Particle-Physics Model for the Voloshin-Vysotski-Okun Solution to the Solar-Neutrino Problem

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A particle-physics model is presented for a large magnetic moment of the electron neutrino as required to explain the anticorrelation between the solar-neutrino flux and the sun-spot number. The model is shown to be also consistent with cosmological constraints as well as with existing laboratory experiments.

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The solar-neutrino experiment[1] has been stimulating a number of theoretical ideas on particle physics and astrophysics from its early days. The well-known issue is the average capture rate which is almost three times smaller[1] than the value predicted in the standard solar model.[2] Even more interesting, however, is that the solar-neutrino data are suggestive of an anticorrelation between the neutrino capture rate and the sun-spot number.[3-5] The anticorrelation appears quite impressive in a (five-point) running average of data and the claimed statistical significance is 5σ.[5] In particular, in the period from 1977 to 1983 the correlation coefficient between the yearly average ^{37}Ar production rate and the sun-spot number is 0.94.[5] This is quite intriguing, because it is quite difficult to imagine a mechanism which correlates the neutrino flux from the core of the sun with an outer-layer phenomenon such as the solar cycle.

More recently, however, a fascinating explanation has been proposed by Voloshin, Vysotsky, and Okun,[6] who suggest that this anticorrelation could be explained if the neutrino has a magnetic moment of the order of

$$\mu_{\nu_e} \sim (0.3\text{-}1)\times 10^{-10}\mu_B, \tag{1}$$

with $\mu_B = e/2m_e$. This value is just below the bound set by laboratory experiments[7] ($\mu_{\nu_e} < 1.5\times 10^{-10}\mu_B$) and by the astrophysical consideration of the stellar cooling ($\mu_{\nu_e} < 1\times 10^{-10}\mu_B$).[8] In the presence of the magnetic moment the left-handed neutrino precesses into the right-handed component under a magnetic field. With the value (1) a significant fraction of left-handed neutrinos rotate into right-handed neutrinos in the period of maximum solar activity under the strong magnetic field in the convective layer of the sun, and the solar neutrino hence becomes sterile to the nuclear neutrino detector. On the other hand, the solar magnetic field is at least an order of magnitude weaker in the quiet time, so that the precession hardly takes place. We then expect a higher capture rate in this period.[6] Evidence for the biennial variation of the solar-neutrino detection rate also supports this interpretation,[6] though the data looks statistically less convincing.

This explanation, while it looks very attractive, leaves us two problems to be answered. The first is the large magnetic moment of the electron neutrino required in this scenario. In the standard Glashow-Weinberg-Salam theory we expect that the Dirac neutrino has a magnetic moment of the magnitude of[9]

$$\mu_{\nu_e} = \frac{3eG_F}{8\sqrt{2}\pi^2} m_{\nu_e} \simeq 3\times 10^{-19}\mu_B \left(\frac{m_{\nu_e}}{1\text{ eV}}\right). \tag{2}$$

This value may get substantially enhanced if there exists a right-handed current. In the left-right-symmetric model,[10] for instance,

$$\mu_{\nu_e} = \frac{G_F}{\sqrt{2}\pi^2} m_e^2 \mu_B \sin 2\phi \simeq 2\times 10^{-13}\mu_B \sin 2\phi, \tag{3}$$

with ϕ the mixing angle between left- and right-handed currents. (In this expression we omitted the lepton mixing.) With the experimental limit[11] $|\phi| < 0.05$ the magnetic moment of ν_e is at most $\mu_{\nu_e} < 10^{-14}\mu_B$, far too small a value as compared with the required number (1). The problem, therefore, is to answer whether there exists a reasonable model giving rise to such a huge magnetic moment of the electron neutrino.

The second problem is that if the neutrino has such a large magnetic moment, $\nu_L e \to \nu_R e$ scattering before the neutrino decoupling would double the effective number of neutrino species in the early Universe, which then would cause an excess abundance of ^{4}He.[12] An analysis has given the upper limit

$$\mu_\nu < 1.5\times 10^{-11}\mu_B, \tag{4}$$

which should not be violated by more than two neutrino species. The value allowed by this limit is already considerably smaller than (1), and the bound hence is violated if μ_{ν_μ} or μ_{ν_τ} is greater than μ_{ν_e}.

In this Letter we shall show that there is a class of models which give a magnetic moment with the required magnitude, satisfying the cosmological constraint at the same time. We also show that the model leads to some novel predictions that can be tested in the near future.

Let us start our discussion by giving a specific model that possesses the required properties. We consider the model in which exists an $SU(2)_L$-singlet charged scalar particle η^- in addition to the standard Weinberg-Salam particles with the three generations. We also assume the presence of the right-handed neutrino ν_R and that the neutrino is of the Dirac type to allow a magnetic moment.

