THE CHARGED NEUTRINO: A NEW APPROACH TO THE 
SOLAR NEUTRINO PROBLEM

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Abstract

We have considered the effect of the reduction of the solar neutrino flux on earth due to the deflection of the charged neutrino by the magnetic field of the solar convective zone. The antisymmetry of this magnetic field about the plane of the solar equator induces the anisotropy of the solar neutrino flux thus creating the deficit of the neutrino flux on the earth. The deficit has been estimated in terms of solar and neutrino parameters and the condition of a 50 % deficit has been obtained: $Q_\nu \grad H \geq 10^{-18} eG/cm$ where $Q_\nu$ is the neutrino electric charge, $\grad H$ is the gradient of the solar toroidal magnetic field, $e$ is the electron charge. Some attractive experimental consequences of this scenario are qualitatively discussed.

The discrepancy between the results of the solar neutrino experiments [1–4] and the predictions of the Standard Solar Models [5,6] is one of the most challenging issues of modern particle physics and astrophysics. Some of the plausible solutions to the solar neutrino problem are neutrino oscillations amplified by the Mikheev- Smirnov- Wolfenstein effect [7,8], neutrino decay [9], neutrino spin-precession [10] in the solar magnetic field and resonant spin-flavour conversion scenario [11] (assuming the twisting structure of the solar magnetic field in the convective zone has recently led to a more complicated variant of the last scenario [12]). However, all the solutions proposed so far rely on some hypothetical properties of the
neutrino and/or the solar magnetic field which have to be confirmed by future evidence—hence no final solution emerged as yet.

In this paper we suggest a quite different approach to the solar neutrino problem which does not employ any detailed assumptions about the small scale structure of the solar magnetic field or the variation of solar density. We assume that the electric charge of the neutrino is non-zero. As for the solar magnetic field, the only property we use is—a well-established fact—its antisymmetry with respect to the plane of the solar equator. In this way, our approach belongs entirely to the realm of classical physics and the Lorentz force is the only essential theoretical tool we need.

In fact, the neutrino is the only elementary particle, besides the gauge bosons, whose electric charge is normally assumed to be zero. But if the neutrality of the gauge bosons is deeply rooted in the principle of gauge invariance, there are no compelling reasons whatsoever for the neutrino to have zero charge.

Of course, the neutrino is assumed to be exactly neutral within the Standard Model. However, the recently developed approach to the problem of the electric charge quantization has led to the realization of the fact that in a fairly large class of gauge models, including the Minimal Standard Model, the electric charge can be dequantized [13] (see also [14]). This means that the electric charges of elementary particles can take different values from those conventionally assumed: $Q_\nu = 0$, $Q_t = -e$, $Q_{u,c,b} = 2e/3$ and $Q_{d,s,b} = -e/3$ (e being the modulus of the electronic charge). In particular, the neutrino can acquire nonzero electric charge. (Another interesting aspect of the theories with dequantized electric charges is that one might speculate about the possibility of time dependence of the electric charges within such theories [15].)

In other words, in Refs. [13] it has been shown that the Standard Model contains an additional free parameter $\epsilon$ which must be determined experimentally along with the other more familiar parameters such as Higgs mass or Yukawa couplings. Of course if it were found that $\epsilon$ is nonzero, it should be very small anyway (see discussion below) and that would create one more hierarchy problem. Yet taking into account the existence of a few
such problems already, the appearance of a new one does not seem strong enough argument to disregard the possibility of nonzero $\epsilon$.

Furthermore, one might argue that nonzero neutrino charge does not follow from any theoretical principle, whether established or hypothetical (with the exception of the well-known rule "all which is not forbidden is allowed"). But now, based on the works [13], we know that the zero neutrino charge does not follow from anywhere, too!

Another possible objection against particles with small fractional charge is that it is difficult to embed them into grand unified theories [16]. Yet theories with paraphoton provide a viable alternative [17].

