MSW Effects on High-Energy Solar Neutrinos from Relic Annihilation

John ELLIS, Ricardo A. FLORES* and Samina S. MASOOD†

Theory Division

CERN

1211 Geneva 23, Switzerland

ABSTRACT

We demonstrate that Mikheyev-Smirnov-Wolfenstein (MSW) matter oscillations can alter significantly the fluxes of high-energy (GeV) solar neutrinos, produced for example by the annihilation of cold dark matter particles in the solar core. We use as illustrations models of neutrino masses and mixings motivated by the low-energy solar neutrino data, and show that the flux of ν_e may be dramatically enhanced and the flux of $\nu_{\mu,\tau}$ correspondingly suppressed, or vice versa. This possible high-energy MSW effect is therefore a source of ambiguity in the interpretation of experimental searches for dark matter annihilations inside the Sun, as we discuss explicitly for sneutrinos, and could eventually be used to discriminate between different solutions to the low-energy solar neutrino problem.

CERN-TH 6616/92

UMSL-TH-4/92

August 1992

* Permanent Address: Department of Physics and Astronomy, University of Missouri, Saint Louis, MO 63121 USA.

† Permanent Address: Department of Physics, Quaid-i-Azam University, Islamabad, Pakistan.

Most theorists expect that neutrinos have masses, since there is no exact gauge symmetry to forbid them. They also expect neutrinos to have non-zero mixing angles, like quarks, and hence to oscillate in general. It was observed several years ago by Mikheyev, Smirnov and Wolfenstein (MSW) [1] that these neutrino oscillations could be enhanced when neutrinos pass through matter. Such MSW neutrino oscillations have now become one of the favoured explanations of the apparent deficit of solar neutrinos now reported by several experiments looking for low-energy $\mathcal{O}(\text{MeV})$ neutrinos produced by nuclear interactions inside the Sun [2]. Other explanations of these low-energy data are still of course possible: for example neutrino oscillations in vacuo, or even some modification of the Standard Solar Model. Two MSW oscillation scenarios are consistent with all the low-energy data [3], one with large mixing $\sin^2 2\theta \gtrsim 0.5$ and one with smaller $\sin^2 2\theta \sim 10^{-2}$, and both with mass-squared differences $\Delta m^2 \sim 10^{-6}$ to 10^{-5} eV^2 . Present low-energy solar neutrino data are not able to say whether one or the other of these interpretations is to be preferred.

In addition to the conventional nuclear source of low-energy solar neutrinos, there could also be sources of higher-energy solar neutrinos. These range from the prosaic, such as cosmic rays hitting the Sun[4], to the more excitingly astrophysical, such as high-energy solar flares, to the speculative particle physical, such as annihilations of relic dark matter particles captured by the Sun[5]. The latter are in principle capable of producing neutrinos with energies of $\mathcal{O}(\text{GeV})$, either by direct annihilations to $\nu\bar{\nu}$, or by first annihilating into higher-generation particles such as $c\bar{c}$, $b\bar{b}$ or $t\bar{t}$ which then produce secondary neutrinos via semileptonic decays. We will use these annihilation sources to illustrate our subsequent discussion of MSW oscillations for high-energy solar neutrinos, but the effects we discuss have far broader applicability.

Our basic point is that MSW oscillations could suppress drastically the high-energy flux of either ν_e , ν_μ or ν_τ , and enhance correspondingly the flux of some other neutrino flavour. Whether this occurs, and if so for which pair of neutrino flavours, depends on the MSW scenario for the low-energy solar deficit which is adopted, and what Ansatz is made for the ratios of different neutrino masses. The most natural explanation for the smallness of the neutrino masses is some variety of GUT see-saw mechanism[6], according to which the neutrino masses scale with the square of some associated fermion masses.

These could be the charge- $\frac{2}{3}$ quarks of the different generations, or perhaps the different charged leptons. As examples, we find enhancements of the ν_e flux and suppressions of the $\nu_\mu + \nu_\tau$ flux if $\sin^2 2\theta \gtrsim 0.5$ and $\Delta m^2 \sim 10^{-5} \text{ eV}^2$, or if neutrino masses scale with the squares of their associated lepton masses[#].

These results complicate the interpretation of experimental searches for the neutrinos produced by the annihilations of dark matter particles in the Sun. Dark matter candidates that had apparently been disallowed could perhaps be re-allowed if MSW oscillations suppressed their neutrino annihilation products after production. Alternatively, some lucky candidates could see their signals enhanced by oscillations into neutrino flavours that were easier to detect. As examples of these possibilities, we consider sneutrino dark matter candidates [9]. Whereas tau sneutrinos would annihilate into tau neutrinos that are relatively difficult to detect in an underground water Cerenkov detector, MSW oscillations could convert the tau neutrinos into ν_μ 's or ν_e 's that are relatively easy to detect.

