Universality of the coupling of neutrinos to Z

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(Received 16 July 2002; published 23 October 2002)

We employ an effective Lagrangian approach and use CERN LEP data to place severe bounds on universality violations of the couplings of ν_e, ν_μ, and ν_τ to the Z boson. Our results justify the assumption of universality in these couplings that is usually made, such as, for example, in the analysis of solar neutrinos detected at SNO.

DOI: 10.1103/PhysRevD.66.077301 PACS number(s): 14.60.Lm

In the analysis of the observations of solar neutrinos at the Sudbury Neutrino Observatory (SNO) [1], one makes the assumption that neutrinos interact with nucleons and electrons according to the predictions of the electroweak standard model (SM). Of course, this assumption ought to be confirmed by experiment. Although many of the basic neutrino properties predicted by the SM and used in the SNO analysis have been tested in accelerator experiments, as we will argue, this is not exactly true for all of them.

A crucial assumption in the SNO analysis involves the coupling of neutrinos to the neutral current. At SNO, neutral current interactions induce the process $\nu_i + d \to p + n + \nu_i$, where i can be e,μ,τ, and $\nu_i + e^- \to \nu_i + e^-$ with $i=\mu,\tau$, and they also participate in the elastic scattering $\nu_e + e^- \to \nu_e + e^-$. To deduce the actual fluxes of neutrinos reaching the Earth, it is assumed that ν_e, ν_μ, and ν_τ couple with the same strength to Z, i.e., that universality in the coupling of neutrinos to the Z boson holds. We will concentrate on the observational evidence for this hypothesis.

Let us first make a very rough estimation of the precision level of SNO. Take, for example, the total flux measured with the neutral current reaction at SNO [1]:

$$\phi_{\rm NC} = 5.09^{+0.63}_{-0.61} \times 10^6 \ \ {\rm cm}^{-2}\,{\rm s}^{-1}, \tag{1}$$

where we have added their statistical and systematic errors in quadrature. The result has a relative error of about 12%, and gives us an idea of the SNO precision. These are their very first results and, of course, with more statistics and refinements, the relative error is going to decrease in the near future.

To set the stage for our discussion, let us write the Lagrangian that in the SM describes the interaction of matter with the Z boson,

$$\mathcal{L}_{\rm NC} = -\frac{g}{\cos\theta_w} J_\alpha^{\rm NC} Z^\alpha \tag{2}$$

with g the $SU(2)$ coupling and θ_w the weak mixing angle. The neutral current $J^{\rm NC}$ in the SM is given by

$$J_\alpha^{\rm NC}({\rm SM}) = \frac{1}{2}\sum_i \,[1+r_i]\overline{\nu_i}\gamma_\alpha \nu_i + \cdots, \tag{3}$$

where the dots refer to other particles and the sum is over $i = e,\mu,\tau$. (ν_i is in fact ν_{Li}; to simplify the notation we omit the left-handed L subscript.) In Eq. (3), r_e, r_μ, r_τ are the usual radiative corrections arising in the SM. At this radiative level, there are universality violations coming from vertex corrections, but they are small. For instance, we have

$$r_\tau - r_e \simeq \frac{\alpha}{4\pi}\log m_\tau^2/m_e^2 \simeq 0.009 \tag{4}$$

and even smaller for $r_\tau - r_\mu$ and $r_\mu - r_e$ (see, for example, Ref. [2]). Certainly, this amount of universality violation is not a concern for the SNO analysis. In our analysis, we can also ignore it, since we will end up with upper bounds on universality violations that are larger than Eq. (4).

In order to check the universality hypothesis in the neutrino coupling to Z, we write the modified neutral current as

$$J_\alpha^{\rm NC} = \frac{1}{2}\sum_i \,[1+\Delta_i]\overline{\nu_i}\gamma_\alpha \nu_i + \cdots. \tag{5}$$

The parameters $\Delta_e, \Delta_\mu, \Delta_\tau$ are possible deviations coming from physics beyond the SM. We will constrain these parameters using experiment.

Data from the CERN e^+e^- collider LEP constitutes a very precise test for the SM. The couplings of neutrinos to Z are constrained by the invisible Z width, or equivalently, in the determination of the number of neutrinos N_ν. A combined fit to all LEP data gives

$$N_\nu = 2.994 \pm 0.012 \tag{6}$$

that we take from the 2001 update of the Particle Data Group (PDG) [3]. Each ν_i contributes

$$(1+\Delta_i)^2 \simeq 1 + 2\Delta_i \tag{7}$$

to N_ν. Thus, the result (6) leads to the relation

$$|\Delta_e + \Delta_\mu + \Delta_\tau| \leqslant 0.009. \tag{8}$$

To be conservative, we have taken the maximal deviation from $N_\nu = 3$ in Eq. (6) to put the bound (8). Also, here and in the following we work at first order in Δ_i.

If there is new physics that alter the $Z\nu\nu$ coupling but respect universality, i.e., $\Delta_e = \Delta_\mu = \Delta_\tau$, then Eq. (8) implies that each individual Δ_i must be very small. However, if universality is violated, then we may have cancellations in the

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sum (8) and, actually, there is no strict bound on individual Δ_i. Such possible cancellations cannot be banned from first principles. The purpose of the present paper is to constrain the breaking of universality in $Z\nu\nu$ interactions.