So, at present the cases of zero/nonzero neutrino charges must be considered as two working hypotheses on the equal footing, only experiment being capable to provide the ultimate answer. The situation with neutrino charge is very similar to the situation with neutrino mass: while zero mass is the prediction of the minimal standard model, most physicists agree that the question of zero/nonzero neutrino mass has much more to do with experimenting than with model-building. While it would not be easy to detect the neutrino charge, the consequences of such discovery should certainly be dramatic, ranging from the prospects of detecting relic neutrino through its electromagnetic interaction to possible better ways of managing neutrino beams, creation of neutrino optics etc.

Finally, let us note that in the present work we are not concerned if the neutrino mass is zero or not. Certainly, there exist well-known difficulties associated with charged massless particles [18]. However, one can take a pragmatic point of view [19] and keep developing a theory until one runs into any inconsistency. No such inconsistency seems to show up in our treatment. An alternative point of view is to give the neutrino a Dirac mass by introducing additional Higgs multiplets.

Note also that even if the neutrino is massless in vacuum, it cannot be considered massless inside plasma. This is because the vacuum dispersion relation $E = |p|$ gets changed by the weak interaction of neutrino with plasma [8]. In other words, there arises a refraction index for the neutrino propagating through plasma. Thus, the situation with infrared divergencies
might be better for a neutrino in plasma than in vacuum.

To conclude, it seems that assuming nonzero neutrino charge is certainly not more heresy than assuming nonzero neutrino magnetic moment, or mass and mixing angles.

In addition, there exist quite an independent motivation to study the behaviour of a charged neutrino inside the Sun. The point is that the neutrino electromagnetic properties get modified by plasma effects and under certain conditions these modifications result in an induced electric charge of the neutrino \[20\]. We stress that it happens in the Minimal Standard Model where the neutrino has zero intrinsic electric charge.

The purpose of this paper is to draw attention to the fact that the possible existence of a very small electric charge of the neutrino may be a clue to the solar neutrino problem\[^1\]. The idea is that the charged neutrinos are deflected by the solar magnetic field while passing inside the Sun. Due to the antisymmetry of that magnetic field about the solar equatorial plane the resulting neutrino flux is made anisotropic which leads to the solar neutrino deficit registered on the Earth. (Within our scenario, this deficit is not real but only apparent in the sense that the total \(4\pi\) solar neutrino flux is not changed as compared with the standard solar models.)

Our key result is:

\[
\frac{\Phi_1}{\Phi_0} \equiv 1 + \delta_0 = 1 + \frac{\epsilon e \langle \frac{\partial H_\phi}{\partial z} \rangle dD}{E}, 
\]

where (all units are Gaussian) \(\Phi_1\) is the neutrino flux observed on the Earth, \(\Phi_0\) is the flux predicted by the standard solar model, \(Q_\nu = \epsilon e\) is the neutrino electric charge, \(\langle \frac{\partial H_\phi}{\partial z} \rangle\) is the average gradient of the toroidal magnetic field in the solar convective zone, taken along the \(z\)-axis, parallel to the rotation axis of the Sun, \(D\) is the width of the convective zone, \(d\) is the distance from the solar centre to the middle of the convective zone, \(E\) is the neutrino

\[^1\]The possible role of the charged neutrino interaction with the terrestrial electric field, in connection with the solar neutrino problem, was discussed previously by G.C.Joshi and R.R.Volkas (unpublished).
energy. The detailed derivation and discussion of this formula are to be given elsewhere [39]. Here, we note that the main assumption behind the Eq. (1) is the smallness of the ratio 
\[ \delta_0 = \epsilon e^{\langle \frac{\partial H}{\partial z} \rangle} dD/E \]
compared to unity (more exactly, it has to be \( \delta_0 \lesssim 0.7 \)).

To obtain, say, a 50% deficit, one needs to have

\[ |\epsilon \langle \frac{\partial H}{\partial z} \rangle| \gtrsim 10^{-18} \text{G/cm} \]  
(assuming \( D = 2 \times 10^{10} \text{ cm}, d = 6 \times 10^{10} \text{ cm}, \) and \( E = 0.8 \text{ MeV} \)).

Since the magnetic field reverses itself with a period of 11 years, our Eq. (1) implies that each 11 year period of neutrino flux deficiency must be followed by 11 year period of neutrino flux excess of the same magnitude so that the flux averaged over the 22 year cycle would be the same as predicted by the Standard Solar Model.

