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SIGNATURES OF SPONTANEOUSLY BROKEN R-PARITY AND SOLAR NEUTRINO OSCILLATIONS *.

A. Santamaria [†]

Departamento de Física Teórica, Universitat de Valencia

46100 Burjassot, Valencia, Spain

and

J W F Valle

Departamento de Física Teórica, Universitat de Valencia

46100 Burjassot, Valencia, Spain

and

Lawrence Berkeley Laboratory, University of California

Berkeley, California 94720, USA

Abstract

Spontaneous R parity breaking in supergravity offers a testable solution of the solar neutrino problem by matter enhanced neutrino oscillations. The supersymmetric spectrum is restricted in a way that will be probed by collider experiments such as TRISTAN, SLC and LEP. In addition there are "dynamical" constraints associated with the existence of a weakly interacting Majoron which follow from stellar energy loss considerations. Majoron emission may be seen in precision tests of μ and τ decays. A signature of the model is the possible observation of the decay $\mu \to e+$ Majoron.

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1. Introduction

The solar neutrino problem may be resolved either by postulating new physics that modifies the solar parameters [1] or by assuming that non-standard weak interactions modify neutrino propagation properties. The physics leading to the second type of solution includes neutrino decay [2], neutrino magnetic moment [3] and neutrino oscillations [4,5,6]. While it is possible to build consistent models for fast neutrino decay [7], the required value of the neutrino magnetic moment needed to solve the solar neutrino problem is inconsistent, in most models, with existing limits on neutrino mass. Neutrino decay, however, has also been rendered unlikely, by the recent observation of neutrinos from the the SN1987 supernova [8] although it has been argued that, for large mixings, the model may still survive [9]. This leaves neutrino oscillations as the most likely explanation of the solar neutrino problem in terms of non-standard neutrino properties. At first sight it seems that it will be quite difficult to test experimentally for the oscillation hypothesis. If oscillations occur *in vacuo* then the required large mixing angle indicates values for the relevant mass squared differences that are too small to be probed [6]. A lot of interest has been recently devoted to the possibility of *matter- enhanced* oscillations [4]. These are possible due to the effect of coherent neutrino scattering in the solar medium even for values of the vacuum mixing angles which are very small. This resonant enhancement is possible, however, only if the neutrino mass difference lies in the range [‡]

$$10^{-7} \lesssim \left(\frac{\delta m}{ev}\right)^2 \lesssim 10^{-4}. \tag{1}$$

Again the oscillation hypothesis indicates mass differences that are too small to allow an experimental check in existing setups. Although experimental effort will be pushed in this direction [11], it will be a number of years before one will be able to start probing the range specified in eq (1). From this point of view a most interesting question is Q1: *What are the physics options for having an experimentally testable solution to the solar neutrino puzzle in terms of neutrino oscillations?* In addition we have Q2: *What is the physical origin for the relevant neutrino mass scale?*

The second question may be answered in a variety of ways *eg* by introducing in the theory heavy singlet fermions such as right handed neutrinos, at a mass scale *above* that of electroweak symmetry breaking. This could, for example, be the grand unification scale in SO(10) models [12] or some intermediate scale in superstring inspired E_6 models [13,14,15]. Alternatively, one may introduce a physical mass scale *below* the Fermi scale and have an "inverted" see-saw mechanism in which the heavy states are at the Fermi scale [16]. The

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[‡]Detailed analysis of the range of parameters required for the resonant amplification of neutrino oscillations to take place has been given by many authors, see *eg* ref [10].

natural framework to implement this idea is supergravity, in which case the heavy states necessary in the see-saw mechanism are just the supersymmetric partners of gauge and Higgs fields. *In both cases we are left with question Q1.*

