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Solar-neutrino-oscillation parameters and the broken-*R*-parity Majoron

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Matter-enhanced neutrino-oscillation parameters can be probed in a variety of *conventional* experiments in supergravity models where the small neutrino mass arises from spontaneous *R*-parity violation. A combined analysis of astrophysical and laboratory limits tends 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}Be neutrino flux even for a mildly reduced ^{8}B neutrino flux, thus stressing the importance of gallium experiments.

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.[2-7] Among the latter possibilities here we focus on the hypothesis that the observed flux of ^{8}B neutrinos may be smaller than the flux emitted by the Sun as a result of neutrino oscillations. These can be affected by matter due to the effect of charged-current (CC) coherent neutrino scattering which exists for electron but not for μ or τ neutrinos.[7] The effect of matter has a resonant nature[6] and can happen even when vacuum mixing angles are very small. There are two extreme limits where matter oscillation [Mikheyev-Smirnov-Wolfenstein (MSW)] effects allow a simple description. (We consider a two-neutrino system. Our model predicts that solar-neutrino oscillations only involve two neutrinos.[8-10]) 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, $(\delta m_\nu/\mathrm{eV})^2 \simeq 10^{-4}$. If the density changes sharply, the transition may be *nonadiabatic* and this implies $(\delta m_\nu/\mathrm{eV})^2 \sin^2 2\theta \simeq 3\times 10^{-8}$. In addition there is a solution corresponding to large mixing, $\sin^2 2\theta \simeq 0.64$. The oscillation parameter values for which the MSW effect can substantially affect solar-neutrino fluxes are shown in Fig. 1 (Ref. 11).

Reducing the solar-neutrino flux this way raises a challenge: *how can we probe these oscillation parameters in the laboratory*? The possibility that *kinematical* neutrino mass effects for masses in this range will be detectable seems out of reach. (This could be avoided in models where, due to some special symmetry, neutrino masses are much larger than mass differences.[12]) It is quite remarkable however that one can get a handle on the oscillation parameters[8-10,13,14] through *dynamics,* if the neutrino mass is related to some new particles in such a way that their effects can be used to probe an otherwise undetectably small mass. Models can be conceived which realize this idea in various ways. They 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. Here we analyze the oscillation parameters of the MSW model in the context of the supersymmetric (SUSY) Majoron model described in Refs. 8–10. We show how in the minimal model the oscillation parameters are severely restricted and how the nonadiabatic 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[15] in which spontaneous violation of total lepton-number symmetry through nonzero vacuum expectation values (VEV's) for the scalar neutrinos $v_i = \langle \tilde{l}_i^0 \rangle$; $i = e,\mu,\tau$ has been introduced. This spontaneous breaking of lepton number[16] 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 can happen in a large class of supergravity models.[17] In addition, we need some mechanism of explicit lepton-flavor violation and this can also be introduced in various ways.[14]

For the sake of simplicity here we describe only the *prototype* *R*-parity Majoron (RPM) model which illustrates more vividly the general predicted trend for solar-neutrino oscillations in these models.

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 field 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 of the Lagrangian, spontaneous breaking generates a physical massless Nambu-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-type processes such as $\gamma + e \rightarrow e + J$, they easily escape. Suppressing the resulting stellar energy loss requires[18]

$$v \leq 10\text{–}20 \text{ keV} , \tag{2}$$

where $v^2 = \sum_i v_i^2$. (The issue of *naturalness* of such a small scale within the full supergravity theory requires a detailed analysis of the one-loop corrections to the scalar potential, along the lines of Ref. 19.) The resulting Majoron is fundamentally different from that in the triplet model[20] because it is the SUSY partner of the neutrino[8,9] 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 (85 MeV) (additional contributions to the Z width could be present in our model[14]) 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; hence, *two* such breakings are needed to generate a (Majorana) mass for the (left-handed) neutrino, giving the quadratic dependence on v_i, in Eq. (1), instead of the *linear* dependence characteristic of the triplet model. Combining with the astrophysical limit in 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 *restricted* choices of the SUSY parameters.[8–10] To a very good approximation (radiative corrections, considered in Ref. 21 are negligible for our purposes) *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 the structure of the CC leptonic weak interaction is considerably simplified and the number of parameters needed to describe neutrino oscillations is reduced to just *three*: 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[22,8,9] one specifies the oscillation channel and is not affected by matter, while the other is the angle shown in Fig. 1.

