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Solar Neutrino Oscillation Parameters in the Supersymmetric Majoron Model

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Abstract

Matter enhanced neutrino oscillation parameters can be probed in a variety of *conventional* experiments in supergravity models with spontaneously broken R parity. We analyse existing *laboratory* restrictions on the oscillation parameters and compare them with the results of the chlorine experiment. We find that the possibility of *adiabatic* ^8B neutrino transitions is severely restricted thus implying that a substantial depletion of low energy *pp* neutrinos should be observed in upcoming gallium experiments.

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The long-standing puzzle of the low flux of solar neutrinos indicated by the results of the chlorine experiment may be resolved either by changing the solar physics [1] or by changing the propagation properties of neutrinos [2,3,4,5,6,7].

Here we focus on the possibility that the observed flux of ^8B neutrinos is smaller than the flux emitted by the sun as a result of neutrino oscillations. These can be strongly affected by matter due to the effect of charged current (CC) coherent neutrino scattering which exists for electron but not muon or tau neutrinos [7] [*]. Since the effect (denoted MSW) has a resonant nature [6] it can happen even when vacuum mixing angles are very small. There are two extreme limits where matter oscillation effects allow a simple description [†]. For slowly varying matter densities the transition can be *adiabatic*: the neutrino state vector "follows" the slowly changing Hamiltonian, along the neutrino path. This requires, for the sun, $(\delta m_\nu/eV)^2 \simeq 10^{-4}$. If the density changes sharply, the transition may be sudden or *non-adiabatic* and this allows an efficient conversion of ^8B neutrinos provided $(\delta m_\nu/eV)^2 \sin^2 2\theta \simeq 3\times 10^{-8}$. In addition there is another solution corresponding to large mixing, $\sin^2 2\theta \simeq 0.64$. These conditions altogether lead to the sides of a "triangle" shown in Fig. 2. Detailed analysis of the parameters required for MSW effect on solar neutrino oscillations to agree with the chlorine experiment leads to the region between curves A and B [12].

This raises a challenge: *how can we probe in the laboratory for these oscillation parameters?* The possibility of detecting *kinematical* effects for neutrino masses in this range seems

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[*] Nonuniversal neutral current coherent neutrino scattering could also affect neutrino propagation in matter, but the effect is expected to be small for solar neutrinos [8]

[†] We consider a two-neutrino system. Our model predicts that solar neutrino oscillations only involve two neutrinos [9,10,11].

out of reach [‡]. It is quite remarkable however that one can get a handle on the oscillation parameters [9,10,14,15,11] through *dynamics*, if the neutrino mass is related to some new particles in a way that their effects can be used to probe an otherwise undetectably small mass. Models which realize this idea share in common the presence of a Majoron arising from the spontaneous breaking (at a low energy scale, eq. (2)) of total lepton number, with the Majoron transforming as an electroweak doublet [9,10,14,15]. Here we analyse the oscillation parameters of the MSW model in the context of the SUSY Majoron model [9,10,11]. We show how in this model the oscillation parameters are severely restricted and how the non-adiabatic regime is selected as the one most likely to be relevant for explaining the solar neutrino puzzle through the MSW effect.

The model is the standard SUSY model [16] in which spontaneous violation of total lepton number symmetry through nonzero VEV's for the scalar neutrinos $v_i = \langle \tilde{\ell}_i^0 \rangle \quad (i = e, \mu, \tau)$. has been introduced.[§] This spontaneous breaking of lepton number [17] also violates a selection rule, usually assumed to hold in most discussions of SUSY models, according to which SUSY particles can only be pair-produced, the lightest of these particles being stable. This discrete symmetry is called R parity: all particles of the standard model (including the Higgs scalars) are R-*even* while their SUSY partners are R-*odd*. R parity is related to total lepton number according to $R_p = (-1)^{3B+L+2S}$ where S denotes spin, B and L denote baryon and total lepton number, respectively. Spontaneous R parity breaking will mix the leptons with the SUSY partners of gauge and Higgs particles: *charginos* and *neutralinos*. Neutral mixing generates a nonzero neutrino mass,

