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NEUTRINO TRANSFORMATION AND REGENERATION IN THE EARTH

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MATTER OSCILLATIONS: NEUTRINO TRANSFORMATION AND REGENERATION IN THE EARTH

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ABSTRACT

Transformation and regeneration phenomena are calculated to result from transmission through the Earth of neutrinos with $\mathrm{E\,(MeV)}/\Delta m^2\,(\mathrm{eV})^2$ in the vicinity of 10^6 to 10^7. As a result, large time-of-night and seasonal variations are predicted for various solar neutrino experiments in this parameter range. Analagous effects are predicted for terrestrial cosmic ray and accelerator experiments.

1. Introduction

The existence of resonant matter-induced neutrino oscillations as a possible resolution of the "solar neutrino puzzle" was originally understood by Mikheyev and Smirnov.[1] That is, the effect of the solar medium on neutrinos emitted in the sun's central region may well provide the basis for understanding the unexpectedly low counting rate observed in the BNL ^{37}Cl experiment.[2] Such an explanation implies a number of characteristic effects that are open to test in other experiments and would serve as clear confirmations of what we will call the MSW (Mikheyev-Smirnov-Wolfenstein) effect. But as we have shown[3] there is an analogous effect brought on by the neutrinos' passage through the Earth which also would lead to characteristic effects open to experimental test.

In this paper we examine the effect of the Earth's matter on the transformation of neutrinos from one species to another. As will be seen, the effects are dramatically large for some regions of the ratio of neutrino energy to the neutrino mass difference squared. In the appropriate parameter range such transmission phenomena translate for solar neutrinos into time-of-night and time-of-year effects that would be observable in real-time experiments. Depending on time resolution and statistics, such effects could appear as well in radio-chemical experiments. Furthermore, our calculations show large effects for neutrinos created at the surface of the Earth and passing through it.

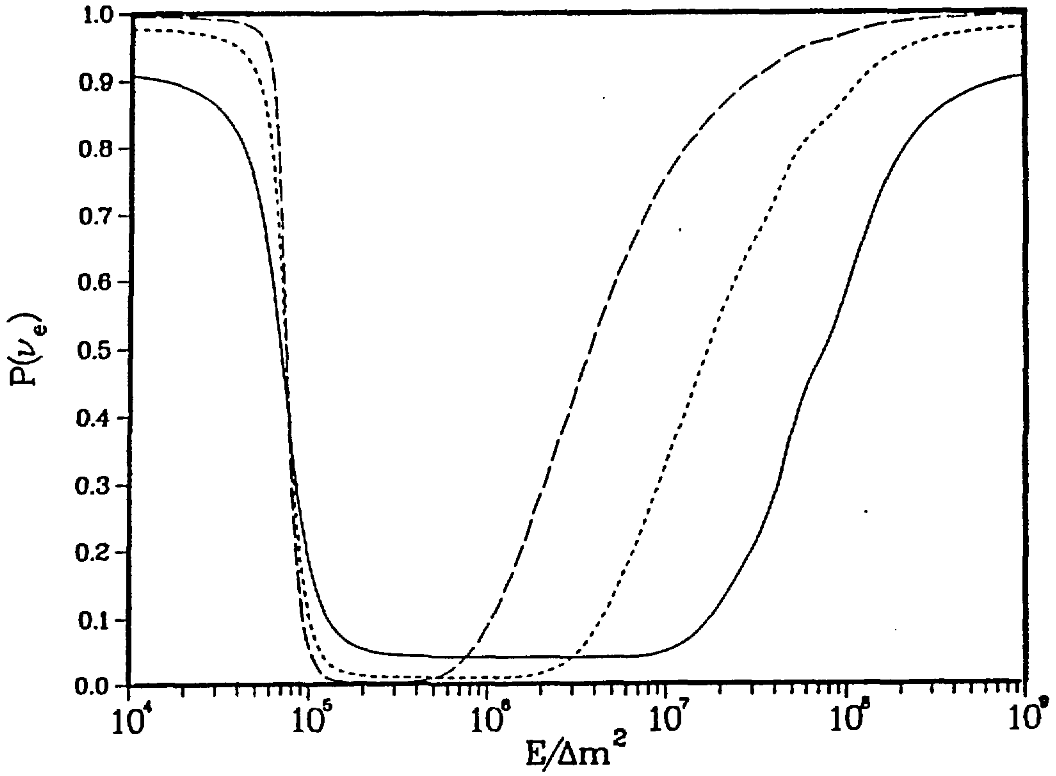


Fig. 1: A recalculation of the Mikheyev-Smirnov solution for the probability that an electron neutrino created in the central solar region will avoid an oscillation transformation and will survive as an electron neutrino in its transit through the solar medium and space to the Earth. Three values of the mixing parameter $\sin 2\theta$ are shown: medium dashes, 0.1; short dashes, 0.2, solid line, 0.4.

We begin our presentation in Section 2 with a discussion of the Mikheyev-Smirnov-Wolfenstein effect in the sun and in the Earth. In Section 3 we discuss the results of the BNL ^{37}Cl experiment in terms of the constraints put on the neutrino mass and mixing angle by it. Seasonal and day-night effects will be considered. Predictions for the MSW effect in the ^{71}Ga solar neutrino experiment are made, including a discussion of its complementarity to the ^{37}Cl experiment and the utility of seasonal and day-night effects. The related phenomenon of matter induced neutrino oscillations in the Earth for accelerator and cosmic ray neutrinos is then treated in Section 4. Next, in Section 5, the proposed detection of spectra of solar neutrinos in a real-time facility such as the Sudbury heavy water detector is investigated with a detailed calculation of the predicted matter effects of the Earth. Finally, in Section 6, some general remarks are made about the effect of the Earth on neutrino oscillations.

