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MATTER ENHANCED OSCILLATIONS OF ACCELERATOR NEUTRINOS

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Abstract

New ranges of neutrino oscillation parameters can be probed by sending accelerator produced neutrinos to large neutrino detectors thousands of kilometers away. Since the neutrino propagation is through the Earth, $\nu_\mu - \nu_e$ and $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations can be quite different from vacuum oscillations. For the accelerator and detector parameters of one such experiment previously suggested, the presence of background matter enhances neutrino mixing for mass differences in the range $0.5 \times 10^{-2} eV^2 < m_2^2 - m_1^2 < 5 \times 10^{-2} eV^2$ and suppresses mixing below this range. The enhanced range is below that probed by present accelerator or reactor experiments and is of current interest for checking whether the anomalous results observed for atmospheric neutrinos are due to neutrino oscillations.

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Accelerators are now commonly used to produce high intensity beams of neutrinos. One use of these neutrino beams is to search for evidence of neutrino oscillations in laboratory experiments. The recent advent of large, independent, neutrino detectors has made it feasible to extend these oscillation experiments outside of a single laboratory. Two such very long baseline neutrino oscillation experiments have been suggested [1,2] that would use a beam of neutrinos from Fermilab and either the IMB or DUMAND detectors. In such experiments, the neutrinos will propagate through the Earth's crust where matter enhanced oscillations can be relevant [3,4]. For two general reviews of neutrino oscillations in matter, see [5,6]. In the following, we discuss how the effects of matter on the neutrino flavor content can be used to aid the search for neutrino masses and mixing angles.

The long neutrino propagation distances in these suggested experiments allow them to probe small values of the neutrino mass difference, $\Delta = m_2^2 - m_1^2$ (see eqs. (2,6)). The relevant range of Δ is below that probed by other laboratory experiments and is especially interesting because of recent evidence for neutrino oscillations in atmospheric neutrino data [7]. Kamiokande-II has recently reported anomalous values for their contained atmospheric neutrino events. These results can be explained by muon neutrino oscillations with Δ in the range of $10^{-4} eV^2$ or larger (95 %CL) with the preferred value of Δ at $1.2 \times 10^{-2} eV^2$ [8,9]. This turns out to be the value of Δ for which matter effects enhance the oscillation of accelerator neutrinos. In contrast to the atmospheric neutrinos, the magnitude and flavor content of neutrinos from an accelerator would be known with greater confidence and the event rate would be much larger. Thus the suggested experiments would allow a much more thorough search for neutrino oscillations.

There are three flavors of neutrinos, and in principle one should consider all three flavors oscillating together. However the main emphasis here is to demonstrate the importance of matter on oscillations of accelerator neutrinos, so only two flavor oscillations will be considered. Normal matter treats ν_e differently than ν_μ or ν_τ since the former can forward scatter via the charged weak current. Thus there are two general types of effective two flavor oscillations for the muon neutrino; oscillations where matter effects are important, $\nu_e - \nu_\mu$ ($\bar{\nu}_e - \bar{\nu}_\mu$), and vacuum oscillations, $\nu_\mu - \nu_\tau$ ($\bar{\nu}_\mu - \bar{\nu}_\tau$).

For vacuum oscillations there is a simple, analytic expression for the probability of a ν_μ becoming a ν_τ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$)

$$P(\nu_\mu \rightarrow \nu_\tau) \;=\; \frac{1}{2}\sin^2 2\theta \left[1 - \cos\left(\frac{2\pi x}{\lambda}\right)\right] \tag{1}$$

Here θ is the vacuum mixing angle, x the propagation distance and λ the vacuum oscillation wavelength,

$$\lambda \;=\; 5.0 \times 10^3 km \left(\frac{10^{-2} eV^2}{\Delta}\right)\left(\frac{E}{20GeV}\right) \tag{2}$$

and E is the neutrino energy.