Finally, we cannot resist pointing out that if high-energy solar neutrinos were ever observed, and their origins were understood, detailed measurements of them might enable us to distinguish between the different explanations of the low-energy solar neutrino deficit that are now on the market, for example by distinguishing large from small mixing angles, and $\nu_e - \nu_\mu$ from $\nu_e - \nu_\tau$ oscillations.

Neutrino flavour oscillations have been extensively discussed in the literature, and here we shall only summarize the main ingredients needed for our purposes [2]. For an electron neutrino produced in the Sun, the average survival probability that it be detected as an electron neutrino at the Earth is:

$$P(\nu_e \rightarrow \nu_e) = \frac{1}{2} + \left(\frac{1}{2} - P_c\right) \cos 2\theta \cos 2\theta_m, \quad (1)$$

[#] We have also investigated the possibility of $\bar{\nu}_\mu - \bar{\nu}_\tau$ matter oscillations for GeV antineutrinos, which could arise as a result of the difference in their one-loop forward scattering amplitude [7]. We find only a small effect, and only for $|\sin^2 2\theta - 1| \ll 1$. There is of course the possibility of significant vacuum oscillations in the $\mu - \tau$ sector if $\sin^2 2\theta_{\mu\tau} = \mathcal{O}(1)$, as needed if neutrino oscillations are the explanation of the apparent deficit in the atmospheric ν_μ flux [8].

where P_c is the level crossing probability, θ is the vacuum mixing angle, and θ_m is the mixing angle in matter and is determined by the electron number density at the source and the neutrino energy ($A \equiv 2\sqrt{2}G_F N_e E_\nu$),

$$\sin^2 \theta_m = \frac{(\Delta m^2 \sin 2\theta)^2}{[(A - \Delta m^2 \cos 2\theta)^2 + (\Delta m^2 \sin 2\theta)^2]}. \quad (2)$$

The physics is embodied in the level crossing probability, for which a convenient analytic formula is:

$$P_c = \Theta(A - \Delta m^2 \cos 2\theta) \frac{\exp(-\frac{\pi}{2}\gamma F) - \exp(-\frac{\pi}{2}\gamma(\frac{F}{\sin^2 \theta}))}{1 - \exp(-\frac{\pi}{2}\gamma(\frac{F}{\sin^2 \theta}))}. \quad (3)$$

For an exponential density profile (as approximately valid in the Sun), $F = 1 - \tan^2 \theta$ and $\gamma \equiv \Delta m^2 \sin^2 2\theta / 2E_\nu \cos 2\theta |N_e^{-1} dN_e / dr|_0 \propto E_\nu^{-1}$, because the logarithmic derivative of the electron density at the resonance point, $|N_e^{-1} dN_e / dr|_0$, is constant.

The survival probability (1) for ν_e 's injected at the solar core is plotted in fig. 1 for the two central values of the 2σ regions where flavour oscillations can explain the combined data set on solar neutrino observations [3]: $(\Delta m^2, \sin^2 2\theta) = (8 \times 10^{-6} \text{ eV}^2, 0.6)$ and $(6 \times 10^{-6} \text{ eV}^2, 7 \times 10^{-3})$. In general resonant flavour conversion occurs mostly for

$$7.3 \times 10^{-1} \left(\frac{\Delta m^2}{10^{-5} \text{ eV}^2} \right) \cos 2\theta \leq \frac{E_\nu}{\text{MeV}} \leq 2.6 \times 10^2 \left(\frac{\Delta m^2}{10^{-5} \text{ eV}^2} \right) \frac{\sin^2 2\theta}{\cos 2\theta}, \quad (4)$$

which is the energy range where $P(\nu_e \rightarrow \nu_e) \leq 0.5$. In fig. 2 we show the region of the $(\Delta m^2, \sin^2 2\theta)$ plane where $P(\nu_e \rightarrow \nu_e) \leq 0.5$ for 1 GeV neutrinos. For higher energy neutrinos the shaded region shifts up, e.g. by a decade for 10 GeV neutrinos. Hence, oscillations of GeV neutrinos will occur for a large range of mixing angles if $\Delta m^2 \gtrsim 10^{-2} \text{ eV}^2$, or for a large range of Δm^2 if $\sin^2 2\theta = \mathcal{O}(1)$ as is the case for one of the MSW explanations of the combined observations on solar neutrinos. We also indicate in fig. 2 the two regions of the $(\Delta m^2, \sin^2 2\theta)$ plane that give MSW explanations of the apparent low-energy solar neutrino deficit, and another region of interest for $\nu_e - \nu_\tau$ oscillations as discussed later.