There are several possibilities to overcome this difficulty.

The most natural one is to go beyond linear approximation on which Eq. (1) is based. This would be definitely required if \( |\epsilon \langle \frac{\partial H}{\partial z} \rangle| \gtrsim 2 \times 10^{-18} \text{ G/cm} \).

Naively, one might expect that the neutrino deficiency must alternate with the neutrino excess at 11 year intervals independently of the magnitude of the gradient: just note that when the magnetic field configuration is defocusing, one would expect the neutrino deficiency and when it is focusing, the neutrino excess. Each reversal of the magnetic field means a switch between focusing and defocusing modes so that any 11 year "deficiency" cycle would be followed by the 11 year "excess" cycle, however great the gradient of the magnetic field is. Nevertheless, there are arguments based on simple geometrical optics considerations which show that it is not the case and if the gradient is large enough then the neutrino deficiency can occur both for the defocusing and the focusing configuration!

Another option is to try to relax the solar upper bound on the possible electric charge of the electron neutrino obtained in [19], since the neutrino charge and the magnetic field gradient come always as the product \( \epsilon \times \langle \frac{\partial H}{\partial z} \rangle \) rather than separately.

Let us also mention briefly that at present we cannot rule out the possible existence of a primordial magnetic field of as much as \( 10^6 \text{ G} \) inside the core of the Sun [32]. Within the
present context, it would very interesting if any evidence could be obtained concerning the existence of significant gradients of that field near the plane of the solar equator.

Finally, although it is not as much appealing, we should not discard the possibility that our mechanism is effective only during alternative 11 cycles or even only during the periods of active sun within the alternative 11 year cycles while some other mechanism is responsible for neutrino depletion during the rest of the time. This possibility will have to be considered much more seriously if the anticorrelation of the neutrino deficiency with solar activity is established firmly by the future experiments.

Now, assuming that the above default is cured in one or another way, let us turn to the experimental implications of our result. At this stage, the status of both the present scenario and the experimental data does not encourage one to make detailed quantitative comparison of theory and experiment. Rather, we confine ourselves to a qualitative attempt to match the general consequences of the proposed hypothesis with the outstanding features of the available data. In this way, one can easily see that our result, Eq. (1), does point to the right direction while confronted with the following main experimental conclusions:

1) Anticorrelation of the neutrino flux with solar activity is probably observed in the Homestake data [36,37].

2) No such anticorrelation is observed in the Kamiokande data [2].

3) The higher neutrino flux (i.e., less neutrino deficit) is observed in Kamiokande experiment than in Homestake experiment.

4) The higher neutrino flux is observed in SAGE [3] and GALLEX [4] experiments than in Homestake experiment.

The reason is that the experimental thresholds of neutrino energy are rather different in those experiments: $E_{Home} = 0.816$ MeV, $E_{Kam} \sim 7.5$ MeV, and $E_{Gallex} = 0.233$ MeV, while our result, Eq. (1) scales in the ratio $\epsilon \langle \partial H_x / \partial z \rangle / E$. Therefore, changing the magnetic field will be equivalent to changing the neutrino energy correspondingly. Furthermore, it is natural to assume that both neutrino flux deficit and anticorrelations grow with the increase of the gradient. Hence we obtain that the anticorrelations have to be smaller for more energetic
neutrinos. And this is exactly what is needed to qualitatively explain the difference between Homestake and Kamiokande data (see 1) and 2) above). Also, by the same reasoning, within our scenario one can expect less deficit in Kamiokande than in the Homestake experiment.

Now, as for the fourth feature, i.e., results of gallium experiments, our hypothesis seems to predict greater deficit than Homestake and thus looks disfavored by gallium results. However, one must remember that: 1) the difference between Gallium and Homestake results, from the viewpoint of our hypothesis, must be less pronounced than the difference between Homestake and Kamiokande data. This follows from the fact that the ratio of the characteristic neutrino momenta for Homestake-Gallium data are, roughly, less than for Kamiokande-Homestake data by a factor of 3:

\[ \frac{E_{Kam}}{E_{Home}} \approx 10, \frac{E_{Home}}{E_{Ga}} \approx 3; \]  

(3)

2) The errors of Gallium data are still larger than those of Homestake data.