$$m = \frac{\mu M \sum_i v_i^2}{2 v_u v_d M - M_1 M_2 \mu} \tag{1}$$

where $2M = g_1^2 M_2 + g_2^2 M_1$, g_i are gauge coupling constants, M_i, $i = 1, 2, 3$, denote gaugino mass parameters, the parameters v_u and v_d are Higgs VEV's, and the Higgsino mixing parameter μ is related to electroweak gauge symmetry breaking. In addition, since B-L is a continuous global symmetry, spontaneous breaking generates a physical massless Goldstone boson - a Majoron - which we denote J. Majoron emission generates new mechanisms of stellar energy loss: being very weakly coupled, once Majorons are produced in a stellar environment, through Compton-like processes such as $\gamma + e \to e + J$, they easily escape. Supressing the resulting stellar energy loss requires [18],

$$v \leq 10\ Kev. \tag{2}$$

where $v^2 = \sum_i v_i^2$. This Majoron is fundamentally different from that in the triplet model [19] because it is SUSY partner of the neutrino [17,9,10] and therefore, (I) is a member of an isodoublet, and (II) carries only *one* unit of total lepton number. This implies (I) the Z width is only mildly increased [¶] by light neutral scalar contributions, unlike the triplet Majoron, whose contribution is four times bigger and, (II) B-L is now broken by just *one* unit through the scalar neutrino VEV. Thus *two* such breakings are needed to generate a (Majorana) mass for the (left handed) neutrino, hence the quadratic dependence on v_i, eq. (1), contrasting with the *linear* dependence characteristic of the triplet model. Combining with the astrophysical limit eq. (2), it follows then that the neutrino mass lies in the range adequate for the MSW effect to explain solar neutrino data for very reasonable, but

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[‡] This could be avoided in models where, due to some special symmetry, neutrino masses are much larger than mass differences [13].

[§] In addition, some mechanism of explicit lepton flavour violation [15] is required.

[¶] Additional contributions to the Z width may, however, be present in our model, which could presumably be probed at LEP [15] *restricted* choices of the SUSY parameters [9,10]. To a very good approximation [‖] *one and only one* neutrino acquires mass, namely, the one which is the SUSY partner of the Majoron. As a result of such a simple pattern only *three* parameters are needed to describe neutrino oscillations: two mixing angles (the third angle can be eliminated, due to the mass degeneracy between two of the neutrinos) and one neutrino mass parameter, m_ν. Of the two angles describing the CC weak interaction mixing matrix [21,9,10], one specifies the oscillation channel and is unaffected by matter, while the other is the angle shown in Fig. 2. Combining the above features leads to a restricted set of resonant oscillation parameters.

We now summarize the results of a detailed study of these *laboratory* restrictions. First we have limits from high energy experimental searches for SUSY fermions, specially the lightest *chargino* whose mass is given by

$$m_{\chi^+}^2 = \frac{1}{2}\{M_2^2 + \mu^2 + 2m_W^2$$

$$- \sqrt{(M_2^2 - \mu^2)^2 + 4m_W^4 \cos^2 2\theta_V + 4m_W^2(M_2^2 + \mu^2 + 2M_2\mu \sin 2\theta_V)}\} \tag{3}$$

If sufficiently light, $\chi^+ - \chi^-$ pairs will be produced in high energy $e^+ - e^-$ collisions. Their non-observation at PETRA implies constraints on the parameters μ, the gaugino mass parameter M_2, and $\tan\theta_V = v_d/v_u$ [9]: some of the values of μ and M_2 lead to an exceedingly small mass of the lightest chargino. [**] In addition, we showed in ref. [10] that limits on these parameters also follow from precision measurements of τ and μ lepton decay parameters due to Majoron emission effects. These constraints have now been determined systematically. For a fixed value of v_d/v_u and M_1/M_2 the restrictions depend only on μ and M_2. The neutrino mass depends also on these two parameters and on the lepton number breaking VEV v which obeys the astrophysical limit of eq. (2). Thus, by scanning all possible (μ, M_2) values we can depict the allowed regions directly in terms of the physical parameters, the masses and the mixing angles.

In Fig. 1 we show in the plane $m_{\chi^+} - m_\nu$ the allowed values of the masses by using the astrophysical bound on the VEV v, eq. (2). Curve 1.a is for $v_u = v_d$ while 1.b is for $v_u = 3v_d$. The region on the left of the vertical line at $m_\chi^+ = 23\ GeV$ is forbidden by PETRA. Clearly this implies an upper bound on the neutrino mass which becomes stronger the more v_u and v_d differ. Thus, for $v_u = v_d$ we obtain, from the figure, that $m_\nu < 1.4 \times 10^{-2}\ eV$ and for $v_u = 3v_d$ the limit is $m_\nu < 2.4 \times 10^{-3}\ eV$. These bounds reflect a strong trend towards non-adiabaticity of the ^8B neutrino transition specially for $v_u > v_d$. Adiabaticity can only be reached marginally if $v_u = v_d$.

