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CHARGED NEUTRINOS?

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Abstract

If right-handed neutrinos are added to the Standard Model (SM), then the charge assignments of the quarks and leptons are not fixed by anomaly cancellation, but depend on a free continuous parameter. Thus if right-handed neutrinos exist then it is possible that there also exist small deviations from the canonical assignments of the electric charge, leading to charged neutrinos and neutrons. Experiment is used to limit this parameter. It is pointed out that a nearly massless neutrino with a small charge may nonetheless have large tree-level and anomalous magnetic moments. Ways that the SM might be extended to yield charged neutrinos are indicated.

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One of the major aims of theoretical particle physics is to explain why the elementary particles of nature have precisely the masses and interactions that are observed experimentally. The Standard Model (SM), which is consistent with all known experimental data, nevertheless does not explain a number of features of particle physics. Why are there three interactions, and what is special about U(1), SU(2) and SU(3)? Why are the masses of the quarks and leptons what we observe? Why is there no strong-CP violation? What is responsible for the generation structure?

In this paper we focus on a small but very interesting issue, namely the question of why neutrinos are electrically neutral (as far as we know). Our main observation in this paper is simply that the theoretical structure of the SM neatly accounts for both the masslessness and neutrality of neutrinos so long as they have no right-handed component. The issue of neutrino mass is of course not new. What we wish to point out is that the neutrality of neutrinos becomes another fundamental mystery of particle physics as soon as right-handed neutrinos are introduced.

Let us first recall some basic aspects of the minimal SM (i.e. without the right-handed neutrino). We know that per generation there is a left-handed SU(2) doublet of leptons together with a right-handed singlet. The quark sector has colour triplets in a left-handed doublet and two right-handed singlets. We have no freedom, experimentally, about this assignment because SU(2) and SU(3) representations form a discrete sequence. The same is not the case for $U(1)_Y$ because the hypercharge can in general take on any of an uncountable infinity of values. It is this "fuzziness" of Y which we wish to examine.

Now given the SU(2) left-handed doublet, right-handed singlet fermion structure, one is bound to introduce a Higgs doublet ϕ to give masses to the fermions while spontaneously breaking $SU(2)_L \otimes U(1)_Y$ to $U(1)_Q$. Let us define the hypercharge of ϕ to be +1 (this can be done because of a rescaling degree of freedom). This implies that the unbroken generator of the gauge group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ is $U(1)_Q$ where $Q = I_3 + \frac{Y}{2}$. In particular note that we are here only considering the case of unbroken $U(1)_Q$, i.e. the photon is still massless and charge is still conserved. We denote the hypercharge of the lepton doublet by Y_ℓ and that of the quark doublet by Y_q. The Yukawa coupling structure then implies the following spectrum for a standard generation under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$[f1]

Higgs: $\phi \sim (1, 2)(+1)$,

Leptons: $L_L \sim (1, 2)(Y_\ell)$, $L_R \sim (1, 1)(Y_\ell - 1)$,

Quarks: $q_L \sim (3, 2)(Y_q)$, $U_R \sim (3, 1)(Y_q + 1)$, $D_R \sim (3, 1)(Y_q - 1)$, (1)

Classically, Y_ℓ and Y_q are arbitrary. However, renormalizability suggests that the theory should be free from gauge anomalies[1]. The only non-trivially vanishing triangle-anomalies are $[SU(2)_L^2 U(1)_Y]$ and $[U(1)_Y^3]$. These anomalies uniquely single out Y_ℓ and Y_q as follows:

$$[SU(2)_L^2 U(1)_Y] \Rightarrow Y_q = -\frac{1}{3} Y_\ell$$

$$[U(1)_Y^3] \Rightarrow Y_\ell = -1. \qquad (2)$$

Remarkably, given the structure of eq.(1), anomaly cancellation is sufficiently constraining to determine all the hypercharges, and hence, all the electric charges of quarks and leptons[f2]. In particular, the neutrino must be neutral. Of course, these values also agree with experiment. Note that we do not need to hypothesize grand unification in order to understand the lepton/quark charge ratios.

