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1. Introduction

This talk focuses on some of the work that has been done in the last year or so on the possibility that spontaneous breaking of lepton number may provide realistic scenarios for a natural solution of the puzzling solar neutrino problem [1]. The data collected by R. DAVIS' ^{37}Cl detector [2], in some twenty years of operation, seems indeed to indicate a substantial depletion of the ^8B electron neutrinos coming from the sun, with respect to the Standard Solar Model (SSM) expectations. A recent reanalysis [3] of the predicted solar neutrino flux within the SSM gives, for ^{37}Cl detectors, a capture rate ranging between 6 and 9 Solar Neutrino Units (1 SNU $\equiv 10^{-36}$ capture/atom·sec), whereas the averaged rate measured in the Homestake mine experiment is 2.1 ± 0.4 SNU [1]. The existence of a deficit in the ^8B solar neutrino flux has been very recently confirmed by the Kamiokande II collaboration which sets an upper bound on the neutrino flux equivalent to about 50% of the SSM prediction [4].

Solutions to the solar neutrino puzzle have been mainly searched for in two directions, resorting, on one hand, to modifications of the standard solar astrophysical scenario, or considering, on the other hand, non standard neutrino properties which would affect their propagation from the interior of the sun to the earth. As suggestive of the first option, we may recall that the production rate of ^8B neutrinos is extremely sensitive to the central temperature of the sun and that a change of 6% in the core temperature would account for a 1/3 depletion. However, within the standard assumptions, the core temperature is predicted to better than 1% [3,5] (for a review on the SSM uncertainties see also Ref. 6) and new mechanisms must therefore be invoked to produce the required change (see Ref. 1 for a review on the existing proposals). As far as "exotic" neutrino properties are concerned, the presence of a large enough neutrino magnetic moment could produce a flip of the original left handed neutrino, interacting with the strong solar magnetic field, into its right handed counterpart, which would then pass through earth undetected [7]. The size of the magnetic moment required is however at the border of the present laboratory limits and may be already excluded by astrophysical considerations [8]. It is also difficult to build models in which such a large neutrino magnetic moment naturally arises. It is nonetheless intriguing that the Davis' data seems to "suggest" an anticorrelation between the solar magnetic activity and the detected neutrino flux. More statistics are needed to test this hypothesis.

Another possibility is provided by the decay of the electron neutrinos into "light" exotic particles and we will come back to that at the end of the talk. At any rate, barring the possible aforementioned correlation with the sun spot number, the most economical and elegant solution to the solar neutrino problem at present available is offered by the so called MIKHEYEV-SMIRNOV-WOLFENSTEIN (MSW) mechanism [9]. The idea is that electron neutrinos may undergo, due to charged current interactions in the dense solar interior, resonant oscillations into heavier species which cannot at present be detected at earth. The elegance of this mechanism resides in the fact that no specific fine tuning of the "vacuum" mixing angles is needed and even for very small flavour mixings, electron neutrinos may completely oscillate before leaving the sun. For the process to occur, some relations among neutrino masses, energy, and matter density have to be satisfied. In particular, neutrino mass squared differences ranging between 10^{-4} and 10^{-8} eV^2 are needed [10-12]. Such a small mass differences may certainly be considered natural if neutrino masses themselves lie in the above regime. It is a feature of the two models which I describe in the following to offer a scenario for naturally generating neutrino masses in the required regime. In addition, the process of neutrino oscillations is reduced in both models to a two dimensional problem, thus simplifying considerably its description. The models are characterized by the spontaneous breaking of global lepton number and the consequent presence of a new physical massless scalar: the *majoron* [13].

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The majoron, which is the Goldstone boson of the globally broken lepton number, was first introduced by CHICASHIGE, MOHAPATRA and PECCEI [13] via a Higgs singlet, in order to naturally provide a large majorana mass for the right-handed neutrino in a see-saw scheme for the neutrino mass. Later on, when it was clearly understood that Goldstone bosons do not mediate long range forces, GELMINI and RONCADELLI (GR) introduced a very simple extension of the standard electroweak model in which the majoron belongs to a Higgs *triplet* [14]. The interesting phenomenological implications of the model were immediately emphasized [15].