From the correction to the Michel parameter in τ and μ decays due to double majoron emission it is possible to put an upper bound on the mixing relevant for neutrino oscillations in matter, $\sin^2 2\theta_{13}$ [10], which can be written as

$$\sin^2 2\theta_{13} < 0.4/\,|h(\mu, M_2)|^2 \tag{4}$$

where the function $h(\mu, M_2)$ is

$$h(\mu, M_2) = m_W^2 \left(\frac{\mu^2 + g_2^2 v_u^2}{(\mu M_2 - g_2^2 v_u v_d)^2} + 2\frac{v_u}{v_d}\frac{1}{(\mu M_2 - g_2^2 v_u v_d)} \right) \tag{5}$$

The bound of eq. (4) depends on the values of μ and M_2. Thus, for each value of the SUSY parameters, the neutrino mass and the neutrino mixing are bounded. By suming up the allowed regions for all values of μ and M_2 we can obtain directly on the plane $\sin^2 2\theta_{13}/\cos 2\theta_{13} - m_\nu^2$ which part of the MSW "triangle" is allowed in the SUSY majoron model. We show all these constraints in Fig. 2, Fig. 2.a is for $v_u = v_d$ and Fig. 2.b is for $v_u = 3v_d$. The combined bounds on the mixing angle and on the neutrino mass, coming

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[‖] Radiative corrections, considered in [20] are negligible for our purposes.

[**] For simplicity we assume $M_1/M_2 = \frac{5}{3}\tan^2\theta_W$ [9].

respectively from the correction to the Michel parameter in τ decay and from the astrophysical limit on the VEV, forbid the regions of *large* masses and large mixings. The bound from PETRA appears in Fig. 2, mainly, through the upper bound on the neutrino mass obtained above. For $v_u = v_d$ this bound is not enough to forbid the region of *large* neutrino masses and small mixings, however, that region, although large in the $\sin^2 2\theta_{13}/\cos 2\theta_{13} - m_\nu^2$ space, is very small in the $\mu - M_2$ plane. Thus, for $v_u = 3v_d$, this adiabatic region disappears completly and the only allowed region is that of very small masses and relatively large mixings (Fig. 2.b). In all of this we used $v < 10\ KeV$ and, we note, from eq. (1), that m_ν depends quadratically on v. So there is still a small window of opportunity for an adiabatic transition of ${}^8B$ neutrinos hidden in the accuracy of the determination of the astrophysical limit, eq. (2).

In summary, if R-parity breaking is the origin of neutrino masses, then the smallness of MSW mass parameter is accompanied by *large* dynamical effects which can be searched also in conventional experiments. These are associated with the possible existence of SUSY at accessible energies and with the possible existence of the Majoron itself, both providing testing grounds for the oscillation hypothesis. A reduced ${}^8B$ neutrino flux implies severe restrictions on the SUSY spectrum and measurable Majoron emission effects in τ decays. Combining these constraints leads to a direct connection between the latter and the adiabaticity in the solar neutrino transition: reducing the solar neutrino flux below 2.1 SNU is only possible to achieve (without violation of laboratory experiments) for a restricted set of oscillation parameters (Figs 1 and 2) where the solar neutrino transition is mostly non-adiabatic. This would imply that, the expected depletion of low energy *pp* neutrinos is at least a factor 7 or so below the standard solar model expectation, in sharp contrast to the adiabatic result. In addition, in this region of oscillation parameters, regeneration of solar neutrinos at the

earth is expected to play an important role [12]. Thus our model can be tested by the results of the gallium experiments. These conclusions rely (i) on R parity breaking being realized minimally and, (ii) on the accuracy of the determination of the astrophysical bound (eq. (2)). Finally, parameters of the broken R parity solar neutrino model are restricted over and above those of standard supergravity, so it will be easier to confront them also with high energy experimental searches. We intend to take up this question in another publication [15].

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Figure Captions

Fig. 1 : Allowed region of the masses of the neutrino and the lightest chargino. The bound from PETRA forbids the region on the left of the vertical line at $m_{\chi^+} = 23\ GeV$. Curve 1.a is for $v_u = v_d$ while 1.b is for $v_u = 3v_d$.