When matter effects are important, as in $\nu_\mu - \nu_e$ or $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations, the flavor amplitude of the neutrino, ν_α, is described by the differential equation [10]

$$i\frac{d}{dx}\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} = \frac{1}{4E}\begin{bmatrix} A - \Delta C_{2\theta} & \Delta S_{2\theta} \\ \Delta S_{2\theta} & -A + \Delta C_{2\theta} \end{bmatrix}\begin{bmatrix} \nu_e \\ \nu_\mu \end{bmatrix} \tag{3}$$

$A = 2\sqrt{2}G_F(Y_e\rho(x)/m_u)$E is the induced mass squared of the electron neutrino where $\rho(x)$ is the density, m_u the nucleon mass and Y_e is the number of electrons per nucleon.

$$A \;=\; 0.76 \times 10^{-2}\ eV^2 \cdot \left(\frac{Y_e\rho}{2.5\frac{gm}{cm^3}}\right) \cdot \left(\frac{E}{20GeV}\right) \tag{4}$$

When the diagonal elements of eq. (3) are equal,

$$A \;=\; \Delta \cos 2\theta \tag{5}$$

a resonance occurs and the off diagonal terms can lead to large flavor mixing, even for small vacuum angles. The resonance occurs for neutrinos if $\cos 2\theta > 0$ or for antineutrinos if $\cos 2\theta < 0$ since for antineutrinos the induced mass changes sign, A$\rightarrow -$A. In the following, the mixing angle is assumed to be small in analogy with the quark sector. Then for neutrinos with A $\ll \Delta \cos 2\theta$ matter effects are unimportant and one has essentially vacuum oscillations, while for A $\gg \Delta \cos 2\theta$ matter effects suppress all mixing between the mass eigenstates. For antineutrinos, the resonance doesn't occur and flavor mixing is suppressed for A $\geq \Delta \cos 2\theta$.

The flavor content of a neutrino beam from an accelerator can be adjusted to aid the search for neutrino oscillations. In particular, it is in principle a simple matter to switch the focusing of the decaying pions and kaons so that the negatively charged mesons are focused instead of the positively charged mesons. Then the neutrino beam changes from predominately muon-neutrinos to predominately muon-antineutrinos, with only a small loss of flux. Since matter effects enhance mixing of one and suppress mixing of the other, such a switching could be used as a test for the presence of matter effects on neutrino oscillations.

The typical length scale for observing enhanced neutrino oscillations in matter is found by using the vacuum oscillation wavelength, eq. (2), with the vacuum mass difference replaced by the matter induced mass squared, eq. (4), to yield

$$\lambda_m^0 \; = \; 6400km \left(\frac{2.5 \frac{gm}{cm^3}}{Y_e \, \rho} \right) \tag{6}$$

The actual oscillation wavelength in matter can be much longer than that given by eq. (6) - at the resonance point it takes its largest value

$$\lambda_m \mid_{res} = \frac{\lambda_m^0}{\sin 2\theta} \tag{7}$$

In the proposed experiments, the neutrino propagation occurs in the outer crust of the Earth where the average density varies on distance scales of hundreds to thousands of kilometers [11]. Since these density changes give rise to variation in A(x) on distance scales comparable to that in eq. (6), the flavor propagation equation, eq. (3), must be solved numerically to obtain quantitative results. For the calculations herein, a predictor-corrector method is used to iterate eq. (3).

The two suggested experiments are to aim a Fermilab neutrino beam at IMB and/or DUMAND which are located at distances 580 km and 6200 km away, respectively. Coincidentally, both detectors subtend about the same solid angle, 30 μSr, so the neutrino flux through both detectors will be similar. The largest neutrino signal in both detectors comes from muons, created in the material surrounding the detectors by charged current interactions, that travel through the detector. The energy distribution of these events goes roughly as the neutrino flux distribution times the energy squared; one energy factor is for the cross section and one for the muon range. Using a neutrino energy distribution for through going muons taken from reference [1], and assuming a detector threshold of 0 GeV, the average neutrino energy from this signal is 23 GeV with $\delta E/E \approx 70\%$.

In Figs.(1) and (2) are shown contours yielding a 10% reduction in the through going muon rate for the two suggested experiments. Parameters to the right of the contour result in larger reductions (generally). The neutrino energy thresholds for detecting through going muons at IMB and DUMAND are taken to be 1 GeV and 20 GeV (also 10 GeV and 30 GeV), respectively. Also shown on the figures are limits on neutrino oscillation parameters from reactor neutrino experiments [12], the limits from other accelerator experiments lie well above the parameter range shown on the graphs.