2. The MSW Effect in the Sun and in the Earth

The necessary formalism can be taken directly from Wolfenstein[4]; we shall here consider only two neutrino mixing. Then, the general state, a mixture of the two-neutrino species, $|\nu_e\rangle$ and $|\nu_X\rangle$,

$$\Psi(t) = C_e^{(t)}|\nu_e\rangle + C_X^{(t)}|\nu_X\rangle,$$

is described by the transmission equation

$$i\frac{d}{dt}\begin{pmatrix} C_e \\ C_X \end{pmatrix} = \begin{pmatrix} \frac{m_1^2}{2E}\cos^2\theta + \frac{m_2^2}{2E}\sin^2\theta + \sqrt{2}Gn_e & \left(\frac{m_2^2}{2E} - \frac{m_1^2}{2E}\right)\sin\theta\cos\theta \\ \left(\frac{m_2^2}{2E} - \frac{m_1^2}{2E}\right)\sin\theta\cos\theta & \frac{m_2^2}{2E}\cos^2\theta + \frac{m_1^2}{2E}\sin^2\theta \end{pmatrix} \begin{pmatrix} C_e \\ C_X \end{pmatrix}. \tag{2.1}$$

The physical combinations $|\nu_e\rangle$, $|\nu_X\rangle$ are understood to be the combinations of the mass eigen-states $|\nu_1\rangle$ and $|\nu_2\rangle$:

$$\begin{aligned} |\nu_e\rangle &= \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle \\ |\nu_X\rangle &= -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle. \end{aligned} \tag{2.2}$$

The transmission equation is governed by the energy differences (for the same momenta) between the two mass components and by the interaction between the electron-neutrino, $|\nu_e\rangle$, and the electrons of the medium, $\sqrt{2}Gn_e$—an interaction not available to the other neutrino species. G is the Fermi coupling constant and n_e is the number of electrons per cubic centimeter.

The large mixing effects, the basis of the MSW phenomenon, occur at or near the degeneracy that occurs when the neutrino-electron interaction balances out the mass effects. This equality between the diagonal elements,

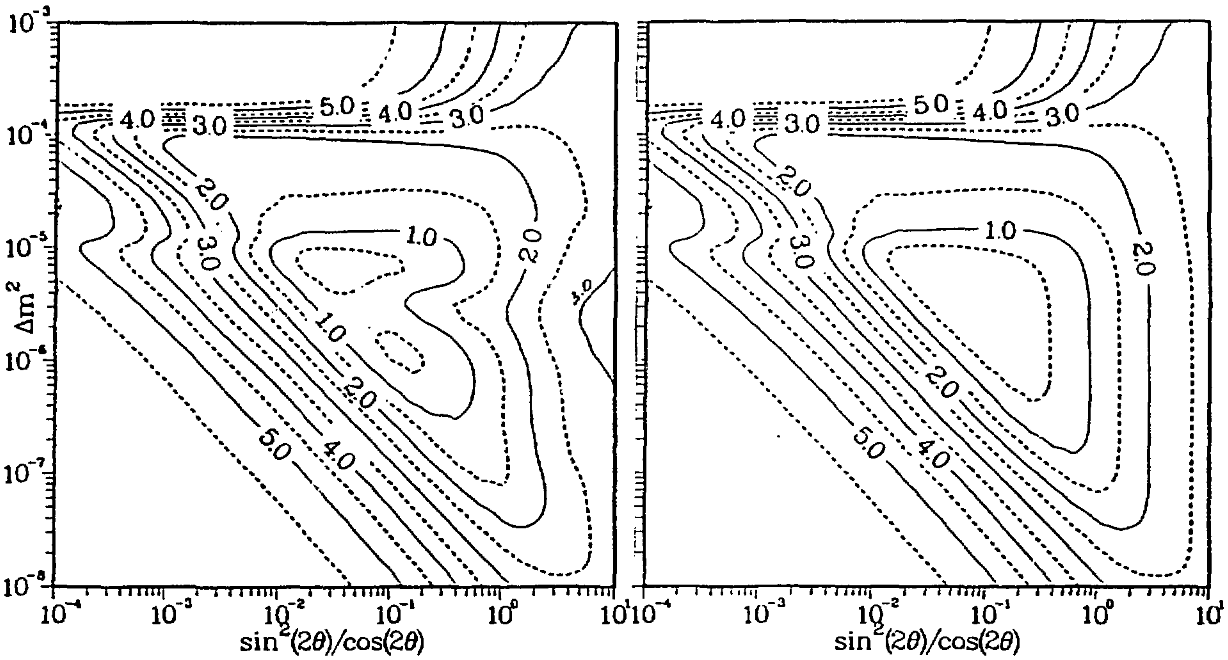
$$\frac{m_1^2 - m_2^2}{2E}\cos 2\theta = -\sqrt{2}Gn_e, \tag{2.3}$$

requires $m_2 > m_1$, which we shall assume to be the case; in familiar units, this optimuum mixing condition is:

$$\frac{E\,(MeV)}{\Delta m^2\,(\mathrm{ev}^2)} \approx \frac{7\times 10^6}{\rho\,(gm/cm^3)\,y_e}\cos 2\theta, \tag{2.4}$$

where ρ is the density of the matter and y_e is the number of electrons per AMU. Since the density of the earth varies from ~ 3 at the surface to ~ 13 at the center[5] and $y_e \sim 1/2$, neutrinos for which $E/\Delta m^2$ lies in the region $\sim 10^6$ to $\sim 10^7$ should show interesting effects.