The direct way to test universality in the neutrino coupling to the Z boson is through the analysis of the scattering $\nu_i+e^-\rightarrow\nu_i+e^-$. Available data on $\nu_\mu+e^-\rightarrow\nu_\mu+e^-$, together with LEP results, allow us to place the limit [4]

$$|\Delta_\mu|\leqslant 0.037. \tag{9}$$

However, the $\nu_e\nu_e Z$ coupling is known at a much worse level. We have the experimental limit on universality violation [5]

$$0.13\leqslant\Delta_\mu-\Delta_e\leqslant 0.20 \tag{10}$$

and of course no limits involving Δ_τ. At the view of the SNO precision, this limit (and the absence of a limit for the τ neutrino) is too loose to be useful.

We will now show that we can improve the limits on universality working with effective Lagrangians. The key point is the following. Deviations from the SM can be treated by using effective Lagrangians. The general idea of the effective Lagrangian approach is that theories beyond the SM, emerging at some characteristic energy scale Λ, have effects at low energies $E\leqslant G_F^{-1/2}$, and these effects can be taken into account by considering a Lagrangian that extends the SM Lagrangian, $\mathcal{L}_{\mathrm{SM}}$:

$$\mathcal{L}=\mathcal{L}_{\mathrm{SM}}+\mathcal{L}_{\mathrm{eff}}. \tag{11}$$

The effective Lagrangian $\mathcal{L}_{\mathrm{eff}}$ contains operators of increasing dimension that are built with the SM fields including the scalar sector, and is organized as an expansion in powers of $(1/\Lambda)$.

The success of the electroweak SM at the level of quantum corrections can be considered as a check of the gauge symmetry properties of the model. To preserve the consistency of the low-energy theory, with a Lagrangian given by Eq. (11), we will assume that $\mathcal{L}_{\mathrm{eff}}$ is $SU(2)\otimes U(1)$ gauge-invariant. Some of the problems that originate when dealing with non-gauge-invariant interactions have been discussed in [6]. The gauge-invariant operators that dominate at low energies have dimension 6 and have been listed in [7].

There are two classes of dimension-6 operators that may originate violations of universality in the neutrino sector of the neutral current:

$$\mathcal{A}_i=i[\Phi^\dagger\mathcal{D}_\alpha\Phi][\overline{L_i}\gamma^\alpha L_i], \tag{12}$$

$$\mathcal{B}_i=i[\Phi^\dagger(\mathcal{D}_\alpha\vec{\tau}+\vec{\tau}\mathcal{D}_\alpha)\Phi]\cdot[\overline{L_i}\gamma^\alpha\vec{\tau}L_i]. \tag{13}$$

Here Φ is the Higgs field and L_i is the lepton isodoublet,

$$L_i=\begin{pmatrix} l_i \\ \nu_i\end{pmatrix}_L, \tag{14}$$

where now l_i are the charged leptons, and the subscript L denotes left-handed. The operators contain the covariant derivative,

$$\mathcal{D}_\alpha=\partial_\alpha+ig\frac{\vec{\tau}}{2}\cdot\vec{W}_\alpha+ig'\frac{Y}{2}B_\alpha \tag{15}$$

with the gauge bosons $\vec{W}$, B, the gauge couplings g,g', and the Pauli matrices $\vec{\tau}$ and the hypercharge Y.

The effective Lagrangian relevant for our purposes can now be written as

$$\mathcal{L}_{\mathrm{eff}}=\sum_i\left(\frac{\alpha_i}{\Lambda_i^2}\mathcal{A}_i+\frac{\beta_i}{\Lambda_i'^2}\mathcal{B}_i\right), \tag{16}$$

where Λ_i,Λ_i' are high-energy scales and α_i,β_i are unknown strength coefficients accompanying the operators. Below the scale of spontaneous symmetry breaking, the effective Lagrangian (16) induces contributions of the type shown in Eq. (5). Substituting

$$\Phi\rightarrow\begin{pmatrix} 0 \\ v/\sqrt{2}\end{pmatrix} \tag{17}$$

with $v^2=1/(\sqrt{2}G_F)\simeq(246\ \mathrm{GeV})^2$, in Eq. (16), we get

$$\Delta_i=-a_i+b_i \tag{18}$$

corresponding to the contributions of the two operators,

$$a_i=\alpha_i\frac{v^2}{2\Lambda_i^2}, \tag{19}$$

$$b_i=\beta_i\frac{v^2}{\Lambda_i'^2}. \tag{20}$$

It is clear that unless the combinations $-a_i+b_i$ for $i=e,\mu,\tau$ are equal, we will have universality violations in the coupling of neutrinos to the Z boson.