There are two generic types of models where the solar neutrino oscillation hypothesis may be experimentally checked. First it can be checked "kinematically" in models where

$$m \gg \delta m \tag{2}$$

where m represents a typical neutrino mass and δm denotes a neutrino mass difference. One way to model this hierarchical difference in the values of m and δm is to attribute it [5] to the presence of a large intermediate scale in superstring inspired models [13,14]. The electron neutrino is just one Weyl component of a four-component Quasi-Dirac neutrino [17] of mass $m \gg \delta m$. The other component may be another neutrino flavour or, as in ref [5], can be a *sterile* neutrino. If ν_e is a Quasi-Dirac particle it can be massive enough as to be *seen* in tritium decay experiments and also to play a role in providing the dark matter of the universe, without conflicting any experimental limit. The solar neutrino problem can then be solved by large vacuum oscillations from the *active* to the *sterile* component as ν_e propagates from sun to earth. Here we focus on the alternative possibility where one has

$$m = O(\delta m) \tag{3}$$

so that "kinematical" neutrino mass effects will not be detectable but the theory contains some new "dynamical" degree of freedom whose "large" effects can be probed and used, in a sense, to "track" an otherwise undetectably small mass. The prototype of this situation is when B-L is a true symmetry of the Lagrangian, broken only spontaneously. If B-L is ungauged, as in the standard model, spontaneous breaking generates a Goldstone boson — a Majoron — which we denote J. [§] The Majoron is a true dynamical degree of freedom so it has interactions which are related in a well defined way with the neutrino mass. Majoron emission generates new mechanisms of stellar energy loss. Due to its flavour non-diagonal couplings, Majoron emission will also produce small changes in the decay parameters of the muon and the τ lepton which could be seen in precision measurements of μ and τ decays. The present good agreement of the observations with the standard model predictions leads to nontrivial constraints. Interestingly enough, these contraints still allow, with a bit of optimism, the possible observation of the decay $\mu \to e + J$ which would provide an interesting signature for this scenario. The smallness of the neutrino mass, required by the resonance condition, eq (1), is dictated by constraints on the couplings of the Majoron that follow from a variety of considerations thus giving a dynamical basis for the see-saw mechanism.

[§]If the gauge group contains B-L there will be an additional gauge boson, coupled to neutrinos [18].

2. The Spontaneously Broken R Parity (SBRP) Model

The SBRP model is described by the minimal supergravity superpotential

$$h_{ij}^u u_i^c Q_j H_u + h_{ij}^d d_i^c Q_j H_d + h_{ij}^e e_i^c \ell_j H_d + \mu H_u H_d \tag{4}$$

where the parameter μ is related with electroweak breaking driven by radiative corrections associated with the top quark. The first three terms give rise to masses for up and down-type quarks, and charged leptons, respectively, once the two Higgs fields H_u and H_d acquire their vacuum expectation values (vevs) v_u and v_d. Supersymmetry is broken explicitly in the scalar potential via soft scalar mass terms and possibly cubic scalar self couplings, and also via $SU(3) \times SU(2) \times U(1)$ invariant gaugino mass terms M_i, i=1,2,3. Gaugino masses break the continuous R invariance of the theory down to a discrete symmetry, called R parity. R parity is *even* for all particles of the standard model (including the Higgs scalars) and *odd* for their supersymmetric partners. R parity too may be broken, either explicitly [19] or spontaneously by nonzero vevs for the scalar neutrinos [20],

$$v_i = \left\langle \ell_i^0 \right\rangle; \quad i = e, \mu, \tau. \tag{5}$$

The conditions for spontaneous R parity breaking are very restrictive. Recent analysis [21] indicates that sleptons lighter than about 65 Gev and a top quark heavier than about 70 Gev are required. This breaking may be far easier to achieve if one adds terms that break lepton flavour and/or total lepton number explicitly as well.

Spontaneously breaking of B-L, an ungauged continuous symmetry, generates a Nambu-Goldstone boson — a Majoron — given in ref [16]. This also gives a neutrino mass

$$m = \frac{\mu M \sum_i v_i^2}{2 v_u v_d M - M_1 M_2 \mu} \tag{6}$$

where

$$2M = g_1^2 M_2 + g_2^2 M_1$$

and g_i are gauge coupling constants. Note that since B-L is broken by *one* unit via the scalar neutrino vev, eq (5), it takes *two* such breakings to generate a (Majorana) mass for the (left handed) neutrino: hence the square in the see-saw formula, eq (6). This contrasts with the non-supersymmetric Majoron model [22] in which a scalar Higgs triplet is introduced to generate neutrino masses directly and therefore *linear* in the lepton number breaking expectation value. In supersymmetry no triplet needs to be added (therefore the ρ parameter is identically one, at tree level) and we note that in fact triplets are absent in superstring inspired models [15] . Another striking difference, which makes the SBRP Majoron model

