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Neutrino oscillations in the Sun probe long-range leptonic forces

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Abstract

Lepton number charges might be the source of long range forces. If one accepts that neutrinos produced in the Sun do indeed oscillate while crossing the interior of the Sun, then the shift in the phase of the neutrino wave-function caused by an hypothetical potential associated to the leptonic charge of the electrons in the Sun could affect the oscillation pattern beyond what is actually observed. We show that a "fine structure" constant α_L in excess of 6.4×10^{-54} is incompatible with present observational data. This bound is not valid for forces whose range is shorter than the size of the Sun.

A recurrent issue in particle physics has been the question of long range fundamental forces, notably, baryonic and leptonic forces. There is already a considerable amount of literature [1] on these topics that started with the seminal work by Lee and Yang on long range forces coupled to baryonic charge [2]. From the analysis of Eotvos-type experiments, the hypothetical vector bosons that mediate baryonic forces should couple to baryons with a strength [3,4]

$$\alpha_B < 10^{-46}\text{–}10^{-47}, \tag{1}$$

where α_B is the corresponding "fine structure constant". Similarly, equivalence principle tests that probe accelerations of different elements towards the Sun, give a limit to the fine structure constant associated to leptonic (electronic, indeed) forces [5]

$$\alpha_L < 10^{-48}\text{–}10^{-49}. \tag{2}$$

However, we now know that these electronic forces cannot be infinitely ranged because their associated vector bosons cannot be strictly massless. A zero mass vector boson would imply exact electronic number conservation and it is by now an established fact that neutrinos oscillate [6] which implies violation of lepton number. Still, if one insists that the associated electronic forces extend over astronomical distances, the mass of the vector boson must be very small. So, the constraint given above (Eq. (2)) should be valid for a "lepto-photon" with mass less than or about 1.5×10^{-18} eV (i.e., corresponding to ranges larger or about 1 au).

It is precisely the fact that neutrinos oscillate that we shall exploit in the present Letter to set an improved limit on the electronic coupling constant in Eq. (2). Laboratory limits on the oscillation process have been used in the past to put constraints on the equivalence principle or, conversely, putative violations of the Principle of Equivalence have been suggested as a source of the solar neutrino deficit [7–11].

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Now that we know that the origin of the solar neutrino deficit is due to mass related neutrino oscillations, we shall use this fact as a handle to constrain an extra source of oscillation, namely that due to long range leptonic forces. Indeed, if a force associated to electron number does really exist then electron flavor neutrinos transiting the interior of the Sun will feel the influence of the electron number density in the Sun while muon flavor neutrinos will not. This interaction, whose lepto-photons should have a Compton wave-length on the order or larger than the radius of the Sun, will induce a phase shift in the neutrino propagation wavefunction that should lead to neutrino oscillations completely analogous to the way weak interactions lead to oscillations in matter as first discussed by Wolfenstein [12,13].

Our starting standpoint is that neutrinos produced in the Sun suffer large mixing angle (LMA) resonant MSW matter oscillations with best-fit parameters given by [14]:

$$\Delta m^2 = 5.5 \times 10^{-5}\ \mathrm{eV}^2, \qquad \sin^2 2\theta = 0.83 \tag{3}$$

as a variety of different experimental inputs indicates. In the case under consideration, the putative leptonic interaction adds a piece in the Hamiltonian that governs the time evolution of neutrinos. In the flavor basis, this piece enters the interaction Hamiltonian as follows

$$\langle \nu_e | H_{\mathrm{int}} | \nu_e \rangle = \sqrt{2}\, G_F N_e + V_L \tag{4}$$

and all other matrix elements vanish.

In Eq. (4) N_e is the electron number density and V_L is the potential energy of the neutrino in the field of the leptonic force. It reads, for $\eta \lesssim R_\odot^{-1}$,

$$V_L(r) = \frac{\alpha_L}{r} \int_0^r d^3 r\, N_e, \tag{5}$$

where η is the lepto-photon mass and the corresponding Yukawa potential has been approximated to a Coulomb-like one in the distance range of interest. This interaction modifies the usual neutrino–electron interaction length into

$$L_e = 2\pi \left(\sqrt{2}\, G_F N_e + V_L\right)^{-1}. \tag{6}$$

The mixing angle in matter is given by the relation

$$\tan 2\theta_m = \tan 2\theta \left(1 + \frac{L_V}{L_e} \sec 2\theta\right)^{-1}, \tag{7}$$

where the vacuum oscillation length

$$L_V = 2\pi \left(\frac{2E_\nu}{\Delta m^2}\right). \tag{8}$$

In the conventional picture (i.e., for $\alpha_L \equiv 0$) and for the values stated in Eq. (3), resonant conversion occurs at 20–30% of the solar radius. Now, if we turn on gradually the new interaction, the resonance region will move to thinner regions of the Sun (i.e., further away from the solar center). This is due to the repulsive character of the interaction that adds positively to the weak potential. Treating the potential (5) as a perturbation to the weak potential we find, upon differentiation of the resonance condition $L_V = L_e \cos 2\theta$,