The interpretation of the observations on solar neutrinos as two-flavour resonant oscillations is of course only an effective description in principle. Since $\mathcal{O}(\text{MeV})$ ν_e 's and ν_μ 's interact identically both in the solar medium and the detectors, solar nuclear-reaction neutrino observations have the intrinsic limitation of being indicative of electron neutrino

conversion to the sum of other flavours only. Thus, solar GeV neutrinos might offer an important handle on this problem, because GeV or higher energy ν_τ 's and ν_μ 's interact differently in the detectors, and for energies above $\sim 100 \text{ GeV}$ would even interact differently in the solar medium. Here we shall consider two possibilities that lead to flavour oscillations of GeV neutrinos:

(a) Neutrinos of energy $1 \text{ GeV} \lesssim E_\nu \lesssim 100 \text{ GeV}$ do not have significant charged-current interactions in the solar medium on their way out of the Sun, and the forward elastic scattering of τ and μ neutrinos off matter via the neutral current is identical. Therefore, the propagation and flavour oscillations of these high energy neutrinos can be described as an effective two-flavour mixing between the ν_e 's and the $\nu_\mu + \nu_\tau$'s. From fig. 1 we can see that there would be flavour oscillations of neutrinos of energy in this range for the high $\sin^2 2\theta$ solution to the solar neutrino problem.

(b) A theory-laden interpretation of the low $\sin^2 2\theta$ solution of the solar neutrino problem is that it directly indicates two-flavour mixing because one expects on the basis of see-saw models that the large split in fermion masses, $m_e \ll m_\mu \ll m_\tau$ (or $m_u \ll m_c \ll m_t$), implies a large split of neutrino masses, $m_{\nu_e} \ll m_{\nu_\mu} \ll m_{\nu_\tau}$. Hence, if the low $\sin^2 2\theta$ solution in fig. 1 is interpreted as reflecting $\nu_\mu - \nu_e$ oscillations, one is led to expect $\nu_\tau - \nu_e$ oscillations characterized by a much larger Δm^2 . Specifically, if neutrino masses scale with the square of the charged lepton masses, then one would expect $\Delta m_{e\tau}^2 \sim 0.4 \text{ eV}^2$. From (4) we get that for neutrino energies $E_\nu \gtrsim 30 \text{ GeV}$ $\nu_\tau - \nu_e$ oscillations would occur nearly independently of the value of $\sin^2 2\theta_{e\tau}$ in that case, as can be seen in fig. 2##.

We consider below these two possibilities for high energy neutrinos injected at the solar core by particle dark matter annihilations.

A possible source of high-energy neutrinos is the annihilation of Cold Dark Matter particles captured by the Sun as it travels through the galactic halo. For relics of mass $\gtrsim 10 \text{ GeV}$ the annihilations occur entirely within the solar core, and the spectra of the neutrinos produced depend on the relative branching ratios for annihilations into neutrinos directly and/or into heavy fermions that subsequently decay giving off neutrinos. The spectra of neutrinos from the annihilations of dark matter particles have been carefully

If the neutrino masses scale with the square of the mass of the charge- $\frac{2}{3}$ quarks instead, then one would expect $\Delta m_{e\tau}^2 \sim 10^2 \text{ eV}^2$ and hence $\nu_\tau - \nu_e$ oscillations of neutrinos of energies $E_\nu \gtrsim 10 \text{ TeV}$.

analyzed in ref. [10]. Annihilations into muons and light quarks do not contribute to the neutrino flux because they lose most of their energy before decaying, and lead to a low-energy neutrino signal that would be overwhelmed by the cosmic-ray neutrino background. Thus, annihilations into τ leptons and b and c quarks and their subsequent decay are the main sources of high energy neutrinos, other than direct annihilations into neutrinos. The latter neutrinos are monoenergetic and therefore the effect of flavour oscillations on those neutrinos can be directly obtained from (1).