A common feature of the two models presented in this talk is that the majoron belongs to an $SU(2)_L$ *doublet* (which, as we will see in the following, has some relevant phenomenological consequences). In the first case, the so called "supersymmetric" (SUSY) majoron model, this property follows from a natural implementation of spontaneous breaking of lepton number in a supersymmetric scenario. In the second case, this is the characteristic feature of a minimal Higgs extension of the standard model, which we will refer to, hereafter, as the "doublet" majoron model. As we will see, in spite of the presence of additional parameters, both models turn out to be very constrained by present phenomenology and the requirement of consistency with the MSW solution of the solar neutrino problem makes them testable in conventional laboratory experiments, possibly in the very near future.

2. The Supersymmetric Majoron Model

The idea of relating R-parity breaking to the breaking of lepton number in a low energy supersymmetric framework was first proposed by AULAKH and MOHAPATRA [16] in the context of a two Higgs doublet plus singlet model. Some detailed aspects of the model were later worked out by the authors in Ref. 17. R-parity is a discrete symmetry, often present in low energy supersymmetric models [18], under which ordinary particles and their superpartners transform differently. If not broken, its presence leads, for instance, to the stability of the lightest "superparticle" (and avoids potentially dangerous contributions to baryon decay). The quantum number assignment is given as $R \equiv (-1)^{3B+L+2S}$, where B, L and S denote respectively baryon number, total lepton number and spin of the particle under consideration.

If at least one scalar partner of the ordinary neutrinos aquires a non vanishing vacuum expectation value, then lepton number and R-parity are spontaneosly broken (family lepton number is supposed to be explicitly but softly broken). The fact that R-parity is broken means that ordinary particles may mix with superpartners. Specifically, neutrinos mix with some of the neutralinos present in the model leading to an enlarged neutralino mass matrix. At the same time, an appropriate linear combination of scalar neutrinos gives rise to a massless scalar field : the majoron.

A simpler two Higgs doublet model exhibiting these features has been recently studied by SANTAMARIA and VALLE [19], with special emphasis on its possible relevance for the solar neutrino problem. There, the analysis of the enlarged neutralino mass matrix reveals that, to a very good approximation, only *one* linear combination of neutrinos aquires a mass. This in turn allows for a description of neutrino mixings in terms of only two angles (and no phases) of which only one is "active" for matter enhanced neutrino oscillations, the other determining the linear combination of μ and τ neutrinos into which the electron neutrino oscillates. The analysis of resonant neutrino oscillations in the sun is therefore reduced to a two dimensional problem. Since sneutrinos carry one unit of lepton number, the majorana neutrino mass is proportional to the *second* power of the lepton number breaking VEV v and its magnitude is roughly given by $gv^2/\widetilde{M}$, where g is a gauge coupling constant and $\widetilde{M}$ denotes a generic SUSY mass parameter. On the other hand, helium ignition in red giant stars sharply constrains the emission of light weak interacting particles from the star and a bound on v of the order of 10 KeV has been derived [20] (the majoron coupling to electrons is proportional to v). The size of the neutrino mass is therefore determined by a kind of "mini" see-saw, in which the largest mass scale is expected to be at the level of the electroweak breaking. This gives a neutrino mass in the required range for implementation of the MSW mechanism.

In this model a pair of majorons may be emitted at the tree level in μ (or τ) decay, leading to a modification of the spectrum of the daughter lepton with respect to the standard $\nu\bar{\nu}$ mode. Requiring the change in the Michel parameter to be within the present experimental accuracy leads to strong constraints on the parameters of the model [19]. Figure 1 shows, in the $\delta m_\nu^2 - \sin^2 2\theta_\nu$ plane, the combined effect of the constraints coming from μ decay and the present e^+e^- lower bound on the chargino masses. This is particularly useful for a direct comparison with the region of neutrino parameters required by the implementation of the MSW mechanism. Various MSW "triangles" are shown corresponding to different neutrino flux reductions (in SNU) from the latest SSM analysis of BAHCALL and ULRICH [3]. The region allowed by the SUSY majoron model is plotted for two values of the VEV ratio. It is worthwhile to recall that the near equality of the VEVs is favoured for a light top quark ($<$ 50 GeV), whereas larger values of the top mass favour substantially different values. Note that a top mass over 70 GeV seems to be required in order to achieve the radiative breaking of R-parity [21].

