.E. Willis[(a)]

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Abstract: No evidence for neutrino oscillations is seen in our experiment 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[1], 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[2] and by Z. Mako, et al[3], 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.,[4] and by J. Blietschau et al.[5]; F. Reines et al. have reported evidence for neutrino instability.[6]

In our analysis we make use of our previously published evidence[1] 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 θ, 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

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

In the experiment we utilized a six-ton water Cerenkov counter to observe ν_e and $\bar{\nu}_e$ from the decay chain $\pi^+ \to \mu^+ \nu_\mu$ (at rest) and $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ (at rest) by the charged current reactions $\bar{\nu}_e p \to n e^+$ (in H_2O) and $\nu_e d \to p p e^-$ or $\bar{\nu}_e d \to n n e^+$ (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[7] are

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

and

$$R' = \nu_e/\mu^+ \text{ decay} = 1.09 \pm {}^{0.37}_{0.41} \qquad (3)$$

where we have added (in quadrature) a $\pm 10\%$ uncertainty in neutrino flux and a +25%/-10% uncertainty[8] in the neutrino deuteron cross-section calculation of J.S. O'Connell[9] 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 Δ and θ. 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 Δ, 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 π-μ-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, ν_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 Δ and θ, we fit the expected spectrum of the original ν_e events, less those that have changed into ν_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 Δ, 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 Δ , dramatically in the case of $\nu_e \leftrightarrow \nu_i$ ($i \neq \mu$). Fig. 3 and Fig. 4 show the large Δ 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_2O data.

Fig. 2 Upper limit on $\nu_e \leftrightarrow \nu_i$ ($i \neq \mu$) from D_2O data.

Fig. 3 Large Δ behavior of $\nu_e \leftrightarrow \nu_\mu$ limit. The allowed region is to the left of the curves.

Fig. 4 Large Δ behavior of $\nu_e \leftrightarrow \nu_i (i \neq \mu)$ limit. The allowed region is to the left of the curves.