For the effects on solar neutrinos the fundamental equations must be solved in both the sun and in the Earth. As we have shown,[3] a narrow energy averaging in detected neutrinos on the Earth is sufficient to justify dropping rapidly oscillating terms related to the Earth-sun separation distance. Figure 1 contains a recalculation of that originally



(a) (b)

Fig. 2: Contours for the ^{37}Cl experiment labeled by SNU values (see text).

given by Mikheyev and Smirnov.[1] It turns out that for these experimental conditions the calculation of the MSW effect in the sun, such as in Figure 1, may be accurately carried out using the adiabatic and Landau-Zener approximations.[6] However for transmission through the Earth, numerical solution of the fundamental Eq. (2.1) appears to be the most satisfactory way to get trustworthy results. The form of the first order coupled differential equations for probabilities as written by Mikheyev and Smirnov,[1] are solved using the Bashforth-Adams-Milne predictor-corrector method.[7] The physically interesting initial conditions at the surface of the earth differ, however, from those usually considered; instead of limiting the discussion to the familiar one in which the initial neutrino state is pure $|\nu_e\rangle$, two different initial mixtures are included in order to accomodate studies of solar neutrinos, which via their oscillation in transit through the solar medium and in space, arrive in a spectrum of mixtures. One obtains[3] an expression for the probability $\overline{P}_{SE}$ that an electron neutrino emitted within the sun remains an electron neutrino after passing through the sun and through the earth

$$\overline{P}_{SE} = 1 + 2\overline{P}_S P_{E1} - \overline{P}_S - P_{E1} - \frac{1}{2}\left(2\overline{P}_S - 1\right)\left(2P_{E2} - 1\right)\tan 2\theta. \qquad (2.5)$$

In this expression $\overline{P}_S$ is the energy averaged (over a part in 100) solution in the sun (Figure 1), P_{E1} is the probability that an electron neutrino emitted at the surface of the earth and passing through it remains an electron neutrino, and P_{E2} is the probability of finding an electron neutrino after transmission that begins at the Earth's surface with the

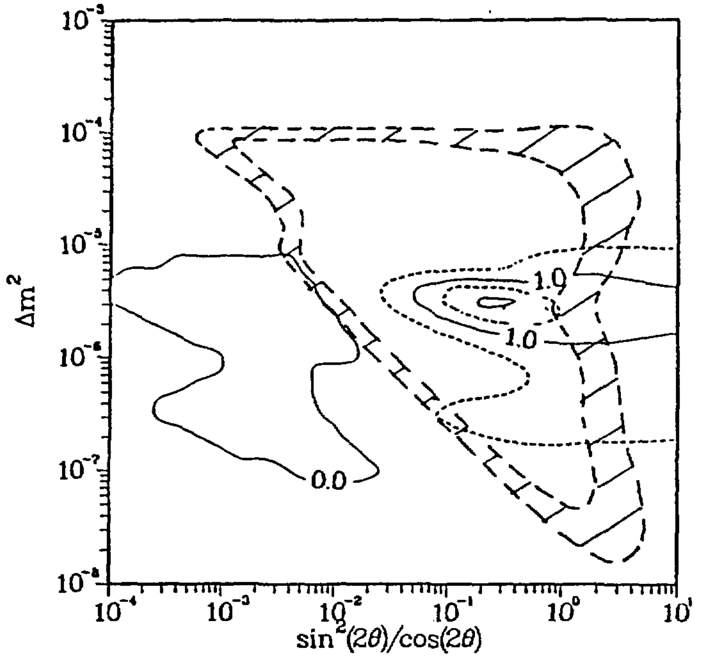
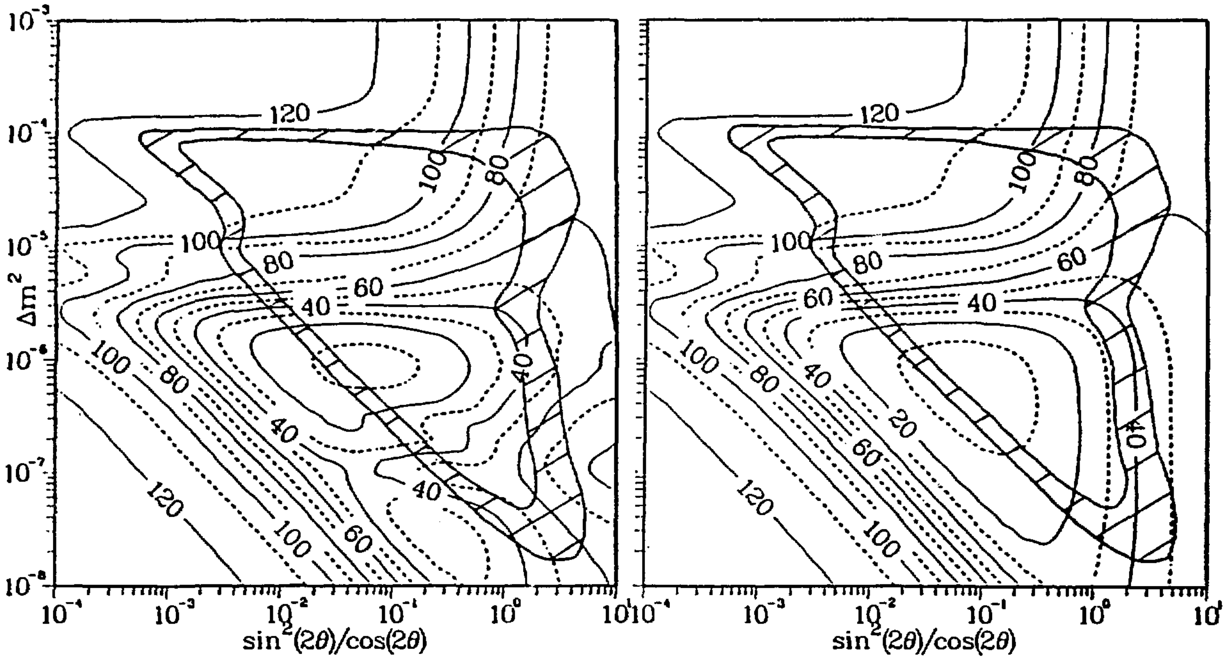


Fig. 3: Night minus day contours for the ^{37}Cl experiment labeled by SNU values (see text). Shaded out is the region consistent with the existing experimental result of 2.1 ± .3 SNU.

boundary condition of equal parts of both species of neutrinos and real relative phases. θ is of course the mixing angle. It is important to note that the oscillation phase must not be averaged for the Earth transmission solutions. Both P_{E1} and P_{E2} are functions of the trajectory from entry to detector.