For the suggested IMB neutrino oscillation experiment, only the contour plot for vacuum oscillations is shown. Including matter effects on oscillations produces only minimal changes from this graph. This is because the propagation distance involved in this experiment is so much shorter than the typical length scale for matter oscillations given in eq. (6). IMB can only probe relatively large values of Δ where the induced mass is much smaller and hence matter effects are negligible. This condition is energy independent since the energy cancels out between the oscillation wavelength and the induced mass. Thus matter effects are of only minor importance for this proposed experiment.

For the suggested DUMAND neutrino oscillation experiment, the effects of matter are quite pronounced. The $\nu_\mu - \nu_e$ contour plot shows a large region where matter effects enhance neutrino mixing. With a 20 GeV threshold, the average neutrino energy is increased to 35 GeV. Plugging this and the average crustal density of $Y_e\rho = 1.8gm/cm^3$ into eqs. (4-5) yields a central resonant value of $\Delta = 1.0 \times 10^{-2} eV^2$ in agreement with the contour plot. At the resonant Δ value, the range of vacuum mixing angles probed is limited by the propagation distance, as given in eq. (7). The largest resonant decrease in the ν_μ will occur when the neutrinos travel for just half of an oscillation wavelength. Using eq. (7), a constant density of $Y_e\rho \approx 1.8 gm/cm^3$ and the propagation distance to DUMAND, yields a central minimum at $\sin^2(2\theta) \approx 0.5$. However the actual central point is at a slightly lower value [a 65% reduction in through going muons occurs at $\sin^2 2\theta \approx 0.3$], because the density is not constant and away from the resonance the oscillation wavelength is smaller. The range of Δ probed agrees with estimates using eq.(5), the spread of energies in the neutrino signal, and that the spread in densities along the propagation path is $\delta\rho/\rho \approx 50\%$ [13]. A comparison of the contour plots with and without matter shows that for Δ of 0.1 eV^2 and larger the matter effects are negligible and only vacuum oscillations are relevant, while for Δ well below $0.5 \times 10^{-2} eV^2$ matter effects suppress neutrino mixing. For antineutrinos matter effects suppress all mixing for Δ at and below the resonance region.

Adjustments in the experimental parameters can expand the region of neutrino vacuum parameters probed. Small changes in the focusing and aiming of the neutrino beam and/or changes in the cuts on the neutrino data could lead to large changes in the average energy and the spread of energies of the neutrino signal. Even though such changes would decrease the signal rate, new ranges of neutrino vacuum parameters could be explored since oscillations in vacuum and oscillations in matter are both very energy dependent. Both decreases *and increases* in the average energy would probe new parameter regions since satisfying the resonance condition, eq. (5), allows small vacuum angles to be probed. To illustrate the effects of such changes, Figs. 1 and 2 show contour plots for through going muons at DUMAND with energy thresholds of 10 GeV and 30 GeV, respectively. Such variations in the threshold might come from cuts on the data pertaining to how far across the detector the muon travels.

In summary, a long baseline neutrino oscillation experiment using a neutrino beam from the Fermilab accelerator directed at the DUMAND and/or IMB neutrino detectors can probe new ranges of neutrino vacuum parameters. For $\nu_\mu - \nu_\tau$ oscillations, the presence of background matter is unimportant. For $\nu_\mu - \nu_e$ oscillations, background matter effects are of little importance for IMB but significantly increase the explorable neutrino vacuum parameter region accessible to DUMAND. Mixing is enhanced at resonant values of the neutrino mass difference and suppressed below that. The mixing enhancement occurs in an area below that accessible to oscillation experiments using reactor neutrinos, but in a region where atmospheric neutrino results suggest some evidence for neutrino oscillations.

