CERN-TH.5184/88
FTUV/14/88

MATTER EFFECTS IN NEUTRINO PROPAGATION

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Invited talk at XXIV International Conference on High Energy Physics
Munich, August 4-10, 1988
To appear in the Proceedings

CERN-TH.5184/88
FTUV/14/88
September 1988

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After briefly reviewing the Mikheyev-Smirnov-Wolfenstein effect, I present a particle physics model where the required small neutrino mass arises from spontaneous R parity violation in supergravity theories. It is related to measurable processes associated with the existence of the Majoron and of supersymmetric (SUSY) particles. Astrophysical and laboratory limits tend to *exclude* regions of oscillation parameters where the high energy neutrinos are *adiabatically* converted. This suggests the possibility of a large reduction in the pp and ${}^7\text{Be}$ neutrino flux even for a mildly reduced ${}^8\text{B}$ neutrino flux, thus stressing the importance of the gallium experiments. Finally I consider *other* types of matter effects, *e.g.* due to the neutral current (NC). As an example, I discuss the case of resonant oscillation of *massless* non-orthogonal neutrinos. While the new effect, *per se* cannot solve the solar neutrino puzzle it opens up a new, as yet unexplored realm of matter effects which could be probed in the laboratory.

1. The Effect of the Charged Current

If neutrinos are massive flavour and mass eigenstates do not coincide, being related by

$$\begin{aligned}\nu_e &= \cos\theta\nu_1 + \sin\theta\nu_2 \\ \nu_\mu &= -\sin\theta\nu_1 + \cos\theta\nu_2\end{aligned}\tag{1}$$

in the simplest case of two neutrino families. This leads to the well-known (but not yet observed) quantum mechanical interference phenomenon of neutrino oscillation. The conversion probability in *vacuo* is

$$P_{vac}(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta) \sin^2\left(\frac{\delta m^2 L}{4E}\right)\tag{2}$$

where L is the distance, E the ultrarelativistic neutrino energy and δm is the

neutrino mass difference. If neutrinos travel through matter then oscillations can be affected due to charged current (CC) forward elastic scattering on electrons, which exists for ν_e but not for ν_μ (or ν_τ) [1]. The system of evolution equations is

$$\begin{aligned} i\frac{dA_e}{dt} &= H_{ee}A_e + H_{e\mu}A_\mu \\ i\frac{dA_\mu}{dt} &= H_{e\mu}A_e + H_{\mu\mu}A_\mu \end{aligned} \quad (3)$$

where A_e is the probability amplitude for ν_e to remain ν_e etc. H_{ij} are the matrix elements of the effective weak Hamiltonian, H_{ee} containing the effect of the CC. Eq. (3) shows the possibility of a *resonant* neutrino conversion [2] in matter whenever the condition $H_{ee} = H_{\mu\mu}$ is satisfied, or

$$\delta m^2 \cos(2\theta) = 2\sqrt{2}G_F EN_e \quad (4)$$

where N_e is the electron number density. Sizeable neutrino conversion in matter is possible even for small values of the vacuum mixing angle θ . However to discuss solar neutrino propagation we need to solve the system of evolution equations describing oscillations in matter of *varying* density. This has been done both analytically (for given density profiles), and numerically [3]. When the density decreases slowly enough a ν_e born *e.g.* in the solar core can simply “follow” the slowly changing Hamiltonian, find the resonance region, and end up still in the same matter eigenstate, but this time as a ν_μ or ν_τ . In this *adiabatic* (AD) approximation an almost complete conversion can take place. This requires for the sun, $\left(\frac{\delta m_\mu}{\text{eV}}\right)^2 \simeq 10^{-1}$, and corresponds to the upper *horizontal* lines in Fig. 1.a. The conversion of neutrinos due to this MSW effect has been analyzed also in the *non-adiabatic* (NAD) approximation where the transition happens for $\left(\frac{\delta m_\mu}{\text{eV}}\right)^2 \sin^2 2\theta \simeq 3 \times 10^{-8}$, leading to the *tilted* lines in Fig. 1.a. There is also a “large mixing” solution indicated by the *vertical* lines on the right of Fig. 1.a. A big effect requires the solar core density to exceed the resonance value so only neutrinos whose $E/\delta m^2 \gtrsim 10^5$ (E in MeV and δm in eV) are converted. For AD one needs $\delta m \simeq 10^{-2}\text{eV}$ so *high* energy neutrinos are the ones converted, as can be seen from the iso-SNU contours shown in Fig. 1.a. However for the NAD solution low energy neutrinos can be strongly suppressed for *larger* mixings (*lower* masses) since in this case the threshold for conversion is *low* as can be seen again from

Fig. 1 Fig 1.a shows the iso-SNU contours for the chlorine experiment in the recent 7.9 SNU solar model [4] (taken from Baltz and Weneser [3] who also included earth effects averaged over day/night and seasonal variations). Shown in Fig. 1.b are gallium iso-SNU contours, for night. In the RPM model only the region left and below curve labelled $v_u = v_d$ or $v_u = 3v_d$ is allowed. Comparing 1.a and 1.b shows that even when the high energy neutrino count rate is high, the model favours a large suppression in the *low* energy neutrino flux.