The spectra from heavy flavour decays are quite soft and therefore even the decay of a heavy Dark Matter relic can inject neutrinos with energies in the GeV range. It is straightforward to obtain the neutrino spectra at the Earth from the spectra of the injected neutrinos. We use the analytic fits of ref. [10] for the rest-frame spectra of neutrinos of flavour i ($=e, \mu, \tau$) from the decay of fermion j ($=\tau, c, b$), dN_{ij}/dy , where $y \equiv 2E_\nu/M \leq 1$ is twice the neutrino energy scaled by the mass of the parent τ or hadron. For relativistic decay products, as will be the case for annihilations of relic particles of mass $\gtrsim 10$ GeV, the spectrum of the neutrinos injected at the solar core can be approximated by [10]

$$\frac{dN_i}{dz} = \sum_{j=\tau, c, b} BR(\chi\chi \rightarrow \bar{j}j) \frac{1}{z_F^2} \int_{z/z_F}^1 \frac{dN_{ij}}{dy} \frac{dy}{y} \quad (5)$$

if we neglect neutrino interactions in the solar medium, which is a good approximation for $E_\nu \lesssim 100$ GeV. Here $z \equiv E_\nu/m_\chi \leq 1$ is the neutrino energy scaled to the annihilating relic mass m_χ , and z_F^j is the average energy of fermion j after fragmentation ($z_F^j = 1(0.55, 0.71)$ for $j = \tau(c, b)$).

In fig. 3 we first show the effect of flavour oscillations on the spectra of annihilation ν_e 's and $\nu_\mu + \nu_\tau$'s for the two cases (a) and (b) above, assuming the ratios of annihilation products given by $U(1)$ gauginos. As can be seen there, quite a significant change is introduced in the spectra of these neutrinos. Because ν_μ 's and ν_τ 's having energies of a few GeV or more would interact differently in detectors, one could in principle sort out how the three flavours mix. For example, in case (b) above ($\Delta m_{e\tau}^2 \sim 0.1 \text{ eV}^2 \sim \Delta m_{\mu\tau}^2 \sim 10^4 \Delta m_{e\mu}^2$ and small mixing angles), GeV ν_μ 's would not oscillate neither into ν_e 's nor into ν_τ 's, whereas ν_e 's would adiabatically convert into ν_τ 's and vice-versa. We find that for neutrinos from heavy-flavour decays, for generic branching ratios one would have $R_{\nu_e+\bar{\nu}_e} \gtrsim R_{\nu_\mu+\bar{\nu}_\mu}$ for the rates of contained events in such a case. On the other hand, fig 3(c) shows what happens for the same oscillation parameters as case

(b) above, if the annihilation products are dominated by $b\bar{b}$ pairs. In this case, the ν_e 's oscillate adiabatically into ν_τ 's, and the detectable ν_e signal is suppressed.

These results imply that one must be cautious in interpreting null results of searches for high-energy solar neutrinos. A bound on one flavour of neutrino produced in the solar core would not be applicable if this flavour converted into another flavour on its way to the Earth. Consider, for example, sneutrino cold dark matter candidates [9] that could have been trapped inside the Sun and annihilated there with each other, assuming there is a $\bar{\nu} - \bar{\nu}$ asymmetry and the $\bar{\nu}$ dominate the cold dark matter [5]. Under these circumstances, the dominant annihilation products would be $\nu\nu$ pairs of the same flavour: $\bar{\nu}_i\bar{\nu}_i \rightarrow \nu_i\nu_i$ ($i = e, \mu, \tau$). Underground detectors tend to have higher efficiencies for $i = e, \mu$, although the ν_τ detection efficiency in at least one recent experiment is not negligible [11]. The conservative analysis assumption should always be that the annihilation products become at the Earth those for which the experimental detection efficiency is the lowest. Previous experiments with low ν_τ detection efficiencies had been used to exclude $\bar{\nu}_e$'s and $\bar{\nu}_\mu$'s as cold dark matter candidates on the strength of the absences of high-energy solar ν_e 's and ν_μ 's [12]. But, for example in case (b) above null searches for electron neutrinos could not have been used to rule out $\bar{\nu}_e$'s of mass $\gtrsim 30$ GeV because their annihilation products would have converted entirely to ν_τ 's. Fortunately, the more recent experiment with a higher ν_τ detection efficiency [11] is sufficiently sensitive to rule out all flavours of $\bar{\nu}$'s, even under the conservative assumption stated above.

One can also take the more optimistic point of view that some cold dark matter candidates will in future be identified, either by accelerator or other non-accelerator experiments. Then the results — even null — of searches for high-energy solar neutrinos could be used to distinguish between different models of neutrino masses and mixings. For example, cases (a), (b) and (c) above could clearly be distinguished in principle. Most importantly, a distinction could be drawn between the two favoured classes of MSW explanations of the apparent low-energy solar neutrino deficit (large vs small mixing angles), and between $\nu_e - \nu_\mu$ and $\nu_e - \nu_\tau$ oscillations.