One might think that adding the second lepton singlet (the putative right-handed neutrino) would only be a minor perturbation. However when we add the right-handed neutrino to eq.(1) ($\nu_R \sim (1, 1)(Y_\ell + 1)$), gauge anomaly cancellation now no longer determines the charges of the quarks and leptons uniquely. Indeed there is now only one relation:

$$Y_q = -\frac{1}{3} Y_\ell \qquad (3)$$

Thus, we now have a spectrum which is arbitrary up to a continuous parameter $Y_\ell = y$:

$$\text{Leptons: } L_L \sim (1, 2)(y),\ L_R \sim (1, 1)(y - 1),\ \nu_R \sim (1, 1)(y + 1))$$

$$\text{Quarks: } q_L \sim (3, 2)(-\tfrac{y}{3}),\ U_R \sim (3, 1)(-\tfrac{y}{3} + 1),\ D_R \sim (3, 1)(-\tfrac{y}{3} - 1). \qquad (4)$$

From this perspective it is clear that one has created a new fundamental mystery in particle physics, by simply introducing the field ν_R: why does nature choose y = -1 to a very high degree of precision? The answer to this question will certainly involve physics beyond the SM, and thus it is of considerable importance.

Right-handed neutrinos obviously change the issue of neutrino mass as well since lepton-number conserving Dirac masses are now allowed. The phenomenon of neutrino masses has been well studied so we will be content to restrict the following discussion to electric charge.

What is the experimental range allowed for y? Let $y = -1 + \delta$. Then the charges of the quarks and leptons are

$$Q(\nu) = \frac{\delta}{2};\;\; Q(e) = -1 + \frac{\delta}{2}$$

$$Q(U) = \frac{2}{3} - \frac{\delta}{6};\;\; Q(D) = -\frac{1}{3} - \frac{\delta}{6} \qquad (5)$$

Thus the proton and neutron charges are given by

$$Q(P) = 1 - \frac{\delta}{2},\;\; Q(N) = -\frac{\delta}{2}. \qquad (6)$$

Note that $Q(P) = -\,Q(e)$ and $Q(N) = -\,Q(\nu)$. Hence hydrogen atoms remain exactly neutral, although deuterium acquires charge $-\frac{\delta}{2}$. In general, ordinary neutral matter would acquire charge through the presence of neutrons. Experimental bounds on the neutron charge should give the best bounds on δ. Direct measurements of the neutron charge, obtained by passing neutrons through a electric field[8] gives the limit

$$|\delta| < 10^{-21} \qquad (7)$$

A slightly less direct experiment is given by the Evötös experiment. We find that this experiment gives the following upper bound[f3]

$$|\delta| < 10^{-23}. \qquad (8)$$

There is an amusing possibility regarding the electromagnetic interaction of a nearly massless, slightly charged neutrino.[f4] Since magnetic moments go as the *ratio* of charge to mass, it is possible for such neutrinos to interact fairly strongly with magnetic fields even though they interact extremely weakly with electric fields. In particular it is possible to choose δ and m_ν so that the anomalous magnetic moment of the neutrino is in the range needed to explain the solar neutrino problem via the VVO mechanism[6].

We now return to theoretical issues. If $y = -1$ exactly, then there should be new physics to explain this. Alternatively, one can ask if it is possible to construct a model in which $y = -1 + \delta$, with $\delta \ll 1$. There is an interesting observation to make here. One might suppose that there is new physics which fixes the $U(1)_Y$ charges to their SM values, but that a small deviation in the formula $Q = I_3 + \frac{Y}{2}$ is introduced by an additional $U(1)_{Y'}$ symmetry. The Higgs fields would then be supposed to leave the generator $Q = I_3 + \frac{Y}{2} + \frac{Y'}{2}$ unbroken (i.e. the actual $U(1)_Y$ is the diagonal subgroup of $U(1)_Y \otimes U(1)_{Y'}$). To implement this idea we first need to work out what the $U(1)_{Y'}$ symmetry is. We assume that the gauge group is

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \otimes U(1)_{Y'} \qquad (9)$$

and that the $U(1)_Y$ assignments are the standard ones. In this case the Higgs, leptons and quarks transform as

Higgs: $\phi \sim (1, 2)(+1)(0)$,

Leptons: $L_L \sim (1, 2)(-1)(\delta)$, $L_R \sim (1, 1)(-2)(\delta)$,

Quarks: $q_L \sim (3, 2)(\frac{1}{3})(-\frac{\delta}{3})$, $U_R \sim (3, 1)(\frac{4}{3})(-\frac{\delta}{3})$, $D_R \sim (3, 1)(-\frac{2}{3})(-\frac{\delta}{3})$,

(10)

Thus it is clear that the $U(1)_{Y'}$ group is just $U(1)_{B-L}$. Furthermore, it is well known that if right-handed neutrinos are present, then the SM extension defined by eq.(9) is free from anomalies. Indeed one way to understand the fuzziness of Y in the right-handed neutrino extension of the SM is simply to note that since both $U(1)_Y$ and $U(1)_{B-L}$ are anomaly free, then so is any linear combination.