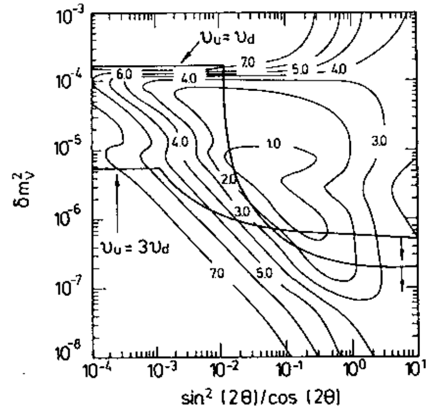

Fig. 1. Region of neutrino parameters allowed by the SUSY majoron model (area below the bold solid lines) overlapped with various iso-SNU contours for the chlorine experiment as calculated in Ref. 3. The Figure is taken from Ref. 22

An immediate consideration which follows from inspection of the plots in Fig. 1, is that present results of conventional laboratory experiments already exclude large regions of parameters allowed by the MSW mechanism. In particular, the adiabatic solution ($\delta m_\nu^2 \simeq 10^{-4}\ eV^2$) is only marginally allowed. The favoured region corresponds to the lower part of the "triangle", where, if the solution of the solar neutrino puzzle has to rely on matter enhanced neutrino oscillations, a large suppression of the electron neutrinos coming from the fundamental *pp* chain is expected [23]. This will be tested by the upcoming generation of ^{71}Ga experiments. The SUSY majoron model is therefore shown to be very sensitive even to small improvements in the relevant low energy experiments, thus offering a predictive framework for resonant neutrino oscillations in the sun.

3. The Doublet Majoron Model

The implementation of spontaneous breaking of lepton number in a *minimal* Higgs extension of the standard electroweak theory (SM) leads either to the introduction of a Higgs triplet (GR model [14]) or to the model described in Ref. 24. There, a charged Higgs singlet (h^+) is directly coupled to the left handed neutrinos and the lepton number is driven onto an *extra* Higgs doublet (ϕ) through the trilinear coupling $\mu_{12} h^- \varphi^T i\tau_2 \phi\ +\ h.c.$, where φ is the "standard" Higgs doublet, which does not carry lepton number and couples directly to the fermions. The coupling μ_{12} is a free dimensionful parameter of the model whose range of values is however bounded, as we will see, by phenomenological considerations. When the neutral component of the new doublet ϕ aquires a non-zero VEV v, lepton number is spontaneously broken by *two* units and neutrinos aquire mass at one-loop through charged Higgs exchange. Analogously to the GR model, only four extra scalar fields are present in the physical spectrum with respect to the SM model: two singly charged scalars, the majoron, and its light neutral partner ρ_L (whose mass is generally bounded to be at most of the same size as v). Due to its radiative origin and the tight astrophysical bound on v, the neutrino mass falls once again in the correct ballpark for implementation of the MSW mechanism. In addition, the simple form of the neutrino mass matrix (the same as in the model of ZEE [25]) allows, as for the SUSY majoron model, for a description of resonant neutrino oscillations in terms of only *one* mixing angle [24].

The exchange of the charged Higgs fields also generates a possible large contribution to the flavour changing $\mu \to e\gamma$ decay. It is the interplay between the experimental bound on this rare decay and the requirement that neutrino masses do not fall below the range required by resonant oscillations that tightly constrains the additional free parameters of the model: μ_{12}, the neutrino mixing angle and the charged Higgs scalar masses (the latter are also constrained by the additional quantum contributions to the $m_Z - m_W$ interdependence and to the ρ parameter [24]).