much more restrictive, is the fact that *one and only one* neutrino acquires mass, namely, the one which is related by supersymmetry to the Majoron. Its mass is given by eq (6).[¶] This simplifies considerably the structure of the CC weak interaction reducing the parameters relevant for describing the resonant neutrino oscillations in the sun to just *three* parameters: two mixing angles (the third angle is not a physical parameter, due to the mass degeneracy between the two massless neutrinos) and one neutrino mass parameter, m. Moreover, CP is conserved in the charged current. The matrix K describing the CC weak interaction, can be put in the canonical form [16,23]

$$K = \omega_{23}(\theta_{23})\omega_{13}(\theta_{13}) \tag{7}$$

where, for example, ω_{13} is a rotation by an angle θ_{13} in the 13 plane,

$$\omega_{13} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}.$$

For $v_\tau \gg v_\mu \gg v_e$ the mixing angles in eq (7) are small so that the massive state is mostly ν_τ and resonant solar neutrino conversions occur from ν_e into ν_τ [16]. Because of such drastic simplification, there are interesting experimental signatures that make the SBRP Majoron model testable. In [16] we showed how the gaugino-Higgsino mass spectrum is restricted by Davis' experimental results and how the allowed range of parameters where resonant amplification of solar neutrino oscillations can occur may be directly explored by searching for charged supersymmetric partners of gauge and Higgs particles, say, in electron-positron machines. Here we concentrate on additional tests of the model based on the dynamics of the Majoron.

3. Constraints on Majoron Couplings

The Majoron couples to quarks through its Higgs doublet admixture via the first two terms in eq (4). These couplings are always flavour diagonal. It couples to charged leptons in the same way, via the third term in eq (4). However, it also does so via mass mixing between the $R - even$ leptons (e, μ and τ) and the $R - odd$ fermion states (called *charginos*: supersymmetric partners of charged gauge and Higgs bosons). This is described by the mass

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[¶]The full tree level neutral lepton mass matrix was given in ref [16] and we note that radiative corrections are negligible for our purposes.

matrix

$$
\begin{array}{c|ccc}
 & e_j^+ & \widetilde{H}_u^+ & \widetilde{W}^+ \\
\hline
e_i^- & h_{ij}v_d & 0 & g_2 v_i \\
\widetilde{H}_d^- & h_{ji}v_i & \mu & g_2 v_d \\
\widetilde{W}^- & 0 & g_2 v_u & M_2
\end{array}
\tag{8}
$$

Since fermions of different weak isospin are mixed in eq (8) it follows that in the SBRP model the Majoron couplings to charged leptons is *not* flavour diagonal. *This is another important difference between the SBRP model and the triplet Majoron model and which as we will see, may be tested experimentally.* The coupling of the Majoron to physical charged leptons is described by the effective interaction Lagrangian,

$$
i\frac{g_2^2}{\sqrt{2}}\frac{vm_j}{m_W^2}\left(\frac{1}{2}\delta_{ij} + fg_{ij}\right)\bar{e}_{Li}e_{Rj}J + \text{H.C.}
\tag{9}
$$

where the function f is given by

$$
f = \frac{1 + x^2}{(1 - xy)^2}
$$

and, for simplicity, we have assumed $v_u \approx v_d$. In eq (9) x denotes the Higgs mixing parameter μ and y denotes the supersymmetry breaking SU(2) gaugino mass parameter M_2, in units of the W mass, $x = \mu/m_W$ $\quad y = M_2/m_W$. The coupling matrix g_{ij} is a projection matrix, and may be written as

$$
g_{ij} = (KPK^\dagger)_{ij}
\tag{10}
$$

where P is the matrix $P = \text{diag}(0,0,1)$.