Such an $SU(2)_L$-singlet η^- couples only to the $l\nu$ channel ($l_L\nu_L$ or $l_R\nu_R$) and not to any other channels. In particular we note that η^- does not couple to quarks. If there is only one Weinberg-Salam Higgs doublet ϕ, the coupling $\eta^-\phi^+\phi^0$ is not allowed by the $SU(2)_L$ symmetry and the model strictly respects the lepton-number conservation. The scalar η^- carries the lepton number 2. (In this respect our model differs from that proposed by Zee,[13] where the lepton number is not conserved, and the neutrino is naturally of the Majorana type rather than the Dirac type.) The two possible Yukawa couplings of η^- to leptons take the form

$$g_{ij}\bar{l}^{ci}_L l^j_L \eta^+ \quad (g_{ij}=-g_{ji}), \quad f_{ij}\bar{\nu}^{ci}_R e^j_R \eta^+, \tag{5}$$

with $l_L=(\nu,e^-)_L$, and the antisymmetry of g_{ij} coming from the $SU(2)_L$ symmetry (i,j are flavor indices). To reduce the number of parameters we may further impose the $SU(2)_R$ symmetry which was already broken in the energy scale considered here, so that we have $f_{ij}=-f_{ji}$ (this is not essential to our model, however). We note that the mass diagonalization of the charged-lepton sector does not disturb the antisymmetry property $g_{ij}=-g_{ji}$, $f_{ij}=-f_{ji}$, as long as the neutrino masses are negligible.

To calculate the magnetic moment it is sufficient to consider two one-loop diagrams (Fig. 1), since the radiative correction due to the gauge boson only gives a negligible contribution as in (2). A straightforward calculation gives

$$\mu_{\nu_i}=e\sum_{j=1}\frac{f_{ij}g^\dagger_{ji}+g_{ij}f^\dagger_{ji}}{32\pi^2}\frac{m_j}{M^2}\left[\ln\frac{M^2}{m_j^2}-1\right], \tag{6}$$

where m_j stands for the charged-lepton mass in the jth generation and M the mass of η^-. The noticeable feature in this expression is that the magnetic moment of ν_i picks up the Dirac mass of the jth ($j\neq i$) charged lepton. Therefore ν_e and ν_μ are expected to have larger magnetic moments. Another feature of (6) is that unlike (3) there is no suppression factor such as $\sin 2\phi$ or the lepton-mixing angles, as a consequence of the off-diagonal nature of the Yukawa coupling. These two facts lead us to the large magnetic moment of ν_e (and

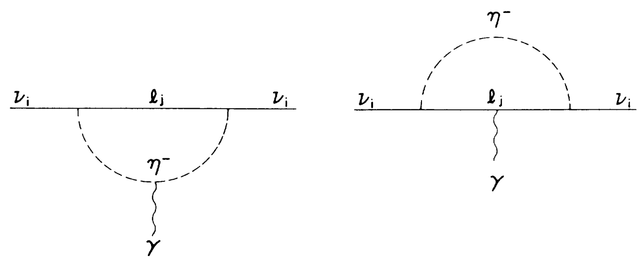

FIG. 1. One-loop diagrams giving rise to a magnetic moment of the neutrino ν_i.

ν_μ). The magnetic moment (1) requires

$$f_{31}g_{13}/M^2 \simeq (0.4\text{–}1.2)\times 10^{-6}\ \mathrm{GeV}^{-2}, \tag{7}$$

where we assumed the Yukawa coupling to be real for simplicity.

As we shall see below the absence[14] of $\mu^-\to e^-\gamma$ indicates that the Yukawa couplings f_{23} and g_{23} should be smaller than f_{13} and g_{13} by almost a factor of 50 or more. The magnetic moment of ν_μ is then necessarily smaller than that of ν_e by 3 orders of magnitude; therefore only ν_e violates the inequality (4) and hence the cosmological constraint is satisfied.

Let us now discuss constraints on the parameters of our model from the existing experiments. For the numerical estimate we take $f_{ij}\simeq g_{ij}$ for simplicity. The scalar particle η^- contributes to the lepton $g-2$ as

$$\delta(g_l-2)=\frac{1}{16\pi^2}\frac{(2m_l)^2}{12M^2}[(gg^\dagger)_{ll}+(ff^\dagger)_{ll}]. \tag{8}$$