3. ^{37}Cl Results and the ^{71}Ga Experiment

Since the data in the ^{37}Cl experiment was taken night and day over a number of years, effects of the Earth would affect the count rate only in an average way in the region of the parameters Δm^2 and $\sin 2\theta$ where an Earth effect occurs. Figure 2a shows contour lines of the expected detected neutrinos by the ^{37}Cl experiment as a function of these parameters. Standard solar model values[8] have been used for sources of neutrinos consistent with a predicted flux of 5.8 SNU in the ^{37}Cl experiment. The effect of the Earth has been included in the calculation of the contours by averaging over day and night and seasonal changes for a year. For comparison Figure 2b displays the contours of equal numbers of counts (in SNU) without the effect of the Earth. If one interprets the ^{37}Cl result of 2.1 SNU as due to a reduction from the expected 5.8 SNU because of matter oscillations, then it is evident that the set of points on the plot that are consistent with the experimental result is affected by the proper inclusion of the averaged effect of the Earth. The so called third solution, the near-vertical portion of the contour on the right of the plot, corresponds to



(a)

(b)

Fig. 4: Contours for the ^{71}Ga experiment labeled by SNU values (see text).

a large mixing angle, $\sin 2\theta$ of .95, without the effect of the Earth. On the other hand, the average effect of the Earth distorts the contour to $\sin 2\theta$ under .8.

For possible development purposes it is also of use to investigate the day-night difference in the number of counts expected in the ^{37}Cl experiment. For simplicity we will present here the results for that part of the year when day and night are approximately equal in length, the six months closest to the two equinoxes. Night and day are each taken to be twelve hours. Figure 3 shows the difference between the number of counts seen at night and the number seen during the daytime. Superimposed is the band corresponding to the solutions valid for the existing data (Figure 2a). For only a small region of the parameter space consistent with the existing data would the taking of data separately night and day show a detectable effect.

The predicted response of the ^{71}Ga detector is different from ^{37}Cl mainly because of the lower energy neutrino threshold of the former. This allows ^{71}Ga to detect the neutrinos from the basic p-p burning process in the sun that are inaccessible to ^{37}Cl. Figures 4a and 4b show the contours of equal SNUs expected night and day respectively in the ^{71}Ga experiment. The superimposed band of the values consistent with the ^{37}Cl experiment indicates that an experimental result of anywhere from near zero to near the full solar model prediction of about 120 SNUs would still be consistent.

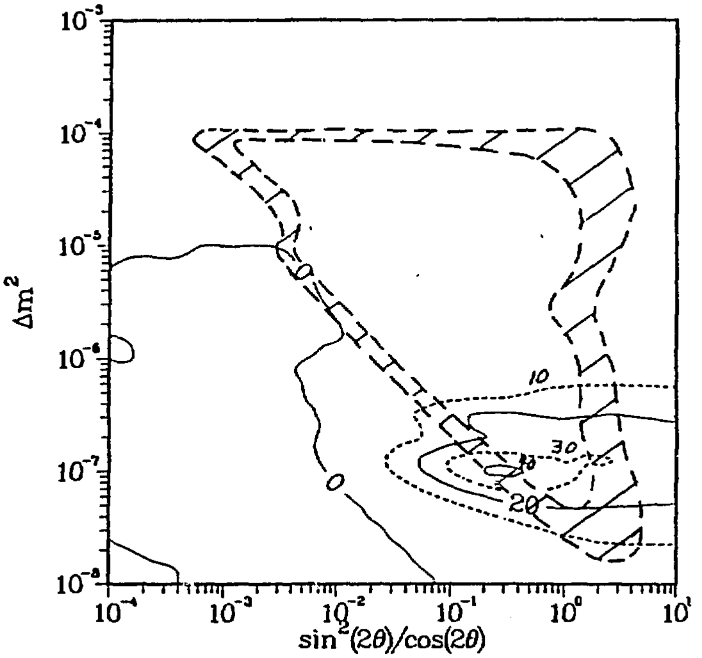


Fig. 5: Night minus day contours for the ^{71}Ga experiment labeled by SNU values (see text). The region consistent with the existing ^{37}Cl experimental result of 2.1 ± .3 SNU is shown as shaded.

If early results from the ^{71}Ga experiment show a low number of counts relative to the solar model prediction, then the night-day differences might well be worth measuring. Figure 5 shows the predicted difference in number of counts between night and day for ^{71}Ga. The difference is sizeable where the ^{71}Ga response would be low. Therefore, if the number of counts turns out low, then the observation of a night-day difference (or lack of it) might further constrain the possible values of Δm^2 and $\sin 2\theta$. In particular, for Δm^2 of about 10^{-7} and $\sin 2\theta$ greater than about .3, a difference of 20 to 40 SNUs between night and day is predicted. The practical difficulty that stands in the way of such a night-day difference experiment is that presented by background and statistics, which, at low counting rates, would make a meaningful result unlikely with the present arrangements.

In short, it seems that the night-day effect could be important for the ^{71}Ga experiment, but only if the counts are low relative to the solar model predictions. However, if the counts are close to the full solar model prediction, indicating a parameter range with little MSW effect in the sun, there can be little MSW effect in the Earth and thus no night-day effect would be expected for the ^{71}Ga experiment.