Fig. 1. We are faced with a challenge: *If the solar neutrino problem is resolved by the MSW effect can one probe the corresponding oscillation parameters in the laboratory?*

2. Probing MSW parameters: a prototype model [5,6]

If neutrino masses are much larger than their mass differences, $m_\nu \gg \delta m_\nu$ [7], one could have substantial solar neutrino oscillation effects and still be able to observe neutrino masses in the laboratory. However if $m_\nu = O(\delta m_\nu) \approx 10^{-2} \text{ eV}$ this seems out of reach. We have searched for models where one can probe MSW parameters in *conventional* as well as *solar* neutrino experiments despite the small m_ν values required. This was achieved by relating the tiny neutrino masses to some new particles (such as the Majoron) whose couplings can cause effects measurable in the laboratory [5]. This way we obtained a model for the MSW effect where the allowed oscillation parameters only cover the region below the curves $v_u = v_d$ and $v_u = 3v_d$ as indicated in Fig. 1. This prediction is relatively *stable* in a wide class of models so I confine myself here only to the simplest [5,6]. Its basic ingredients

are: (1) *spontaneous violation of total lepton number* symmetry in standard supergravity through non-zero *scalar* neutrino vacuum expectation values (VEV's) $v_i = \langle \tilde{\nu}_{Li} \rangle$ $i = e, \mu, \tau$ and (2) some mechanism of explicit *lepton flavour violation* [8]. Condition (1) implies violation of a SUSY selection rule, called R parity. R parity is *even* for all standard model particles (including Higgs scalars) and *odd* for their SUSY partners. It can be expressed as $R_p = (-1)^{3B+L+2S}$ where S denotes spin, B and L denote baryon and total lepton number, respectively. Since $B - L$ is a continuous ungauged symmetry spontaneous breaking is accompanied by a physical massless Goldstone boson - the Majoron - denoted J . Majoron emission generates new stellar energy loss mechanisms: once produced in a stellar environment, in Compton-like processes *e.g.* $\gamma + e \rightarrow e + J$ the weakly coupled Majorons easily escape. Suppressing the resulting energy loss requires [9],

$$v \leq 10 - 20 \text{ KeV} \quad (5)$$

where $v^2 = \sum_i v_i^2$. The neutrino mass arises from gauge interactions due to the exchange of heavy fermions, (*e.g.* the SUSY partner of the Z boson, $\tilde{Z}$) and is given as

$$m_\nu = \frac{\mu M v^2}{2v_u v_d M - M_1 M_2 \mu} \quad (6)$$

where $2M = g_1^2 M_2 + g_2^2 M_1$, g_i are gauge coupling constants, M_i , $i = 1, 2$, denote electroweak gaugino mass parameters, μ is the Higgsino mixing parameter and v_u and v_d are Higgs VEV's. The highest energy scale directly involved in generating the neutrino mass is the electroweak scale characterizing SUSY breaking. In addition, the Majoron is the SUSY partner of the neutrino. Because it lies in an isodoublet, it increases the Z width by 80 MeV *i.e.* *one half* generation of neutrinos. Because it carries $L = 1$ one needs a *double* breaking to generate the left handed Majorana neutrino mass. This quadratic dependence on v , eq. (6), when combined with the astrophysical limit eq. (5), then implies a neutrino mass in the range where the MSW effect can substantially affect the solar neutrino flux for very reasonable, yet *restricted* choices of the SUSY parameters (μ, M_i). In addition, out of the three neutrinos, to a very good approximation *only one* acquires a mass, namely the one which is the SUSY partner of the Majoron. As

Fig. 2 Region of neutrino mass allowed in the RPM model. The bound from PETRA on the lightest chargino mass forbids the region on the left of the vertical line at $m_{\chi^+} = 23 \text{ GeV}$ and thus leads to an upper bound on m_ν .

as a result the number of parameters describing neutrino oscillations is reduced to *three*: two mixing angles and one mass parameter, m_ν . One of the two angles specifies whether the oscillation channel is $\nu_e \rightarrow \nu_\mu$ or $\nu_e \rightarrow \nu_\tau$ and is not affected by matter, while the other is the angle shown in Fig. 1 [5].