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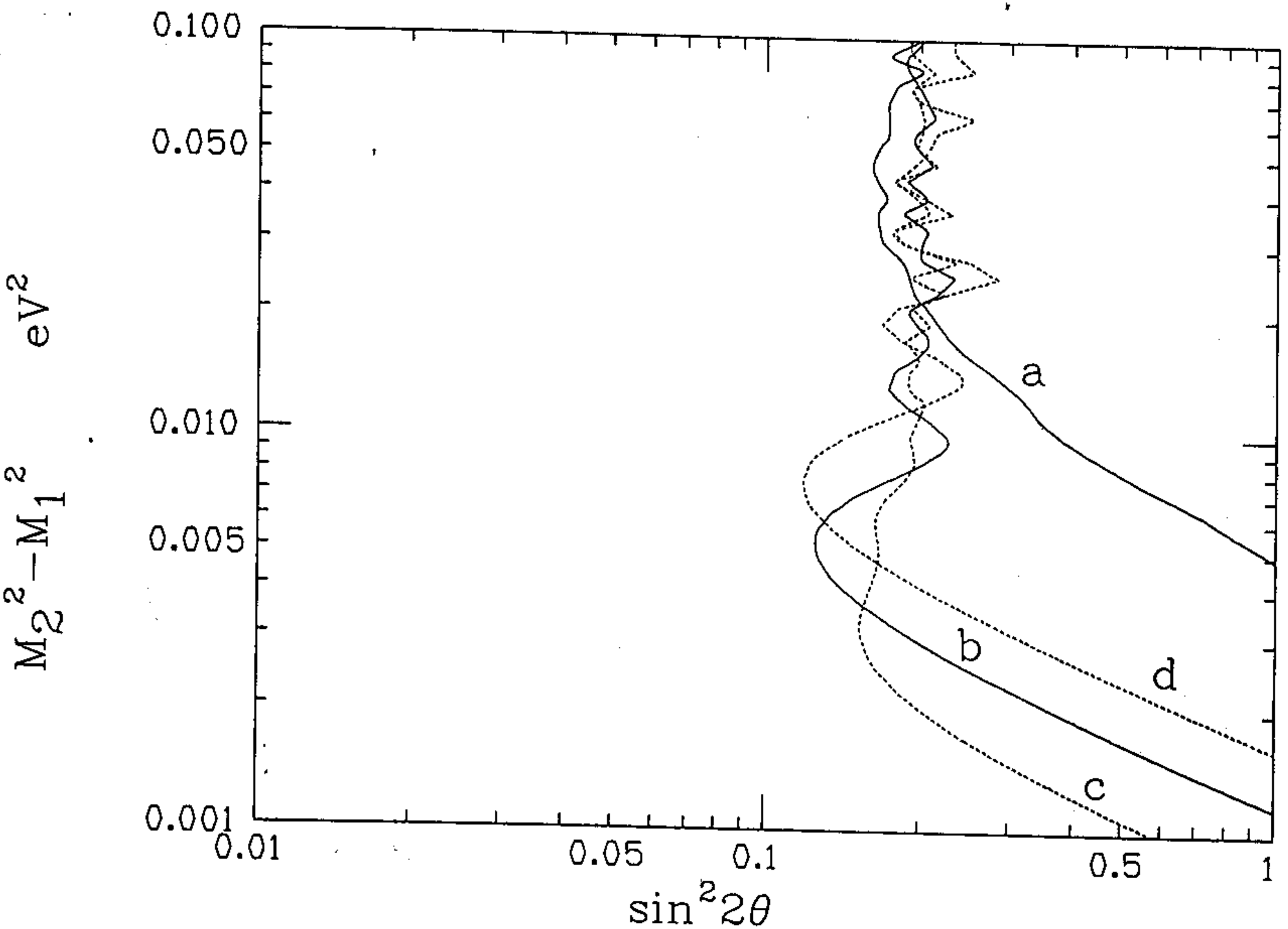
13. Footnote: Propagation through the core would give rise to a much larger range of density variations than propagation through the crust and hence a much larger range of Δ. The higher densities in the core would enhance neutrino mixing at larger Δ values.

Captions

Fig. 1 Contours which yield a 10% reduction in the through going muon rate from vacuum oscillations ($\nu_\mu - \nu_\tau$ or $\bar{\nu}_\mu - \bar{\nu}_\tau$): at IMB with $E^{\nu}_{thr} = 1 GeV$ (a), and at DUMAND with $E^{\nu}_{thr} = 20$ GeV (b), 10 GeV (c) and 30 GeV (d).