4. Accelerator and Cosmic Ray Neutrinos

One of the ingredients of our Equation (2.5) for $\overline{P}_{SE}$, the probability that a solar neutrino remains an electron neutrino after passing through the sun and through the Earth, is the probability P_{E1} that an electron neutrino emitted at the surface of the Earth will remain an electron neutrino after passing through it. This is, of course, the physical situation that obtains for a neutrino created at the surface of the Earth either by an accelerator or by a cosmic ray event which then passes through a portion of the Earth to be detected at the far surface. It turns out that for the two-neutrino mixing case, by symmetry, P_{E1} is equally valid as the solution for the probability that a muon neutrino, for example, created at the surface of the Earth will remain a muon neutrino and not change into an electron neutrino after passing through it. This situation seems experimentally more feasible than the converse.

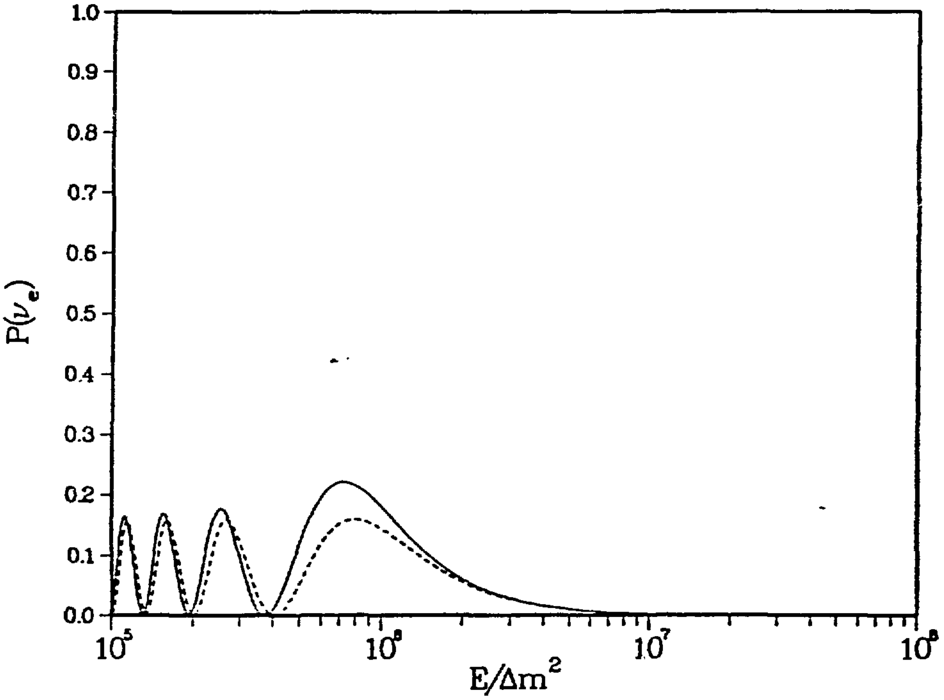


Fig. 6a: Probability of a muon neutrino turning into an electron neutrino after passing into the Earth and emerging at a detector 1000km surface distance from the source. $\sin 2\theta = .4$. The solid line represents the effect of the Earth and the dashed line the replacement of the Earth's matter by vacuum.