Now, we would like to draw attention to a curious coincidence in the solar neutrino data. Kamiokande does not see anticorrelations during the whole period of its operation, i.e., 1987-1993 (part of solar cycle # 22). And, according to [37] there are no anticorrelation in Homestake data during the years 1970-1977 (of which the period 1970-1976 is a part of solar cycle # 20). Also, the latest data do not confirm the anticorrelation: large number of the sunspots in 1991–1992 was accompanied by high counting rate [38]. Therefore, one is tempted to speculate that, due to some reason, the anticorrelations are much more prominent in the odd-numbered solar cycles while being suppressed in the even-numbered cycles. If we take this conjecture seriously, it would be easy to conclude that the neutrino-depleting mechanism must somehow be correlated not only with the strength of the solar magnetic field but also with the direction of the toroidal solar magnetic field which reverses every 11 years. Obviously, this feature would be difficult to accommodate within any of the existing scenarios except the present one.

Apart from the reduction of the conventional (i.e., thermonuclear) neutrino flux, a spectacular feature of our scenario is the prediction of a "second flux" of electron neutrinos and
antineutrinos from the Sun. While thermonuclear neutrinos are produced due to the weak interactions of the neutrino, the second flux arises due to the electromagnetic production of neutrino-antineutrino pairs. The most important process would be that of plasmon decay into a neutrino-antineutrino pair. Thus the second flux would consist of low-energy (about 200 eV) neutrinos produced in plasmon decays in the core of the Sun, the number of such neutrinos being much greater than that of the thermonuclear neutrinos. It would be very interesting to consider the possibility of detecting this second neutrino flux, about $10^{16} \times (\epsilon/10^{-13})^2 \text{s}^{-1}\text{cm}^{-2}$ in magnitude, on the Earth.

Let us now turn to the current limits on the neutrino electric charge and the gradient of the solar magnetic field to assess if the criterion Eq. (2) can realize or not.

Various bounds on the neutrino charges have recently been analysed in a systematic way in Ref. [21]. The strongest model-independent constraints on the electron neutrino charge, $Q(\nu_e) = \epsilon e$, come from three sources: analysis of $\nu_e e$ elastic scattering [19]: $\epsilon \lesssim 3 \times 10^{-10}$; study of plasmon decay into neutrino-antineutrino pairs [13]: $\epsilon \lesssim 10^{-13}$; detection of a neutrino signal from SN1987A supernova explosion [22]: $\epsilon \lesssim 10^{-15(15\div17)}$.

Yet it is generally believed (see, e.g. [24]) that the constraint based on SN1987A arguments, although stronger, is less reliable than the previous ones because it involves the details of the galactic magnetic field which are not very well known.

There exist even more severe, but less direct constraints. They are based on the experimental data on the neutrality of atoms and neutrality of the neutron. These data give limits on the sum of the proton and electron charges [25]: $Q(p) + Q(e) = (0.8 \pm 0.8) \times 10^{-21}e$ and the neutron charge [26]: $Q(n) = (-0.4 \pm 1.1) \times 10^{-21}e$. Then, assuming charge conservation in the neutron beta-decay $n \rightarrow p + e^- + \bar{\nu}_e$ we can obtain the bound on the electron charge $\bar{\nu}_e$.

\[ \bar{\nu}_e \rightarrow \nu_e \text{ (assumed).} \]

By model-independent we mean the constraints that do not rely on additional assumptions such as charge conservation or the equality $Q(\nu_e) = Q(\bar{\nu}_e)$. 