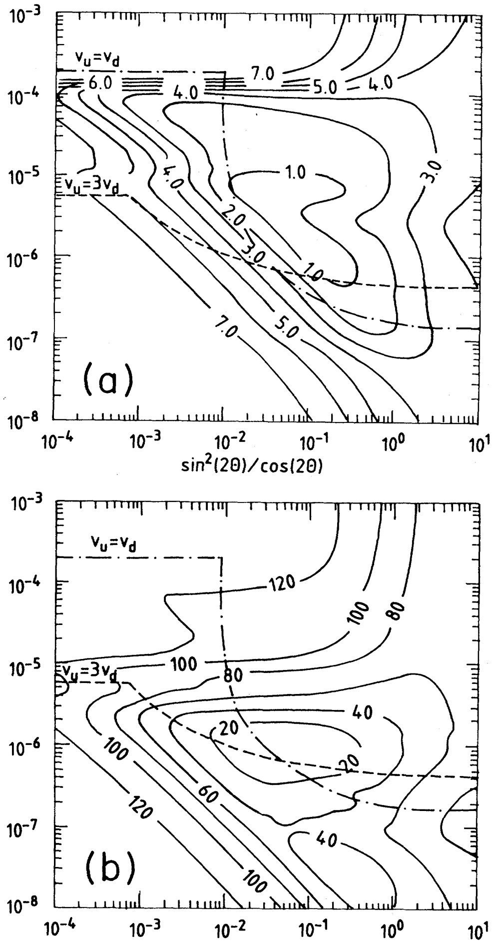

FIG. 1. (a) shows the iso-SNU contours for the chlorine experiment [taken from Baltz and Weneser (Ref. 11) who calculated in the recent 7.9 SNU solar model, including Earth effects averaged over day/night and seasonal variations]. Shown in (b) are gallium iso-SNU contours, for night. In the RPM model only the region to the left and below the curve labeled $v_u = v_d$ or $v_u = 3v_d$ is allowed. This follows from the combined constraints coming from the correction to the Michel parameter in τ and μ decays due to Majoron emission, from *chargino* searches at PETRA and the astrophysical limit on the lepton-number-breaking VEV in Eq. (2). Comparing (a) and (b) shows that even when the high-energy neutrino count rate is high, the RPM model favors a large suppression in the *low*-energy neutrino flux.

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

$$\begin{aligned} m_{\chi^+}^2 = \tfrac{1}{2}\{ & M_2^2 + \mu^2 + 2m_W^2 \\ & - [(M_2^2 - \mu^2)^2 + 4m_W^4 \cos^2 2\theta_V \\ & + 4m_W^2 (M_2^2 + \mu^2 + 2M_2 \mu \sin 2\theta_V)]^{1/2}\} \ . \end{aligned} \tag{3}$$

If sufficiently light, χ^+-χ^- pairs will be produced in high-energy e^+-e^- collisions. Some of the values of μ and M_2 lead to an exceedingly small mass of the lightest chargino. We assume a fixed M_1/M_2 value which we take to be $M_1/M_2 = \frac{5}{3}\tan^2\theta_W$ (Ref. 8) and vary as $\tan\theta_V = v_d/v_u$. The nonobservation of χ^+-χ^- pair at the DESY e^+e^- storage ring PETRA implies constraints on the parameters μ, the gaugino mass parameter M_2 (Ref. 8). The neutrino mass depends also on these two parameters and on the lepton-number-breaking VEV v in 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. 2 we show in the m_{χ^+}-m_ν plane the allowed values of the masses by using the astrophysical bound in Eq. (2). The upper curve is for $v_u = v_d$ and the lower one 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 nonadiabaticity of the solar-neutrino transition specially for the favored case where $v_u > v_d$. Adiabaticity can only be reached very marginally if $v_u = v_d$.