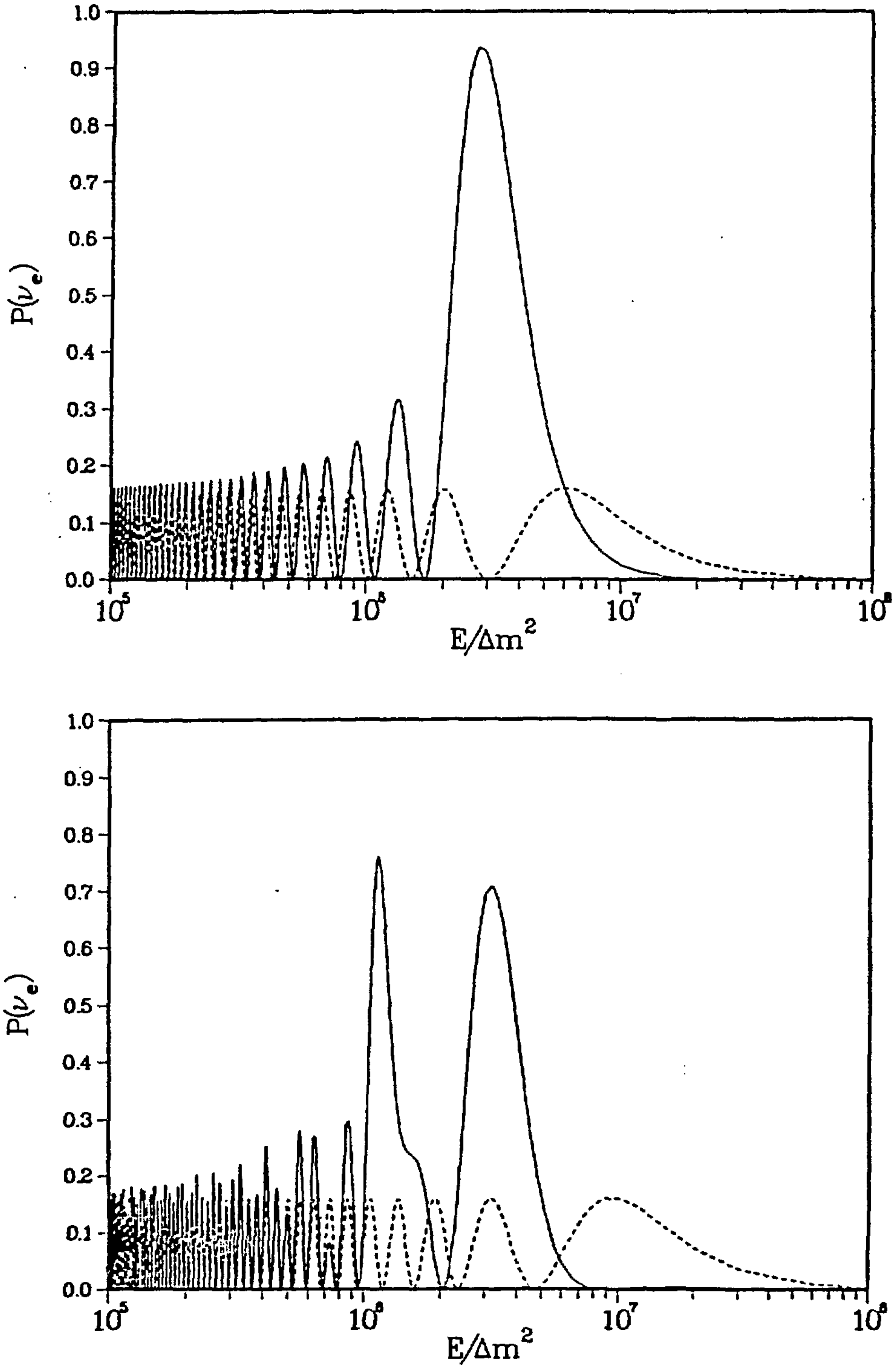


Fig. 6b,c: Same as 6a for a detector 8000km (b,top) and 15000km (c,bottom) surface distance from the source.

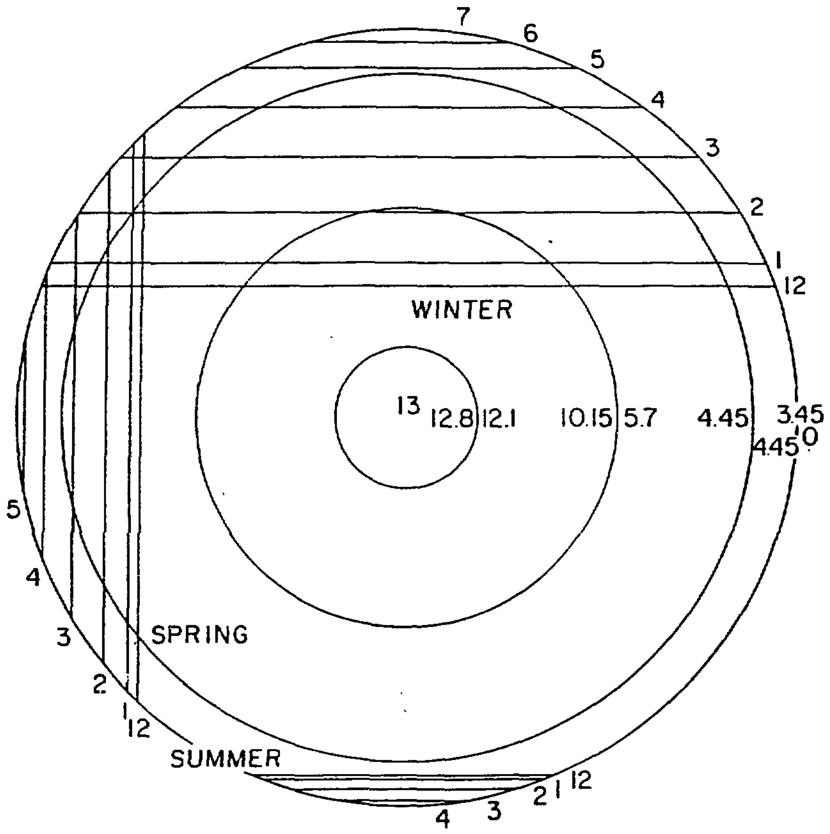


Fig. 7: Principal density zones of the Earth marked together with the densities (in gm/cm^3) at the beginning and ends of these zones. Trajectories through the Earth followed by a solar neutrino to reach a detector located at 43° north latitude at various times of the night at the winter and summer solstices and the spring-fall equinoxes, are also shown.

Figures 6a,b,c show the results of calculations for the probability that a muon neutrino will change into an electron neutrino after passing through the Earth. The mixing angle $\sin 2\theta$ was chosen to be .4. Fig. 6a is a calculation for a chord which corresponds to a surface distance of 1000 km around the Earth (i.e. roughly the distance from BNL to the Sudbury detector). Matter oscillations are just beginning to differ significantly from the vacuum solution for the same distance. At shorter distances the matter oscillation solution approaches the vacuum solution. However, at 8000 km around the Earth, seen in Fig. 6b, the effect of matter is dramatic for $\mathrm{E\,(Mev)}/\Delta m^2\,(\mathrm{ev})^2$ in the vicinity of 3×10^6. The distance can be further tuned to obtain complete transformation in this region. In contrast to these trajectories which only involve the mantle of the Earth we show in Fig 6c the results of putting a detector 15000 km around the earth where neutrinos would go through both mantle and core. The discontinuity at the mantle-core interface (Figure 7) results in the peculiar pattern of oscillations seen in Fig. 6c. Thus matter effects can be quite large for accelerator neutrinos passing through a sufficient length of the Earth. However the number of counts obtained in any conceivable experiment at 1000 km or more is not encouraging (as is pointed out by M. Murtagh in these proceedings).