The operators in the effective Lagrangian (16) have other effects at low energy. They contribute to the couplings of the Z boson to the charged leptons l_i. Indeed, we find

$$J_\alpha^{\mathrm{NC}}=\sum_i\left[-\frac{1}{2}+\sin^2\theta_w-\frac{a_i}{2}-\frac{b_i}{2}\right]\overline{l}_{iL}\gamma_\alpha l_{iL} \tag{21}$$

$$+\sin^2\theta_w\sum_i\overline{l}_{iR}\gamma_\alpha l_{iR}+\cdots, \tag{22}$$

where the dots indicate other particles than charged leptons. We see that the couplings to right-handed charged leptons l_{iR} are not modified.

Also, the charged current coupling to the charged W gets a contribution,

$$\mathcal{L}_{\mathrm{CC}}=-\frac{g}{\sqrt{2}}J_\alpha^{\mathrm{CC}}W^{+\alpha}+\mathrm{H.c.}, \tag{23}$$

$$J_\alpha^{\rm CC}=\sum_i\ [1+b_i]\overline{\nu_i}\gamma_\alpha l_{iL}+\cdots, \tag{24}$$

where again the dots stand for the part involving other SM fields. In the charged current sector there are also violations of universality coming from radiative corrections in the SM framework, but numerically they have at most the value shown in Eq. (4) and we will neglect them.

Our purpose is to constrain universality violations in the couplings $\nu\nu Z$. We can reach our objective by considering the constraints on the nonstandard contributions to the coupling of Z to charged leptons (22) and on the similar contributions in the charged current sector (24). The experimental information we need is taken from the 2001 PDG update that uses LEP data [3].

For example, in our scheme we have

$$\frac{\Gamma(W\to\tau\nu)}{\Gamma(W\to e\nu)}\simeq 1+2(b_\tau-b_e), \tag{25}$$

where we work at first order in b_i and neglect lepton masses in front of the W mass. The experimental ratio

$$\frac{\Gamma(W\to\tau\nu)}{\Gamma(W\to e\nu)}=1.002\pm 0.029 \tag{26}$$

leads to the bound

$$2|b_\tau-b_e|\leqslant 0.031, \tag{27}$$

where again we conservatively use the maximal deviation from 1 in Eq. (26). We also consider

$$\frac{\Gamma(Z\to\tau^+\tau^-)}{\Gamma(Z\to e^+e^-)}\simeq 1+\frac{1-2s_w^2}{8s_w^4-4s_w^2+1}\times 2(a_\tau+b_\tau-a_e-b_e) \tag{28}$$

($s_w=\sin\theta_w$) and use [3]

$$\frac{\Gamma(Z\to\tau^+\tau^-)}{\Gamma(Z\to e^+e^-)}=1.0020\pm 0.0030, \tag{29}$$

which leads to

$$|a_\tau+b_\tau-a_e-b_e|\leqslant 0.0019. \tag{30}$$

The inequality

$$|\Delta_\tau-\Delta_e|=|-a_\tau+b_\tau+a_e-b_e| \tag{31}$$

$$\leqslant|a_\tau+b_\tau-a_e-b_e|+2|b_\tau-b_e| \tag{32}$$

allows us, from Eqs. (27) and (30), to get

$$|\Delta_\tau-\Delta_e|\leqslant 0.033. \tag{33}$$

This is our main result concerning the limit on universality violation for ν_e and ν_τ. We can do a totally parallel exercise for ν_e and ν_μ, with the result

$$|\Delta_\mu-\Delta_e|\leqslant 0.040. \tag{34}$$

We finally would like to mention that another assumption of SNO is the absence of neutrino flavor changing neutral currents (FCNC). Such exotic interaction would be a contribution to $J^{\rm NC}$ of the form

$$\delta J_\alpha^{\rm NC}=\Delta_{e\mu}\overline{\nu_e}\gamma_\alpha\nu_\mu+\text{H.c.} \tag{35}$$

and similar for $\nu_e\nu_\tau$ and $\nu_\mu\nu_\tau$. The contributions of these FCNC parameters to N_ν have no interference, like the universality violations, see Eq. (7). It follows that now cancellations are no longer possible. We can assume nonzero $\Delta_{e\mu}$, $\Delta_{e\tau}$, and $\Delta_{\mu\tau}$ and employ the experimental limit on N_ν (6) to infer

$$[(\Delta_{e\mu})^2+(\Delta_{e\tau})^2+(\Delta_{\mu\tau})^2]^{1/2}\leqslant 0.095. \tag{36}$$

In conclusion, we have placed severe constraints to universality violations of the couplings of neutrinos to Z. We have introduced the parameters Δ_i in the neutral current expression (5) and showed which operators in an effective Lagrangian approach may lead to universality breaking. We have constrained the effects of this Lagrangian in the sector involving charged leptons, and these constraints have been used to reach our numerical results (33) and (34). We have shown that universality holds at the level of 4% in the current that couples to Z. Our results can be interesting in all the analysis making the assumption of $\nu\nu Z$ universality, like in the solar neutrino experiment at SNO.

Work partially supported by the CICYT Research Project AEN99-0766, by the EU network on Supersymmetry and the Early Universe (HPRN-CT-2000-00152), and by the *Departament d'Universitats, Recerca i Societat de la Informació,* Project 2001SGR00188.

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