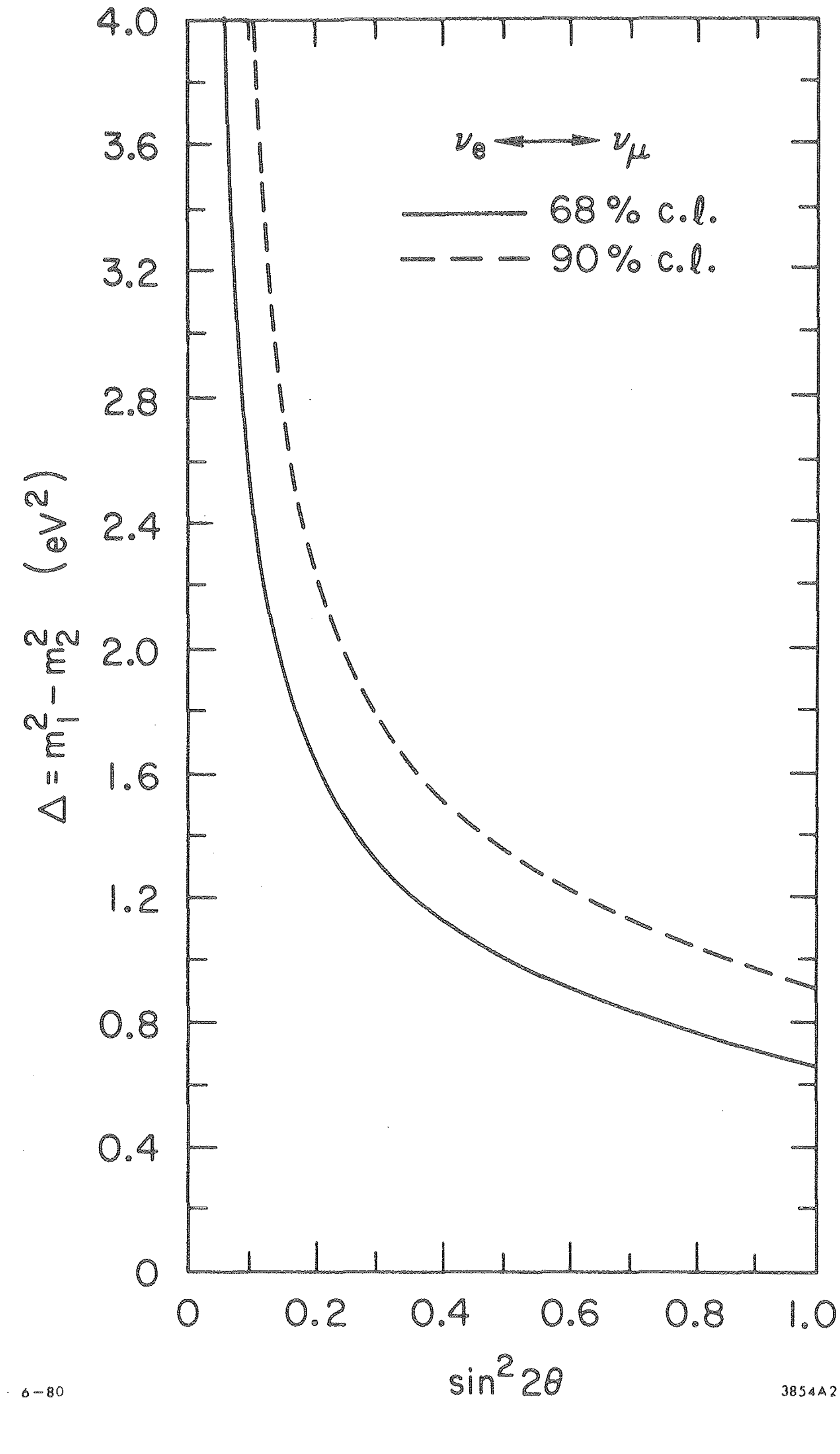
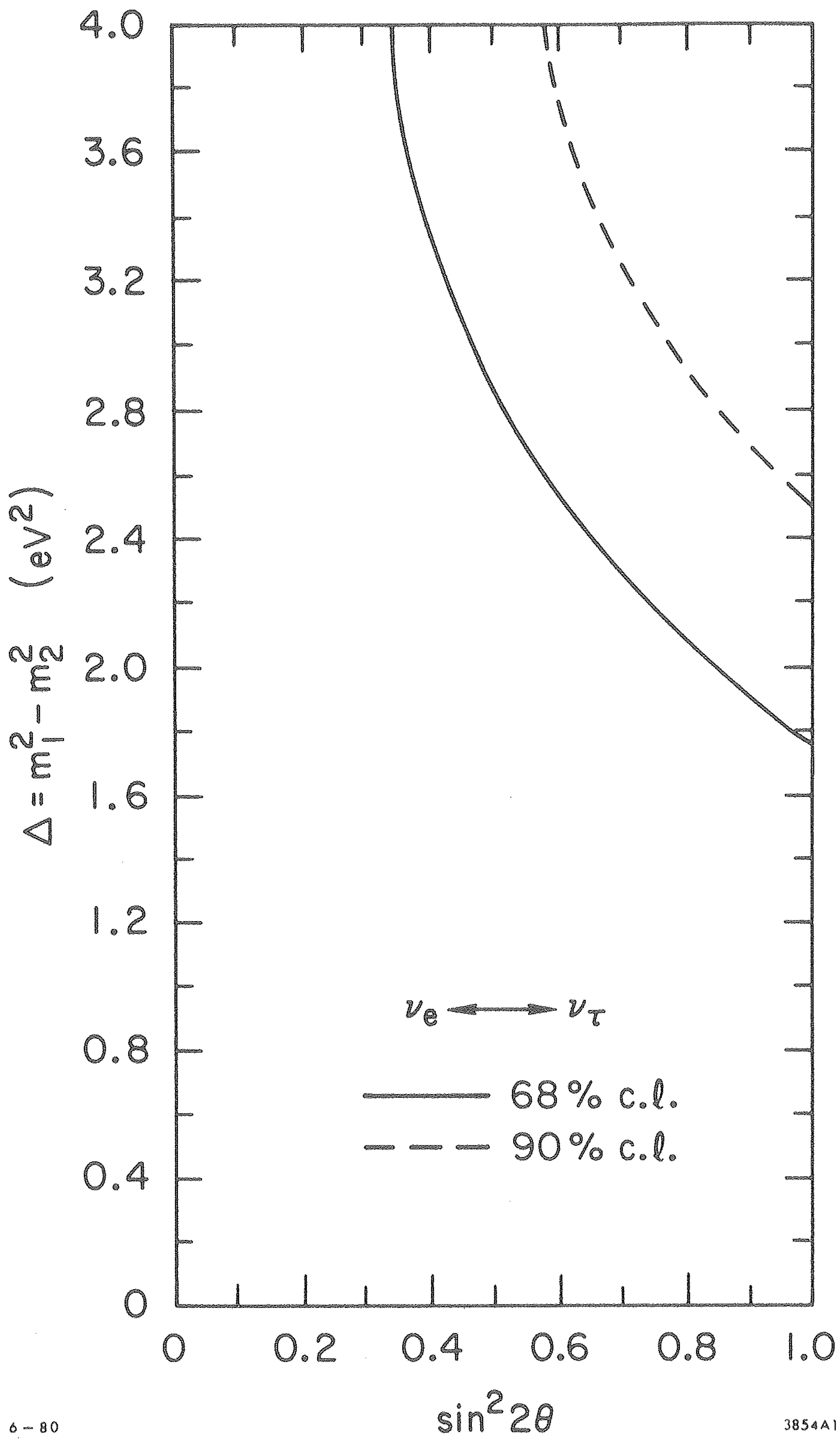