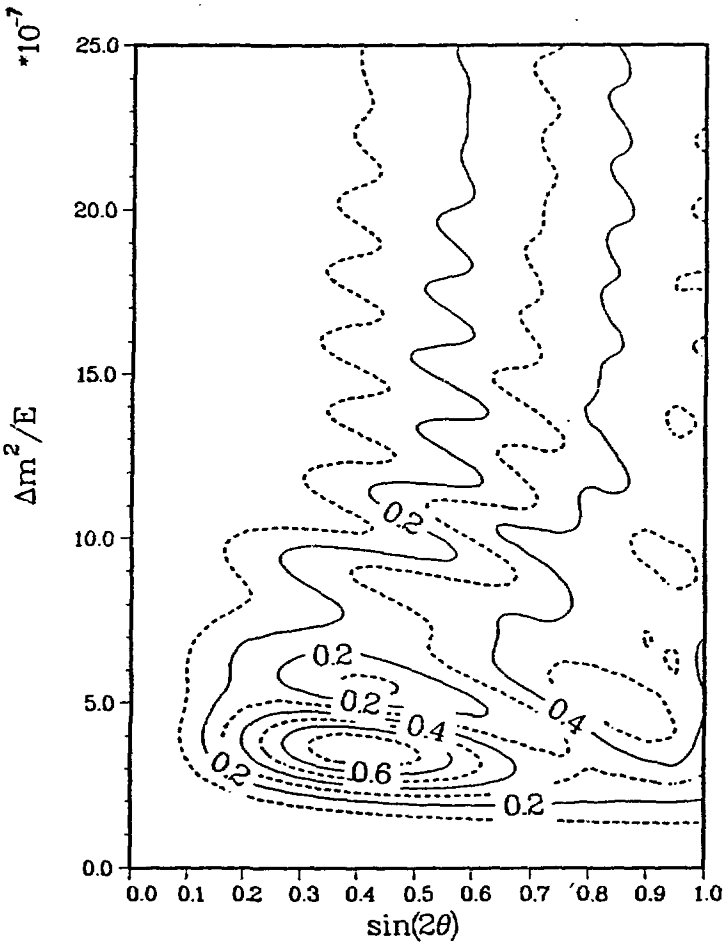


Fig. 8: Probability that muon neutrinos would change into electron neutrinos after passing through the Earth. An average of all events entering the detector from 30° or more below the Earth's horizon is taken. In this illustration the neutrino flux is taken as independent of angle.

LoSecco[9] has estimated that it is possible to put a rough limit on the value of $\sin 2\theta$ from the lack of up-down asymmetry in already existing data from the Kamiokande experiment.

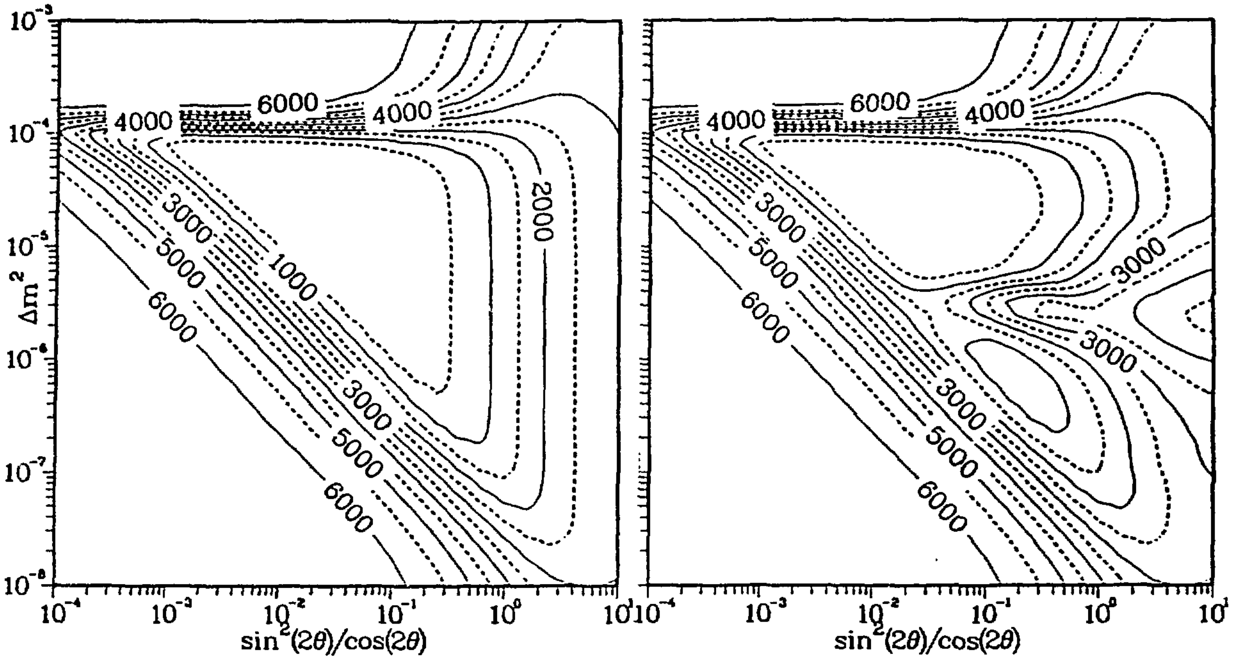


Fig. 9: Number of events per kilotonne year to be detected by the Sudbury heavy water detector as a function of Δm^2 and $\sin 2\theta$. The daytime rate is on the left and the spring or fall nighttime rate is on the right.

We have calculated the fraction of electron neutrinos expected to be detected from events that started as muon neutrinos at the surface of the earth as a function of the mixing angle and mass-energy parameter. Figure 8 shows a contour plot of that fraction for all neutrinos coming from 30° or more below the Earth's horizon (one fourth of the total solid angle). There are two regions where the transformation is large. For large mixing angles ($\sin 2\theta$ greater than about .7) and $\Delta m^2/E$ large enough there is a broad region of transformation due partially to the vacuum mixing. But there is an additional island of large transformation at $\Delta m^2/E$ of about 3.5×10^{-7} largely due to the Earth's matter. If the detector is sensitive to neutrino energy of about 300 Mev, then for Δm^2 of about 10^{-4} and $\sin 2\theta$ between .25 and .6, more than half of the muon neutrinos from this lower direction will change to electron neutrinos. In contrast, all the muon neutrinos produced above will travel a relatively short length and presumably remain muon neutrinos. This calculation shows the usefullness of the up-down asymmetry in constraining the neutrino mass and mixing angle in a limited range of these parameters.