To break the gauge symmetry of eq.(9), we introduce in addition to the Higgs doublet ϕ, a Higgs singlet H. The Higgs field H is assumed to transform as a (1, 1)(1)(-1) under the group eq.(9), i.e. it contains both Y and B-L. When the symmetry eq.(9) is spontaneously broken (i.e. both ϕ and H develop vacuum expectation values (VEVs)), then the unbroken (and hence massless) generator which is interpreted as the photon couples to

$$Q = I_3 + \frac{Y}{2} + \frac{(B-L)}{2}. \qquad (11)$$

When $\delta = 0$, the quarks and leptons have their usual charges. However, if $\delta \neq 0$ but $\delta << 1$, then the quarks and leptons have the charges given in eq.(5).

It is perhaps relevant to compare our analysis with an alternative possibility, namely that the neutrino can gain charge at the expense of charge conservation. This might not be palatable at first sight, but this approach has the merit of relating the charge of the neutrino to the mass of the photon acquired after symmetry breaking. A model of this sort can be easily constructed by adding a charged Higgs singlet field (h ~ (1,1)(2)) to the stanoard model. When the Higgs doublet and singlet gain non zero VEVs the gauge symmetry is broken (now without the residual $U(1)_Q$ symmetry). The photon becomes massive and it turns out that the charge operator becomes

$$Q = e(I_3 + \frac{Y}{2} - \frac{m_\gamma^2}{4\,m_W^2}Y), \qquad (12)$$

where $e = g\sin\theta_W$ and $\tan\theta_W = \frac{g_1}{g}\frac{2\,m_W^2}{2\,m_W^2 - m_\gamma^2}$ and g, g_1 are the SU(2), $U(1)_Y$ gauge couplings respectively. Also, the parameters m_W, m_γ represent the W-boson and photon masses respectively. Now, there is a stringent experimental bound on the mass of the photon given by $m_\gamma < 3 \times 10^{-36}$ GeV[7]. Thus, the deviation of charges from their standard model values, embodied by eq.(12), must be less than about 10^{-72} e. This deviation of charge is presumably too small to ever be experimentally measured (c.f. eqs.(8-9)).

In conclusion, we have considered the extension of the minimal SM defined by the addition of a right-handed neutrino. Such an extension requires new physics in order to explain the charges of the quarks and leptons. This theoretical freedom of the electric charge quantum number, allows us to postulate that the neutrino and neutron have a small but non zero charge. However, we were unable to find a model where the neutrino and neutron charges were very small naturally. Nevertheless, we did briefly examine an approach based on gauged B-L. We also compared our results with a simple model where charge is spontaneously broken.

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Footnotes

f1 Actually, there is one other $U(1)_Y$ assignment, with the lepton field $(1, 1)(Y_\ell - 1)$ in eq.(1), replaced by $(1, 1)(Y_\ell + 1)$. Anomaly cancellation in this case leads to a SM mirror generation.

f2 Geng and Marshak Ref[2] have turned the anomaly argument around and have shown that the minimal SM generation is (essentially) uniquely singled out as the simplest non trivial $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ structure.

f3 We are using the experimental result $\eta[\text{Al}, \text{Pt}] < 0.9 \times 10^{-12}$, where $\eta[A, B] = [\left(\frac{M}{m}\right)_A - \left(\frac{M}{m}\right)_B]/[\frac{1}{2}\left(\left(\frac{M}{m}\right)_A + \left(\frac{M}{m}\right)_B\right)]$, where M, m represent the gravitational and inertial mass respectively. See Ref[4].

f4 Note that experimental determinations of the neutrino charge are not very stringent. For instance the limit $|\delta| < 10^{-7}$ has been obtained from observations of neutrinos from the SN87A. See Ref[5].

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