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antineutrino charge: $Q(\bar{\nu}_e) < 3 \times 10^{-21}e$. Finally, assuming validity of CPT symmetry\footnote{Note also that recently there has been considerable interest in discussing the possible existence of new particles carrying very small electric charge ("milli-charged particles")\cite{14}. These works contain detailed discussion of many phenomenological constraints on such particles obtained from a variety of sources (including astrophysics, cosmology, geophysics and macroscopic electrodynamics). Many of those constraints apply to the case of electron neutrino, too; we shall not repeat that material here.} with respect to $\nu_e$ and $\bar{\nu}_e$ charges, one can claim that $Q(\nu_e) < 3 \times 10^{-21}e$. Yet the requirements of the electric charge conservation and CPT symmetry, although very general and perfectly valid up to now, are themselves a subject of current experimental testing\footnote{Note that it is possible to constrain the $\nu_e$ charge assuming only charge conservation in the decay $\beta^+$ decay, but not the equality $Q(\nu_e) = Q(\bar{\nu}_e)$. Naturally, this constraint turns out to be much weaker than $3 \times 10^{-21}e$ namely: $Q(\nu_e) < 4 \times 10^{-8}e$\cite{28}.}. Furthermore, there exist several models in which charged neutrino arises as a natural consequence of the electric charge violation\footnote{Besides charge conservation and CPT, a number of usually unspoken but very important assumptions underlying the last constraint are made. For instance, one has to assume that the electric charges of free electrons and protons are exactly the same as those of atom-bound electrons and protons. Another fundamental assumption, as noted in Ref.\cite{19}, is that the electric charge, as measured by interaction with an electromagnetic field, coincides with the electric charge assigned by the charge-conservation law (see also a discussion of that point in\cite{27}). According to Ref.\cite{19}, it is possible to construct models in which it is not the case. Under ordinary circumstances there is no doubt in the correctness of the above axioms, but when it comes to such outstanding accuracies as $10^{-21}$, it does not seem unreasonable to question those axioms, too.}.

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Now, let us discuss the gradient of the toroidal magnetic field in the convective zone of the Sun. A crude estimate of the gradient can be obtained by dividing $H$ by $h$ where $H$ is...
the maximum value of the magnetic field reached at the latitudes of about $\pm 10^\circ$ \cite{32} and $h$ is the distance from that latitude to the solar equatorial plane, $h = d \sin 10^\circ \approx 10^{10}$ cm.

As for the possible value of $H$, it is a subject of a debated controversy. On the one hand, it is claimed \cite{33} that values of $H$ greater than $10^4 G$ are ruled out by the non-linear growth-limiting effects; on the other hand, there are arguments based on the helioseismology data that it can reach as large values as a few million G \cite{34}. Anyway, magnetic fields up to $10^4$ G (or even $10^5$ G, see e.g. \cite{35}) are widely used by many authors trying to explain the solar neutrino puzzle. So, we leave it to the reader to make his/her own judgement on that point. Note also, that it is the magnetic field close to the surface of the Sun which reaches its maximum at $10^\circ$ latitude, and this latitude may be higher (or lower) for magnetic fields located at larger depths. That brings in an additional uncertainty to the estimate of the gradient. If we do admit that the magnetic field in the convective zone may vary in the range $H = 10^3 \div 10^6 G$ than the value of the gradient may vary in the range

$$\left\langle \frac{\partial H_\phi}{\partial z} \right\rangle \simeq \frac{H_\phi}{h} \approx (10^{-7} \div 10^{-4}) \, G/cm. \quad (4)$$

Hence we see that if we take $\epsilon \simeq 10^{-13}$ as a conservative upper bound on the neutrino charge, the value of the gradient needed to explain the neutrino deficit, $\left\langle \frac{\partial H_\phi}{\partial z} \right\rangle \simeq 10^{-5} \, G/cm$ may indeed exist in the convective zone of the Sun.

To conclude, in the context of the solar neutrino problem we studied the consequences of the hypothesis that the electron neutrino has a small but non-vanishing electric charge. The main general consequence is that the solar neutrino flux can be anisotropic. That anisotropy is driven by the Lorentz force acting on the charged neutrino on the part of the solar toroidal magnetic field which is antisymmetric about the solar equatorial plane. The general formula for the neutrino flux deficit is obtained which leads to a certain condition on the product of the neutrino electric charge and the gradient of the magnetic field which has to be met to obtain an observed value of the deficit.

We then discussed some attractive experimental implications of this scenario as well as the problems which have to be solved so that this scenario could be considered as a full-
fledged solution to the solar neutrino puzzle.

Independently of whether this scenario survives or not in its present form, our arguments show that a more general problem of the possible anisotropy of the neutrino flux due to the interactions of the neutrino with the solar matter and electromagnetic fields is certainly worth further pursuing.

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