Fig. 2 : Constraints on matter enhanced neutrino oscillation parameters in the supersymmetric majoron model. Combined bounds coming from the correction to the Michel parameter in τ decay due to majoron emission and the astrophysical limit on the lepton number breaking VEV. The allowed region is the one left and below curve labelled C. The region above the horizontal D is forbidden by PETRA. The region between the two triangular shaped curves denoted A and B correspond to a count rate of $2.1 \pm 0.35\, SNU$ in a $5.8\, SNU$ solar model. They are taken from Baltz and Weneser [12]. Figures 2.a and 2.b, as before, are for different values of the ratio v_u/v_d.

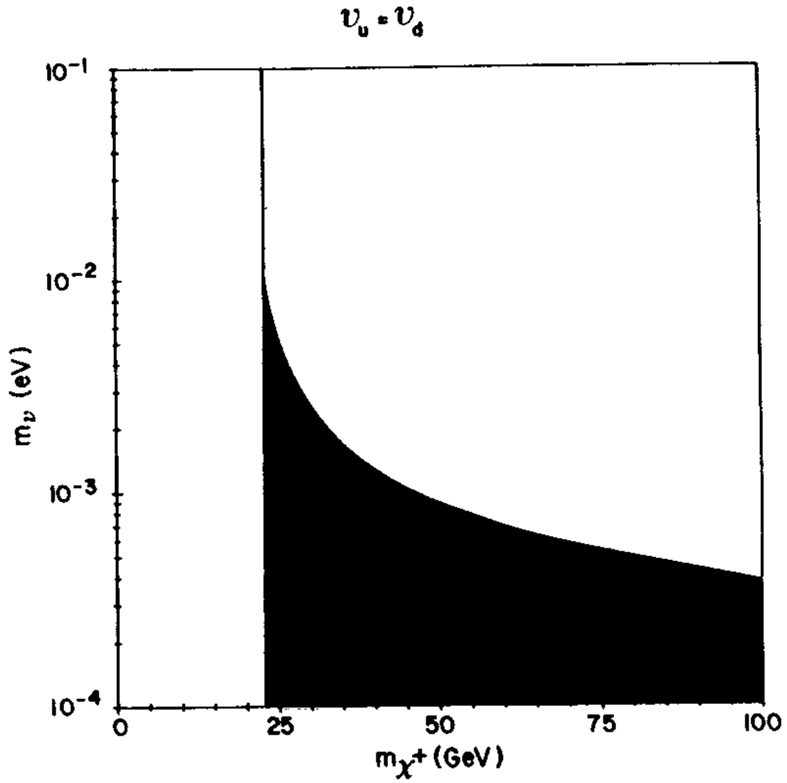
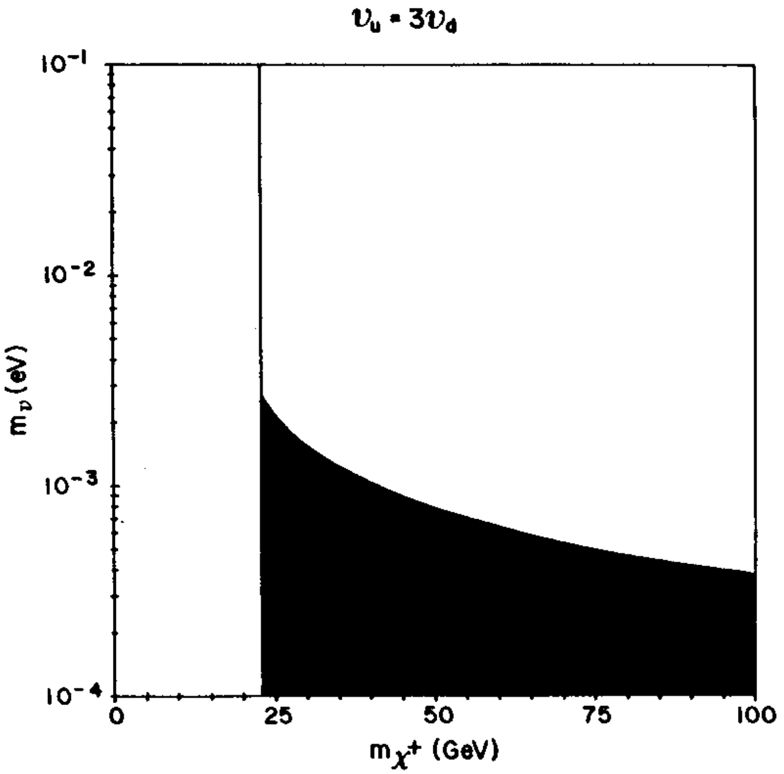
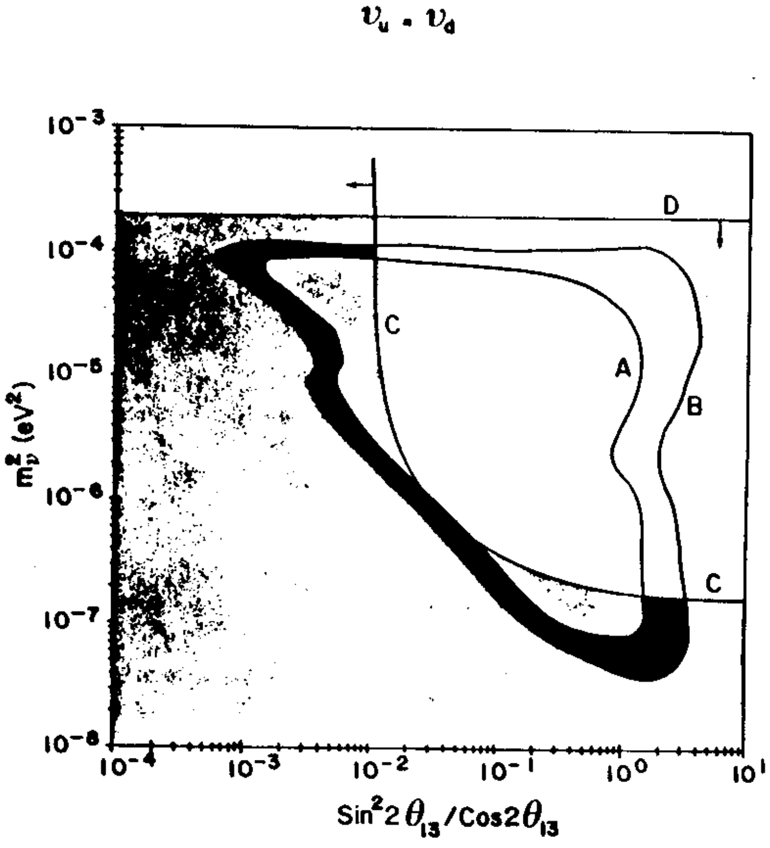