These constraints are synthetically shown in Fig. 2, where the horizontal solid lines represent, as a function of μ_{12}, the resulting upper bound on the neutrino mass, and the dashed lines include the experimental bound on $\mu \to e\gamma$ (for given μ_{12} there are values of the charged Higgs masses which maximize these contributions). As we see, analogously to the SUSY majoron model (but for completely independent reasons), the model favours the lower portion of the MSW triangles for the chlorine experiment. Reversing the argument, we may say that consistency with the MSW solution of the solar neutrino deficit forces the rate for $\mu \to e\gamma$ to be very close to the present experimental limit (within two orders of magnitude for most of the parameter space). This is certainly interesting in view of the presently proposed experiments which should improve the existing bound by two-three orders of magnitude.

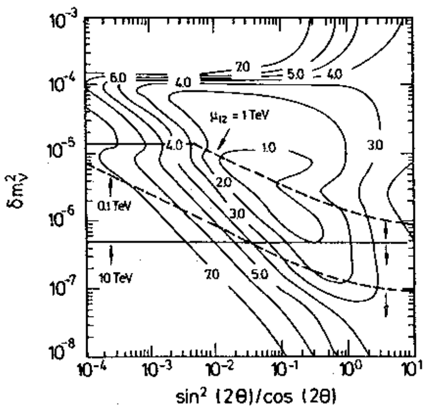

Fig. 2. Same as in Fig. 1, for the doublet majoron model

A crucial experimental test for this, as well as other non-singlet majoron models, is given by the measurement of the "invisible" width of the Z boson. In majoron models there exist indeed a characteristic additional contribution to the neutrino-like Z width, given by the emission of the majoron and the light ρ_L scalar. This contribution corresponds, for a doublet majoron, to 1/2 (in rate) a $\nu\bar{\nu}$ mode, whereas for a triplet majoron (GR), it is four times larger (a simple result of the different hypercharge). In the SUSY model, which shares with the present one the feature of a doublet majoron, further contributions may also come from the presence of light neutralinos and/or sneutrinos. Since at LEP this component of the Z width is expected to be measured with an accuracy of 0.2-0.3 of a $\nu\bar{\nu}$ width, this result may turn out to be the crucial one in discriminating among (or ruling out altogether) these models.

Further possible phenomenological constraints on the doublet majoron model have been recently analyzed [26-28]. In particular, in Ref. 26 the additional contributions to the $K \to \pi +$ "*nothing*" decay have been studied. It is noteworthy that the replacement of the standard $\nu\bar{\nu}$ mode with a pair of majorons (or ρ_L) leads to a different pion energy distribution. The size of the new contributions turns out to be generally comparable to an extra neutrino mode, with the potential exception of a contribution generated by the exchange of the neutral Higgs boson (the analogous exchange of ρ_L is, in comparison, suppressed by a factor $m_{\rho_L}^2/m_K^2$). Due to our ignorance of the Higgs mass and the arbitrariness of the Higgs boson coupling to majorons, this contribution could be by far the dominant one and be at the edge of the present experimental bound. This arbitrariness can however be limited by observing that the same coupling would lead to excessive energy loss in red giant stars through the process $\gamma + e \to e + JJ$, when the neutral Higgs boson is exchanged (ρ_L exchange may be neglected if $m_{\rho_L}^2 \ll E_\gamma^2$, which is the case for the relevant part of the photon spectrum). An analysis of the resulting bound [28] shows that the Higgs mediated contribution to $K \to \pi +$ *nothing* can be at most comparable to a standard neutrino mode. On the other hand, the same bound still allows for a large contribution of the invisible majoron modes to the Higgs boson width [27]. It is also peculiar that an analysis of the stability of the hierarchy between the lepton number breaking scale and the Fermi scale, under radiative corrections, leads to the parametrization of the same unknown ratio of scalar couplings, which appear in the previous issues, in terms of the top quark mass [27]. Values of the top mass above m_W are favoured by the perturbative consistency of the model (whereas slightly larger values are required for the GR model). Further analysis of specific signatures of the model are in progress.

In conclusion, we have discussed two possible scenarios which allow for a natural and simple implementation of the MSW mechanism as a solution of the observed depletion in the solar neutrino flux. They have in common the feature of breaking spontaneously total lepton number by means of a weak scalar isodoublet, although presenting characteristic different signatures. It is encouraging that the analysis of the phenomenological implications of the models shows the possibility for experimental tests in the very near future.

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