4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0
$\Delta = m_1^2 - m_2^2$ (eV^2)
$\nu_e \longleftrightarrow \nu_\mu$
68 % c.l.
90 % c.l.
0
0.2
0.4
0.6
0.8
1.0
$\sin^2 2\theta$
6-80
3854A2

Fig. 1


4.0
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2.8
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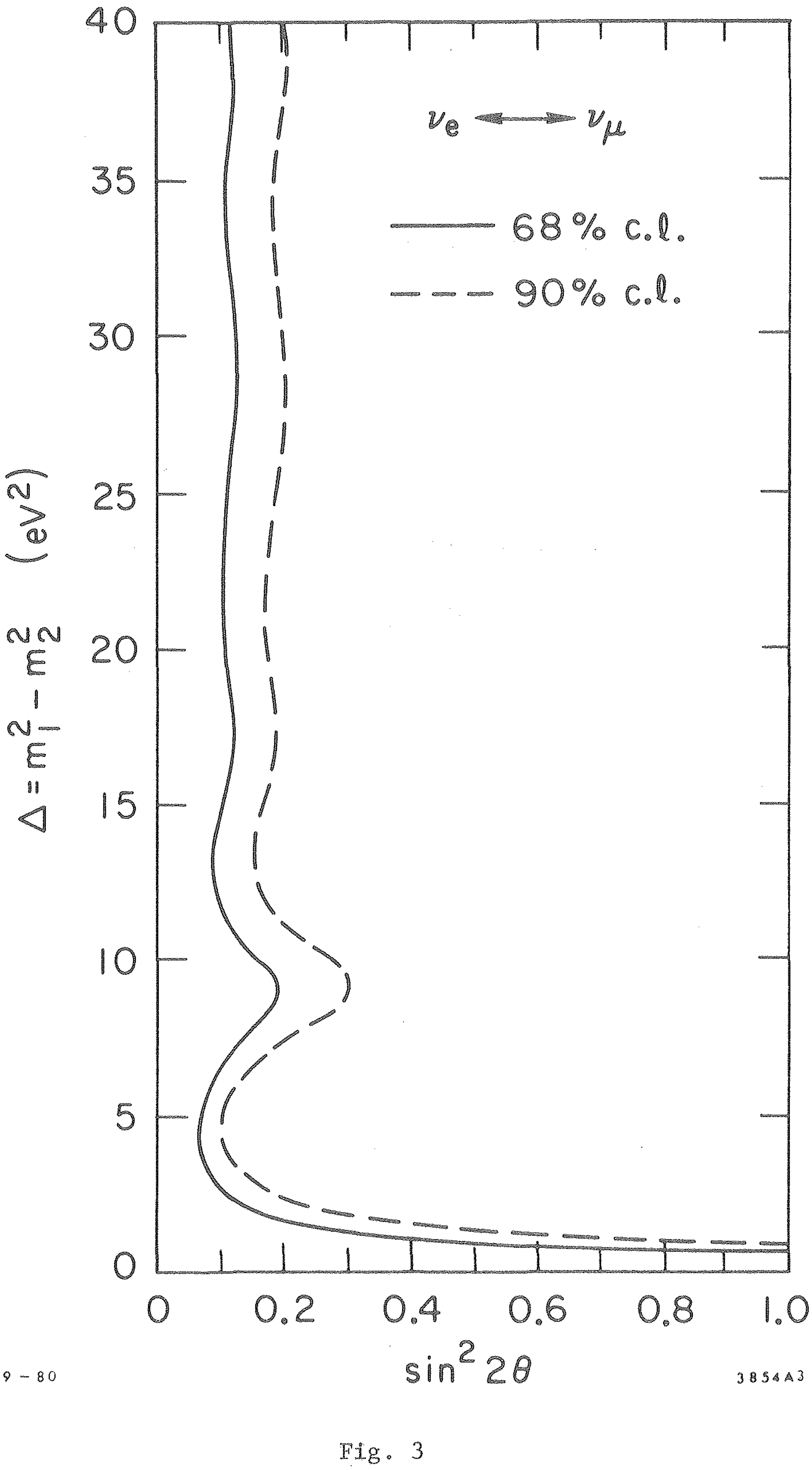
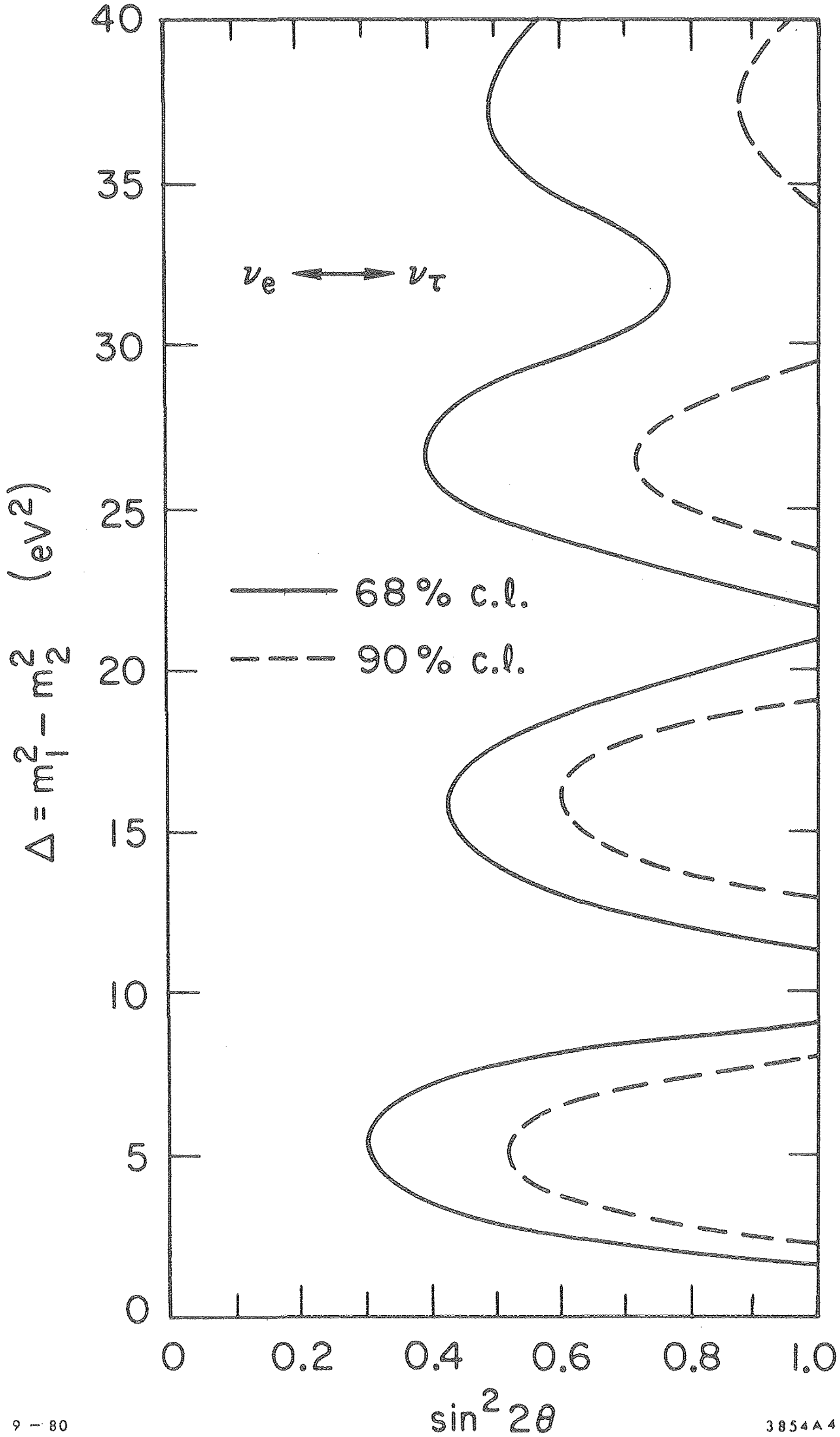
2.0
1.6
1.2
0.8
0.4
0
$\Delta = m_1^2 - m_2^2$ (eV^2)
$\nu_e \longleftrightarrow \nu_\tau$
68 % c.l.
90 % c.l.
0
0.2
0.4
0.6
0.8
1.0
$\sin^2 2\theta$
6-80
3854A1

Fig. 2



$\nu_e \longleftrightarrow \nu_\mu$
68% c.l.
90% c.l.
$\Delta = m_1^2 - m_2^2 \quad (eV^2)$
0
5
10
15
20
25
30
35
40
0
0.2
0.4
0.6
0.8
1.0
$\sin^2 2\theta$
9 - 80
3854A3

Fig. 3



40
35
30
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1.0
$\nu_e \longleftrightarrow \nu_\tau$
68% c.l.
90% c.l.
$\Delta = m_1^2 - m_2^2$ (eV^2)
$\sin^2 2\theta$
9-80
3854A4

Fig. 4