Fig. 1.a



$v_u = 3v_d$

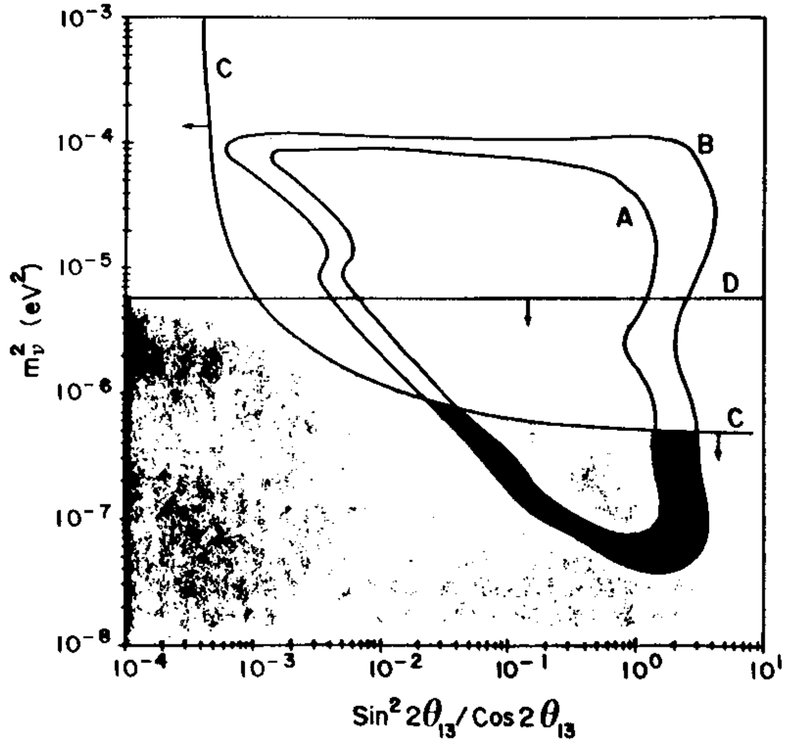
Fig. 1.b



$v_u = v_d$

Fig. 2.a

$v_u = 3\,v_d$



m_ν^2 (eV^2)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$\sin^2 2\theta_{13}/\cos 2\theta_{13}$
C
B
A
D
C

Fig. 2.b