$$\frac{\delta \cos 2\theta}{\cos 2\theta} + \frac{\delta |\Delta m^2|}{|\Delta m^2|} = 2E_\nu V_L(r_{\mathrm{res}}) \frac{\sec 2\theta}{|\Delta m^2|}, \tag{9}$$

i.e., for the perturbed potential the resonance condition is met for slightly different oscillation parameters whose relative variations are given by this formula. Now, we can feed the 95% C.L. allowed deviations away from the oscillation parameters in Eq. (3) into the above relation to obtain the maximum α_L compatible with the data. To do the numerical work we shall use a convenient parameterization of the electron number density in the Sun, namely [15]

$$\frac{N_e}{N_A} = 245 e^{-10.54 r/R_\odot}\ \mathrm{cm}^{-3}, \tag{10}$$

where N_A is Avogadro's number. This fit to the number density is not exact, particularly near the solar center (in the range 0–$0.17 R_\odot$), but this fact is immaterial for our purposes since (i) the resonance position lies beyond $0.26 R_\odot$ and (ii) V_L itself vanishes in the central region. So, using the above parameterization for the electron number density and a mean neutrino energy of 10 MeV (with these inputs $r_{\mathrm{res}} \simeq 0.27 R_\odot$) we find from Eq. (9) the constraint

$$\alpha_L \leqslant 6.4 \times 10^{-54}. \tag{11}$$

We have checked that the adiabaticity of the oscillations is preserved when we incorporate the effects of the leptonic potential with its maximum allowed strength given by Eq. (11). Indeed, we have scanned the whole region enclosed in the 95% C.L. contour of the LMA domain and found that for no choice of the parameters $\sin 2\theta$ and $|\Delta m^2|$ the matter oscillation length $L_M = L_V / \sin 2\theta$ at resonance exceeds the width of the resonance in physical space. In fact, in all instances explored, this latter quantity is much larger than L_M. This guarantees that the neutrino can adjust itself to the matter eigenstate while this latter slowly changes across the resonance region. Furthermore, we verified explicitly that the resonant transition is fully contained inside the Sun.

We remind the reader that the above limit on α_L is valid only for $\eta \lesssim R_\odot^{-1} \sim 10^{-15}$ eV. It is appropriate at this point to say that our phenomenological approach to the issue of lepto-photon mass could run into serious difficulties should this mass be too small [16, 17]. Indeed, one might have to face catastrophic decay processes where a huge number of longitudinal lepto-photons are radiated carrying away the available energy (e.g., a muon decaying into an electron and invisible energy). However, for the values of α_L obtained above (see Eq. (11)) and $\eta \sim 10^{-15}$ eV, one can easily verify using the results in Ref. [16,17] that we are still very far from an infrared catastrophe. In fact, not even one single longitudinal lepto-photon would be emitted in a muon to electron transition.

To end this Letter we should address the question whether screening by the leptonic charges carried by electron neutrinos and antineutrinos in the relict neutrino background affects the result just derived. Indeed, the relict neutrinos in the cosmic plasma might effectively screen the field created by the leptonic charge associated to the electrons in the Sun and therefore invalidate the bound given in Eq. (11) above. The problem of screening of leptonic forces by cosmological neutrinos has been discussed in the literature [18,19]. The relevant quantity that enters in those studies is the Debye length [20], i.e., the distance beyond which the screened potential effectively vanishes. It is given by the expression

$$l_D = \left(\frac{T_\nu}{8\pi n_\nu \alpha_L}\right)^{1/2}, \tag{12}$$

where $T_\nu \simeq 1.7 \times 10^{-4}$ eV and $n_\nu \simeq 115\ \text{cm}^{-3}$ are the cosmic neutrino temperature and cosmic electron neutrino density, respectively. Even allowing for the maximal strength of the coupling displayed in Eq. (11) the Debye screening length turns out to be on the order of ten Mpc, which is an order of magnitude larger than the typical intergalactic distance. Notice that Debye screening can be physically relevant only in the case where the range of the leptonic potential is greater than l_D, otherwise the potential dies off before screening takes over. Since, in our case, we need only the potential to be felt by neutrinos over the size of the Sun, it is clear that screening plays no role at solar radius ranges.

One may wonder whether l_D could be affected by the fact that electronic charge is not conserved, i.e., whether a cosmological lepton asymmetry obtains as a result of neutrino oscillations. This is however not the case because ever since neutrino decoupling, i.e., when neutrinos had their last weak interaction, electron neutrinos have been oscillating into muon neutrinos and muon neutrinos into electron neutrinos at the same pace. Hence, in a comoving volume the net leptonic (electronic) charge is conserved because as much electron number is destroyed as it is created.

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