The Yukawa coupling receives the constraints $(gg^\dagger)_{11}/M^2\leq 1\times 10^{-1}$ GeV^{-2} from $\delta(g_e-2)\leq 10^{-10}$ and $(gg^\dagger)_{22}/M^2\leq 2\times 10^{-4}$ GeV^{-2} from $\delta(g_\mu-2)\leq 10^{-8}$.[15] Since η^- induces a flavor-changing charged current in the lepton sector, it causes exotic decays such as $\tau\to\bar{\nu}_e e\nu_\mu$, $\mu\to\bar{\nu}_e e\nu_\tau$, etc. The agreement of the measured lifetime of τ with that predicted from the standard model leads to the constraint that such extra modes should be smaller than 5% of the leptonic decay rate, giving

$$g_{3i}g_{kj}/M^2<10^{-5}\ \mathrm{GeV}^{-2} \quad (i,j,k\neq 3).$$

Similar constraints can be derived from the limit on the deviation from e-μ universality in τ decay: The presently available value[16] $B_\mu/B_e=1.03\pm 0.05$ as compared with the universality value 0.97 leads to a constraint about 2 times stronger than the limit quoted above. For the μ decay the agreement with the standard theory gives $g_{2i}g_{1j}/M^2<10^{-6}$ GeV^{-2}.

The most stringent constraint on the Yukawa coupling is derived from the empirical absence of $\mu\to e\gamma$.[14] The diagrams contributing to this process are similar to those in Fig. 1, but the amplitude picks up the Dirac mass term on the external fermion lines rather than those inside the loop. A simple calculation results in

$$\Gamma(\mu \to e+\gamma) \simeq \frac{\alpha}{2}\left(\frac{1}{32\pi^2}\frac{m_\mu}{12M^2}[(gg^\dagger)_{12}+(ff^\dagger)_{12}]\right)^2 m_\mu^3. \quad (9)$$

If we take the upper limit $B(\mu \to e+\gamma) < 2\times 10^{-10}$,[14] we obtain

$$(gg^\dagger)_{12}/M^2 < 1\times 10^{-8}\ \mathrm{GeV}^{-2}.$$

Therefore the requirement (7) is consistent with the absence of $\mu \to e+\gamma$ if there is a disparity in the Yukawa couplings as $g_{13}, f_{13} > (30-100) g_{23}, f_{23}$. This disparity leads to $\mu_{\nu_\mu} < 10^{-3}\mu_{\nu_e}$.

We should comment here that no prediction can be made on the neutrino mass in our model, or in other words that our consideration on the magnetic moment does not directly refer to the neutrino mass. The radiative correction due to η^- generally induces a neutrino mass term. The term, however, is logarithmically divergent and its divergence, in any case, should be cancelled by the addition of a mass counter term. Therefore the neutrino (Dirac) mass is arbitrary in our model.

The generalization of the model is now obvious. A variety of models giving the neutrino a large magnetic moment may be found by the introduction of some charged scalar particles which couple to flavor off-diagonal channels in a manner similar to the model given above. However, such models in general cause various unwanted effects connected with the flavor-changing neutral current. For example, one can obtain a result similar to (6) by introducing an extra Higgs doublet ϕ' instead of our singlet η^-. The neutral partner of ϕ'^-, however, has a coupling to the quark channel as $(h_{12}\bar{s}d + h_{21}\bar{d}s)\phi'^0$ and the model receives quite a strong constraint on its parameters, $h_{12}h_{21}^\dagger/M^2 < 10^{-12}$ GeV^{-2}, from the $K_S^0 - K_L^0$ mass difference. A further device is necessary to avoid such an unwanted effect. In this sense we may regard the model presented in this paper as "minimal" to explain the large magnetic moment consistently with experiments.

Let us finally discuss possible experimental tests of the model. Besides the direct test of the observation of the magnetic moment of ν_e, there are some novel predictions characteristic of our model which can be tested in the near future. The presently available limit[14] on $B(\mu \to e+\gamma)$ already requires a disparity in the Yukawa couplings, and we may hope that a signal might be observed at the present level of upper limit.

A more inevitable consequence for the class of our models is the presence of a physical charged scalar particle, say η^- in our prototype model. The production of η^- in $e^+e^- \to \eta^+\eta^-$ or $pp \to \eta^+\eta^- + X$ gives a signal which resembles the W^+W^- pair production but it lacks the e-μ-τ universality in the decay mode because of the disparity in the Yukawa couplings. The signature of this process also resembles that for the scalar-electron pair production, and the bound[17] for the scalar-electron mass also applies to our case, giving $M \gtrsim 25$ GeV. The condition (7) then gives $g^2 \gtrsim (2-5)\times 10^{-4}$. On the other hand, if we require $g^2 \lesssim 1$ to make a perturbative analysis valid, we may set an upper bound on the mass M, i.e., hence we hope such a scalar might be observed in the range

$$25\ \mathrm{GeV} \lesssim M \lesssim 10^3\ \mathrm{GeV}.$$

The search for such a charged scalar particle may be an interesting task for e^+e^- (or $\bar{p}p$) collider experiments.

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