In this model stellar energy loss will proceed via *single* Majoron emission in Compton-like process $\gamma + e \to e + J$. From the cross section given in ref [24] we have

$$
\frac{4}{\pi}G_F^2 m_e^2 v^2 a^2 \lesssim 3 \times 10^{-26}
\tag{11}
$$

where

$$
a = \frac{1}{2} + fg_{ee}
$$

which gives

$$
va \lesssim 30 \text{ KeV.}
\tag{12}
$$

In addition, energy loss also proceeds via *double* Majoron emission in $\gamma + e \to e + J + J$. This process occurs with normal gauge strength couplings but is mediated by the heavy charginos. We have calculated the total cross section for this process,

$$
\sigma = \frac{\alpha^3}{60 \sin^4\theta_W}\frac{E_\gamma^2}{M_W^4}f^2 g_{ee}^2
\tag{13}
$$

in the approximation where the photon energies $E_\gamma \ll m_e$. From this we obtain the independent limit

$$f^2 g_{ee}^2 \lesssim 10. \tag{14}$$

How about limits on the *flavour non-diagonal* Majoron couplings? This leads us to study the decays $e_j \rightarrow e_i + J + J$ and the associated change in the charged leptons decay parameters [25]. The amplitude for this process is [26]

$$T_{ij} \approx -2\sqrt{2}G_F f g_{ij} \bar{u}(p_i)(\not{p}_i + \not{p}_j)Lu(p_j) \tag{15}$$

where $p_{i,j}$ is the $e_{i,j}$ momentum. Requiring the fractional change in the Michel parameter for each case to be within the accuracy of present experimental determination gives, for the case of $\mu \rightarrow e + J + J$ decay, the limit

$$f^2 g_{e\mu}^2 \lesssim 10^{-2} \tag{16}$$

while for the corresponding τ decays the limits are

$$f^2 g_{e\tau}^2 \lesssim .35 \tag{17}$$

and a similar bound on $fg_{\mu\tau}$. These bounds pose non-trivial constraints on the parameters of our model and from this point of view precision measurements of μ and τ decays are theoretically very interesting.

4. The Decay $\mu \rightarrow e+$ Majoron

We now analyse the possible effect of *single* Majoron emission in μ and τ decays. The existence of these decays is predicted in the SBRP model as a result of mixing among charged fermions of different weak isospin. The branching ratio B_{ij} for $e_j \rightarrow e_i + J$, relative to $e_j \rightarrow e_i + \nu + \nu$, is given by

$$B_{ij} = 96\pi^2 \left(\frac{v}{m_j}\right)^2 f^2 g_{ij}^2. \tag{18}$$

For the case of $\mu \rightarrow e+$ J decay the branching ratio may be as large as

$$B_{e\mu} \approx 3 \times 10^{-7} \times \left(\frac{v}{30Kev}\right)^2 \tag{19}$$

thus suggestively close to the present experimental limit of TRIUMF $B_{e\mu} < 2.6 \times 10^{-6}$[27]. For τ decays, however, the corresponding allowed branching ratios are far below what can

be experimentally probed.

5. Discusssion

We find most encouraging that effects of Majoron emission in μ and τ decays can be at the cutting edge of experimental test! In this model the tiny neutrino mass needed for the MSW effect [4,10] is accompanied by "large" dynamical effects associated with the existence of the Majoron. These provide a dynamical testing ground for our scenario. Interestingly, there can be large observable effects for parameter values which solve the solar neutrino problem by the enhanced oscillation effect. Under reasonable assumptions, mixing angles s_{23} and s_{13} are small and in this case resonant solar neutrino conversions occur, in the adiabatic regime, from ν_e into ν_τ [16]. A reduction in solar neutrino flux below 2.6 SNU implies severe restrictions on the supersymmetric spectrum [16] and potentially large effects in μ and τ decays.

As an example we take $v \approx 30Kev$, $s_{13} \approx .05, s_{23} \approx .2$, $x \approx 2$ (Higgsino mixing $\mu \approx 160Gev$) , $y \approx 1$ (gaugino mass $M_2 \approx 80Gev$). For this case we have a change in the τ decay Michel parameter about a factor three *larger* than present experimental limit allows and a BR for $\mu \rightarrow e + J$ of $\approx 2 \times 10^{-7}$. A smaller value for s_{23} would decrease both the deviation in Michel parameter and the BR for single Majoron emission in μ decay. On the other hand, a larger value for v would increase $B_{e\mu}$ without changing the Michel parameter. In addition, for these parameter values, the lightest *chargino* weighs less than half of the Z mass and thus might be seen at accelerator experiments.

Finally we note that slightly stronger constraints on the lepton number breaking vev v have been recently suggested from the analysis of helium ignition in stars and from the recent neutrinos from SN1987 [28].

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