In addition, we showed in Ref. 9 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. From the correction to the Michel parameter in τ and μ decays due to Majoron emission,[9] it is possible to put an upper bound on the mixing relevant for neutrino oscillations in matter, $\sin^2 2\theta$ which can be written as

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

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 in Eq. (4) depends on the values of μ and M_2. Thus, for each value of the supersymmetric parameters, the neutrino mass and the neutrino mixing are bounded. By summing up the allowed regions for all values of μ and M_2 we can obtain directly on the plane $\sin^2 2\theta / \cos(2\theta)$-$m_\nu^2$ the part of the MSW "triangle" allowed in the RPM model. We show all these constraints in Fig. 1. The combined bounds on the mixing angle and on the neutrino mass, coming, 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. 1, 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, this region, although large in the $\sin^2 2\theta$-m_ν^2 space, is very small in the μ-M_2 plane. Thus, for the preferred case $v_u > v_d$, this adiabatic region tends to disappear, as can be seen from the $v_u = 3v_d$ curve, where the only allowed region is that of very small masses and relatively large mixings. 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 window for an adiabatic transition hidden in the accuracy of the determination of the astrophysical limit, Eq. (2).

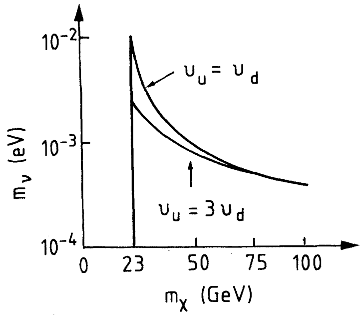

FIG. 2. Allowed region of the masses of the neutrino and the lightest chargino. The bound from PETRA forbids the region on the left of the vertical line at $m_{\chi^+} = 23$ GeV, thus leading to an *upper* bound on m_ν.

In summary, if R-parity breaking is the origin of neutrino mass, then the smallness of the 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. A reduced solar-neutrino flux implies severe restrictions on the SUSY spectrum and measurable Majoron emission effects in τ decays. Reducing the solar-neutrino flux below 2.1 SNU (solar-neutrino unit) is only possible to achieve (without violation of laboratory limits) for a restricted set of oscillation parameters (Figs. 1 and 2) where the solar-neutrino transition is mostly *nonadiabatic*. This implies that the expected depletion of low-energy neutrinos can be up to a factor of 7 or so below the standard solar-model expectation, in sharp contrast to the adiabatic result. This reduction of the *low*-energy neutrino flux is likely to be large in our model even if we take at face value the increased high-energy neutrino count rate of 5 SNU or so observed in the latest run of the Davis experiment. Thus the R-parity Majoron model can be excluded by the forthcoming gallium experiments. These conclusions rely on R-parity breaking being realized minimally and, in addition, on the accuracy of Eq. (2).

The idea of R-parity breaking as a model for the MSW resonance is however more *general* than the minimal realization we have presented. It can be implemented in a wide class of supergravity models and, interestingly enough, there is a *common* trend towards nonadiabaticity of the ^{8}B neutrino transition in all of these models.[14] The importance of the gallium experiment (generally accepted from the point of view of separating the physics of the Sun from that of neutrino propagation as the cause for a reduced solar-neutrino flux) is now highlighted in the RPM models also from the point of view of the physics of the MSW effect itself: the nonadiabatic transition of the high-energy neutrinos favored in these models makes it natural to expect a large reduction in the *pp* and ^{7}Be neutrino flux even if the high-energy neutrino count rate in chlorine happens to be fairly high.

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