Fig. 2 Contours which yield a 10% reduction in the through going muon rate at DUMAND from oscillations in matter. For $\nu_\mu - \nu_e$ oscillations with $E^{\nu}_{thr} = 20$ GeV (a), 10 GeV (b) and 30 GeV (c) and $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations with $E^{\nu}_{thr} = 20$ GeV (d). Also shown are limits on neutrino parameters from reactor experiments [12] (dashed line).



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a
b
c
d

Fig. 1

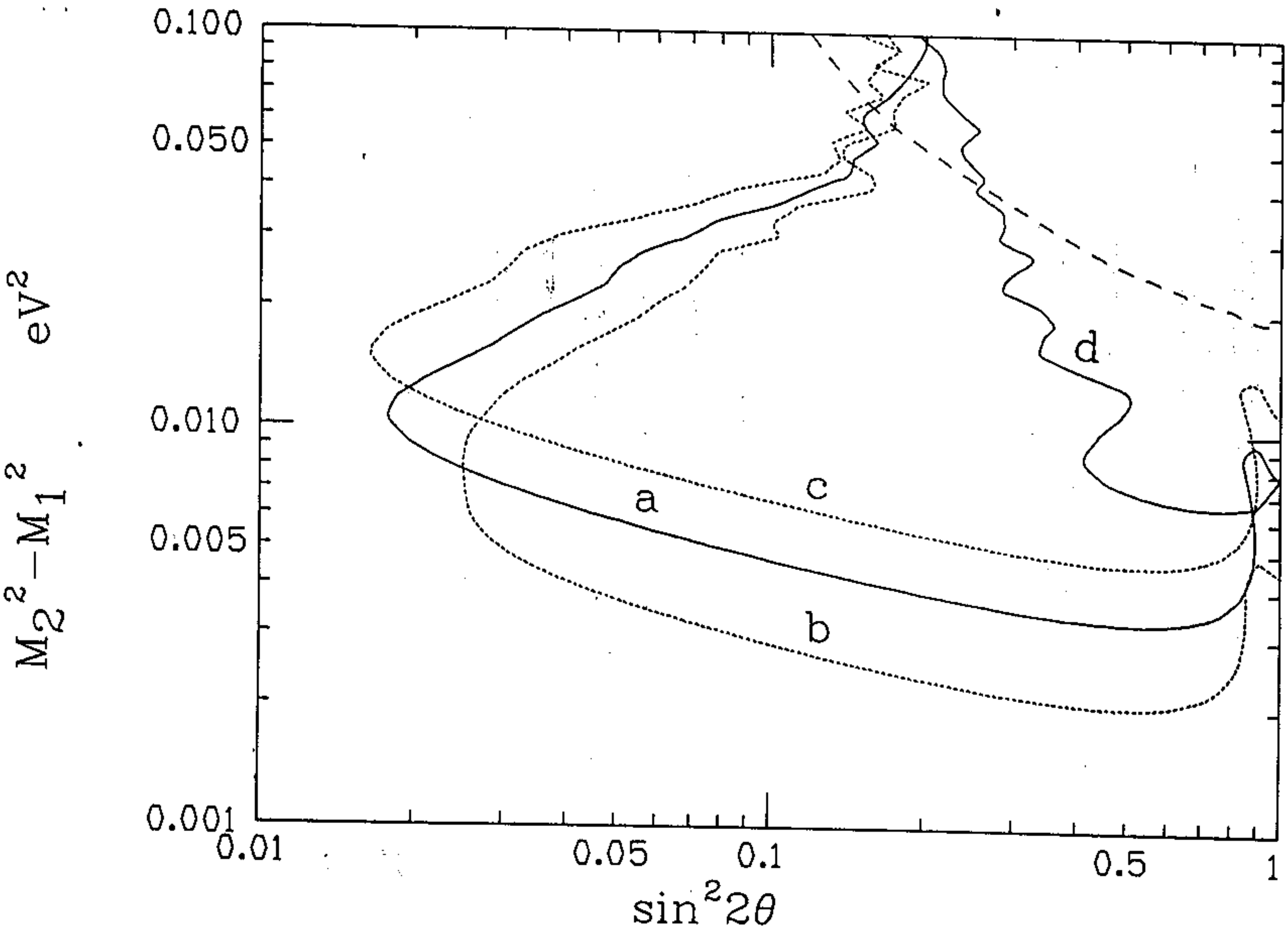
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Fig. 2