We have shown in this paper that MSW oscillation phenomena are of potential importance for high-energy solar neutrinos, as they have been shown to be for the apparent $\bar{\nu} - \bar{\nu}$ annihilation products in diluted form if $\bar{\nu} - \bar{\nu}$ annihilations dominate, or if there are equal numbers of $\bar{\nu} - \bar{\nu}$ and $\bar{\nu} - \bar{\nu}$ annihilations.

low-energy solar neutrino deficit reported by several experiments. We are aware that MSW oscillations are not the only explanations of this apparent deficit, and that cold dark matter particles are still speculative, but should their physical reality be established, they would open a fascinating new physics window.

ACKNOWLEDGEMENTS

One of us (MS) would like to thank Dr. P. Krastev for some helpful discussions.

References

- [1] S. P. Mikheyev and A. Yu. Smirnov, *Nuovo Cimento* 9C (1986) 17 ;
L. Wolfenstein, *Phys. Rev. D* **17** (1978) 2369.
- [2] For a review, see e.g. T. K. Kuo and J. Pantaleone, *Rev. Mod. Phys.* **61** (1989) 937.
- [3] GALLEX Collaboration, P. Anselmann *et al.*, *Phys. Lett.* **285B** (1992) 376,390 ;
S. A. Bludman, N. Hata, D. C. Kennedy and P. G. Langacker, University of Pennsylvania preprint UPR-0516T (1992).
- [4] I. V. Moskalenko, S. Karakula, and W. Tkaczyk, *Astron. Ap.* **248** (1991) 5.
- [5] M. Srednicki, K. A. Olive and J. Silk, *Nucl. Phys.* **B279** (1987) 804.
- [6] T. Yanagida, in Proc. of the "Workshop on the Unified Theory and the Baryon Number in the Universe", ed. by O. Sawada and A. Sugamoto, KEK report 79-18 (1979) p. 95 ;
M. Gell-Mann, P. Ramond and R. Slansky, in "Supergravity", ed. by P. van Nieuwenhuizen and D. Z. Freedman (North Holland, Amsterdam, 1979) p. 315.
- [7] F. J. Botella, C. S. Lim, and W. J. Marciano, *Phys. Rev.* **D35** (1987) 896.
- [8] For a recent review of the data, see e.g. M. Mori, KEK preprint 92-24 (1992).
- [9] L. E. Ibáñez, *Phys. Lett.* **B137** (1984) 160 ;
J. Hagelin, G. L. Kane and S. Raby, *Nucl. Phys.* **B241** (1984) 160.
- [10] S. Ritz and D. Seckel, *Nucl. Phys.* **B304** (1988) 877.
- [11] KAMIOKANDE Collaboration, N. Sato *et al.*, *Phys. Rev.* **D44** (1991) 2220.
- [12] See e.g. K. A. Olive and M. Srednicki, *Phys. Lett.* **B205** (1988) 553.

Figure Captions

Fig. 1. Persistence probability $P(\nu_e \rightarrow \nu_e)$ as a function of neutrino energy E_ν for two MSW scenarios: (a) $(\Delta m^2, \sin^2 2\theta) = (8 \times 10^{-6} \text{ eV}^2, 0.6)$ (solid line) and (b) $(6 \times 10^{-6} \text{ eV}^2, 7 \times 10^{-3})$ (dashed line).

Fig. 2. Region of the $(\Delta m^2, \sin^2 2\theta)$ plane where $P(\nu_e \rightarrow \nu_e) \leq 0.5$ for 1 GeV neutrinos from the solar core. This region is moved up by a decade for $E_\nu = 10 \text{ GeV}$. Also indicated are two regions (a,b) of interest for the apparent solar neutrino deficit, and a region of possible interest for $\nu_e - \nu_\tau$ oscillations.

Fig. 3. The effects on ν_e and $\nu_\mu + \nu_\tau$ fluxes as functions of the scaled neutrino energies E_ν/m_χ for relic particles of mass $m_\chi = 20 \text{ GeV}$, in 3 different cases: (a) $\Delta m_{e\mu}^2 = 8 \times 10^{-6} \text{ eV}^2$, $\sin^2 \theta_{e\mu} = 0.6$, (b) $\Delta m_{e\tau}^2 = 4 \times 10^{-4} \text{ eV}^2$, $\sin^2 \theta_{e\tau} = 0.01$, in both cases assuming the ratios of annihilation products given by $U(1)$ gauginos, (c) as for (b), but with $b\bar{b}$ pairs dominant among the annihilation products and $m_\chi = 40 \text{ GeV}$.

Figure 1

Figure 2

Figure 3a

Figure 3b

Figure 3c