Apart from the *astrophysical* constraint, eq. (5), there are two types of restrictions on the oscillation parameters that follow from conventional *laboratory* experiments. First there are limits from high energy searches for the lightest charged SUSY fermions (*charginos*), denoted $\chi^\pm$ [5]. Their non-observation *e.g.* at PETRA restricts the SUSY parameters in eq. (6). Thus by using eq. (5) one can determine the allowed m_ν values shown in Fig. 2. Clearly there is an *upper* bound on m_ν which becomes stronger the more v_u and v_d differ. Thus, for the case $v_u = v_d$ one obtains from Fig. 2, that $m_\nu < 1.4 \times 10^{-2} \text{ eV}$ while for $v_u = 3v_d$ the limit is $m_\nu < 2.4 \times 10^{-3} \text{ eV}$ reflecting a strong trend towards non-adiabaticity of high energy solar neutrino conversions, especially for our favoured case $v_u > v_d$. In addition, there are various spectral distortions in weak decay processes due to Majoron emission [5]. The correction to the Michel parameter in τ decays due to double Majoron emission leads to an upper bound on the mixing angle θ , also depending on the SUSY parameter values. By summing over all of these allowed values one obtains the region of oscillation parameters shown in Fig. 1. For $v_u = v_d$ the region of *large* m_ν and *small* θ is allowed. However, for $v_u = 3v_d$ this

AD region disappears, the only allowed region being that of very small m_ν and relatively large θ . In this case we expect a depletion of low energy neutrinos up to a factor 7 or so *below* the standard solar model prediction, in sharp contrast to the AD case. In addition, in this region of parameters, regeneration of solar neutrinos at the earth could be important [3]. This large reduction in the expected pp and ${}^7\text{Be}$ neutrino fluxes is expected even in cases where the high energy neutrino count rate in chlorine is fairly large, say 5 *SNU* or so, thus stressing the importance of gallium experiments. Note that m_ν depends quadratically on v , so there is still a window for an adiabatic high energy neutrino conversion due to the uncertain determination of the astrophysical limit $v < 10\text{KeV}$ used above. Majoron emission in $K \rightarrow \pi + \text{nothing}$ decays, *e.g.* $K \rightarrow \pi + J + J$ could also lead to measurable signatures [10]. Another interesting consequence of our $\Delta L = 1$ Majoron is the possibility of a new nuclear $\beta\beta$ decay mode involving *two* Majorons, as the single emission process is negligible because of our $\Delta L = 1$ rule [6]. The existence of these new modes may enable one to place additional restrictions on our parameters [8]. Similarly, the new structure of the Majoron couplings to neutrinos present in our model may be further constrained by cosmology and astrophysics [8].

3. Beyond the MSW Effect [13,18]

So far we have assumed that the NC being the same for all neutrinos can be consistently ignored. This is only justified however if there are no gauge-singlet leptons *e.g.* right-handed neutrinos. If these exist then the neutrinos produced in low energy weak decay processes can be *effectively* non-orthonormal and the resulting lepton mixing matrix non-unitary [11]. The NC in the neutrino sector becomes non-trivial [11] and leads to flavour violating effects in the standard $SU(2) \otimes U(1)$ theory, *even if neutrinos are strictly massless due to an exact total lepton number symmetry* [12]! These new effects may be seen at low energy, *e.g.* $\mu \rightarrow e + \gamma$, as well as at high energies, in the decays of the Z *e.g.* $Z \rightarrow e + \bar{\tau}$, $Z \rightarrow \mu + \bar{\tau}$ and their conjugates. With the luminosities expected at LEP these processes can occur with measurable branching ratios at the Z peak [12]. Non-orthogonal neutrinos also lead to a new type of *resonant* oscillation effect in matter [13] very different from

the MSW effect. First the massless oscillation effect has an energy *independent* resonance condition

$$N_e^{net} = \delta h^2 N_n \quad (7)$$

where $\delta h \ll 1$ due to limits on weak universality violation, N_e^{net} is the net electron number density and N_n is the neutron density. This is to be contrasted with eq. (4) which holds in the MSW model. In matter, such as the sun, with a "normal" concentration of electrons relative to nucleons, the large CC contribution masks the NC effect making it impossible for the massless neutrino system to undergo resonant oscillation in the $\nu_e \rightarrow \nu_{\mu,\tau}$ channel of interest to the *solar* neutrino problem [13]. Oscillations such as $\nu_\mu \rightarrow \nu_\tau$ or $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ could be large, since there is no CC coherent scattering term for ν_μ or ν_τ on electrons. However in the general case that m_ν is non-zero *and* neutrinos are *non - orthonormal* as well, the picture can change [14]. While the MSW effect can affect *either* neutrinos or anti-neutrinos, *but not both*, the massless resonant oscillation, if it occurs, will affect *both* ν 's and $\bar{\nu}$'s. It could then substantially affect the propagation of $\nu - \bar{\nu}$ pairs emitted in the thermal phase of a supernova explosion, and the resulting neutrino signal.

Finally, matter can affect neutrino propagation in other ways *e.g.* neutrino decay [15], the neutrino magnetic moment (MM) [16] and the neutrino transition magnetic moment (TM) [17]. Recent work on these topics is reported in [18].

This work was supported by CICYT under grant number AE-88-0021-04. I am grateful to the organizers for their kind invitation.

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