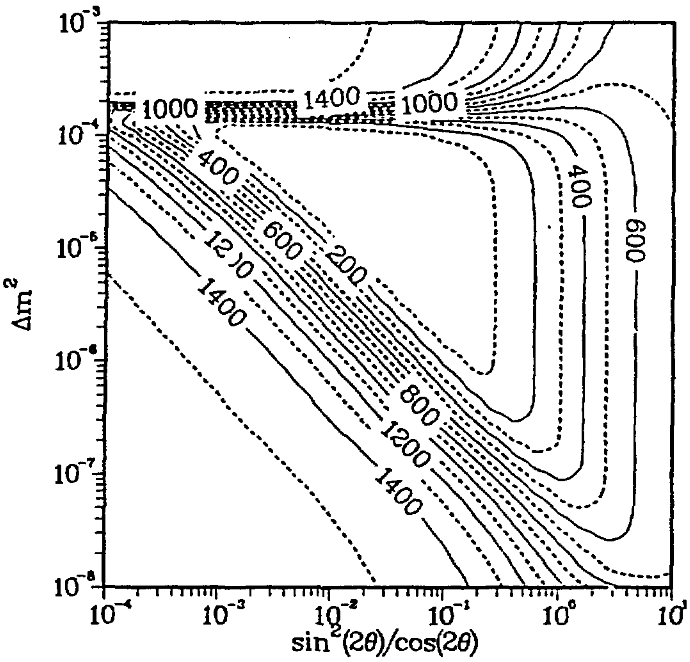


Fig. 10: As in Fig 9, but only the high energy daytime events.

5. Detection of Neutrino Spectra: the Sudbury Heavy-Water Detector

A large heavy-water Cerenkov detector has been proposed[10] that would be sensitive to the solar ^{8}B electron neutrino flux, spectrum, and direction. In addition, the detector might also measure the ^{8}B neutrino flux independent of flavor. We have investigated the effects of the Earth on the expected number of counts for the electron neutrino part of the experiment. The product of the neutrino spectrum and the detector response has been taken from the Sudbury write-up.[10]

Figure 9 shows the daytime and nighttime number of expected counts as a function of Δm^2 and $\sin 2\theta$. With a threshold of 5 MeV, the detector will be sensitive only to ^{8}B neutrinos from the sun. Thus the shape of the contours is similar to that for the ^{37}Cl detector, except that the contour for ^{37}Cl (Fig. 2) shows a small bump at Δm^2 of 10^{-5} indicating the onset of an outward shift of the diagonal contours at lower Δm^2 corresponding to the contribution of neutrinos between the .81 MeV threshold and 5 MeV.

A crucial advantage of the Sudbury experiment is that it is designed to detect the energy of the neutrinos to 15% at 10 MeV and their direction to 25°. This makes possible the determination of distortion of spectrum shape, which is characteristic of an MSW effect.

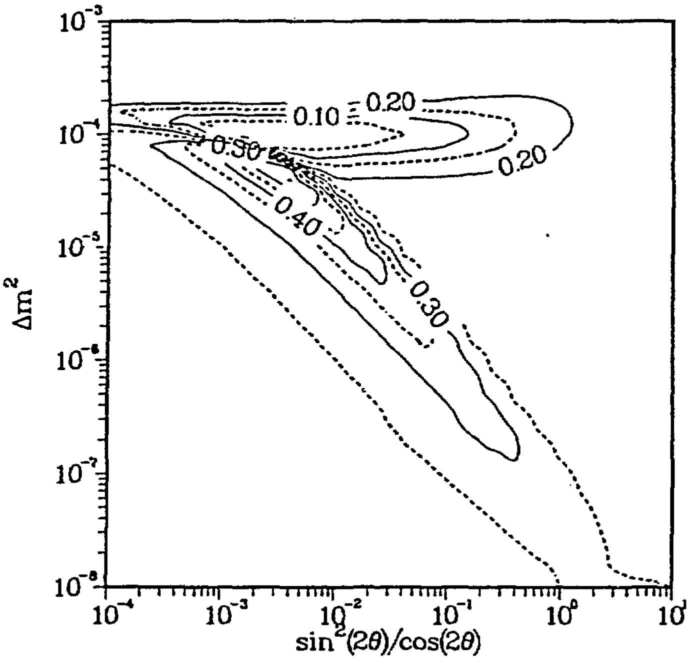


Fig. 11: Ratio of high energy events to total events seen in the daytime at the Sudbury heavy water detector.

Figure 10 shows the expected number of daytime counts for E > 9 MeV. Not only is the number of counts reduced but also the contour shapes are shifted relative to the fuller (E > 5 MeV) spectrum inclusion. Figure 11 exhibits this spectrum distortion effect as the ratio of E > 9 MeV events (from Fig 10) to E > 5 MeV events (from Fig 9a). Determining such a ratio experimentally might provide a constraint on allowable values of Δm^2 and $\sin 2\theta$.

Of course, since this is a real time experiment, one could use the difference between nighttime and daytime counts (such as is seen in Figure 9) to obtain information on Δm^2 and $\sin 2\theta$. In fact a real time experiment allows one to tag events by time of night and date, thus identifying a trajectory length with each event. This would allow the events to be binned most efficiently for isolating effects of the Earth in terms of length of matter traversed rather than some time-of-day or season of year variable which involves an average over a number of trajectories.

6. Conclusions

Our calculations have shown that for values of the two-neutrino mixing angle $\sin 2\theta \geq .1$ there is a large transformation effect induced by passage through the Earth. This transformation from one species to the other (either ν_X to ν_e or vice versa) occurs in the E/Δm^2 range of about $1 - 7 \times 10^6$. Depending on Δm^2, this transformation effect could turn out to provide a spectacular determination of the neutrino mass and mixing parameters. With different solar neutrino, cosmic ray neutrino, and accelerator neutrino experiments probing different ranges of neutrino energy, one can hope to eventually hit on the sensitive E/Δm^2 range for transformation in the Earth.

ACKNOWLEDGMENT

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